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Nuclear Science Division

Annual Report for the Period

October 1, 1985 – September 30, 1986

Division Head
T.J.M. Symons

Assistant Division Head
Janis Dairiki

Editor
Jeannette Mahoney

Editorial Committee
N.K. Glendenning, H.S. Matis, E.B. Norman

Lawrence Berkeley Laboratory
University of California
Berkeley, California, 94720, USA

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Editor

Introduction

This report summarizes the activities of the Nuclear Science Division during the period October 1, 1985 to September 30, 1986. 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, a highlight during this time was the initiation of a new generation of relativistic heavy-ion experiments at CERN. Oxygen-16 beams were accelerated to 3.2 TeV using the LBL-GSI heavy ion injector into the CERN SPS. First results obtained during the beam test period are presented in this report. Six experiments with LBL participation are poised to take data during the two running periods scheduled in FY87.

Bevalac research has probed new regions of the nuclear matter equation of state. Studies of collisions between the most massive nuclei, often producing over 150 charged particles, have revealed rich new phenomena such as collective flow, where the pressures generated force the emerging particles away from the beam direction. Experiments on dileptons (e^+e^- pairs) utilizing the newly completed Dilepton Spectrometer (DLS) are being carried out to glean new insights into the hot, high-density stage of the collision. Major new results on the nuclear structure of exotic, very neutron-rich light nuclei are being obtained by exploiting the projectile fragmentation process to produce secondary radioactive beams.

The Laboratory has proposed the Bevalac Upgrade Project to further enhance the Bevalac's position as a world leading accelerator for the study of heavy-ion collisions. Specifically, the Upgrade would replace the Bevalac's weak-focusing synchrotron–the Bevatron–with a modern, strong-focusing synchrotron to provide higher intensity and higher quality beams to continue the forefront research program.

The significant enhancement of the heavy ion capability at the 88-Inch Cyclotron as a result of the recent development of the ECR source has led to a renaissance of the cyclotron as indicated by the increased demand for beam time. Together with innovative detector development, this capability has enabled the scientific program to extend its very strong leadership in many areas of nuclear science.

A variety of other scientific activities were also carried out during this period. The Isotopes Project published the first edition of a new radioactivity reference book for applied users–**The Table of Radioactive Isotopes**. Division members organized several major scientific meetings including the annual fall meeting of the APS Division of Nuclear Physics, Quark Matter '86 (held at Asilomar) and the First Workshop on the Nuclear Equation of State. These meetings enhance our understanding of current results and, even more importantly, serve as guide posts to future exciting possibilities.

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L.S. Schroeder

PART V: APPENDICES

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PART I: PROGRAMS

Nuclear Astrophysics and Fundamental Symmetries

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 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}Hf^{m} and their significance for the nucleosynthesis of ^{180}Ta.
3. Level scheme of ^{180}Ta and the survivability of ^{180}Ta in stars.
4. 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. Specific studies include:

5. Searches for several different modes of double beta decay.
6. Improved tests of the exponential decay law
7. Search for neutrino oscillations (LAMPF E645)
8. Searches for massive, long-lived, negatively charged elementary particles.

Group Leader
E.B. Norman

K.T. Lesko
R.M. Larimer
S. Kuhn

S.G. Crane,*
University of Puget Sound Tacoma, Washington

D.M. Meekhof,*
California Institute of Technology, Pasadena, California

H.G. Bussell,†
Albany Junior High Albany, California

**Undergraduate Students*
†High School Teacher

Members of our group preparing for measurements of γ-ray production cross sections using germanium detectors. Left to right: Stephanie Crane, Kevin Lesko, Ruth-Mary Larimer, Dawn Meekhof, Eric Norman, and Hugh Bussell.

XBC 867-5659

Exotic Nuclei and Decay Modes

Group Leader
Joseph Cerny

M.A.C. Hotchkis
F. Blönnigen
W.F. Knoll*
T.F. Lang*
D.M. Moltz
J.E. Reiff*

X.-J. Xu,
Institute of Modern Physics, Lanzhou, People's Republic of China

**Graduate Students*

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. More recently 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. To search for other predicted beta-delayed two-proton emitters with short half-lives, we have constructed a fast rotating wheel, suitable for measuring nuclides with $t_{1/2} > 100\mu s$. Possible evidence for the beta-delayed two-proton decay of ^{31}Ar has been obtained utilizing this technique but will require a confirmatory experiment.

The beta-delayed single proton emissions from the A=4n+1 T_z=–3/2 nucleus ^{61}Ge have been studied. Although ^{61}Ge had been previously observed in a pulsed beam experiment, we have confirmed the prior results in a helium-jet experiment employing the same ^{24}Mg + ^{40}Ca reaction. Attempts to extend these measurements to the next member of this series, ^{65}Se, by observing products from the ^{28}Si + ^{40}Ca reaction failed. This failure could easily be explained if ^{65}Se had a half-life <25ms, the effective transport time of the helium-jet system.

Nuclear Structure Studies at High Angular Momentum

Group Leaders:
R.M. Diamond
F.S. Stephens

M.-A. Deleplanque
J.C. Bacelar
E.M. Beck*

J.E. Draper,
C. Duyar,*
Department of Physics
U.C. Davis

M.J.A. deVoigt,
K.V.I. University
of Groningen
The Netherlands

**Graduate students*

The Berkeley High Energy-Resolution Array, HERA, was used in all the group's experiments performed at the 88-Inch Cyclotron, and sets of the Compton-suppressed Ge detectors were used in experiments at the SuperHILAC. A stand is planned for the SuperHILAC, so that next year the full array can be used there. The NaI caps to the BGO suppression shields have been obtained and boost the peak/total ratio for ^{60}Co γ rays from 50 to 55% (above 300 keV). The small central ball of 40 BGO sectors has been ordered and should be in place by next Summer, completing the project.

Discrete γ-ray studies have continued with the publication of papers on ^{158}Er, ^{158}Yb, and ^{165,166}Yb, and there are new studies on ^{150}Dy, and ^{135}Nd, and a collaboration with a group from the Hahn-Meitner Institute in Berlin on ^{152}Er. In ^{135}Nd a discrete superdeformed (SD) band has been observed, the first odd-mass example, and it appears to lie lowest in energy relative to the yrast line and to have the largest population ($\sim$10% at spin 31/2). Studies on ^{152}Dy have confirmed the beautiful band to spin 60 discovered at Daresbury, but we differ in seeing more intensity in the first ridge of the $E_\gamma(1)$–$E_\gamma(2)$ matrix indicating additional SD (continuum) bands which, however, show decay out of the band after two or three transitions (no 2nd ridge observed). In contrast, in double-gated spectra all 18 of the ridges of the discrete band are seen.

The Doppler-shift lifetime studies have continued with development of a Monte Carlo program for calculating the lineshapes, and this has been applied to the ^{166}Yb yrast-band data for Au-, Pb-, and Mg-backed targets. Good agreement was obtained for the same transition in different backings and between forward and backward groups of detectors.

Two collaborative experiments were performed at the SuperHILAC: a Coulomb excitation study with ^{136}Xe on ^{235}U and ^{165}Ho with a University of Rochester group, and an attempt, with a Stanford group, to see back-to-back coincident γ rays from a 6 MeV/nucleon U beam on a ^{232}Th target of a possible alternate decay mode of the neutral particle suggested to explain the coincident e^+e^- peaks observed in such reactions at GSI.

Finally, our continuum γ-ray studies have also profited greatly from HERA. As mentioned in last year's report, damping of the rotational cascades is thought to occur at excitation energies above an MeV or so where the level density gets so high that residual interactions can mix the states of a given spin over quite an interval. If these states have a distribution of moments of inertia, then the expected valley along the diagonal in an $E_\gamma(1)$–$E_\gamma(2)$ matrix will be filled in rather efficiently. There is considerable discussion at this time as to the magnitude of this spread in γ-ray transition energies at a given spin and how this spread varies with spin and excitation energy. Although there is general agreement that the damping process occurs, little is known yet about the details or whether the predicted rotational narowing at high excitation energies takes place. This topic and the others require a lot more work in the coming year, and we look forward to these studies with a completed HERA.

Heavy-ion Reactions at Low and Intermediate Energies

Group Leaders:
R.G. Stokstad
Y.D. Chan

S. Gazes
B.G. Harvey

E. Chavez,*
Instituto de Física, Universidad Nácional Autónoma de México

K. Siwek-Wilczynska,
Institute of Experimental Physics, Warsaw University, Poland

E. Plagnol,
Institut de Physique Nucléaire Orsay, France

J. Wilczynski,
Institute for Nuclear Studies, Swierk (Warsaw), Poland

**Graduate Student*

The previous annual report described a series of experiments on peripheral heavy ion reactions. The reader is referred there for a more extensive description of our group's activities. Abstracts of published papers, papers in press and of LBL preprints covering this work are contained in this annual report. They provide information on our studies of

i. the partition of excitation energy in heavy ion reactions,
ii. the ^{12}C decay of ^{24}Mg following nuclear inelastic scattering,
iii. projectile breakup and transfer-reemission reactions in the $^{12}C + {}^{20}Ne$ system,
iv. incomplete fusion for light heavy-ion systems,
v. a microscopic model for nucleus nucleus collisions, and
vi. the fusion of $^{16}O + {}^{144}Sm$ at sub-barrier energies.

During this last period, our group has extended its study of ^{16}O-induced transfer/breakup reactions to 32.5 MeV/nucleon utilizing fully stripped ^{16}O beams from the ECR source + 88-Inch Cyclotron, and has continued to develop new variations of the plastic phoswich detectors. New experiments on the fusion of heavy ions have also been made possible by the ECR source. The capture reactions of $^{40,48}Ca$ on ^{197}Au and ^{208}Pb were studied from subbarrier energies to 10 MeV per nucleon. The emission of complex fragments produced in the reaction of $^{40}Ar + {}^{12}C$ at energies from 8.5 to 20 MeV per nucleon has been investigated together with the Moretto/Wozniak group.

We have also developed a modular phoswich hodoscope and a position-sensitive Plastic Curtain Array for detecting charged energetic light particles ($v \geq v_{Beam}$). Both the fast and slow components of our phoswich detectors are plastic scintillators. The hodoscope consists of 25 compact, identically cube-shaped units and the Plastic Curtain is made up of 10 25-cm long one dimensional position-sensitive phoswich modules.

In the spring of this year our group enjoyed collaborations with physicists from Buenos Aires (D. Di Gregorio, J. Fernandez-Niello, and A. Pacheco) and from Mexico (A. Dacal and M.E.Ortiz.)

Heavy Element Radiochemistry

The group uses all three of the LBL accelerators to produce and characterize new elements and isotopes, to study nuclear reaction mechanisms, and to educate 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, and studies of nuclear and chemical properties of the heaviest 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 ($\geq$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. These studies have been extended to calcium-40 and 48 and 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 heavy 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 being carried out at ultra relativistic heavy ion accelerators. An international collaborative radiochemical search for anomalons is also being pursued at the Bevalac and other accelerators.

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

Group Leaders
D.C. Hoffman
G.T. Seaborg

R. Agarwal†
D. Bennett
R. Chasteler*
Y.Y. Chu†
D. Dorsett†
C. Gannett
K. Gregorich
H. Hall*
R. Henderson*
W. Kot*
D. Lee
P. Wilmarth*

S-Y. Cai,
Institute of Atomic Energy, Beijing, People's Republic of China

H.A. O'Brien,
Los Alamos National Laboratory

W. Loveland,
C. Casey,*
Z-Y. Xu,*
Oregon State University

K. Aleklett,
L. Sihver,*
Studsvik Science Research Laboratory, Nyköping, Sweden

H. von Gunten,
A. Türler,
Institut für Anorganische, Analytische und Physikalische Chemie, University of Bern, Switzerland

**Graduate Students*
†*Undergraduates*

New Element and Isotope Synthesis

Group Leaders:
A. Ghiorso
J.M. Nitschke

Y. Lee**
M.J. Nurmia
P.A. Wilmarth*
S. Yashita
R.B. Firestone

P. Möller,
Lund University, Sweden

J. Gilat,
Soreq Nuclear Research Center, Israel

K.S. Toth,
J. Ellis-Akovali,
Oak Ridge National Laboratory

F.T. Avignone III,
University of South Carolina, Columbia, South Carolina

K. Takahashi,
Lawrence Livermore National Laboratory

**Graduate student*
***Summer student*

The heavy element research program is still planning for LEAP (Larger Einsteinium Activation Program) even though that initiative has not been funded yet. With a limited amount of Director's Funds we are continuing with the development of SASSY II since that instrument promises to be vital to our future program as well as a good training ground for graduate students interested in the techniques of nuclear physics.

We had hoped that SASSY II would have been ready for first operation in the spring of 1986. Unfortunately, a series of mechanical problems plagued us and it was not possible to make any meaningful tests before the five-months SuperHILAC shutdown which began in May. During the shutdown, tests with a ^{249}Cf alpha source did demonstrate some ion optic problems and these difficulties were eliminated (hopefully) by a realignment of the three magnetic elements. As of November 1986 we have remeasured the magnetic fields and gradients and find them to be within our specifications. The instrument should be ready for testing with beam and recoils soon.

Another major research tool of the New Element and Isotope Synthesis Group is the On-line Apparatus for SuperHILAC Isotope Separation (OASIS). Due to a unique design of the ion source that permits operating temperatures near 3000 K, heavy ion reaction products can be mass separated and analysed in a fraction of a second. Several short-lived new isotopes in the rare earth region have been synthesized in (HI;xn,yp) reactions with heavy ion beams from the SuperHILAC. For the first time a unique series of six β^+-delayed proton precursors with the same neutron number (N=81) has been produced. Since the β^+-decay proceeds to N=82 it has been possible to study proton decay from six adjacent closed shell nuclei at excitation energies from 3 to 11 MeV. While it is in general true that at these excitation energies high level densities in the A=150 region make a statistical description of the decay processes most appropriate, this approach does not seem valid for odd-even proton emitters since they show proton spectra with distinct structure. This structure has been interpreted as a reflection of the low level density associated with the magicity of the emitters. It has in fact been possible in two precursors ($^{151}_{70}$Yb and $^{149}_{68}$Er) to observe "statistical" as well as "discrete" proton decay from the *same* (magic) nucleus. As in earlier investigations near Z=50 the question arises to which extent the observed structure is due to Porter-Thomas fluctuations of the beta decay width and the proton width, or whether it reflects resonances in the Gamow-Teller beta strength. Preliminary calculations carried out with a Nilsson-model, a harmonic oscillator potential, and a residual GT interaction treated in RPA approximation indicate that resonances with the correct spacings and amplitudes can occur if it is assumed that the deformation of the proton emitting nucleus is slightly larger than the static ground state deformation, and includes a hexadecapole degree of freedom. This effect has also been seen in the systematics of first excited 2^+ states in other nuclei. The study of the discrete structure in the proton spectra of magic emitters has recently been complemented by measurements of the competing γ-decay up to excitation energies of 5 MeV. This will elucidate the nature of the proton emitting levels and yield information about the ratio of

proton-to-gamma-decay widths.

Detailed gamma-ray analysis has also been extended to more deformed nuclei. From the resulting decay schemes absolute branching ratios for beta-delayed proton emission can be extracted. These ratios are crucial for delimiting parameter values in the statistical model used to extract beta strength information from the experimental proton spectra. More generally, nuclear structure effects (e.g., the predicted breakdown of the Z=64 proton shell gap around N=77) near the proton drip line will be explored in the future.

Isotopes Project

Group Leaders
E. Browne
R.B. Firestone

V.S. Shirley

The past year marked a watershed in the history of the Isotopes Project. After seven editions of the *Table of Isotopes* since 1940, the group finished a new book titled the *Table of Radioactive Isotopes*. This book, published by John Wiley & Sons, Inc., was developed for applied users of radioactivity data. The 1056 page reference contains listings of nuclear and atomic properties for more than 2000 known radioactive isotopes. In addition to tabular data, the book contains descriptions of the methods of analysis and 69 pages of appendices.

The Isotopes Project is a member of the U.S. Nuclear Data Network (USNDN) with responsibility for evaluating nuclear structure and decay data for mass chains A=167-194. The evaluation of A=183 was submitted for publication in *Nuclear Data Sheets* this year, and the evaluations of A=168 and A=180 are near completion. The Isotopes Project also honored a request from the IAEA Nuclear Data Committee to implement radioactive decay data for the $33 \leq A \leq 44$ region in the Evaluated Nuclear Structure Data File (ENSDF).

The Isotopes Project provides the LBL/ENSDF database which contains numerical information from the *Table of Radioactive Isotopes*, from the ENSDF file, and from *The 1983 Atomic Mass Table* of Wapstra et al. A computer guest account is now available for remote users of the database. This account also provides access to the Physics Program Library (PPL) and to the databases of the National Nuclear Data Center at Brookhaven National Laboratory. The PPL program library contains interactive computer codes for calculating commonly used quantities such as log*ft* and internal conversion coefficients. Computer access may be obtained by telephone or through the HEPnet, MILNET and TYMNET computer networks. In addition, the Isotopes Project performs database searches on request.

The Isotopes Project is leading the development of methodology for nuclear data evaluation. Topics of particular interest include the normalization of decay scheme intensity data and the adoption of transition energies and branching ratios. Computer codes have been developed to implement our methodology and are being distributed to other evaluation centers.

The Isotopes Project maintains an extensive collection of bibliographical references. It subscribes to major nuclear physics journals and acts as a specialized library and local resource at LBL.

Deep Inelastic Reactions and Highly Excited Compound Nuclei

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

In the reaction ^{80}Kr + ^{174}Yb at 684 MeV, observation of the discrete γ-ray lines associated with both the heavy and the light partner as a function of Q-value has shown that more energy than predicted from equilibrium conditions seems to be deposited in the light fragment, in agreement with recent dynamical theories on energy transfer. Observation of complex fragment emission in intermediate-energy nuclear reactions has been interpreted as evidence for the onset of new reaction mechanisms. However, at low bombarding energies (50–100 MeV) the angular distributions and kinetic energy distributions for fragments from Li to Na in the ^{3}He + Ag reaction were consistent with compound nucleus decay. The rapid rise of the individual fragment excitation functions with energy from just above the barriers to 130 MeV of total excitation energy quantitatively confirmed the compound nucleus hypothesis and provided the means to obtain the individual barrier heights. Strong finite range effects predicted by modern versions of the liquid drop model were verified in detail.

The reactions, ^{93}Nb +^{9}Be, ^{12}C, ^{27}Al and ^{139}La + ^{12}C, ^{27}Al, at energies ranging from 8 to 50 MeV/nucleon at the SuperHILAC, the UNILAC and the Bevalac, have greatly extended the energy domain of our complex fragment formation study. The use of reverse kinematics (projectile much heavier than target) presents many advantages in this kind of experiment and the use of light target nuclei limits the range of impact parameters available and hence the number of sources. Kinematic focusing provides coverage of a very large angular range in the center of mass with a small laboratory acceptance angle, greatly enhancing the detection efficiency for both singles and coincidences. The large center-of-mass velocity enables us to detect and identify the atomic number of the entire range of products. It is important to have access to products with masses between that of the projectile and the target because in this region a much cleaner differentiation of the mass distributions associated with the different mechanisms is expected.

Large area ΔE-E telescopes with a very large dynamic range are required to study inclusive and coincident complex fragments emitted from the binary decay of a very hot compound nuclei. Quad telescopes placed on either side of the beam cover a very large range of c.m. angles for reverse kinematics reactions, allowing singles and coincidence data to be accumulated very efficiently in low intensity beams at the 88-Inch Cyclotron and the Bevalac. Both the ΔE and E sections are position sensitive in one dimension so that events which traverse the gas and stop in the silicon have both their x and y coordinates determined with position resolutions of 0.2°. For asymmetric entrance-channel reactions up to 50 MeV/nucleon, we have verified that binary decay of the equilibrated compound nucleus can account for the major production of complex fragments. In both complete fusion

Group Leaders
L.G. Moretto
G.J. Wozniak

D.R. Bowman*
R.J. Charity
L.Vinet

R.J. McDonald,
M.A. McMahan,
A&FRD, LBL

H. Han,
Institute of Atomic Energy, Beijing, China

W.L. Kehoe,*
A.C. Mignerey,
Department of Chemistry, University of Maryland

L.G. Sobotka,
D.G. Sarantites,
Chemistry Department Washington University St. Louis, MO

M.N. Namboodiri,
Nuclear Chemistry Division, LLNL

A. Moroni,
A. Bracco,
I. Iori,
INFN and Department of Physics, University of Milano, Italy

G. Guarino,
A. Pantaleo,
L. Fiore,
INFN, 70100, Bari, Italy

A. Gobbi,
K. Hildenbrand,
GSI, Darmstadt, West Germany

**Graduate students*

reactions at bombarding energies near the Coulomb barrier and incomplete fusion reactions at higher energies, highly excited compound nuclei are formed that move forward with high velocity. 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. From these reactions we expect to learn a great deal about the stability of nuclei at high excitation energy, in particular about the effect of high temperature on size and surface energy, and about their modes of decay.

This series of experiments has 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. To study the mechanism of multifragmentation at higher bombarding energies will require the measurement of the relative amounts of binary, ternary, quaternary, etc, decays as a function of bombarding energy.

Exit channels with more than two fragments require an array of high efficiency detectors. For excitation functions in reverse kinematics reactions we plan a close-packed array of fifty ΔE-E telescopes, each with a cross sectional area of 5×5 cm^2 and consisting of three elements: a 0.3 mm thick Si, a 5 mm thick Si, and a 7.5 cm thick plastic detector. The two silicon detectors are position sensitive in one dimension, allowing both the x and y coordinates to be determined for particles which traverse the first element and stop/traverse in the second element of the telescope. These telescopes will stop and identify heavy ions up to 100 MeV/nucleon.

On the theoretical side, we are studying in some detail the process of incomplete fusion that seems to prevail 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 and the exit channel velocity of the ensuing products. We have extended a speculation by Aichelin and Huefner that multifragmentation is akin to the shattering of a brittle object to include the constraints of a fixed amount of created surface and fragment multiplicity. A possible connection between the potential energy associated with the new surface and the fragment kinetic energy through the virial theorem is being investigated. The light particle spectra at intermediate and high energies show components which are most likely associated with the evaporation from a hot compound nucleus. We have derived theoretical expressions for their energy spectra which incorporate the effects of nuclear vibration during particle emission.

Relativistic Nuclear Collisions: Nucleus-Nucleus Collisions

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. Scientific support of instruments for a 50 m^2 detector for a five-year space exposure starting early 1988,

   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 $E < 1$ GeV;

4. Development of new types of glass detectors and an automated measurement system for experiments to resolve isotopes of relativistic nuclei up to lead (NASA support);

5. Ultrarelativistic nucleus-nucleus collisions (DOE support):
   a. 200 GeV/nucleon collisions of ^{16}O and ^{32}S at CERN,

   b. 15 GeV/nucleon collisions of ^{16}O and ^{32}S at Brookhaven,

   c. Detector response as a function of Lorentz factor,

   d. Planning for heavier projectiles.

Group Leader
P.B. Price

S. Barwick*
R. Claxton
T. Coan*
J. Drach*
D. Ifft*
D. Lowder*
Hye-Sook Park
M. Salamon
M. Solarz
W. Williams*

**Graduate Students*

Relativistic Nuclear Collisions: Pion and Correlation Studies

Group Leaders
K.M. Crowe
J.O. Rasmussen

J.A. Bistirlich
R.R. Bossingham*
A.D. Chacon*
M. Justice*
S. Ljungfelt
C.A. Meyer*
M. Stoyer*
K. Wyatt*

R. Van Dantzig,
F.W.N. DeBoer,
NIKHF-K,
Amsterdam,
Netherlands

C. Grab,
SLAC, Stanford
University, Stanford
California

P. Kammel,
Austrian Academy of
Science, Vienna,
Austria

C. Petitjean,
Swiss Institute for
Nuclear Research,
Villigen, Switzerland

A. Van der Schaaf,
Physik Insititut der
Universität, Zurich
Switzerland

**Graduate Students*

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 can 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}Ne + NaF, 1.7 GeV/nucleon ^{56}Fe on Fe, and 1.5 GeV/nucleon ^{93}Nb on ^{93}Nb.

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 been found between INC and measured source parameters (see LBL-19420).

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. 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.

Detailed information about muon catalyzed fusion ($d+t+\mu \rightarrow \alpha+n+\mu$) was gained in the analysis of our SIN experiments. In particular, the basic reaction rates of the fusion kinetics were determined and striking features of resonant $d\mu t$ formation were revealed (density effect, epithermal behavior). With high fusion rates of $\sim 1.5 \cdot 10^8$ observed, further analysis concentrated on the ultimate limits restricting the number of fusions per muon. The most important factor, losses of muons to the recoiling α, was determinedd to be $0.45 \pm 0.05\%$ per fusion. Fusion yields per muon of 113 ± 10 were directly observed, and from our results yields exceeding 200 are anticipated at optimal conditions (see LBL-21174 and LBL-21366).

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.

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.

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

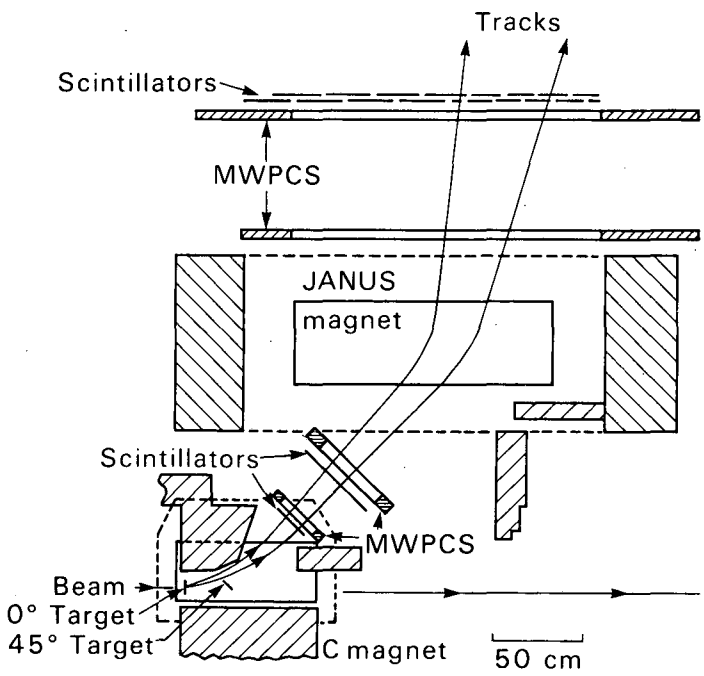


Fig. 1. The JANUS spectrometer as set up for the run of 1982.

XBL 867-8851

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

Group leaders
L.S. Schroeder
I. Tanihata

J.R. Alonso
T. Kobayashi
G. Krebs
Y. Nojiri
K. Sugimoto
O. Yamakawa

H. Hamagaki,
O. Hashimoto,
Y. Shida,
INS, University of Tokyo, Japan

H. Hayashi,
Y. Miake,
S. Nagamiya,
Department of Physics, University of Tokyo, Japan

K. Matsuta,
T. Minamisono,
N. Takahashi,
K. Takeyama,
Laboratory of Nuclear Studies, Osaka University, Japan

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}He, ^{6,7,8,9,11}Li, and ^{8,10}Be at 790 MeV/nucleon. Beams of radioactive nuclei were produced through the projectile fragmentation of 800 MeV/nucleon ^{11}B and ^{20}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}He-^{6}Li, ^{8}He-^{8}Li, and ^{9}Li-^{9}Be) were observed for the first time. The nucleus ^{11}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 projectile fragmentation. Test runs have already begun in Bevalac beam line B-44 to confirm the separability of isotopes. In the test run, ^{20}F and ^{21}F nuclei were successfully collected and the nuclear lifetimes were obtained by detecting β rays. Preparation of hardware for magnetic measurements, such as tilted foils for polarizing isotopes and an NMR system, is in progress.

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}He, and ^{4}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 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 final state interactions.

Relativistic Nuclear Collisions

Group Leaders:
V. Perez-Mendez, *LBL*
G. Igo, *UCLA*

Zhi-Fu Wang,
B. Keay,
LBL

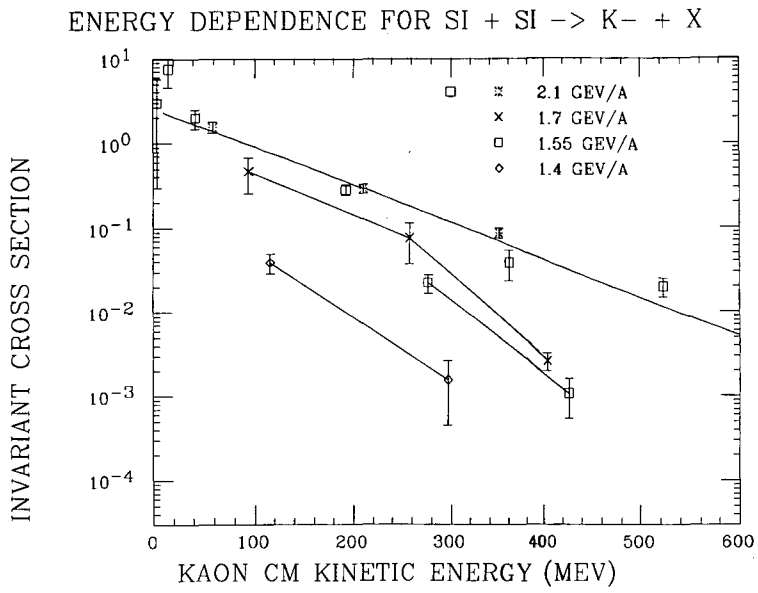
S. Carlson,
J. B. Carroll,
J. Gordon,
S. Trentalange,
UCLA

The main topic of research by this group is the study of nuclear matter in relativistic nuclear collisions. Our work has concentrated on the use of unusual probes or the detection of rare signatures to indicate the state of matter reached during these collisions. The experimental program represents work done by the listed personnel in collaboration with A. Shor (BNL), P. Lindstrom (LBL) and groups from Johns Hopkins University (L. Madansky, T. Hallman), Northwestern University (D. Miller, F. Luehring, A. Yegneswaran), and Lousiana State University (P. Kirk, J. F. Gilot).

Previous measurements of direct single lepton production in hadron collisions exhibit nearly universal behavior for bombarding energies in the range 10-300 GeV. At large transverse momenta the ratio of single electrons to charged pions is approximately constant at about 10^{-4} but increases rapidly for Pt $<$ 1 GeV/c. Low energy experiments at Columbia (580 MeV) and LAMPF (256 and 800 MeV), however, find no evidence for direct lepton production and place the upper limit on the electron to negative pion ratio at $3\text{-}5\times10^{-6}$. Our work partially bridges a gap in the data from Ep=1-10 GeV. During the last report period we completed a measurement of the direct electron to pion ratio in the p+Be system at proton kinetic energies of 2.1 and 4.9 GeV. Analysis of this data is continuing.

Our investigations of lepton production will be extended to measurements of electron-positron pair production in hadron- and heavy ion-induced reactions with the completion of the Di-Lepton Spectrometer (DLS) during this report period. A significant part of the instrumentation for one arm of the DLS system was tested during a May run at the Bevalac. Considerable experience was gained in operation of the full system and the availbility of full system data has been an enormous help in constructing the analysis code. Installation of the apparatus will be completed in November, with a second test run to follow immediately. First measurements for 2.1 and 4.9 GeV protons incident on Beryllium are expected to occur in December, 1986. The measurement program is expected to be extended to nuclear systems in the spring of 1987.

We have extended our study of subthreshold K^- production to include measurements of the excitation function in Si + Si collisions, and have begun a study of the mass dependence of this cross section. Preliminary results of this study are shown in Fig. 1. These data show that the "slope parameter" depends only weakly on incident energy and mass. Comparisons with the theoretical calculations of Zwermann and Schuermann, and of Barz and Iwe await completion of the analysis and further communications with the therorists to obtain directly comparable numbers. This program will be continued in the spring of 1987 with the following goals: measurements of slope parameters for K^- production – at incident Si energies down to 1 GeV/nucleon; for La + La at 1.3 GeV/nucleon; measurement of slope parameter for K+ production – for Si + Si at 1.42 GeV/nucleon (where Q is equal to that for K^- production in Si + Si at 2.1 GeV/nucleon); measure slope parameter for 2.1 GeV/nucleon Si + Si at 90 deg. in CM; perform a dedicated search for anti-proton production which will include several improvements in instrumentation.



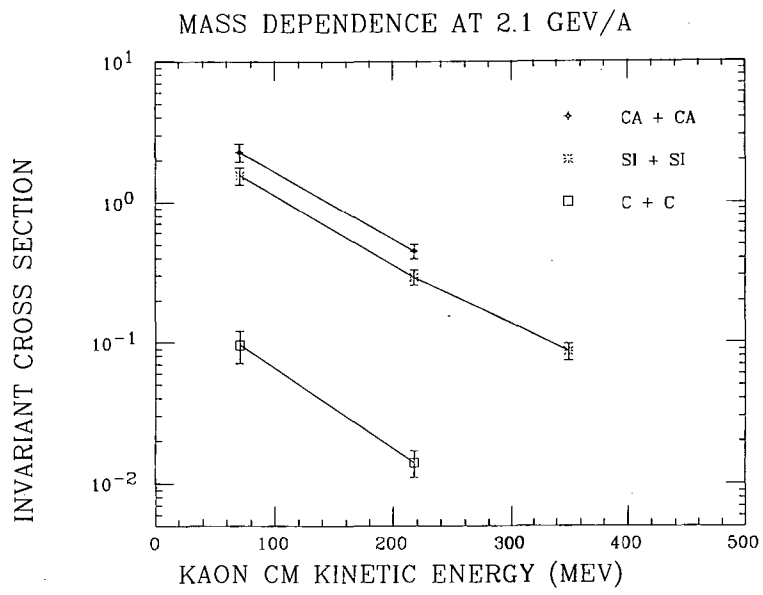


Fig. 1. Compilation of our results on subthreshold production of K^- mesons. The plots show the invariant cross section $E/p^2\ d^2\sigma/dpd\Omega$ mb/sr/(GeV/c)^2 for production at 0 degrees in the laboratory versus the kinetic energy of the kaon in the nucleon-nucleon center of mass. The data (other than the previously published momentum dependence of the yield for 2.1 GeV/nucleon Si + Si) are still preliminary. XBL 8611-4682 XBL 8611-4683

Relativistic Nuclear Collisions: Interactions in Emulsions

Group Leaders
P. J. Lindstrom
Emeritus
H. H. Heckman

S. Chatterji
F. Godek
Y. Karant
H. Yee

The Relativistic Heavy Ion Group's experimental program primarily employs nuclear emulsion visual track detectors to carry out studies on the interaction of nuclei in matter. Despite a change in group structure significant progress has been achieved, tending toward a total discontinuation of the Relativistic Heavy Ion Group work in the Nuclear Science Division at the end of calendar year 1987.

Several technical matters have been resolved. The nuclear emulsion processing facilities have been completely modernized, allowing versatility in the mounting and developing of emulsion pellicles and backed emulsions.

ICAMS (the Interactive Computer Assisted Measurement System) has been made fully functional through two sets of upgrades. In hardware, high speed input/output devices were added to free up wasted processor time from single character transmissions. Meanwhile, the software was completely changed to BSD UNIX. UNIX gives the PDP-11 processors almost the functionality of a VAX, and has full networking support along with a C compiler. For much real time systems work, C is a more versatile language than FORTRAN; most of ICAMS programs have been rewritten in C.

In terms of basic physics, several experiments were advanced. The completion of Bevalac Experiment 730H marked a significant increase in our knowledge of the effective rate of energy loss of a heavy nucleus in cold matter. This work has applications not only to atomic physics, but also to applied fields such as heavy ion inertial fusion.

CERN Experiment EMU-01 moved along on schedule to a November, 1986, run date. The emulsion chamber concept was verified using beams at the Bevalac, and the results compared with predictions for detector response. Two track resolution in the forward cone, which is a significant detector characteristic at CERN energies, was evaluated and found to be at the known systematic limit of emulsion chambers.

Using programs on ICAMS, data was collected on the exclusive angular distributions and multiplicities of projectile fragments of charge greater than or equal to that of He coming from 1.88 GeV/nucleon ^{56}Fe and 1 GeV/nucleon ^{238}U. The data is in apparent disagreement with the predictions of the thermal models.

Progress was made on the Si stack detector as well. Detectors actually arrived from the manufacturer and were tested for response. This detector is designed to look at the exclusive fragmentation of Li to He and H, and for interactions of ions up to O which result in projectile fragments of charge within a few charges of the beam. It is being readied for preliminary tests at the 88-Inch Cyclotron, and then to move on to Bevalac energies. The experiment is in collaboration with the group under Prof. J. Cerny's leadership.

Relativistic Nuclear Collisions: HISS

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 $^{12}C \rightarrow 3\alpha$ and $^{12}C \rightarrow {}^{11}B + p$.

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 ^{8}He. 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$2m chamber. This will be an important addition to the equipment available at the facility.

Group Leader
T.J.M. Symons
Technical Director
H. Wieman

M. Baumgartner
E. Beleal
F.S. Bieser
T. Kobayashi
P.J. Lindstrom
D.L. Olson
J. Wolf

H.J. Crawford,
I. Flores,
UCSSL

F.P. Brady,
J. Romero,
C. Tull,
M. L. Webb,
W. Christie,
J. Young,
U.C. Davis

Relativistic Nuclear Collisions: The Plastic Ball

Group Leaders
A.M. Poskanzer
H.-G. Ritter

K.G.R. Doss,
A. Franz,
P. Kristiansson,
LBL

H.-A. Gustafsson,
H.H. Gutbrod,
B. Kolb,
H.-R. Schmidt,
H. Wieman,
GSI

K.-H. Kampert,
H. Löhner,
University of Münster
West Germany

B. Jacak,
Los Alamos National Laboratory

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 and other detectors to study central collisions of relativistic and ultrarelativistic 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. The sidewise flow of the participants is taken as direct evidence of the production of high density nuclear matter. The systematics of the flow has now been quantified as a function of multiplicity, projectile-target mass, and beam energy, providing a broad spectrum of result which should be useful in better specifying an equation of state.

The Mall part (10 to 30 deg.) of the Plastic Ball has been 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.

The last experiment of the Plastic Ball at the Bevalac was aimed at collecting high statistics data for the study of the two pi-plus correlation.

Much of the past year was spent preparing for an experiment at the CERN Laboratory's Super Proton Synchrotron (SPS) using 60 and 200 GeV/nucleon ^{16}O beams. This is an expanded collaboration involving the University of Münster, Lund University and Oak Ridge National Laboratory. The experiment consists of five major detectors: The Plastic Ball, Multiplicity Arrays, a Lead Glass Spectrometer, a Wall Calorimeter, and a Zero-Degree Calorimeter.

Relativistic Nuclear Collisions: DLS

The construction of the Dilepton Spectrometer (DLS) during this period continued to be the central focus of activity of the collaboration. The DLS is a large aperture two-arm magnetic detector being constructed by a consortium involving the Lawrence Berkeley Laboratory, Johns Hopkins University, Louisiana State University, Northwestern University, UCLA and Clermont-Ferrand. As shown in Fig. 1 the DLS consists of large scintillation hodoscopes, drift chambers, Čerenkov counters and a multiplicity array for tagging central events. The DLS will be used to study the mass spectrum of e^+e^- pairs up to $M_{e^+e^-} < 800$ MeV which should probe the hot, compressed stage in a nucleus-nucleus collision. At Bevalac energies the DLS will be most sensitive to e^+e^- pairs arising from cascading baryons (via hadronic bremsstrahlung) and $\pi^+\pi^-$ annihilation processes and represents a major new tool at the Bevalac for exploring the nuclear matter equation of state at high temperature and density.

In the spring of 1986, one arm of the DLS was successfully tested in a brief run with ^{20}Ne at 800 MeV/nucleon. The complete system will be in place by mid-November of 1986 for a final shake-down run. First data (proton–nucleus at 2.1 and 4.9 GeV) with the DLS is expected to be taken in a 5-day running period scheduled for December 1986. Preliminary results will be available by spring 1987.

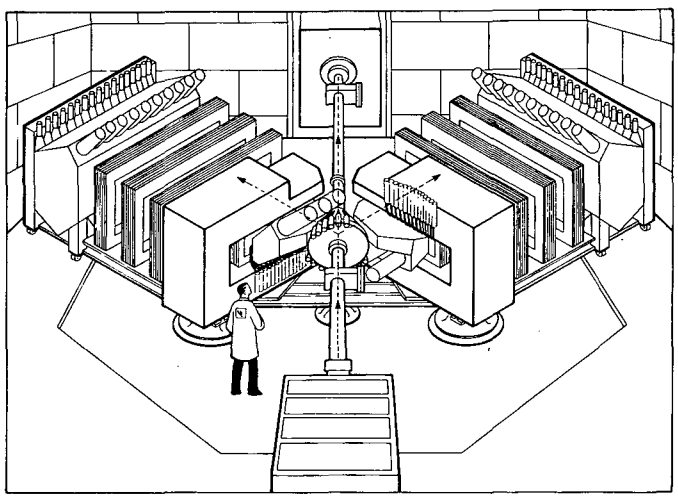


Fig. 1. Artist's Conception of the Dilepton Spectrometer (DLS). XBL-8512-9589

Group Leaders:
H.G. Pugh
G. Roche
L.S. Schroeder

R.L. Fulton
G. Krebs
E. Lallier
H.S. Matis
C. Naudet
Z.F. Wang
A. Yegneswaran*

S. Christo,
P.N. Kirk,
Louisiana State University
Baton Rouge, Louisiana

T. Hallman,
L. Madansky,
Johns Hopkins University
Baltimore, Maryland

D. Miller,
Northwestern University
Evanston, Illinois

J. Bystricky,
J. Carroll,
J. Gordon,
G. Igo,
University of California at Los Angeles

G. Landaud,
Université de Clermont-Ferrand
Aubière, France

**Graduate student*

Ultrarelativistic Nuclear Collisions

Group Leaders
J.W. Harris
H.G. Pugh
L.S. Schroeder

S. Chase*
G. Odyniec
G. Rai
L. Teitelbaum*
L.M. Tinay
M. Tincknell
J.-M. Walker

**Graduate student*

The NA35 experiment at the CERN Super Proton Synchrotron is a collaboration of about 60 physicists from 14 institutions: Athens – Bari – Berkeley – CERN – Cracow – Darmstadt (GSI) – Frankfurt – Freiburg – Heidelberg – Marburg – Munich (MPI) – Warsaw – Zagreb. This experiment (and, in fact, the entire heavy ion program at CERN) developed from a proposal submitted by the GSI-LBL collaboration at the Bevalac, with R. Stock as spokesman. The proposal, approved as experiment PS190, was subsequently split into two parts: NA35, using a streamer chamber, and led by R. Stock; and WA80, using the Plastic Ball, and led by H.H. Gutbrod. The experiments were made possible by the joint construction by GSI, LBL, and CERN, of a new heavy ion injector for the CERN complex of accelerators. LBL's Accelerator and Fusion Research Division constructed a radio-frequency quadrupole linac (RFQ) as part of this injector.

The NA35 experiment had its first run, using a beam of 200 GeV/nucleon (3.2 TeV) ^{16}O ions produced during an accelerator test period in September, 1986. A paper based on that run has already been submitted to Physics Letters. A major data acquisition run is in progress (Nov.–Dec., 1986) and another is planned for October, 1987.

The objective of the NA35 experiment is to explore the prediction of strong interaction lattice gauge theory that the hadronic state of matter is transformed, at sufficiently high energy density, into a new phase consisting of deconfined quarks and gluons. Such extreme conditions, with an energy density of several GeV/fm^3 (more than ten times that of ground state nuclear matter) could be reached in central nucleus-nucleus collisions by converting the initial c.m. energy into internal excitation of a "fireball" formed at rapidities intermediate between those of target and projectile, provided sufficient beam energy and sufficient "stopping power" in the nuclear interaction. In the initial phase of the study, the emphasis has been to find out if such conditions are reached in ^{16}O-nucleus collisions at 200 GeV/nucleon. The first indications are favorable.

The NA35 set up consists of a $2 \times 1.2 \times 0.72$ m^3 **Streamer Chamber** in the 1.5 Tesla field of a superconducting "vertex" magnet. Three cameras, each equipped with two-stage magnetically focused image intensifiers, view the Streamer Chamber, and record events on 70 mm film. Downstream, a highly segmented **Photon Position Detector** (PPD) measures most of the energy of photons and π° particles. Directly behind the PPD is a **Ring Calorimeter** of thickness sufficient to absorb all the energy of hadronic showers produced in the interaction. These two detectors cover the mid-rapidity region $2.5^\circ < \theta < 12^\circ$. The internal aperture of the Ring Calorimeter is filled by the **Intermediate Calorimeter**, covering the angular range $0.3^\circ < \theta < 2.5^\circ$. The energy flux in the projectile fragmentation domain $\theta < 0.3^\circ$ is measured by a **Veto Calorimeter**.

LBL contributions to the experimental hardware include the Intermediate Calorimeter and high voltage power supplies for the Ring Calorimeter. A major feature of the experiment, provided by LBL, is the **Streamer Chamber Supervision System**. This uses two CCD cameras with 1024×1024 pixels each. The

CCD pixels are digitized to 9 bits and transferred in parallel to an on-line image processing system based on a VAXstation II computer (Micro-VAX II). Attached to this is a 10 million-instruction-per-second integer coprocessor, the Mercury Computer Systems 3216, and peripherals. This system, fully operating for the November 1986 run, provides quantitative analysis of streamer chamber performance and event topology to optimize the use of beam time. It provides, for example, a measure of the multiplicity of charged particles produced in each event, which can be correlated on line with such measured quantities as transverse energy in the PPD and Ring Calorimeter, or the energy in the Veto Calorimeter.

LBL's contribution to the data analysis is focused on the scanning and measuring tables developed for use in Bevalac Streamer Chamber experiments. The secondary particle multiplicities are substantially higher than those in Bevalac collisions. Nevertheless, events with up to 371 charged particle tracks have been successfully measured. Each such event, on its own, contains a substantial amount of information and warrants careful study. As experience is gained, emphasis is expected to be placed on specific attributes of the events such as the production of strange particles and antiparticles.

Streamer Chamber Experiments

Group Leaders
J.W. Harris
H.G. Pugh
L.S. Schroeder

J.P. Brannigan,
S. Chase,*
I.W. Muskovich,
G. Odyniec,
G. Rai,
L. Teitelbaum,*
L.M. Tinay,
M. Tincknell,
J.-M. Walker,
LBL

W. Rauch,*
R. Stock,
University of Frankfurt,
W. Germany

R. Bock,
R. Brockmann,
A. Sandoval,
H. Ströbele,
Gesellschaft fur
Schwerionenforschung,
Darmstadt, W. Germany

R.E. Renfordt,
D. Schall,
University of Heidelberg,
W. Germany

D. Bangert,
University of Marburg,
W. Germany

J.P. Sullivan,
K. Wolf,
Texas A&M University,
College Station,
Texas 77843

A. Dacal,
C. Guerra,
M.E. Ortiz,
Instituto de Física,
UNAM, 21 DF,
México

**Graduate students*

The Streamer Chamber allows the study of charged particles as well as K^0 and Λ^0 over most of the 4π solid angle in high energy heavy ion collisions. Using it, and a forward angle 384-element scintillator array, we have made measurements of π^- multiplicities and spectrum shapes as a function of beam energy and of participant number (i.e., impact parameter). We have studied Λ^0 production in near-central collisions, and we have reconstructed and measured all the tracks in a large sample of events, to extract such quantities as flow and transverse momentum distributions. Our results indicate that the nuclear matter equation of state is stiffer than had been supposed.

Several improvements to the Streamer Chamber facility are underway to extend these studies to the heaviest projectiles (which is desirable to minimize surface effects and to emphasize bulk properties of the "fireball"); to provide enhanced particle identification (and hence more complete evaluation of individual events); and to permit greater efficiency in data analysis.

High-gain image intensifiers and CCD cameras are being installed, together with a fully digitized data acquisition and analysis system which we have developed and tested on the NA35 experiment at CERN. Several advantages result. Firstly, the Streamer Chamber can be operated at lower voltages, with consequent reduction of "flares", improvement of track definition, and linearity of response (which is important for particle identification by dE/dn measurement). Secondly, on-line monitoring of the chamber performance and on line studies of event topologies (with, for example, on-line availability of track multiplicities) will be improved. Finally, the complete digitization of the data acquisition and analysis system will permit rapid automatic scanning and preselection of events, and a major enhancement in the speed of (operator-assisted) total event reconstruction.

The CCD camera system uses three cameras, each with 1024×1024 pixels. The information in the pixels is digitized to 9 bits and transferred in parallel to an on-line image processing system based on a VAXstation II computer (Micro VAX II). Attached to this is a 10 million-instruction-per-second integer coprocessor, the Mercury Computer System 3216, and peripherals. Data are to be stored on optical laser disks. Operation of the full system is expected for Spring, 1987.

EOS - Time Projection Chamber

Group Leader
H.G. Pugh

J. Biderbost*
S. Chung†
C. Kim†
G. Odyniec
G. Rai
P. Seidl
P. Simon†

**Graduate Student*
†Undergraduate Student

EOS is a time projection chamber designed for studies of the Equation of State of nuclear matter at the high densities and temperatures achieved at Bevalac energies. The name EOS, for the Greek Goddess of the Dawn, reflects the importance of such studies for understanding the origin of the universe, as well as the obvious acronym for the equation of state.

During the past year a design study has been completed. The starting point was the recommendation made by a working group of the Bevalac Users' Association in May 1984 that a 'continuous-tracking detector with magnetic field' be constructed to extend the physics of the Plastic Ball and the Streamer Chamber, and the conclusion of a series of follow-up meetings within Nuclear Science Division that the optimum device would be a time projection chamber (TPC) in a solenoidal magnetic field. In the present work the performance of such a detector has been evaluated in detail.

For this study, the magnetic field was 2 m diameter, at a strength of 1.5 Tesla. The TPC was single-ended, 1.8 m outside diameter, 0.2 m inside diameter (with an evacuated beam pipe), and 2 m long. The gas mixture was 9% CH_4 and 91% Ar. The end cap contained 25000 pads and 1000 wires, with a non-uniform radial distribution. The time-of-flight path was 1.0 m at 90° and 3.6 m at 0°. With these parameters, almost complete coverage of the "fireball" kinematic regime is obtained for p, d, t, ^{3}He, ^{4}He, π^+, π^-, K^+ and Λ^0. The probability of separating and identifying any individual particle is about 99% for Ar + KCl central collisions, and about 95% for Ar + Au central collisions.

Detailed studies have been carried out for the magnetic field design, the transverse and longitudinal diffusion of the drift electrons, the momentum resolution, and the effect of field non-uniformities. The efficiency of particle identification by dE/dx measurement and by time-of-flight has been evaluated, as well as the Λ^0 reconstruction efficiency. The design has been optimized for multiple bit separation. The effects of space change accumulation in the TPC, and of saturation of the multi-wire proportional counters for heavily ionizing particles, have been evaluated. The feasible data acquisition and transfer rates have been evaluated, as well as data storage needs.

The project is ready for prototyping of specific components, for determination of the overall construction schedule and cost within the constraints of available funding, and for construction with a target data of 1991 for data acquisition. The EOS detector will be valuable either with the existing Bevalac or with the Bevalac upgrade, for which operating conditions would be greatly improved.

Nuclear Theory

Group Leaders:
N.K. Glendenning
M. Gyulassy
W.D. Myers
J. Randrup*
W.J. Świątecki

F.R. Klinkhamer
D. Hahn
A. Iwazaki
K. Kolehmainen
M. Redlich

T. Elze,
D. Vasak,
University of Frankfurt, West Germany

P. Möller,
Lund University Sweden

C. Dorso,
University of Buenos Aires, Argentina

S. Duarte,
Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

F. Brut,
Institut des Sciences Nucléaires University of Grenoble, France

**Scientific Director of the Theory Program*

The nuclear theory program covers many of the major topics in nuclear physics, partly reflecting but also extending beyond the already rather broad range of our experimental program.

Non-perturbative aspects of field theories are becoming increasingly relevant to nuclear physics. The areas of research include the form of the interactions in superstring theory, the quark-confinement mechanism, and topological solutions to effective meson field theories, possible candidates for novel nucleonic states. The internal nucleon structure is being investigated with soliton models and the effect on matter properties is being examined.

Matter at high energy density as may arise in high-energy collisions and neutron stars. Using relativistic hadronic field theory, the existence of phase transitions, abnormal matter and hyperons in neutrons stars have been studied. Current studies include a hot metastable state of matter, the effect of hyperons on neutron-star equation of state, and neutron-star masses as a contraint on the nuclear compression modulus.

Nuclear collisions at ultra-relativistic energies. Studies of nuclear stopping power and the space-time development of hadronization seek to determine the energy densities achieved. A transport theory has been developed for the description of chromodynamic plasmas far from equilibrium. Microscopic studies of the transition from plasma to hadronic matter and possible experimental signatures for the quark-gluon phase are being studied.

Nuclear collisions at intermediate energies. Cascade, fluid dynamic, and statistical models are employed in order to elucidate the complicated reaction dynamics. Recent studies have focussed on the determination of the nuclear equation of state and the character of the disassembly of a hot nucleonic source, particularly the relation of composite-fragment formation to entropy. A microcanonical description of interacting fragments at subsaturation densities has been developed.

Nuclear dynamics at moderate energies. Further evidence is accumulating for the discovery that ordered nucleonic motions result in a solid-like behavior of the nucleus, whereas nucleonic chaos produces a fluid-like nucleus. The dynamics of dinuclear systems is being further pursued, with notable advances in treating the angular-momentum transport, and in understanding the transition between mono- and dinuclear regimes on the basis of linear-response theory. The evolution of the dynamics with increasing energy is receiving increased interest.

Macroscopic nuclear properties. The predictive power of the Droplet Model is being steadily improved. Recent advances include a finite-range correction term and the surface contributions to nuclear moments. For fission of the heaviest elements, it was found that qualitatively different fission paths exist and yield bimodal fission-fragment energy distributions. The exotic "evaporation" of heavy ejectiles has also been studied and succesfully described.

88-Inch Cyclotron Operations

D.J. Clark
D.R. Elo
L.R. Glasgow
R.S. Lam
R.M. Larimer
C.M. Lyneis
R.A. Peterson
J.W. Roberts
R.G. Stokstad

The 88-Inch Cyclotron continued operation as a reliable source of light and heavy ions, benefiting greatly from the ECR source, which was installed in 1985. The operation now requires less operating manpower than with the PIG sources, since the ECR source needs essentially no maintenance between the weekly shutdown maintenence shifts. The ECR source is described in a separate article in this report.

The 88-Inch Cyclotron is a national facility and is used extensively by outside groups from many institutions in the U.S. and abroad. Table I shows the numbers of users from LBL and elsewhere. Allocation of beam time is done on the basis of recommendations by a Program Advisory Committee, which considers proposals for individual nuclear science experiments on a four-month cycle. The scheduling of experiments is done on a weekly basis, although experiments involving users who must make travel arrangements are scheduled further in advance. The members of the PAC during the period covered by this report were Charles Goodman (IUCF), Jørgen Randrup (LBL), John Rasmussen (LBL), and Robert Vandenbosch (U. Washington). Karl Van Bibber and Richard Hoff (both from LLNL) served at the August 1986 meeting. Table II shows the ratio of requested to available beam time for recent allocation cycles. Note the large increase in the demand for time. The distribution of beam time among various categories (nuclear science, beam development, inside use, outide use, etc.) is shown there. Recharge use is the category in which the users of the cyclotron pay for the time on an (operating) cost-recovery basis. Since the funds provided by the DOE to operate the cyclotron for nuclear science have become increasingly inadequate, even for a 14-1/2 shift per week schedule, the recharge use has become a correspondingly important item in the total operations budget. Without this source of income, the operation for nuclear science would have to be curtailed even more, since operation at less than our present rate would be less cost effective. The members of the Users Executive Committee were Kenneth Hulet (LLNL) and, from LBL, Yuen-dat Chan, Marie-Agnes Deleplanque, and Eric Norman.

The cyclotron plays a significant educational role. In FY86 eleven graduate students from the University of California at Berkeley employed this facility in their research toward the PhD degree. In addition 28 graduate students from other universities participated in research at the cyclotron.

The cyclotron was operated 14-1/2 eight hour shifts per week. In addition one shift was used for maintenance at the beginning of each week and one half shift at the end for shutdown over the weekend. The distribution of cyclotron time is shown in Table III. The light ion beams of protons, deuterons, ^{3}He and α-particles are available using either the ECR source or the standard internal filament source. The polarized ion source operates reliably and provides beams of polarized protons and deuterons. Heavy ions (A>4) occupied 73% of the scheduled time, using only the ECR source. Some of the optimized beams are shown in Table IV.

Improvements to the Facility

A. Electrical improvements:

1) The commissioning of the new 2 megawatt transformer, which will eliminate the limitation on maximum power availability.

2) A project to improve the regulation of cyclotron trim coil power supplies, which are unable to remove the power line bumps caused by Bevatron pulsing. A prototype was built using SCR's instead of magamps.

3) The installation of a millisecond beam pulsing system on the ECR injection line. Here the beam energy is only 10 kV, so electrostatic sweeping plates with several hundred volts switched electronically will pulse the beam.

4) The construction of a new 455 MHz amplifier for the intermediate cavity in the polarized ion source.

5) Construction of a new power supply for the X-Y magnetic beam sweeper used in the transuranic research beam line to produce more uniform beam on the target.

B. Mechanical improvements:

1) Modifications to the center iron plug in the cyclotron pole to give better pumping on the trapped volumes.

2) The inflector system which bends the ECR beam into the cyclotron was modified to hold voltage more reliably.

3) A fire protection sprinkler system was installed in the cyclotron vault and experimental caves.

4) A new beamline was installed for gamma-ray experiments in Cave 4C.

5) Design work was completed on an atomic physics beamline, which can use the ECR source beam when it is not needed for the cyclotron.

C. Miscellaneous improvements:

1) The installation of a new telephone system in the cyclotron building which greatly improved communications in the building. Paging can now be done from any phone, and each phone has an extension.

2) The purchase of several personal computers. They are being used by the operating and development staff to keep records and to write memos, letters, reports and research papers.

Table I

Distribution of Cyclotron Users in FY86

LBL, U.C. Berkeley Staff			25
Graduate Students			31
	U.C. Berkeley	13	
	Other Institutions	18	
Post-doctoral Scientists			10
	LBL	8	
	Other Institutions	2	
Outside User Staff			108
	Universities	13	
	Other Institutions	26	
	Industry	68	
Total			173

Table II

Cyclotron Time Allocation Summary for Five Scheduling Periods

		July–Sept 85	Oct–Dec 85	Jan–April 86	May–Sept 86	Oct 86–Feb 87
Total Requests						
Total Allocations		1.20	1.47	1.40	1.53	2.01
Nuc. Sci. Requests						
Nuc. Sci. Allocations		1.17	1.75	1.63	1.72	1.91
Allocated Time	(%)					
Recharge		5	36	16	13	17
Beam Dev.		5	4	6	4	5
Discretionary		0	6	6	8	7
Nuclear Science		90	54	72	75	71
Nuc. Sci outside						
Nuc. Sci.	(%)	22	30	23	32	55
Nuc. Sci LBL						
Nuc. Sci.	(%)	78	70	77	68	45
LBL Alloc.						
Total Alloc.	(%)	70	54	55	51	42

Table III

Cyclotron Time Distribution for FY86

	Hours		%
Operating Time			
Machine Studies		165	2.9
Cyclotron, ECR Tuning		450	7.8
Beam Optics		388	6.7
On Target		4045	70.3
Nuclear Science	3438		
Other	607		
Wait for Experimenter		14	.2
		5062	**87.9**
Maintenance Time			
Scheduled Maint.		568	9.9
Weekly	384		
Summer	184		
Unscheduled Maint.		47	.8
Power outages, etc.		78	1.4
		693	**12.1**
Total		**5755**	**100.0**
Holiday		336	
Budgetary Shutdown		2669	
Total Time		8760	

Table IV. Some Optimized Beams

Ion	Cyclotron Energy (Mev)	Harm.	Source Current (eμA)	Cyclotron External Current (eμA)	Trans-mission (%)
$^{14}N^{5+}$	180	1	60	7	11
$^{16}O^{2+}$	20	3	69	2	3
$^{16}O^{2+}$	20	5	67	0.15	0.2
$^{18}O^{5+}$	117	1	60	10	17
$^{16}O^{6+}$	315	1	40	3	7
$^{16}O^{7+}$	429	1	10	0.2	2
$^{22}Ne^{6+}$	151	1	40	7	17
$^{24}Mg^{7+}$	192	1	20	1.5	7
$^{28}Si^{6+}$	180	1	60	3	5
$^{40}Ar^{9+}$	180	3	30	3	10
$^{40}Ar^{12+}$	504	1	6	0.2	3
$^{86}Kr^{14+}$	301	3	2.5	0.08	3
$^{129}Xe^{21+}$	451	3	0.8	0.02	3

The s-Process Branch at ^{148}Pm

*E.B. Norman, K.T. Lesko, S.G. Crane, R.M. Larimer, R.M. Diamond, F.S. Stephens, M.A. Deleplanque, J.C. Bacelar, E.M. Beck, and A.E. Champagne**

We have continued our studies of the level scheme of ^{148}Pm in order to exploit the s-process branching that occurs at this nucleus to determine the s-process neutron density. Using the Princeton University cyclotron and Q3D spectrograph, we have employed the ^{149}Sm(d,^{3}He) reaction to determine the energies of a large number of excited states in ^{148}Pm.

At LBL we have studied γ-ray transitions in ^{148}Pm using the ^{148}Nd(p,n) reaction. Gamma-ray singles and γ-γ coincidence data have been acquired with the High Energy Resolution Array. Analysis of these data is currently in progress.

Footnotes and References

*Physics Department, Princeton University, Princeton, NJ 08544

Search for the Beta Decay of ^{180}Lu to ^{180}Hf^{m}*

S.E. Kellogg† and E.B. Norman

The $t_{1/2}$ = 5.7 minute ^{180}Lu isotope was produced in the ^{180}Hf(n,p) reaction and its subsequent β decay back to ^{180}Hf was studied with a Ge(Li) spectrometer. A radiochemical technique was used to measure the fractional population of the I^{π},K=(8^-,8) isomer in ^{180}Hf to be $f_m = 0.005 \pm 0.018\%$. The limit on f_m is shown to be too small to account for the nucleosynthesis of ^{180}Ta^m in the r-process. The possible existence of a high-spin isomer in ^{180}Lu and its astrophysical consequences has been examined.

Footnotes and References

*Condensed from Phys. Rev. C **34**, 2248 (1986).

†Nuclear Physics Laboratory, University of Washington, Seattle, Washington 98195.

Isomeric Levels in ^{180}Lu and the Nucleosynthesis of ^{180}Ta^{m}*

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

Searches have been made for short-lived isomers in ^{180}Lu suggested by previous studies. Samples of ^{180}Lu were produced via the ^{180}Hf(n,p) reaction. Evidence for decay of a ^{180}Lu isomer was sought by examining the decay curves of the known ^{180}Lu and ^{180}Hf^m delayed γ rays, and by searching for previously unidentified delayed γ rays. No evidence for a ^{180}Lu isomer was observed for half-lives between 10 and 300 seconds. The relevance of these observations for understanding the nucleosynthesis of ^{180}Ta^m has been examined.

Footnotes and References

*Condensed from Phys. Rev. C **34**, 2256 (1986).

†Nuclear Physics Laboratory, University of Washington, Seattle, Washington 98195.

Gamma-Ray Transitions in ^{180}Ta

E.B. Norman, K.T. Lesko, R.M. Larimer, R.M. Diamond, F.S. Stephens, M.A. Deleplanque, J.C. Bacelar, and E.M. Beck

We are interested in the question of whether the naturally occurring isomer $^{180}Ta^m$ can survive in the high-temperature environments found in stars in which s- and r-process nucleosynthesis occurs. In particular, we would like to know if $^{180}Ta^m$ can be destroyed via photo-deexcitation to the $t_{1/2}$ =8.1 hour $^{180}Ta^g$. In order to answer this question, we have used the ^{180}Hf(p,n) reaction to study γ-ray transitions in ^{180}Ta. Gamma-ray singles and γ-γ coincidence data have been acquired with the High Energy Resolution Array. Analysis of the data is currently in progress.

Measurements of Cross Sections Relevant to γ-ray Line Astronomy*

K.T. Lesko, E.B. Norman, R.M. Larimer, S. Kuhn, D.M. Meekhof, S.G. Crane, and H.G. Bussell

Observations of discrete γ-ray lines can provide unique signatures of nuclear reactions occurring in astronomical environments. Because of their highly penetrating nature, γ rays may provide specific information on astrophysical sites that are opaque to longer wavelength radiation. γ-ray lines have been observed within the solar system, in solar flare events, and in extra-solar system sites such as the galactic center, Centaurus A, SS-433, and perhaps the Crab Nebula. In principle, discrete line γ-ray spectra can be used to obtain the relative abundances and energy spectra of the particles responsible for the γ-ray production. However, in order to make use of such spectra, cross sections for the production of nuclear γ rays must be known.

We have measured production cross sections for the γ-ray lines which are most strongly excited in the proton bombardment of C, O, Mg, Si, and Fe targets of natural isotopic composition. High resolution germanium detectors were used to collect γ-ray spectra at proton bombarding energies of 20, 30, 33, 40 and 50 MeV.

Footnotes and References

*Condensed from LBL-21858.

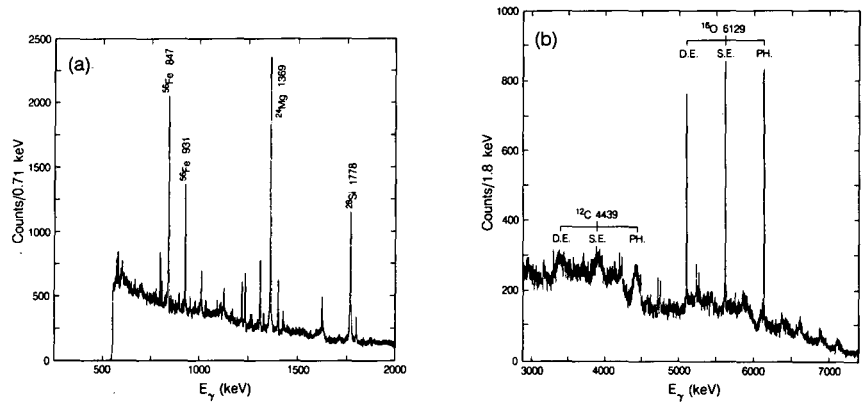


Fig. 1. γ-ray spectrum observed during the bombardment of a thick sample of the Allende meteorite with 33 MeV protons. The prominent γ rays are identified by target isotope. PH, SE, DE stand for, respectively, photo peak, single escape peak, and double escape peak. XBL 865-10783

PART II: EXPERIMENTS

New Limits on the Double Beta Decay Half-Lives of ^{94}Zr, ^{96}Zr, ^{116}Cd, and ^{124}Sn

E.B. Norman and D.M. Meekhof

Searches have been made for the double beta decays of ^{94}Zr, ^{96}Zr, ^{116}Cd, and ^{124}Sn to excited states in their respective daughter nuclei. High purity samples of natural isotopic composition zirconium, cadmium, and tin were each counted for approximately one month with a 110 cm^3 Ge detector in LBL's Low Background Counting Facility. The sought-for signatures of such decays were known gamma-ray transitions in the daughter nuclei. No evidence of any of these decays was found. From these measurements, however, the half-lives of ^{94}Zr, ^{96}Zr, ^{116}Cd, and ^{124}Sn against double beta decay to excited states in their daughter nuclei have been established to be $> 1 \times 10^{18}$ years.

Improved Tests of the Exponential Decay Law

E.B. Norman, S.B. Gazes, S.G. Crane, and D.A. Bennett

We have continued our studies of the exponential nature of the radioactive decay law at both short and long times with respect to the lifetime of the unstable system. We have produced a 15μCi source of ^{60}Co in a 12 millisecond (FWHM) neutron pulse at the U.C. Berkeley TRIGA reactor. Counting was begun within 7×10^{-5} of a ^{60}Co half-life and the decay rate from this source was compared to that of an "old" ^{60}Co sample, i.e., one that was about 1 half-life old. These measurements showed that the ratios of the decay rates from the "new" and "old" samples were constant over all time intervals studied—as would be expected for purely exponential decay.

We have also extended our studies of ^{56}Mn decay out to about 45 half-lives. In order to reach this sensitivity, several post-irradiation radiochemical purifications had to be employed. Again, our data are consistent with purely exponential behavior out to the limit of our measurements.

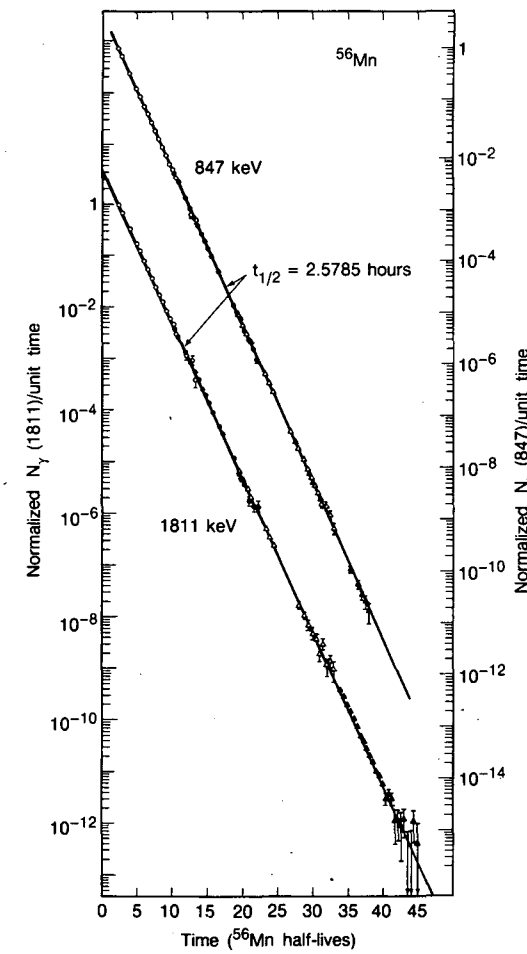


Fig. 1. Composite decay curves for the 847 and 1811 keV γ-rays obtained from ^{56}Mn sources. The slope of the straight lines represents the known half-life of ^{56}Mn. XBL-8510-9584

Searches for Supermassive X^- Particles in Iron*

E.B. Norman, S.B. Gazes, and D.A. Bennett

Two searches have been made for negatively-charged massive elementary particles (X^-) in iron nuclei by utilizing the fact that such systems would have the nuclear properties of iron but the chemical properties of manganese. We have looked for $^{56,58}FeX^-$ by searching for gamma rays emitted following the beta decays of $^{56}CoX^-$ and $^{59}FeX^-$ produced by (p,n) and (n,γ) reactions, respectively. No evidence of such particles was observed in either experiment, but a limit has been established on the possible concentration of X^- particles in iron of $< 1.2 \times 10^{-12}$ per nucleon.

Footnotes and References

*Condensed from Phys. Rev. Lett. **58**, 1403 (1987).

Beta Decay Asymmetry of Polarized ^{35}Ar

J. Garnett, E. Commins,* E.B. Norman, and K.T. Lesko*

The observed[1] beta decay asymmetry in the decay of polarized ^{35}Ar has led to a persistent puzzle in weak interaction physics. If the experimental value of the ground-state→ground-state asymmetry, A_0, is taken, the value of the Cabibbo angle deduced for ^{35}Ar decay is consistent with zero. This disagrees with the value of $\theta_c = 0.23 \pm 0.01$ radians obtained from other nuclear and particle decay experiments. As a result of this continuing puzzle, we have decided to reinvestigate the beta decay asymmetry of ^{35}Ar.

We utilize the polarized proton beam at the 88-Inch Cyclotron to produce polarized ^{35}Ar nuclei by the ($\vec{p}$,n) reaction on ^{35}Cl in CCl_4 vapor, and observe the beta decay asymmetry directly in the target.

An essential feature of the experiment is that one *calibrates* the ^{35}Ar polarization by observing the asymmetry Δ_1 in the decay

$$^{35}\vec{Ar}(3/2^+) \xrightarrow{\beta} {}^{35}Cl^*(1/2^+) \rightarrow {}^{35}Cl(3/2^+) + \gamma(1.219\ \text{MeV}) \qquad (1)$$

by $\beta\gamma$ coincidence. The branching ratio of this transition is 1.27% and the asymmetry coefficient for this purely axial beta transition is $A_1 = +1$. One then measures the asymmetry coefficient Δ_0 for the ground state transition:

$$^{35}\vec{Ar}(3/2^+) \xrightarrow{\beta} {}^{35}Cl(3/2^+) \qquad (2)$$

with asymmetry coefficient A_0. In the ratio Δ_0/Δ_1, instrumental asymmetries and unknown polarization transfer factors cancel, as do geometric factors. So far we have a promising preliminary result, and hope to complete the experiment in the very near future.

Footnotes and References

*Physics Department, University of California, Berkeley California 94720.

1. F.P. Calaprice, E.D. Commins, and D.A. Dobson, Phys. Rev. **137**, B1453 (1965).

LAMPF E645: A Search for Neutrino Oscillations

S.J. Freedman, M.C. Green,* J.W. Mitchell,* J.J. Napolitano,* B.J. Fujikawa,† R.D. McKeown,† F. Blönnigen, K.T. Lesko, E.B. Norman, R. Carlini,‡ J.B. Donohue,‡ G.T. Garvey,‡ V.D. Sandberg,‡ K.W. Choi,§ A. Fazely,§ R.L. Imlay,§ W.J. Metcalf,§ R.W. Harper,** T.Y. Ling,** E.S. Smith,** T.A. Romanowski,** and M. Timko***

We are continuing our participation in this search for neutrino oscillations at LAMPF. During the past year, the central detector and active shield have been brought together in full operation. The detector is now installed in the experimental tunnel and data acquisition with the LAMPF beam is now in progress.

Footnotes and References

*Physics Division, Argonne National Laboratory, Argonne, Illinois 60439.

†Department of Physics, California Institute of Technology, Pasadena, California 91125.

‡Los Alamos Meson Physics Facility, Los Alamos, New Mexico 87545.

§Physics Department, Louisiana State University, Baton Rouge, Louisiana 70803.

**Physics Department, Ohio State University, Columbus, Ohio 43210.

Radiative Capture Experiments and the D-State of ^{4}He

H.R. Weller, M. Whitton,* E. Hayward,† W. Dodge,† S. Kuhn, R.M. Larimer, K.T. Lesko, and E.B. Norman*

The aim of our work is to study the D-state part of the ground state wave function of ^{4}He.

The presence of even a small amount of D-state probability in the ground state of ^{4}He has significant effects on the radiative deuteron-deuteron fusion reaction ^{2}H(d,γ)^{4}He, which in turn can be used to determine the properties of the D-state wave function.

The contribution of the D-state gives rise to nonzero values of the tensor analyzing powers in the ^{2}H($\vec{d}$, γ)^{4}He reaction.

A precise measurement of analyzing powers such as A_{yy}, using tensor polarized deuterons, is thus the best tool to study the radial behaviour of the D-state wave function. Up to now, there have been several measurements below 15 MeV deuteron energy at Duke University. The reason to raise the energy is that at higher energies we can study the properties of the D-state for small distances, which, in turn, are most sensitive to the underlying tensor forces. Using the two recently installed 10″ × 10″ NaI detectors at the 88-Inch Cyclotron, we have measured A_{yy} at a deuteron bombarding energy of 20 MeV. Further measurements at higher energies are planned.

Footnotes and References

*Physics Department Duke University, Durham, North Carolina 27706.

†National Bureau of Standards, Gaithersburg, Maryland 20899.

High Energy Gamma Emission Following Heavy Ion Collisions

C.A. Gossett, J.A. Behr,* J.H. Gundlach,* K.A. Snover,* K.T. Lesko, and E.B. Norman*

Using the recently installed 10″ × 10″ NaI detector at LBL's 88-Inch Cyclotron, we have measured continuum γ-ray spectra following heavy ion collisions to investigate nonstatistical processes in these reactions and to search for possible nuclear shape changes at finite temperature and spin. Extending earlier work[1]

in which we observed a splitting of the giant dipole resonance (GDR) built on excited states in ^{160,166}Er, indicating that these nuclei have the same prolate deformation at temperature T~1 MeV as is observed for the ground state, we have studied the γ decay of ^{166}Er* formed at initial excitation energies of 70 and 105 MeV in the ^{12}C+^{154}Sm reaction at E(^{12}C)=84 and 121 MeV, respectively. Preliminary analysis suggests that the high energy γ yield from measurements at 84 MeV can be accounted for by decay from a thermally equilibrated system, while that measured at 121 MeV is well in excess of a statistical model calculation. In studies of ^{12}C+Ta and ^{12}C+^{98}Mo for E(^{12}C)=200 Mev, the measured γ spectra exhibit a bump near the GDR energy and extend to E_γ ~50–60 MeV.

Footnotes and References

*Nuclear Physics Laboratory, University of Washington, Seattle, Washington 98195.

1. C.A. Gossett *et al.*, Phys. Rev. Lett. **54**, 1486 (1985).

Exotic Nuclei and Decay Modes

*Joseph Cerny, F. B. Blönnigen, M. A. C. Hotchkis, W. F. Knoll, T. F. Lang, D. M. Moltz, J. E. Reiff, X. Xu**

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 for A<70, 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. Recently 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. Use of this spectroscopic tool has been used more recently in a search for the decay of a second T_z= −5/2 nucleus, ^{23}Si. Results to date have proven inconclusive.

The beta-delayed single proton emissions from the A= 4n+1, T_z= −3/2 nucleus ^{61}Ge had been previously observed in ^{24}Mg + ^{40}Ca reactions utilizing a technique which viewed activity remaining in a target between macroscopic (100 ms) cyclotron beam bursts. More recently, ^{61}Ge was observed using the helium-jet recoil transport method. Attempts to extend this series of delayed proton emitters to ^{65}Se by observing the products of ^{28}Si + ^{40}Ca reactions were unsuccessful despite the fact that a wide range of bombarding energies and lifetimes were covered. Although ^{65}As is predicted to be a strong candidate for ground state proton emission, ^{65}Se is predicted to be particle stable. Thus our failure to observe ^{65}Se is not fully understood.

Since the study of these exotic nuclei is often hampered by very short lifetimes and by copiously and simultaneously produced radioactivities with similar decay modes, much effort this past year has been put into revamping the on-line mass separator RAMA and into designing a fast rotating wheel suitable for studying nuclides with half-lives in the 100 ms to 100 μs range. Both of these experimental tools should be heavily utilized in the very near future.

Footnotes and References

*Inst. of Modern Physics, Lanzhou, China

The Beta-Delayed Proton Decay of ^{61}Ge*

M.A.C. Hotchkis, J.E. Reiff, D.J. Vieira,† F. Blönnigen, T.F. Lang, D.M. Moltz, X. Xu, and J. Cerny

The decays of many proton rich light nuclei have been identified by their beta-delayed proton emission. All members of the $T_z = -3/2$, $A = 4n + 1$ series of nuclei from ^{9}C to ^{57}Zn exhibit this decay mode. In this work, we have extended the series by observing the delayed proton decay of ^{61}Ge. Two different beams were used to confirm the existence and decay of this nucleus. ^{61}Ge was produced in the ^{40}Ca(^{24}Mg, 3n) and ^{40}Ca(^{28}Si, α3n) reactions at energies ranging from 73 to 128 MeV. Fig. 1 shows the spectrum resulting from the 120 MeV ^{24}Mg + Ca bombardment. A single proton group at 3.11 ± .03 MeV with $t_{1/2} = 40 \pm 15$ ms is evident corresponding to the decay of the T = 3/2 isobaric analog state in ^{61}Ga to the ground state of ^{60}Zn. Also present are protons from the decays of ^{53}Co^{m}, ^{59}Zn, ^{57}Zn, and ^{25}Si, which are produced concurrently. The next member of the series, ^{65}Se, was searched for but not found.

Footnotes and References

*Condensed from LBL-22006; Phys. Rev. C **35**, 315 (1987).

†Present address: Isotope and Nuclear Chemistry Division, Los Alamos National Laboratory, Los Alamos, NM 87544.

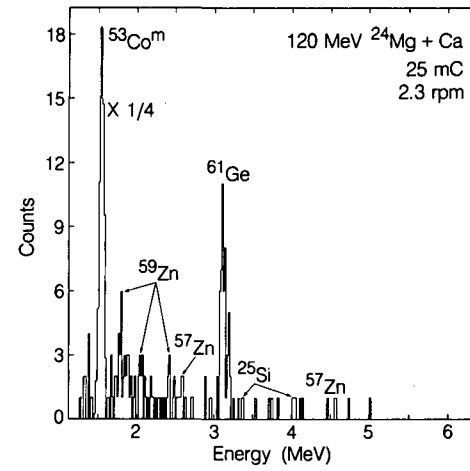


Fig. 1. Energy spectrum from 120 MeV ^{24}Mg on Ca.
XBL 864-10764B

E2 Properties of the Ground-State Band in ^{248}Cm*

*T. Czosnyka,† D. Cline,‡ L. Hasselgran,§ C.Y. Wu,‡ R.M. Diamond, H. Kluge,** C. Roulet, E.K. Hulet,†† R. W. Lougheed,†† and C. Baktash‡‡*

The transuranium nucleus ^{248}Cm has been Coulomb excited using 641 MeV ^{136}Xe from the LBL SuperHILAC and 260 MeV ^{58}Ni projectiles from the Brookhaven tandem. Only the ground band was excited with measurable cross sections. The E2 transition matrix elements involving the ground-band states up to spin 24^+ have been extracted from these Coulomb excitation data using a new semiclassical Coulomb-excitation least-squares search code. The extracted E2 transition matrix elements agree with the spheroidal rigid-rotor relation to within the experimental errors. In addition static electric quadrupole moments have been measured up to spin 20^+ for the first time for a strongly deformed nucleus, uniquely determining the prolate shape of the ground band of ^{248}Cm.

Footnotes and References

*Abstracted from Nucl. Phys. **A458**, 123 (1986).

†SLCJ, University of Warsaw, Hoza 69, OO-681 Warsaw, Poland.

‡Nuclear Structure Research Laboratory, University of Rochester, Rochester, New York 14627.

§Institute of Physics, University of Uppsala, Box 530, S-751 Uppsala, Sweden.

**Hahn-Meitner Institute, D-1000 Berlin, 39, West Germany.

††Lawrence Livermore National Laboratory, Livermore, California 94550.

‡‡Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830.

Lineshape Analysis of High Spin States: Collectivity in ^{166}Yb*

J.C. Bacelar, R.M. Diamond, E.M. Beck, M.A. Deleplanque, J. Draper, and F.S. Stephens

The Doppler-shift attenuation method was used to measure lifetimes of yrast states in ^{166}Yb. Three different stopping materials were used and consistent results were obtained over a large range of spins. Values of τ range from 1.20(10)ps at 18^+ to 0.05(1)ps at 34^+. The B(E2) values steadily decrease from 200 spu to 120 spu as the spin increases above $24\hbar$ (Fig. 1). This loss of collectivity is likely to reflect a change towards triaxial shapes. Such a change would cause an increase in the moment of inertia, $\mathcal{J}$, but over this spin range the experimental values of $\mathcal{J}$ are remarkably constant. It would appear that simultaneous changes in the pairing correlations and/or particle alignments would be necessary to cancel the effect of the shape change. But it is puzzling why this apparently accidental cancellation should be so good and should occur for a half-dozen nuclei in this region.

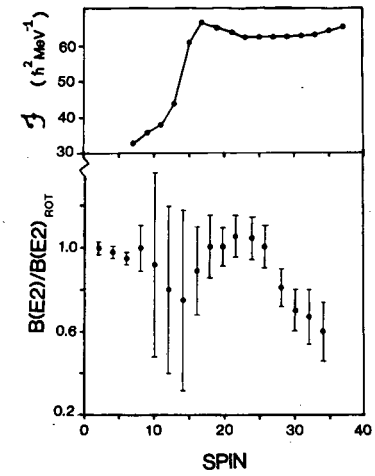


Fig. 1. Variations of B(E2)/B(E2)$_{rotor}$ (normalized to 1.0 for the $2^+ \rightarrow 0^+$ transition) and the kinematic moment of inertia $\mathcal{J}$ versus spin are shown for the yrast states of ^{166}Yb. The low spin ($<18^+$) B(E2) data are recoil-distance measurements taken from the literature. XBL-8610-4081A

Footnotes and References

*Abstracted from LBL-22410.

Gamma Decay of Isovector Giant Resonances Built on Highly Excited States in ^{111}Sn*†

J.J. Gaardhøje,‡ C. Ellegaard,‡ B. Herskind,‡ R.M. Diamond, M.A. Deleplanque, G. Dines, A.O. Macchiavelli, and F.S. Stephens

Gamma-ray transition-energy spectra up to E_γ = 33 MeV have been measured for the decay of the compound nucleus ^{111}Sn* populated at excitation energies up to ~100 MeV. The reaction ^{20}Ne+^{91}Zr→^{111}Sn* was used with 100 and 140 MeV ^{20}Ne beams from the 88-Inch Cyclotron. The high-energy γ rays were detected in six (vertically arranged) pairs of 12.5×15 cm NaI(Tl) crystals 50 cm from the target. The cosmic-ray background was reduced by requiring; a high data rate, only one γ ray with $E_\gamma > 6$ MeV per event, and a fast coincidence with a CsF detector near the target. Above

$E_\gamma \sim 20$ MeV an excess of gamma rays over the contribution from the isovector giant dipole resonance (at ~15 MeV) is observed in the energy range where the isovector giant quadrupole resonance (~27 MeV) built on excited states is expected, and this excess corresponds to the full sum-rule strength for the GQR. Finally, a comparison of the width of the GDR at ~100 MeV excitation with widths determined at lower excitation shows a large increase (doubling) with increasing excitation and angular momentum.

Footnotes and References

†Condensed from Phys. Rev. Lett. **56**, 1783 (1986).

‡The Niels Bohr Institute, University of Copenhagen, Copenhagen 2100 Ø, Denmark.

The Damping of Nuclear Rotational Motion at Modest Temperatures*

F.S. Stephens, J.E. Draper,† J.L. Egido,‡ J.C. Bacelar, E.M. Beck, M.-A. Deleplanque, and R.M. Diamond

There is mounting evidence that the nuclear rotational motion is damped at modest (~0.5 MeV) temperatures, which reduces correlations between the energies of γ rays emitted in a rotational cascade. The nucleus ^{160}Er has been produced at the LBL 88-Inch Cyclotron, and studied using the HERA detector system. For this case we found these $E_\gamma - E_\gamma$ correlations to be completely washed out above γ-ray energies of ~1.3 MeV (corresponding to the highest temperatures), which requires a damping width around 250 keV. This is presumably the main effect of the damping. There are $E_\gamma - E_\gamma$ correlations observed below 1.3 MeV, an example of which is shown in Fig. 1. The dip observed in the gated spectrum reflects the fact that no two (perfect) rotational γ rays can have the same energy. The dip in Fig. 1 is quite small, due, we believe, to the fact that most cascades at this γ-ray energy (1.1 MeV) already feel the main damping effect. The dip, itself, we propose, is generated in lower-temperature regions where the damping is quite weak or absent.

This damping is the first small step in the transition from order (the deformed nucleus rotating collectively) to chaos (a hot nuclear gas) or equivalently in the restoration of rotational invariance to the deformed nuclei, whose intrinsic shapes break this symmetry. It is not often in nuclei that this first step can be so well isolated and studied.

Footnotes and References

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†University of California, Davis, California 95616.

‡Departmento de Física Teórica, Universidad Autónoma, Madrid, Spain.

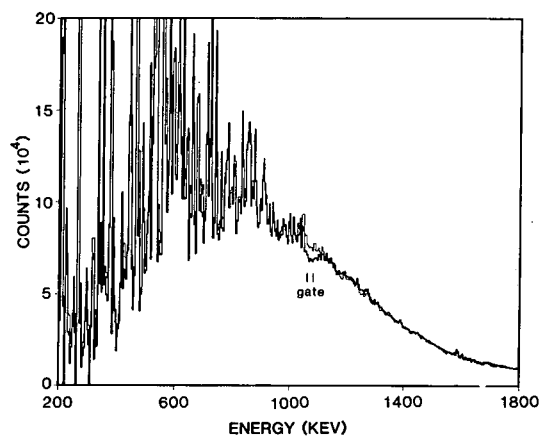

Fig. 1. Spectra from two 0.5 mg/cm^2 ^{124}Sn targets bombarded by 180 MeV ^{40}Ar ions producing mainly ^{159}Er and ^{160}Er. The lighter line is the full projection of all coincidences, whereas the darker one is coincident with the narrow gate indicated. The two-dimensional matrix from which these spectra were taken has been unfolded. XBL 865-1834

High-Spin State Spectroscopy in ^{165,166}Yb*

E.M. Beck, J.C. Bacelar, M.A. Deleplanque, R.M. Diamond, F.S. Stephens, J.E. Draper,†
B. Herskind,‡ *A. Holm,*‡ *and P.O. Tjøm*§

The first data from the complete High Energy-Resolution Array (HERA) were presented in this paper. High-spin states in ^{165,166}Yb were populated by means of the reaction ^{130}Te (^{40}Ar, xn), the experiments being carried out at the 88-Inch Cyclotron. Level schemes of ^{165}Yb and ^{166}Yb were studied up to high spins. Triple γ-ray coincidence spectra were analyzed for the first time. The observed bands in both nuclei were interpreted in terms of the cranked-shell model. In particular, the continuation of the lowest $i_{13/2}$ single quasineutron aligned band beyond the first observed backbend was seen in an odd-N nucleus and the interaction strength between this band and the three-quasiparticle band was evaluated. Constancy of the moment of inertia in ^{166}Yb was observed at high spins and interpreted.

Footnotes and References

*Condensed from Nucl. Phys. A (in press)

†University of California, Davis, CA 95616

‡The Niels Bohr Institute, University of Copenhagen, DK 2100 Copenhagen, Denmark

§University of Oslo, Oslo, Norway

1. W. Walus, N. Roy, S. Jonsson, L. Carlen, H. Ryde, G.B. Hagemann, B. Herskind, J.D. Garrett, Y.S. Chen, J. Almberger, and G. Leander, Phys. Scr. **24**, 324 (1981)

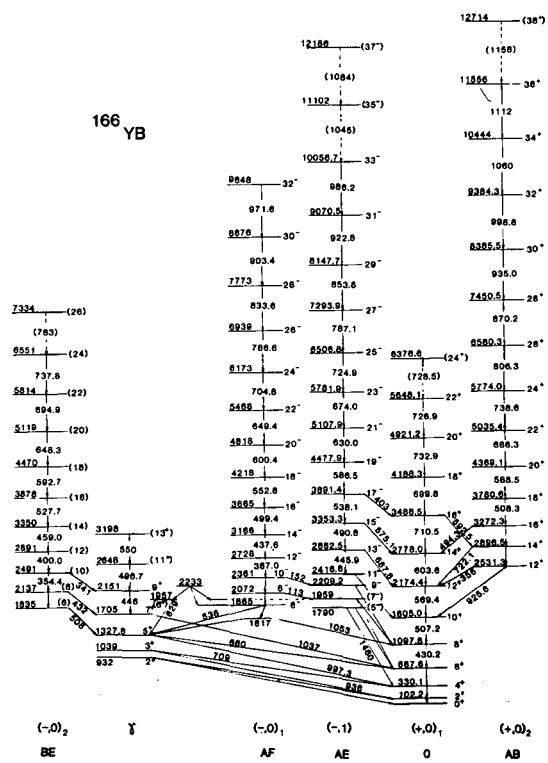

Fig. 1. Level scheme of ^{166}Yb as obtained from the present analysis. Cross-band transitions in the lower part of the scheme and the positive-parity band with its band-head at 932 keV are taken from ref. 1.

XBL 865-2099

Particle-Hole States in ^{150}Dy*

M.A. Deleplanque, J.C. Bacelar, E.M. Beck, R.M. Diamond, F.S. Stephens, J.E. Draper, Th. Døssing, and K. Neergård

The nucleus ^{150}Dy was studied at the 88-Inch Cyclotron of the Lawrence Berkeley Laboratory by the reaction ^{40}Ar(^{114}Cd,4n). Its γ-ray decay was observed with the HERA array of 21 Compton-suppressed germanium detectors. The level scheme has been constructed up to around spin 40 (see Fig. 1) and shows a non-collective behavior all the way up. Three different regions of excitation energy and spin can be distinguished and interpreted in the framework of the Deformed Independent Particle Model. Up to spin 20–22, valence particle excitations form subshell seniority multiplets. Above, the ^{146}Gd core has to be broken. The most remarkable feature in this nucleus is that the one proton particle-hole (p-h) and the one neutron p-h states occur in mostly separate and competitive cascades at the same excitation energy and spin. This is a result of a balance, for this nucleus, of the effects of (1) (proton) pairing forces, (2) the number of available high-j proton versus neutron orbitals, and (3) the deformation driving properties of the neutron hole orbitals. At the highest spins, one proton p-h and several neutron p-h states are observed, probably because more neutron high-j orbitals are available.

Footnotes and References

*Condensed from LBL report 21664 and submitted to Phys. Lett.

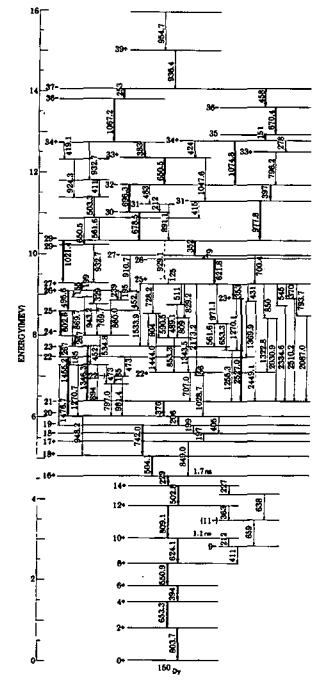

Fig. 1. Level scheme of ^{150}Dy. XBL 868-3184

Search for Correlated Narrow-Peak Structure in the Two-Photon Spectrum from 6-MeV/Nucleon U+Th Collisions*

*W.E. Meyerhof,† J.D. Molitoris,‡ K. Danzmann,† D.W. Spooner,† F.S. Stephens, R.M. Diamond, E.M. Beck, A. Schäfer,§ and B. Müller***

We have searched for 180° (c.m.) correlated equal-energy two-photon decays produced in 6-MeV/nucleon U+Th collisions at the LBL SuperHILAC. In the summed-energy region between 1.5 and 1.8 MeV, we set an upper limit of 3×10^{-10} decay per projectile for the yield integrated over a target thickness of 3.6 mg/cm^2, which corresponds to a cross section of 3×10^{-29} cm^2 averaged over the target. This can be compared to a production cross section of $(1-2)\times10^{-28}$ cm^2, averaged over a target thickness of 0.3-0.6 mg/cm^2 found by others for correlated electron-positron pairs in the same reaction.

Footnotes and References

*Abstracted from Phys. Rev. Lett. **57**, 2139 (1986).

†Department of Physics, Stanford University, Stanford, California 94305.

‡Present address: Lawrence Livermore National Laboratory, Department of Physics/E-Division, Livermore, California 94550.

§Present address: W.K. Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California 91125.

**Institut für Theoretische Physik, J-W. Goethe Universität, 6000 Frankfurt 11, West Germany.

^{12}C Decay of ^{224}Mg Following Nuclear Inelastic Scattering*

J. Wilczynski,† K. Siwek-Wilczynska,‡ Y. Chan, E. Chavez,§ S.B. Gazes and R.G. Stokstad

We have observed three states (21.9, 23.6 and 24.8 MeV) in the spectrum of ^{24}Mg that decay into two ground-state ^{12}C nuclei following the inelastic-scattering reaction (Fig. 1):

$$^{12}\mathrm{C}(^{24}\mathrm{Mg}, ^{24}\mathrm{Mg}^* \rightarrow ^{12}\mathrm{C}_{g.s.}{}^{12}\mathrm{C}_{g.s.})^{12}\mathrm{C}_{g.s.}.$$

There are strong indications for a non-statistical nature of these states. From a study of angular correlations of ^{12}C – ^{12}C coincidences, the spins have been determined to be $2^+, 0^+(2^+)$, and 0^+ respectively. It seems that in both inelastic hadron scattering and electromagnetic reactions, a specific group of low-spin states in ^{24}Mg of considerable ^{12}C + ^{12}C parentage is excited. An interesting open question is whether the 2^+ states are coupled to the giant quadrupole resonance in ^{24}Mg and whether the 0^+ state(s) might be interpreted as some kind of β-vibrations. A coupling of the 0^+ state(s) observed in this work to the giant monopole resonance seems unlikely.

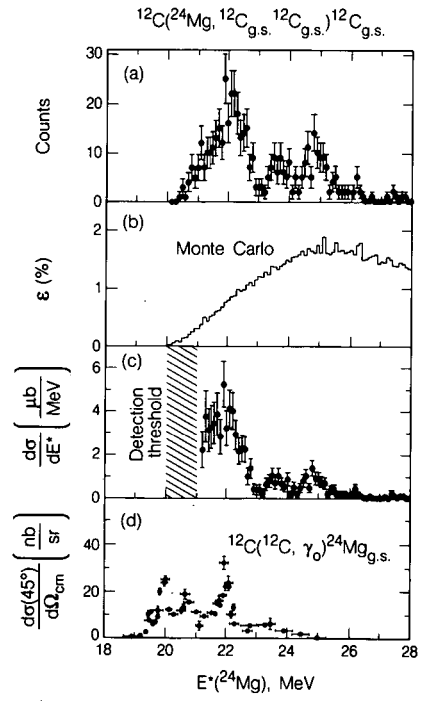

Fig. 1. (a) Spectrum of the ^{12}C(^{24}Mg, ^{12}C$_{g.s.}$ ^{12}C$_{g.s.}$)^{12}C$_{g.s.}$ reaction as a function of the excitation energy of ^{24}Mg; (b) Detection efficiency, ϵ, calculated with the Monte Carlo method; (c) Spectrum (a) corrected for the energy dependence of the efficiency, ϵ; (d) Spectrum of the radiative-capture reaction ^{12}C(^{12}C, γ_0)^{24}Mg$_{g.s.}$, redrawn from Fig. 7a of ref. 1. XBL 862-9765

Footnotes and References

*Condensed from LBL 21415, Phys. Lett. B **181**, 229 (1986).

†Permanent address: Insititute for Nuclear Studies, 05-400 Swierk/Warsaw, Poland.

‡Permanent address: Insititute of Experimental Physics, Warsaw University, 00-681 Warsaw, Poland

§Permanent address: Insitituto de Física UNAM, A.P. 20364, México, 01000, D.F. México.

1. A.M. Nathan *et al.* Phys. Rev. **C24**, 932 (1981).

Study of Heavy Fragment Emission in Excited Light Nuclei

E.Plagnol, G. Auger, D.R.Bowman, Y.D.Chan, R.J.Charity, E.Chavez, S.B.Gazes, H.Han, W.L.Kehoe, M.A.McMahan, L.G.Moretto, R.G.Stokstad, L.Vinet, G.J.Wozniak*

A series of experiments was performed on the $^{40}Ar+^{12}C$ system at 8,10,15 and 20 MeV/nucleon to search for evidence of heavy fragment emission following fusion. The inverse kinematic technique, using the heavier ^{40}Ar as the beam, was used to focus the events in the forward angular cone and to achieve high detection efficiency. Two ionization chambers (Φ = 5cm., at d = 25 cm. from target)were positioned on either side of the beam to detect both single and coincidence (between the emitted fragment and the residual nucleus) events. Events were charge identified from Z=3 to 21, and at all energies but the lowest, extensive and continuous angular distributions were obtained (4deg $< \Theta_{lab} <$ 40 deg).

The data collected show that, for 15 MeV/nucleon: i) there is a continuous evolution from evaporation of light particles (n,p and α) to heavy fragment emission and fission processes, ii) a large majority of the binary events can be associated with the decay of the compound nucleus (the mean velocity of the emitter was found to be independent of the assymetry of the break-up and identical to the velocity of those events that proceed through light particle emission only) ,iii) the relative probabilty of heavy fragment emission can be estimated to be of the order of ~15% of those events that proceed only through light particle emission. Fig 1. shows an example of a two dimensional velocity plot for the production of Z=8 nuclei. The circle is a guide for the eye representing the approximate locus of the more probable events.

From the coincidence events one can measure that the total charge detected has a average value of Z~20 (the complete fusion process should lead to a Z=24 compound nucleus, however at this energy, preequilibrium effects limits the maximum value to Z~23), indicating that these heavy fragment emissions are also associated with complementary particle evaporation. On the other hand, heavy fusion residues that would normally be associated with light particle evaporation are also seen to proceed, in some cases, by heavy fragment emission.

Footnotes and References

*Nuclear Chemistry Division, Stony Brook, SUNY

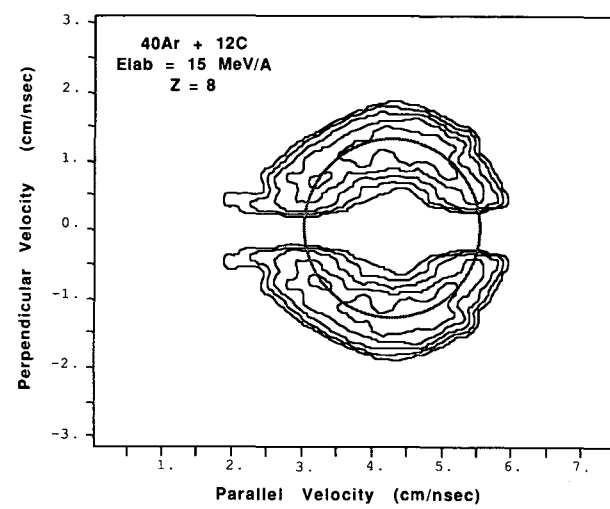

Fig. 1. Two dimensionnal plot of the production of Z=8 nuclei versus the laboratory velocity parallel to the beam and the velocity perpendicular to the beam. XBL 8611-4612

3-Body Final States in Peripheral Heavy-ion Collisions: Nuclear Clustering Structure and Projectile Excitation Revisited*

*Y. Chan, E. Chavez,† S.B. Gazes, R. Kamermans,‡ H.R. Schmidt, J. Siwek-Wilczynska,§ R.G. Stokstad, and J. Wilczynski***

Even though peripheral heavy-ion collisions are less violent than their central counterparts, the large energy exchange between the reactants often leaves the primary products in excited particle-unstable states whose subsequent decay leads to 3 or more nuclei emerging in the final exit channel. These post-reaction, predominantly sequential de-excitation processes can sometimes provide interesting structural information about the parent nuclei. We have provided evidence for the existence of states (or groups of states) in ^{24}Mg that have significant widths decaying into two ^{12}C nuclei following nuclear excitation in the ^{12}C(^{24}Mg, ^{12}C^{12}C) reaction. Also by studying breakup processes in reactions induced by 10–32 MeV/nucleon ^{16}O and ^{20}Ne projectiles the partition of excitation energy between the projectile-like and target-like primary fragments are examined.

Footnotes and References

*Condensed from LBL-21650

†Permanent address: Insitituto de Física UNAM, A.P. 20364, México, 01000, D.F. México.

‡Present address: Fysisch Laboratorium, University of Utrecht, The Netherlands.

§Permanent address: Insititute of Experimental Physics, Warsaw University, 00-681 Warsaw, Poland.

**Permanent address: Insititute for Nuclear Studies, 05-400 Swierk/Warsaw, Poland.

Fusion of ^{16}O + ^{144}Sm at Sub-barrier Energies*

*D.E. Di Gregorio,† J.O. Fernandez Niello,† A.J. Pacheco, D. Abriola,† S. Gil,† A.O. Macchiavelli,† J.E. Testoni,†‡ P.R. Pascholati,§ V.R. Vanin,§ R. Liguori Neto,§ N. Carlin Filho,§ M.M. Coimbra,§ P.R. Silveira Gomes,** and R.G. Stokstad*

Fusion cross sections have been measured for the system ^{16}O + ^{144}Sm at bombarding energies in the range 63 MeV$<E_{lab}(^{16}O)\leq$72 MeV by observation of delayed X-rays emitted by the evaporation residues. Comparison of the present results for the magic nucleus ^{144}Sm with those already existing for the fusion of ^{16}O with other samarium isotopes shows that the enhancement of the cross sections at sub-barrier energies can be explained in terms of a one-dimensional barrier-penetration model that incorporates the quadrupole deformation parameter, β_2. There is no need to invoke the neck degree of freedom.

Footnotes and References

*Condensed from LBL-20968 and Phys. Lett. B **176**, 322 (1986).

†Departamento de Física, Comisión Nacional de Energía Atómica (1429) Buenos Aires, Argentina.

‡Fellow of CONICET, Argentina,

§Instituto de Fisica da Universidade de Sao Paulo, Caixa Postal 20516, Sao Paulo, Brazil.

**Instituto de Fisica da Universidade Federal Fluminense, Caixa Postal 296, Niteroi, Brazil.

Partition of Excitation Energy in Peripheral Heavy-Ion Reactions*

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

The partition of excitation energy between target-like and projectile-like primary fragments from 11 MeV/nucleon ^{20}Ne + ^{197}Au quasi-elastic reactions was determined from kinematic analyses of three-body final states. Projectile breakup following stripping, pickup, and inelastic scattering was studied, and the excitation-energy partition was found to be strongly correlated with the direction of the mass transfer. Results are in quantitative agreement with optimum-Q-value calculations.

Footnotes and References

*Condensed from LBL-21822 and Phys. Lett. B **160**, 9 (1986).

†Present address: Fysisch Laboratorium, University of Utrecht, The Netherlands.

Projectile Breakup and Transfer Reemission Reactions in the ^{12}C + ^{20}Ne System*

K. Siwek-Wilczynska,[†] *J. Wilczynski,*[‡] *C.R. Albiston, Y. Chan, E. Chavez,*[§] *S.B. Gazes, H.R. Schmidt, and R.G. Stokstad*

The ^{12}C(^{20}Ne, α^{16}O$_{g.s.}$)^{12}C$_{g.s.}$, ^{12}C(^{20}Ne, α^{20}Ne) ^{8}Be$_{g.s.}$, and ^{12}C(^{20}Ne, α^{12}C)^{16}O* reactions at E(^{20}Ne) = 157 MeV were studied by using position-sensitive telescopes. It was established that α^{16}O coincidences in the first reaction result not only from sequential breakup of the projectile, but also from the transfer- reemission process

$$^{12}\mathrm{C}(^{20}\mathrm{Ne}, ^{16}\mathrm{O}_{g.s.})^{16}\mathrm{O}^* \rightarrow \alpha + ^{12}\mathrm{C}_{g.s.}.$$

By using 3-body final-state ($\mathbf{P + T \rightarrow 1 + 2 + 3}$) analysis methods it was found that both states corresponding to the (**1,2**) and (**1,3**) subsystems were observed (Fig. 1). Distributions of the excitation energy in the primary reaction products were deduced by calculating respective branching ratios with a Hauser-Feshbach statistical decay code. It was found that excitation energy is generated in mass transfer reactions quite asymmetrically: it is mostly concentrated in the nucleus that acquires mass while the "donor" nucleus, on the average, remains cold. These results clearly support the basic concept of "spectator" models of heavy-ion reactions.

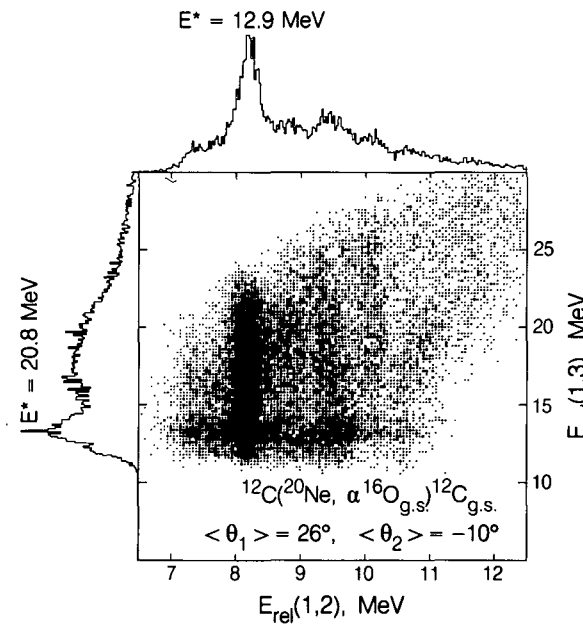

Fig. 1. Scatter plot for the analysis of two-body intermediate states in the reaction with three particles in the final state to sequential breakup of the projectile. Intermediate states in both E_{rel}(1,2) and E_{rel}(1,3) are seen. They correspond to projectile breakup and transfer reemission reactions, respectively.

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Footnotes and References

*Condensed from LBL-21723, submitted to Phys. Rev. C.

†Permanent address: Insititute of Experimental Physics, Warsaw University, 00-681 Warsaw, Poland

‡Permanent address: Insititute for Nuclear Studies, 05-400 Swierk/Warsaw, Poland.

§Permanent address: Insitituto de Física UNAM, A.P. 20364, México, 01000, D.F. México.

Study of Incomplete Fusion for Light Heavy-ion Systems Using Velocity Distributions*

*Y. Chan, C. Albiston, M. Bantel,† A. Budzanowski,‡ D. DiGregorio,§ R.G. Stokstad, S. Wald,** S. Zhou,†† Z. Zhou‡‡*

The fusion between two light heavy-ions to form a medium mass compound nucleus ($A_{CN} \leq 80$) has been an active area of research in the past two decades. This report presents experimental results on velocity distribution of fusion-like residues in the energy range of 6–20 MeV/nucleon. Besides our own measurements, results from other groups at the Hahn-Meitner Institute and the Argonne National Laboratory are also cited.

In summary, the residue velocity distributions indicate that incomplete fusion is important in this mass region for $E_{Beam} \geq 5$ MeV/nucleon above the Coulomb barrier. An interesting systematics for complete fusion versus incomplete fusion has been established based on the center of mass velocity of the lighter reactant. The mechanism responsible for this behavior, however, is still not clear. While the schematic nucleon Fermi-velocity models provide interesting insight into this problem, quantitative agreement with experimental data is still lacking. It is likely that only at the very high bombarding energies that fast nucleon emission can play an important role.

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†Present address: The Max-Planck Institute, Heidelberg, West Germany.

‡Present address: Institute for Nuclear Physics, Cracow, Poland.

§Present address: Tandar, Buenos Aires, Argentina.

**Present address: The Weizmann Institute, Rehovot, Israel.

††Present address: The Institute of Atomic Energy, Beijing, China.

‡‡Present address: Physics Department, Nanking University, Nanjing, China.

Transfer and Breakup Reactions at Intermediate Energies*

R.G. Stokstad

The origin of the quasi-elastic peak in peripheral heavy-ion reactions is discussed in terms of inelastic scattering and transfer reactions to unbound states of the primary projectile-like fragment. The situation is analogous to the use of reverse kinematics in fusion reactions, a technique in which the object of study is moving with nearly the beam velocity. It appears that several important features of the quasi-elastic peak may be explained by this approach. Projectile-breakup reactions have attractive features for the study of nuclear structure. They may also be used to determine the partition of excitation energy in peripheral reactions. At intermediate energies, neutron-pickup reactions leading to four-body final states become important. Examples of experiments are presented that illustrate these points.

Footnotes and References

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Heavy-Ion Induced Adhesion of Thin Gold films to Oxidized Substrates of Tantalum and Silicon*

R.G. Stokstad, P.M. Jacobs,† I. Tserruya,†
L. Sapir,† and G. Mamane†

Energetic heavy ion beams are capable of enhancing the adhesion of metallic films to a variety of substrates. Gold films (200-600 Å) evaporated onto substrates of tantalum and silicon (with native oxides) were bombarded with ions of ^{12}C, ^{16}O, ^{28}Si, ^{35}Cl and ^{58}Ni at 2.85 Mev/nucleon. The threshold dose required to produce a peel strength greater than the Scotch tape peel strength for a gold surface was measured as a function of ion species and angle of incidence. We observed the threshold dose to vary as the cosine of the angle with respect to normal incidence. The dependence on particle type for the Au-Ta system (with approximately 40 Å native oxide) was found to be $D^{th}(cm^{-2}) = 10^{17}(dE/dx)_{Au}^{-3.0\pm0.2}$ for all particle beams where $(dE/dx)_{Au}$ is the electronic stopping power (MeV cm^2/mg) of the ion in gold. A substrate of 6000 Å of tantalum oxide gave identical results. The value of the exponent, -3.0 ± 0.2, differs significantly from the value -1.6 ± 0.2 reported earlier by Tombrello *et al.* for Au-Ta. The Au-Si system is described by $D^{th} = 6 \times 10^{18}(dE/dx)_{Au}^{-4.1\pm0.3}$. Auger analysis of the Au-Ta interface suggests a migration of the native oxygen as a result of ion bombardment. For the Au-Ta system, some irradiated regions that passed the Scotch tape test just after bombardment were observed to fail when the test was repeated a few days later. Thicker gold films and higher doses resulted in longer adhesion times. These and other observations suggest that the post-irradiation decline of adhesion for Au-Ta is caused by diffusion of ambient atoms through the gold film rather than by an intrinsic time dependence of the adhesive forces.

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*Condensed from LBL-19872 and Nucl. Inst. and Meth. **B16**, 465 (1986).

†Department of Nuclear Physics, Weizmann Institute of Science, Rehovot 76100, Israel.

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

R.G. Stokstad P.M. Jacobs,† I. Tserruya,†
L. Sapir,† and G. Mamane†

The ability of heavy-ion beams to enhance the adhesion of thin metallic films to substrates has been studied as a function of projectile species. Measurements of the adhesion enhancement of a thin gold film to substrates of tantalum and silicon (with native oxides) have been made for beams of ^{12}C, ^{16}O, ^{28}Si, ^{25}Cl, and ^{58}Ni at 2.85 MeV per nucleon. The threshold dose required to pass the Scotch tape peel test was found for the Au-Ta system to be D^{th} (cm^{-2}) $= 10^{17}$ $(dE/dx)^{-3.0\pm0.2}$ where dE/dx is the electronic stopping power (MeV mg^{-1}cm^2) of the ion in Au. For the Au-Si system, $D^{th} = 6 \times 10^{18}$ $(dE/dx)^{4.1\pm0.3}$. The steep dependence of Dth on dE/dx found here is in contrast with an earlier measurement for the Au-Ta system by Tombrello *et al.* The adhesion enhancement was observed to decrease

with time after the bombardment in a manner suggesting that diffusion of atoms through the gold film is important. The possible importance of small concentrations of extraneous atoms at the interface is discussed.

Footnotes and References

*Condensed from LBL-20302 and J. Mater. Res. **1**, 231 (1986).

†Department of Nuclear Physics, Weizmann Institute of Science, Rehovot, Israel.

Evolution of Intermediate Energy Target Fragmentation Mechanisms with Increasing Projectile Size

W. Loveland, K. Aleklett,† G.T. Seaborg, C. Casey,* J.V. Kratz,‡ J.O. Liljenzin,§ A. Rojas,* and L. Sihver†*

Changes in the systematics of linear momentum transfer in intermediate energy nuclear collisions occur in going from lighter (C–Ne) to heavier projectiles (Ar–Kr).[1] We thought it would be informative to search for other changes in the target fragment properties as the projectile size increases (at approximately constant projectile velocity). We have measured the properties of Au target fragmentation in reactions induced by 35–50 MeV/nucleon ^{12}C, ^{20}Ne, ^{40}Ar and ^{84}Kr. The heavy ($A_{frag} \geq 2/3A_{tgt}$) fragment moving frame angular distributions in the Kr induced reaction are symmetric about 90°, while for the C, Ne and Ar induced reactions, the heavy fragment moving frame distributions are *asymmetric* with respect to 90°. For all systems the fission fragment moving frame distributions are symmetric about 90°. The energy spectra of typical heavy fragments from the Kr induced reaction are Maxwellian in shape while those from the C induced reaction are not. We interpret these results as supporting the idea that the dominant heavy fragment production mechanism changes with increasing projectile size from a fast, non-equilibrium process for the lighter projectiles to a slower process with the establishment of statistical equilibrum for Kr.

Footnotes and References

*Oregon State University, Corvallis, Oregon.

†Studsvik Neutron Research Laboratory, Nyköping, Sweden.

‡University of Mainz, Mainz, Federal Republic of Germany.

§University of Oslo, Oslo, Norway.

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Pre-Equilibrium Emission and Target Fragmentation in Intermediate Energy Nuclear Collisions*

W. Loveland,† A.N. Behkami,† K. Aleklett,‡ and G.T. Seaborg

We have used the 88-Inch Cyclotron along with other intermediate energy heavy ion accelerators (MSU, CERN SC, GANIL), to study the properties of target fragmentation in intermediate energy nuclear collisions. Using radiochemical techniques, we have measured the fragment yields, angular distributions and velocity spectra for a wide variety of reactions involving $^{144,154}Sm$, ^{165}Ho and ^{197}Au targets. In Fig. 1, we show the isobaric yields of target fragments from such reactions as a function of projectile energy. The solid lines represent the results of calculations using a parameter-free Boltzmann transport equation to follow the propagation of excitation energy through the target nucleus. In these calculations, nucleons from the projectile are added to the target nucleus in states above the Fermi level. The

relaxation of these initial configurations by internal nucleon-nucleon scattering or emission into the continuum is followed using a Boltzmann equation appropriately modified to take in account Pauli blocking.

The agreement between calculation and data is excellent. This agreement represents the first successful attempt to describe the essential features of target fragmentation in intermediate energy nuclear collisions and shows the expected importance of nucleon-nucleon collisions.

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‡Studsvik Neutron Research Laboratory, Nyköping, Sweden.

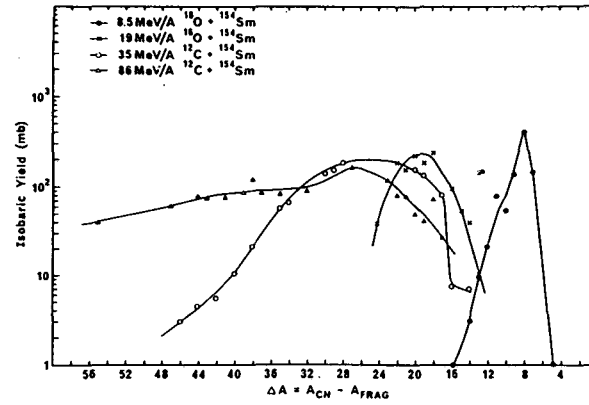

Fig. 1. Isobaric yields of target fragments from the interaction of intermediate energy heavy ions with ^{154}Sm. The solid lines represent calculations using a Boltzmann transport equation. XBL 8610-4169

Production of New Heavy Nuclei

*G.T. Seaborg and W. Loveland**

In preparing a review article[1] on current attempts to synthesize superheavy nuclei, we assembled, in graphical form: (a) the best current estimates of the spontaneous fission and α decay halflives of the heavy nuclei, (b) a semi-empirical representation of the probability of fusion at the s-wave fusion barrier for various projectile-target combinations leading to heavy product nuclei, and (c) the best estimates for the minimum excitation energy of heavy nuclei formed in synthesis reactions.

Application of these systematics to the problem of synthesizing element 110 leads to predicted production cross sections of $\sim 10^{-36}$ cm^2, posing a formidable problem for these efforts. Equally, if not more pessimistic predictions follow from the application of these systematics to the production of superheavy elements ($Z \geq 114$).

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

A. Türler, H.R. von Gunten,*† D.C. Hoffman, K.E. Gregorich, D.M. Lee, M.J. Nurmia, R.A. Henderson, H.L. Hall, R.M. Chasteler, G.T. Seaborg*

Below-target yields in the reaction of ^{40}Ca and ^{48}Ca with ^{248}Cm were reported in the last annual report.[1] In the ^{48}Ca-induced reactions remarkably high cross sections for nuclides far below the target were found even though the bombarding energy was only 10-20 MeV above the Coulomb barrier. Peak cross sections of some 200 microbarns were measured for ^{219}Rn, ^{222}Ra, ^{225}Ac and ^{227}Th. For reactions with ^{40}Ca, yields were measured for only a few isotopes of Th, U, and Pu; these data indicated that the cross sections are lower by two orders of magnitude relative to reactions with ^{48}Ca. We reinvestigated these reactions by bombarding a 640 μg/cm^2 ^{248}Cm target with ^{40}Ca projectiles at three different energies (233 MeV, 255 MeV and 289 MeV on target) at the 88-Inch Cyclotron. Reaction products were collected on Cu-catcher foils, radiochemically separated, and identified by gamma-ray spectroscopy. It was only possible to measure cross sections for Am-isotopes. Peak cross sections are of the order of only 100 microbarns for nuclides with Z of one less than the Z of the target (Fig. 1). The excitation functions of all measured Am isotopes increase with increasing bombarding energy. For Pu, Np, U and Pa isotopes only upper limits of the order of 10 microbarns could be determined. In comparison, the cross section for ^{243}Pu from the ^{48}Ca reactions is almost 1 millibarn. This effect may be due to several reasons: a) It may be that the tendency to reach N/Z equilibrium favors a transfer of protons from the proton-rich projectile to the neutron-rich (proton-deficient) target. b) Calculated excitation energies for below target products indicate that in the case of Th the excitation energy can reach 20 Mev for ^{48}Ca reactions and almost 40 MeV for ^{40}Ca reactions. That means that below target products may be lost by fission. In addition we have measured below target yields in the reaction of ^{18}O + ^{248}Cm. Peak cross sections for Am isotopes reach 200 microbarns and are of the order of 10 microbarns for Pu isotopes. Only upper limits of the order of less than 2 microbarns could be determined for isotopes of Np, U and Pa. Experiments with ^{44}Ca, a projectile between the doubly magic ^{40}Ca and ^{48}Ca are in progress to study the influence of the magic proton and neutron numbers on transfer reactions.

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*Universität Bern, Switzerland

†Eidg. Institut für Reaktorforschung, Würenlingen, Switzerland

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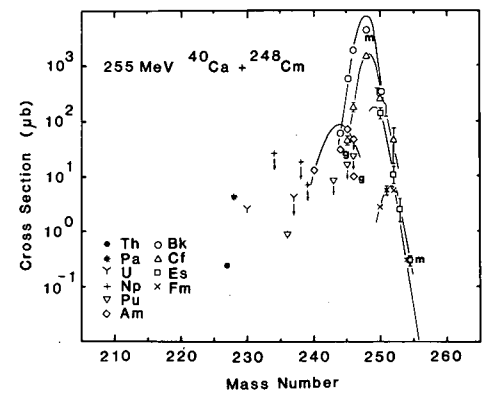

Fig. 1. Mass-yield distributions from the reaction of ^{40}Ca with ^{248}Cm. Symbols m or g indicate that only the cross section for the ground state (g) or the metastable state (m) of this nuclide was measured. Symbols with an arrow indicate upper limits. Data for this plot from D.C. Hoffman *et al.* Phys. Rev. **C 31**, 1763 (1985), M. Lerch, Univ. Mainz and this work. XBL 8611-4414

Reactions of ^{18}O with ^{249}Bk

H.L. Hall, R.A. Henderson, R.M. Chasteler, C.M. Gannett, D.A. Bennett, K.E. Gregorich, S.Y. Cai, R. Chadwick, M.J. Nurmia, Y.Y. Chu, R.A. Agarwal, D.M. Lee, and D.C. Hoffman

As part of our continuing studies of transfer reactions and target-projectile combinations in the heavy actinide region, a target of ^{249}Bk was irradiated with a beam of ^{18}O (102 and 109 MeV on target) at the LBL 88-Inch Cyclotron. The recoiling reaction products were caught on a gold catcher foil placed just downstream from the target. The catcher foil was then removed and processed radiochemically.

Two types of experiments were performed for each run. The first consisted of a short bombardment (about 30 minutes) after which the catcher foil was dissolved, ^{241}Am tracer added, and the Au was removed using an anion exchange column. The sample was then electrodeposited on platinum foil and alpha counted. This allowed us to determine the production cross section of ^{250}Fm as well as giving us a point other than the ^{241}Am tracer to which we could normalize our chemical yields in the longer chemistry. In the second type of experiment, the target was irradiated for 3-6 hours. The catcher foil was again dissolved, ^{241}Am tracer was added, and the Au removed with an anion exchange column. Rare earth elements and +1, +2 ions were removed using a cation exchange column. An elemental separation among the actinides was then performed using a cation exchange column with α-hydroxyisobutyrate as the eluent. The various samples were evaporated onto Pt foils and counted repeatedly.

The production cross sections for the actinides were determined using the measured activities, and corrected for yield using ^{250}Fm and the added ^{241}Am tracer. The cross sections were also corrected for growth of ^{249}Cf[1] in the target. The mass-yield curves are shown in Fig. 1. In general, they are consistent with our other measurements on transfer reactions. The $^{3\pm N}Li$ transfers to make $^{252\pm N}Fm$, however, are considerably larger than results for ^{249}Cf. This is probably a result of the low excitation energy of the Fm products, which is in the range 0-7 MeV. Since the transfers are of similar magnitude to others we've seen before, though, this means ^{249}Bk would be a good choice of target material for production of the heaviest actinides. Admittedly, the cross sections for a given Z tend to be about an order of magnitude less than the cross sections for $^{18}O + {}^{254}Es$,[2] but a ^{249}Bk target can be made two orders of magnitude larger than present Es targets. Thus, while an Es target is the best choice available for transactinide studies, a Bk target is good for studying the chemistry of the Z = 98-103 region.

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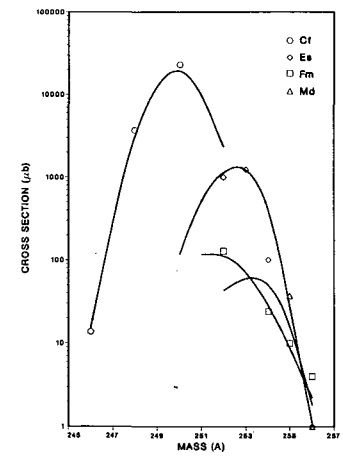

Fig. 1. Mass yield curve for the reactions of ^{18}O and ^{249}Bk. XBL 8612-4925

Possible Detection of New Isotope 263-105

K. E. Gregorich, R. Leres, D. Lee, D. C. Hoffman

A search for an isotope of element 105 with mass 263 was conducted in the early 1970s by Ghiorso *et al.*[1] using the vertical wheel system at the HILAC. They were successful in detecting time-correlated alpha decays from 34-s ^{262}Ha and its 4.3-s ^{258}Lr daughter produced via the ^{249}Bk(^{18}O,5n) reaction. At energies more appropriate for the 4n reaction no time-correlated alpha decays were seen which could be attributed to the alpha decay of ^{263}Ha and its 5.4-s daughter, ^{259}Lr. Recently we conducted a new search for a possible longer-lived ^{263}Ha using the ^{18}O + ^{249}Bk reaction and the MG-RAGS.[2] An 836 μg/cm^2 ^{249}Bk target was bombarded with an ^{18}O beam from the 88-Inch Cyclotron at an energy only slightly above the Coulomb barrier. The reaction products recoiling from the target were attached to KCl clusters and transported out of the recoil chamber, through a capillary, and deposited on thin polypropylene foils on the perimeter of the rotating wheel of the MG. The foils were then stepped between pairs of surface barrier detectors for the detection of alpha and spontaneous fission activities. In 12 μAh, one pair of time correlated alpha decays was recorded which could be attributed to the decay of ^{263}Ha followed by the decay of ^{259}Lr. The lifetime of the potential ^{263}Ha was between 24 and 28 minutes and the alpha energy was 8.3 MeV. The ^{259}Lr alpha at 8.45 MeV followed 2.4 seconds later. In the off-line search for time correlated alpha pairs, when the energy windows of the parent and daughter activities were set from 7.9 MeV to 10.0 MeV, and the maximum time interval between parent and daughter events was 20 seconds, only 4 additional (random) correlated pairs were seen, lending credibility to the assignment of this correlated pair of alpha particles to ^{263}Ha–^{259}Lr. It seems that the earlier experiments performed with the vertical wheel were unsuccessful because they were not sensitive to the long parent lifetimes detected in the current experiment.

Footnotes and References

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β-Delayed Fission from ^{256}Es^{m} and the Level Scheme of ^{256}Fm

H.L. Hall, R.A. Henderson, K.E. Gregorich, D.M. Lee, D.C. Hoffman, J.B. Wilhelmy, M.E. Bunker,* J.W. Starner,* M. Fowler,* and P. Lysaight**

β-Delayed fission (βDF) is of interest for several reasons. First, it allows study of the fission behavior of heavy nuclei. In the heaviest elements, the liquid drop fission barrier is diminishing, thus the fission barrier is mostly due to shell effects. As the nucleus becomes excited, the liquid drop effects may wash out entirely, leaving a fission barrier based purely on shell effects. Such a fission barrier is expected to govern the fission behavior of the super heavy elements.[1] βDF allows investigation of the fission barrier heights in the heavy actinide region,[2,3] which is important to theoretical predictions for superheavies.

In this experiment, a 0.1 μg target of ^{254}Es was bombarded with a 16 MeV tritium beam from the Tandem Van de Graaff Accelerator at the Ion Beam Facility of the Los Alamos National Laboratory, forming ^{256}Es^{m} by the (t,p) reaction. The recoiling reaction products were caught on a gold catcher foil and the Es isotopes were then separated from the other products radiochemically. The β-decay of ^{256}Es^{m} to levels about 1.5 MeV above the ground state in the daughter ^{256}Fm and subsequent γ-decays were then followed using $\beta-\gamma$ correlations, $\gamma-\gamma$ correlations, and β-SF correlations. From these measurements, we were able to construct a more com-

plete level scheme for ^{256}Fm than the earlier one,[4] as well as search for β-delayed fission.

The overall half-life of the 1425 keV level in ^{256}Fm was determined to be 68 ns. Two delayed fission events were observed and a β-delayed fission (βDF) probability of 2×10^{-5} relative to total decay was obtained. This probability and the level half-life yields 3.4 ms as the fission half-life, although the timing of the two events implies a fission half-life of $\approx$0.8 ms and a 95% confidence level range of 0.11 ms to 9.6 ms. An earlier prediction (assuming an even-even nucleus) gave the half-life as ≈ 2.5 μs.[5] Thus, a hindrance factor of about 10^3 was determined for fission from the 1425 keV level in ^{256}Fm. The magnitude of this hindrance factor is consistent with odd-particle fission hindrances determined earlier, although it is important to note that this hindrance factor is for a nucleus in an excited state rather than its ground state.

This is the heaviest system in which β^- decay has been observed. Unfortunately, the small fission branching ratio precludes a study of the fission properties of the ^{256}Fm excited states. However, the results are important for the search for heavier elements. Since spontaneous fission is expected to be the limiting factor in producing new elements, a fission half-life at least three orders of magnitude larger than that predicted theoretically is encouraging for the continuing search for the super heavy elements.

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Preliminary Result on the Ionic Radius of Lawrencium

R. A. Henderson, R. J. Silva, K. E. Gregorich, M. Nurmia, H. L. Hall, C. M. Gannett, D. A. Bennett, R. M. Chasteler, Y. Y. Chu, Shanyu Cai,† A. M. Charlop, R. Agarwal, D. Lee, D. C. Hoffman, and G. T. Seaborg*

Silva *et al*[1] in 1970 showed that the stable oxidation state of lawrencium in aqueous solution is +3. To date this is the only chemical property of lawrencium that has been measured. This measurement, performed with 25-sec ^{256}Lr, helped to confirm that Lr was indeed the last member of the actinide family. With the discovery of three-minute ^{260}Lr, more chemical information can be obtained about Lr. Thermodynamic information about Lr can be obtained from a measurement of the ionic radius, from which the single ion hydration energy can be calculated by using an empirical form of the Born equation. This value can then be inserted into the Born-Haber cycle for the heat of formation of Lr^{+3} in aqueous solution. The object of our study is to infer the ionic radius of Lr^{+3} by comparing its elution position relative to adjacent rare earth elements whose ionic radii are known.

The method used to determine the ionic radius was elution of Lr from a cation exchange column using alpha-hydroxyisobutyrate as the eluant. By bombarding ^{249}Bk with ^{18}O we produce ^{260}Lr, currently the longest-lived known isotope of Lr. We determined that the production cross section for ^{260}Lr is 8 nb. With a chemical processing time of about six minutes, we detected Lr at the rate of one atom per seven experiments (about ninety minutes elapsed time). We have determined the elution position of Lr

with respect to two pairs of rare earth tracers, Tm-Ho and Yb-Er, for which the ionic radii are known. A plot of the ionic radii of the tracers versus the log of the distribution coefficient will result in a straight line, from which we can interpolate the ionic radius of Lr^{+3}.

We found that Lr eluted just beyond the Er elution position, in contrast to the predictions of Goldman and Morss,[3] who predicted that Lr should elute slightly before Er. Using the values for the rare earth radii from the compilation of Templeton and Dauben,[2] we have inferred a preliminary value of 0.885 angstroms for the ionic radius of the Lr^{+3} ion. More data are currently being taken to improve the precision of the determination.

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*Lawrence Livermore Laboratory

†Institute of Atomic Energy, Beijing, China

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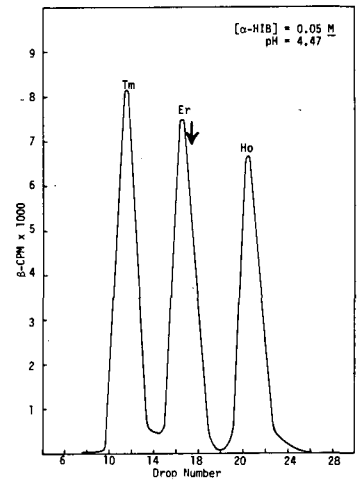

Fig. 1. Schematic elution curve. The arrow points to the Lr elution position. XBL 8611-4363

Attempts to Reduce Lr(III)

K. E. Gregorich, R. A. Henderson, R. J. Silva, R. M. Chasteler, H. L. Hall, C. M. Gannett, D. A. Bennett, D. M. Lee, M. J. Nurmia, A. M.Charlop, Y. Y. Chu, R. Agarwal, and D. C. Hoffman

Calculations of the electronic configurations of the heaviest elements have predicted that relativistic effects play an increasingly important role in the electronic configurations and consequently in the chemical properties of these elements. In fact, the ground state configuration for lawrencium (element 103) is expected to be $[Rn]5f^{14}7p_{1/2}7s^2$ rather than $[Rn]5f^{14}6d_17s^2$ because of stabilization of the $7p_{1/2}$ shell relative to the 6d shell. The normal oxidation state of Lr ions in aqueous solution is +3 with a presumed electronic configuration of $[Rn]\ 5f^{14}$. It has been postulated that the relativistic stabilization of the 7s electrons is sufficient so that the 7p or 6d electron can be selectively removed, and that Lr^{+1} with the $[Rn]\ 5f^{14}7s^2$ configuration, might be accessible in aqueous solution. We have conducted a preliminary experiment to check this possibility. The 3-minute ^{260}Lr was produced by the $^{249}Bk(^{18}O,alpha\ 3n)^{260}Lr$ at the 88-Inch Cyclotron. The recoiling products were transported via a helium jet to a glove box for chemical processing. In the reduction attempts, the Lr^{+3} was adsorbed from 0.3M HNO_3 80°C. Elements in +1 and +2 oxidation states, along with Ac^{+3}, were removed from the column with 0.3M HCl. In an attempt to reduce the Lr, 0.06M NH_2OH in 0.3M HCl was passed through the column. Any activities which were reduced to a charge state of +2 or lower would be removed from the column. Next, any elements in the +3 oxidation state were removed from the column with 3.0M HCl. The fractions were dried, flamed and counted for the 8.03 MeV alpha particles from ^{260}Lr. After 24 experiments, four ^{260}Lr events were recorded in the non-reduced +3 fraction, and none were detected in the reduced fractions. These

results indicate that Lr^{+3} is not reduced by NH_2OH at 80°C in about 20 seconds. It should be noted that NH_2OH has a large reduction potential (−1.8V) but the kinetics for reductions with this reagent are known to be relatively slow.

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Decay Studies of Neutron-Deficient Rare Earth Isotopes: A=124, 125

J. Gilat, P.A. Wilmarth, R.B. Firestone, and J.M. Nitschke*

The decay of very neutron deficient nuclides in the A=124,125 isobaric chains, produced by the ^{92}Mo(^{36}Ar,xpyn) reaction at the SuperHILAC, was investigated with the OASIS on-line mass separator facility. Results of a preliminary analysis of the data are summarized below:

A=124. A 1.2±0.2 s beta-delayed proton activity is assigned to the new isotope ^{124}Pr. Gamma rays of 70, 113 and 166 keV seen in coincidence with the protons represent heretofore unobserved transitions in ^{123}La. A 142 keV gamma ray also associated with this activity is probably the 2+ → 0+ transition in ^{124}Ce. The decay of the 30 s ^{124}La is dominated by the 2+ → 0+ (230 keV), 4+ → 2+ (421 keV), 6+ → 4+ (576keV) and 8+ → 6+ (694 keV) transitions in the ground state rotational band of ^{124}Ba, indicating a high (6- or 7- ?) spin assignment for the La parent.

A=125. Our previous report of a delayed proton branch in the decay of ^{125}Ce has been confirmed and the half-life of ^{125}Ce has been re-determined as 10±1 s. A spin of 5/2 for this isotope can be inferred from the relative intensities of the 230, 421 and 576 keV transitions in ^{124}Ba (see above) in coincidence with the protons. About 25 previously unobserved gamma transitions in the range of 50 to 1700 keV have been assigned to the decay of ^{125}Ce. In the decay of 70 s ^{125}La, the dominant gamma rays represent transitions from known 11/2 and 9/2 levels in ^{125}Ba, indicating a high (11/2−?) spin assignment for the parent ^{125}La, in agreement with the high spin we assign to the adjacent odd-odd ^{124}La.

Footnotes and References

*On leave from the Soreq Nuclear Research Center, Yavne, Israel

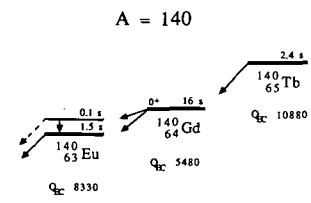
Decay Studies of Neutron-Deficient Rare Earth Isotopes: A=140

R.B. Firestone, J. Gilat, P.A. Wilmarth, and J.M. Nitschke

The decay of the very neutron deficient nuclides in the A=140 isobaric chain was investigated at the SuperHILAC with the OASIS on-line mass separator facility. Preliminary decay schemes have been constructed on the basis of γ-ray singles and half-life measurements. Beta-delayed protons were assigned to ^{140}Tb decay on the basis of x-ray coincidences. The results are summarized in the accompanying table and figure.

Fig. 1. Preliminary decay schemes for A=140.

XBL 8611-4504



ISOTOPE Z, A	HALF-LIFE This work	HALF-LIFE Literature	DECAY
$^{140}_{65}$Tb	2.4 ± 0.4 s	—	βp. Gd γ-ray : 329
$^{140}_{64}$Gd	16 ± 1 s	—	Eu γ-rays : 175, 192, 379, 722, 750, ~10 more
$^{140g}_{63}$Eu	1.5 ± 0.1 s	1.3 s	Sm γ-rays : 460, 531, 1068, ~10 more
$^{140m}_{63}$Eu	~ 0.1 s	~ 20 s	IT, Eu γ-rays : 185, 175. Gd γ-rays : ???

Decay Studies of Neutron-Deficient Rare Earth Isotopes: A=141

J. Gilat, R.B. Firestone, P.A. Wilmarth and J.M. Nitschke*

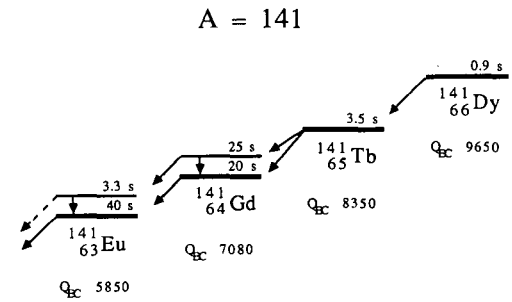
The decay of very neutron deficient nuclides in the A=141 isobaric chain, produced by the ^{92}Mo (^{54}Fe;xp,yn) reaction at the SuperHILAC, was investigated with the OASIS on-line mass separator facility,[1] by means of gamma, x-ray and beta-delayed particle spectroscopy, in singles and coincidence modes. Over one hundred gamma transitions in the energy range of 50-1500 kev were identified and assigned to the decay of ^{141}Tb, ^{141}Gd^{g,m}, and ^{141}Eu^{g,m}, on the basis of coincident x-rays and half-life measurements. Results are summarized below and in the accompanying table and figure.

^{141}Dy. Our previously reported beta-delayed proton activity associated with the decay of this new isotope has been confirmed, and its half-life has been re-determined as 0.9±0.2s. The observation of the ^{140}Gd $2^+ \rightarrow 0^+$ (329 kev) and $4^+ \rightarrow 2^+$ (508 kev) in coincidence with the protons indicates a relatively high spin (probably $11/2^-$) for the ^{141}Dy precursor. Gamma rays of 53, 140 and 190 kev are also tentatively assigned to this decay.

^{141}Tb. Our previous tentative assignment of a ~3s activity to the new isotope ^{141}Tb has been confirmed, and its half-life measured as 3.5±0.3s. Over thirty gamma transitions associated with the decay of this isotope to the $1/2^+$ and $11/2^-$ isomers of ^{141}Gd (see below) were identified and placed in a level scheme containing 14 excited levels. This decay scheme indicates a relatively high spin for the ground state of ^{141}Tb, consistent with a spin of $11/2^-$ predicted by the shell model; however, a spin as low as $7/2^+$, resulting from deformation induced breakdown of the Z=64 shell gap,[2] is not excluded by the data.

^{141}Gd. Two previously unreported[3] β-decaying isomers of ^{141}Gd with half- lives of 20±2s and 25±4s were identified. From our gamma ray analysis we assign the two species to the $1/2^+$ ground state and an $11/2^-$ isomer at 378 kev of ^{141}Gd, respectively. An E3 12±5% IT branch between the two species via a $5/2^+$ level at 258 kev is also observed. These findings are in good agreement with N=77 systematics. A ^{141}Eu level scheme has been constructed, comprising 14 excited levels and over 20 gamma transitions. A 20±4s ^{141}Gd delayed proton activity was also measured, but cannot at present be identified with a specific isomer.

^{141}Eu. Our results on the decay of the 40s ^{141}Eu^g and 3.3s ^{141}Eu^m are in good agreement with published data,[4] with one exception: the β^+/EC branch in the decay of the $11/2^-$ isomer is only ~4%, rather than the reported 67%; this corresponds to a logft value of 5.2 for the transition to the 175.8 $11/2^-$ state in ^{141}Sm, in much better agreement with beta decay systematics than the previous value of 4.0.



ISOTOPE Z, A	HALF-LIFE This work	Literature	DECAY
$^{141}_{66}$Dy	0.9 ± 0.2 s	—	ßp. Tb γ-rays : 53, 140, 190
$^{141}_{65}$Tb	3.5 ± 0.3 s	—	Gd γ-rays : 113, 136, 198, 258, 293, ~25 more
$^{141g}_{64}$Gd	20 ± 2 s	22 s	ßp? Eu γ-rays : 120, 216, 336
$^{141m}_{64}$Gd	25 ± 4 s	—	ßp? IT, Gd γ-rays : 60, 113, 119, 145, 198, 258 Eu γ-rays : 224, 351, 361, 526, ~20 more
$^{141g}_{63}$Eu	40 ± 5 s	40 s	Sm γ-rays : 369, 383, 385, 394, 396, ~20 more
$^{141m}_{63}$Eu	3.5 ± 0.3 s	3.3 s	IT, Eu γ-rays : 96 Sm γ-rays : 519, 804, 1595

Fig. 1. Summary of decay data for the A=141 isobaric chain. XBL 8611-4505

Footnotes and References

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3. In a recent paper Redon *et al.* report the identification of a 22±2s $11/2^-$ ^{141}Gd species. [Z. Phys. A **325**, 127 (1986)]

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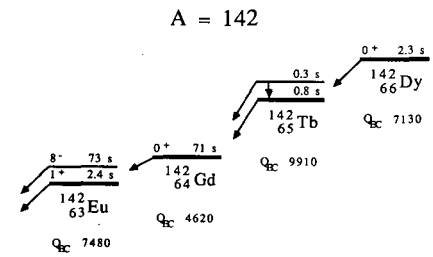
Decay Studies of Neutron-Deficient Rare Earth Isotopes: A=142

R.B. Firestone, J. Gilat, P.A. Wilmarth, and J.M. Nitschke

The decay of the very neutron deficient nuclides in the A=142 isobaric chain was investigated at the SuperHILAC with the OASIS on-line mass separator facility. Preliminary decay schemes have been constructed on the basis of γ-ray singles, coincidence, and half-life measurements. β-delayed protons were assigned to ^{142}Dy decay on the basis of x-ray coincidences. These results are summarized in the accompanying table and figure.

The decays of ^{142}Dy and ^{142}Tb^g are observed in equilibrium. No significant β decay is observed to populate either the ^{142}Tb or ^{142}Gd ground states or the 4^+ level in ^{142}Gd. This indicates that the systematic 1^+ ground state of the heavier odd-odd Tb isotopes no longer holds for N=77. The spin must be low suggesting a new ground state configuration perhaps indicative of the expected breakdown of the Z=64 shell.[1]

^{142}Tb^m is observed to deexcite primarily through the 212 keV γ-ray. The excitation energy of this isomer is not known, however Tb K x-rays were not observed strongly in coincidence with this transition indicative that the isomer lies within 50 keV of the the 212 keV level. A weak β-decay branch appears to deexcite this level through low-spin states in ^{142}Gd, however the possible co-existence of two low-spin isomers in ^{142}Tb would be remarkable.



ISOTOPE Z, A	HALF-LIFE This work	HALF-LIFE Literature	DECAY
$^{142}_{66}$Dy	2.3 ± 0.8 s	—	βp. Tb γ-rays: 182, 212, ~ 20 more
$^{142g}_{65}$Tb	0.8 ± 0.4 s	—	βp ???. Gd γ-rays: 389, 465, 515, 853
$^{142m}_{65}$Tb	0.3 ± 0.1 s	—	IT, Tb γ-ray : 212 Gd γ-rays: 515, 465
$^{142}_{64}$Gd	71 ± 1 s	90 s	Eu γ-rays: 179, 280, 284, 526, 620, ~ 30 more
$^{142g}_{63}$Eu	2.4 ± 0.2 s	2.4 s	Sm γ-rays: 768, 890, 1288, 1405, 1658, 2056
$^{142m}_{63}$Eu	~ 70 s	73 s	Sm γ-rays: 556, 768, 1024

Fig. 1. Decay scheme for A=142 XBL 8611-4506

An extensive decay scheme has been constructed for ^{142}Gd decay. This decay is observed in equilibrium with ^{142}Eu^g affording an absolute normalization. In addition the decays of ^{142}Sm and ^{142}Pm were observed in equilibrium and new normalizations were obtained.

Footnotes and References

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Radioactive Decay of $^{144}Tb^{m+g}$

R.B. Firestone, W.-Y. Chen, P.A. Wilmarth, and J.M. Nitschke

The decay of $^{144}Tb^{m+g}$ was investigated at the SuperHILAC with the OASIS on-line mass separator facility. Preliminary decay schemes have been constructed on the basis of γ-ray singles, coincidence, and half-life measurements. The results are summarized in Table I. $^{144}Tb^{m}$ was reported by Nolte *et al.*[1] and Sousa *et al.*[2] Our half-life of 4.1±0.1s is consistent with Nolte (4.5±0.5s) and Sousa (5±1s). We propose $J^{\pi}=5^{-}$ for the isomer on the basis of an E3 transition to the 283.7 keV (2^{+}) level, an (M4) transition to the 1^{+} ground state, and strong β-decay feeding to the $J^{\pi} = 5^{-}$ level at 2302.7 keV. Nolte *et al.*[1] previously reported $^{144}Tb^{g}$ decay with a half-life of 1.5±1.0 s decaying to the levels at 0.0(0^{+}) and 743.0(2^{+}) keV in ^{144}Gd. We propose two additional levels at 1877.2(2^{+}) and 1886.8(0^{+}) keV. A half-life as long as 4s could not be eliminated in these experiments because $^{144}Tb^{g}$ was produced in equilibrium with the isomer and ^{144}Dy.

Table I.
γ rays from $^{144}Tb^{m+g}$ Decay

Isomer	E_{γ}	I_{γ}	Placement
$^{144}Tb^{m}$	113.0(IT)	3.7	396.7 – 283.7
	139.7($\epsilon+\beta+$)	1.5	2442.5 – 2302.7
	169.1($\epsilon+\beta+$)	3.6	2471.8 – 2302.7
	283.7(IT)	100	283.7 – 0.0
	315.1($\epsilon+\beta+$)	3.1	2786.9 – 2471.8
	396.7(IT)	1.2	396.7 – 0.0
	544.5($\epsilon+\beta+$)	0.8	3016.2 – 2471.8
	558.1($\epsilon+\beta+$)	8.4	2302.7 – 1744.6
	600.4($\epsilon+\beta+$)	5.9	2302.7 – 1702.3
	628.5($\epsilon+\beta+$)	1.5	2330.8 – 1702.3
	697.9($\epsilon+\beta+$)	2.5	2442.5 – 1744.6
	713.5($\epsilon+\beta+$)	2.0	3016.2 – 2302.7
	743.0($\epsilon+\beta+$)	~53	743.0 – 0.0
	959.3($\epsilon+\beta+$)	11	1702.3 – 743.0
	1001.6($\epsilon+\beta+$)	19	1744.6 – 743.0
$^{144}Tb^{g}$	743.0	~10	743.0 – 0.0
	1134.1	1.5	1877.2 – 743.0
	1143.8	7.7	1886.8 – 743.0
	1877.3	2.2	1877.2 – 0.0

Footnotes and References

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2. D.C. Sousa, K.S. Toth, C.R. Bingham, A.C. Kahler, and D.R. Zolnowski, Phys. Rev. C **25**, 1012(1982).

Radioactive Decay of ^{144}Dy

R.B. Firestone, W.-Y. Chen, P.A. Wilmarth, and J.M. Nitschke

The decay of ^{144}Dy was investigated at the Super-HILAC with the OASIS on-line mass separator facility. A preliminary decay scheme was constructed on the basis of γ-ray singles, coincidence, and half-life measurements. β-delayed protons were assigned to ^{144}Dy decay on the basis of x-ray coincidences. These results are summarized in Table I. The half-life of ^{144}Dy was measured as 9.1±0.5s. Levels at $0(1^+)$, $196.5(1^+)$, $298.7(2^-)$, 532.2, 615.9, 620.0, 774.4, 793.3 and 1237.2 keV in ^{144}Tb are postulated. The J^π value for the 196.5 keV level is based on strong β-decay feeding from the 0^+ parent and, for the 298.7 keV level, from no feeding by the 5^- isomer at 396.7 keV and no direct β-decay feeding. Weak evidence exists for a level at 469.5 keV which de-excites through the 283.7 keV level that is strongly populated by IT decay.

Table I:
γ rays from ^{144}Dy Decay

E_γ	I_γ	Placement
185.8	3	469.5 – 283.7 ?
196.5	100	196.5 – 0.0
260.9	9	793.3 – 532.2
298.7	85	298.7 – 0.0
305.1	2	774.4 – 469.5 ?
317.3	17	615.9 – 298.7
321.3	10	620.0 – 298.7
335.4	8	532.2 – 196.5
419.4	9	615.9 – 298.7
423.5	6	620.0 – 196.5
462.5		1237.2 – 774.4 ?
469.6	7	469.5 – 0.0 ?
475.7	44	774.4 – 298.7
494.6	5	793.3 – 298.7
532.2	12	532.2 – 0.0
596.0	13	793.3 – 196.5
615.9	5	615.9 – 0.0
620.0	7	620.0 – 0.0
793.3	20	793.3 – 0.0
1040.7	17	1237.2 – 0.0
1237.4	21	1237.2 – 0.0

Beta-Delayed Proton Emission in the Lanthanide Region*

P. A. Wilmarth, J. M. Nitschke, J. Gilat,† and R. B. Firestone

Several β-delayed proton precursors were produced in (HI;xn,yp) reactions at the LBL SuperHILAC and studied with the isotope separator OASIS. Unambiguous Z-identifications were obtained in all cases by observing characteristic x-rays coincident with the protons. Ground state spins were determined in favorable cases. The lowest 2^+ levels in the rotational bands of ^{126}Ce and ^{130}Nd were confirmed. Decay properties of the delayed proton emitters are summarized in Table I.

Footnotes and References

*Condensed from LBL-22253

†On leave from Soreq Nuclear Research Center, Yavne 70600, Israel

Table I.

E_{lab} = bombarding energy; $T_{1/2}$ = weighted half-life from all available OASIS data; $\bar{E}_p$ [Range] = average energy and energy range of the observed β-delayed protons.

ISOTOPE	REACTION	E_{lab} (MeV)	$T_{1/2}$ (s)	$\bar{E}_p$ [Range] (MeV)
^{124}Pr	^{92}Mo(^{36}Ar,p3n)	174	1.2±0.2	3.7 [2.1 - 5.9]
^{125}Ce	^{92}Mo(^{36}Ar,2pn)	153	9.2±1.0	3.3 [1.7 - 5.1]
^{127}Nd	^{92}Mo(^{40}Ca,2p3n)	208	1.8±0.4	3.7 [2.2 - 6.0]
^{131}Nd	^{94}Mo(^{40}Ca,2pn)	168	25 ±4	3.1 [1.7 - 6.4]
^{131}Sm	^{96}Ru(^{40}Ca,2p3n)	208	1.2±0.2	3.7 [1.8 - 6.6]
^{140}Tb	^{92}Mo(^{54}Fe,3p3n)	298	2.4±0.4	4.2 [2.2 - 6.6]
^{141}Gd	^{92}Mo(^{54}Fe,4pn)	276	20 ±4	3.6 [2.2 - 4.9]
^{141}Dy	^{92}Mo(^{54}Fe,2p3n)	276	0.9±0.2	4.1 [2.1 - 7.2]
^{142}Dy	^{92}Mo(^{54}Fe,2p2n)	247	2.3±0.8	3.9 [2.5 - 5.2]
^{144}Dy	^{92}Mo(^{56}Fe,2p2n)	245	9.1±0.5	3.2 [2.6 - 4.5]
^{144}Ho	^{92}Mo(^{58}Ni,3p2n)	325	0.7±0.1	4.2 [2.2 - 7.0]
^{146}Ho	^{92}Mo(^{58}Ni,2p2n)	261	3.1±0.5	4.1 [2.4 - 6.3]

Investigation of A = 152 and A = 150 Radioactivities with Mass-Separated Sources; Identification of ^{152}Lu

K.S. Toth, D.C. Sousa,† J.M. Nitschke, and P.W. Wilmarth*

Since its commissioning, the isotope separator OASIS has been used primarily in the investigation of short-lived nuclides on the neutron-deficient side of N = 82. Much of the research has involved a systematic study of β-delayed-proton spectra. More recently γ-ray spectral data has been utilized[1] to sort out low-lying levels in ^{149}Er and ^{149}Ho. Here we summarize briefly the γ-ray decay properties of A = 152 and A = 150 isotopes produced in ^{58}Ni bombardments of ^{96}Ru; these are data obtained in concurrent studies of the ^{152}Lu and ^{150}Tm β-delayed proton spectra.

In our investigation of A = 152 nuclides ^{152}Lu ($T_{1/2}$ = 0.7 ± 0.1s) was identified by γ rays in its β-decay daughter ^{152}Yb. Based on its decay scheme the parent state has a probable spin and parity assignment of (4,5,6$^-$). Several new transitions were observed to follow β decays of ^{152}Yb and the ^{152}Tm low-spin isomer; they established previously unknown levels in both ^{152}Tm and ^{152}Er. The additional γ rays in ^{152}Yb decay reduce from 100% to 88% the direct feeding to the one excited state at 482 keV in ^{152}Tm that had been known earlier. Nevertheless, the corresponding log*ft* value is calculated to be 3.5 indicating that this is an allowed β transition which connects the 0^+ parent with a 1^+ excited state in ^{152}Tm. By comparing the β-decay rates of ^{148}Dy and ^{152}Ho, and, the α- and β-decay rates of ^{152}Er, an α branch of 90 ± 4% was deduced for ^{152}Er.

In the study of A = 150 nuclei the half-life of ^{150}Tm was measured to be 2.2 ± 0.2 s rather than the value of 3.5 s available in the literature. Based on its decay characteristics, we suggest that this high-spin ^{150}Tm isomer has a spin assignment of 6^-. Among the ^{150}Er states fed by this 6^- isomer is the yrast 4^+ level (2294.8 keV) which up to now has been observed in neither β-decay nor in-beam γ-ray studies. New transitions observed in ^{150}Er decay establish several previously unknown levels in ^{150}Ho. While the additional γ rays reduce from 100% to 95% the feeding to the 476-keV state in ^{150}Ho known earlier, the corresponding log*ft* value is calculated to be 3.6 indicating that this is an allowed, $0^+ \rightarrow 1^+$, beta transition. Photon intensities obtained for γ rays following the decay of the ^{150}Ho low-spin isomer resolve inconsistent values measured in two previous investigations.

Footnotes and References

*Oak Ridge National Laboratory, Oak Ridge, TN 37831

†Eastern Kentucky University, Richmond, KY 40475

1. K.S. Toth, Y.A. Ellis-Akovali, F.T. Avignone, R.S. Moore, D.M. Moltz, J.M. Nitschke, P.A. Wilmarth, P.K. Lemmertz, D.C. Sousa, and A.L. Goodman, Phys. Rev. C **32**, 342 (1985).

Delayed Proton Emission from the N=82 Shell

*J.M. Nitschke, P.A. Wilmarth, and J. Gilat**

Using beams of ^{58}Ni from the SuperHILAC and targets of ^{96}Ru, ^{94}Mo, and ^{93}Nb we produced for the first time a unique series of six beta-delayed proton emitters in a closed shell (N=82). These nuclei were mass separated with the on-line isotope separator OASIS and studied with p-, β-, x-, and γ-spectrometers. The resultant proton spectra are shown in Fig. 1.

In each case it was established, through proton-coincident x-ray analysis, that only a single element is associated with the proton activity. A comparison of the six proton spectra shows several distinct features: (1) a pronounced odd-even effect in the centroid of the spectra, (2) discrete peaks at excitation energies between about 3.5 and 5 MeV and (3) in the case of $^{151}_{70}$Yb$_{81}$, and $^{149}_{69}$Er$_{81}$ a superposition of a statistical spectral shape and a structured part. The higher average proton energies seen for odd-odd precursors are explained by the fact that the intermediate nucleus—being even-even—has to break a proton pair which results in a high proton separation energy that shifts the proton spectrum by a corresponding amount. In the case of $^{151}_{70}$Yb and $^{150}_{65}$Tm, for example, this difference is on the order of 2 MeV, equivalent to ~2Δ. The excitation energies from which the unstructured proton decay occurs range from about 5.5 to 11 MeV, a region characterized by high level densities that result in the characteristic *statistical* shape of the proton spectra. On the other hand the second effect—the discrete peaks observed for even-odd precursors—is associated with the low level density of the magic intermediate nucleus at excitation energies between ~3.5 and 5.5 MeV. In recent experiments, where protons

in coincidence with positrons were separated from those in coincidence with high-lying high spin levels in the daughter nucleus, it has been shown[1] that—in the case of even-odd precursors—the statistical part of the proton spectrum originates from the decay of the h11/2$^-$ isomeric states in $^{147}_{66}$Dy, $^{149}_{68}$Er, and $^{151}_{70}$Yb. Additional information currently being extracted from the data concerns ground state spins and parities of odd-odd precursors, proton branching ratios, final state proton branching ratios, the ratio of positron coincident protons to the total number of protons, high energy gamma emission from levels that compete for proton emission, and effects due to Gamow-Teller strength functions.

Footnotes and References

*On leave from Soreq Nuclear Research Centre, Yavne 70600, Israel.

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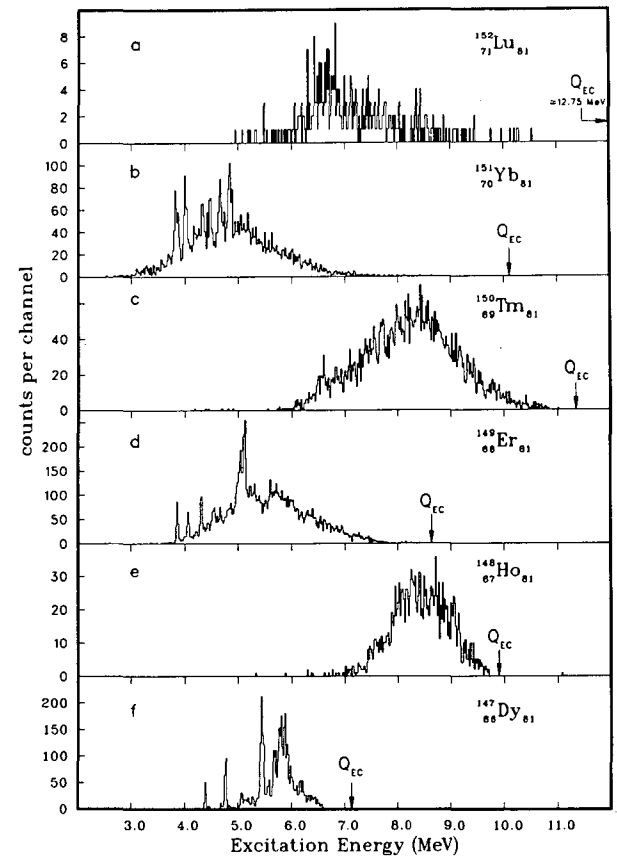

Fig. 1. Beta-delayed proton spectra of N=81 precursors as functions of the excitation energy in the intermediate, magic nucleus. Proton separation energies from ref. 2 were assumed. The indicated Q_{EC} values are taken from ref. 3. XBL 872-559

Proton Decay as a Sensitive Probe for Beta Strength Distributions

J.M. Nitschke, P.A. Wilmarth, J. Gilat, and P. Möller

Pronounced structure in the beta-delayed proton decay of e–o precursors with N=81 has been observed (c.f. preceding contribution). There is a long-standing debate as to whether this structure, that is also observed near the Z=50 shell, is due to fluctuations or a result of distinct nuclear structure effects.[1] One would expect in principle fluctuations in the following quantities: level distances, proton- and gamma level widths, and the beta decay width. It can be shown that contributions from level distances and gamma width are small and that the remaining two follow a Porter-Thomas product distribution. To show that a major contribution to the observed structure is due to resonances in the beta-strength

we have carried out calculations of Gamow-Teller β-strength functions in the RPA approximation with Nilsson model wave functions[2] and combined them with calculations for proton- and gamma emission from excited states of the intermediate nucleus to appropriate final states in the daughter nucleus. The result is a proton energy spectrum that can be compared to experiment, as shown for the case of ^{151}Yb in Fig. 1. The two parameters that were varied in the RPA model to obtain agreement with the experiment are the deformations ϵ_2 and ϵ_4. This is justified on the following grounds: (1) the static deformation obtained from the minimization of the potential mass/energy surface is not necessarily identical to the dynamic deformation at several MeV excitation energy, (2) it is inherent in the Nilsson/RPA model that the deformations of the precursor and the intermediate nucleus are the same which is in general not a good assumption in the transition region, and (3) the calculations carry an uncertainty in the deformations on the order of the differences to the nearest isotopes or isotones. Comparison between the model calculation and the experimental proton spectra for $^{151}_{70}$Yb, $^{149}_{68}$Er, and $^{147}_{66}$Dy led to the following observations: (1) the static ground state deformations taken from ref. 3 gave rise to a concentration of the proton intensity in *one* major peak located about .5 to 1 MeV above the highest observed proton peak, in strong disagreement with experiment, (2) an increase in ϵ_2 shifted this peak to lower energies but did little to redistribute the strength, away from the single resonance, and (3) only the *combined* increase of ϵ_2 and ϵ_4 gave satisfactory agreement with experiment as shown in Fig. 1. The introduction of the ϵ_4 deformation seems to be necessary to create a mixing effect that causes a distribution of the beta strength over several lower lying resonances. Our preliminary conclusions are that beta-delayed proton decay is a sensitive tool for the study of Gamow-Teller strength distributions and dynamic, nuclear deformations, and that a major part of the structure in the observed proton spectra results from Gamow-Teller resonances rather than Porter-Thomas fluctuations.

Footnotes and References

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2. J. Krumlinde and P. Möller, Nucl. Phys. **A417**, 419 (1984).

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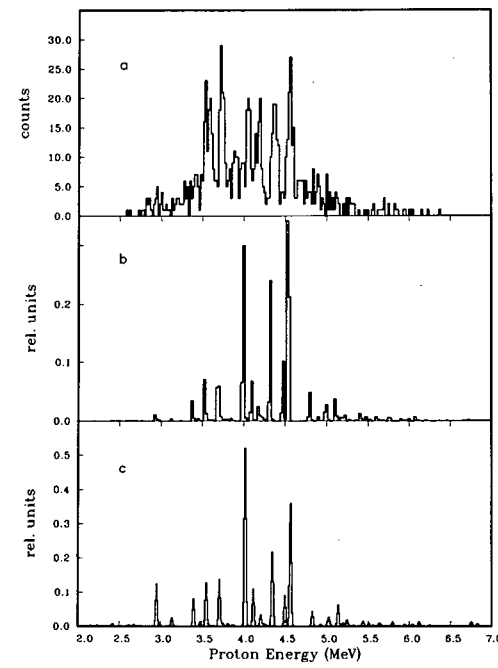

Fig. 1. (a) Beta-delayed proton spectrum of $^{151}_{70}$Yb measured in coincidence with positrons; (b) calculated proton spectrum using the beta-strength distribution shown in (c); (c) beta-strength distribution for $^{151}_{70}$Yb calculated with $\epsilon_2 = -.150$, $\epsilon_4 = +.040$, and $\epsilon_6 = 0$, (the static ground state deformation for $^{151}_{70}$Yb is $\epsilon_2 = -.091$, $\epsilon_4 = +.015$, $\epsilon_6 = +.002$.)[3]

XBL 872-558

Complex Fragment Emission at 50 MeV/nucleon: Compound Nuclei Forever?*

D.R. Bowman, R.J. Charity, R.J. McDonald, M.A. McMahan, G.J. Wozniak, L.G. Moretto, W.L. Kehoe,† S. Bradley,† A.C. Mignerey,† A. Moroni,‡ A. Bracco,‡ I. Iori,‡ and M.N. Namboodiri§

Fragments with $12 \leq Z \leq 35$ have been detected in the reaction of 50 MeV/nucleon ^{139}La on ^{12}C and are shown to be produced solely by the binary decay of a compound nucleus formed in an incomplete fusion reaction. The source velocity, c.m. velocities, cross-sections, and angular distributions extracted from the inclusive data are entirely consistent with this mechanism. The binary coincidence data confirm this interpretation and can be quantitatively accounted for by the singles data.

A vivid way of portraying the binary nature of the decay is to plot, for a given Z, the invariant cross-section in the $v_{\|}$, $v_{\perp}$ plane, as in Fig. 1(a). Shown here is a schematic representation of the equilibrium emission of complex fragments from a source formed by fusion of the projectile with approximately one half of the target. The fast moving equilibrated source has a velocity represented by the arrow labelled V_s. This source decays statistically, the main channels being evaporation of neutrons, protons, and alpha particles. The less probable emission of complex fragments appears as a Coulomb circle centered at the arrowhead. Following the binary decay, each of the hot primary fragments evaporates light particles statistically, thus smearing out the Coulomb circles. The dashed lines in the figure correspond to the limits of detector acceptance at 3.0° and 8.0° in the laboratory. The solid area between the lines is the predicted experimental distribution.

In Fig. 1(b,c,d) the experimental data are presented in the same way as in Fig. 1(a) for Z bins of 21–23, 24–26, and 27–29, respectively. The observed distributions exhibit fairly sharp rings, strikingly similar to the schematic representation. Arrows 1 and 3 represent the beam velocity and the velocity resulting from complete fusion, respectively. Approximately midway in between, the experimentally determined source velocity is indicated by arrow 2. One should note that the circles associated with various Z bins are centered at approximately the same value of $v_{\|}$, suggesting that all of these fragments are emitted from a single source, and that the radii of the circles decrease with increasing Z, as one would expect from Coulombic acceleration of the fragments in the binary decay. This is exactly the behavior expected from the formation and decay of an equilibrated compound nucleus moving with a well-defined velocity.

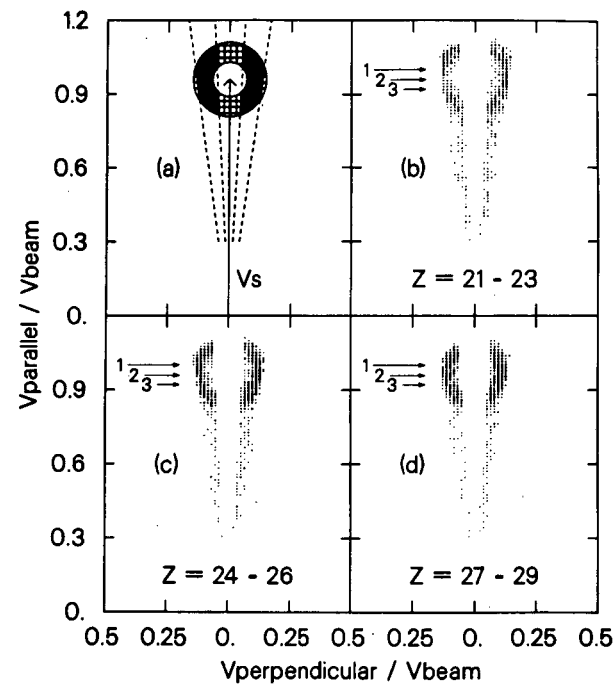

Fig. 1(a) Schematic representation of the invariant cross section in the $v_{\|}$, $v_{\perp}$ plane for complex fragment emission from a compound nucleus with a well-defined velocity, V_s. (b,c,d) Experimental distributions for various Z bins. XBL 8611-4288

The quest for the mechanism of production of complex fragments has led us to the incontrovertible and surprising conclusion that binary compound nucleus decay still prevails at these very high energies and that no other process is involved in the production of fragments with Z≥12, other than that of sequential light particle emission for the largest Z values.

Footnotes and References

*Condensed from LBL-22483

†Permanent address: Department of Chemistry, University of Maryland, College Park, Maryland, 20742.

‡Permanent address: INFN and Department of Physics, University of Milano, Via Celoria 16 20133 Milano, Italy.

§Permanent address: Nuclear Chemistry Division, Lawrence Livermore National Laboratory, Livermore, California, 94550.

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

R.J. Charity, M.A. McMahan, D.R. Bowman, Z.H. Liu,† R.J. McDonald, G.J. Wozniak, L.G. Moretto, S. Bradley,‡ W.L. Kehoe,‡ A.C. Mignerey,‡ and M.N. Namboodiri§

The emission of complex particles at intermediate energies has been characterized through the reverse-kinematics reactions 25 and 30 MeV/nucleon ^{93}Nb + ^{9}Be, ^{27}Al. Complex particles observed in binary decays from very hot incomplete-fusion intermediates are shown to originate from compound-nucleus decay, by means of kinetic energies, angular distributions, and absolute yields. The process of complex-particle emission provides a method, applicable throughout the Periodic Table, for studying compound nuclei with temperatures and excitation energies near the expected limit of their existence.

Footnotes and References

*Condensed from Phys. Rev. Letters **56**, 1354 (1986).

†Permanent address: Institute of Atomic Energy, Beijing, P. R. China.

‡Permanent address: Department of Chemistry, University of Maryland, College Park, Maryland 20742.

§Permanent address: Nuclear Chemistry Division, Lawrence Livermore National Laboratory, Livermore, California 94550.

Complex Fragments Originating in the Decay of Hot Compound Nuclei Formed in Heavy Ion Reactions at 25–30 MeV/nucleon

R. J. Charity, M. A. McMahan, D. R. Bowman, Z. H. Liu, R. J. McDonald, G. J. Wozniak, L. G. Moretto, S. Bradley,† W. L. Kehoe,† A. C. Mignerey,† and M. N. Namboodiri§*

In an effort to determine the origin of complex fragments in intermediate-energy heavy ion reactions, we have studied the reactions ^{93}Nb + ^{9}Be, ^{27}Al at 25–30 MeVA in reverse kinematics. The experiments were carried out at the Low Energy Beamline of the Bevalac.

From the singles data it has been possible to produce invariant cross-section plots as a function of $v_{\parallel}$, $v_{\perp}$. For atomic numbers Z > 10 the invariant cross-section appears as a fairly sharp Coulomb circle. The radii of the circles as a function of Z value follow closely the Coulomb dependence for two body decay, thus supporting binary decay and complete kinetic-energy thermalization. The distribution along the circles corresponds to $1/\sin\theta$, which is also consistent with compound nucleus decay. The source velocity obtained from the center of the circle indicates that the source is formed in an incomplete fusion process

corresponding to a momentum transfer in agreement with the Viola systematics. The compound nuclei formed in these incomplete fusion processes are extremely hot, their excitation energy ranging from 150 to 450 MeV. The absolute cross-sections can be reproduced assuming compound nucleus decay.

The coincidence data show that the fragments are indeed produced in a binary decay. The sum of their charge is approximately constant as a function of exit-channel asymmetry, and can be quantitatively reproduced by determining the missing charge due both to incomplete fusion from the source velocity and to sequential evaporation from the excitation energy.

Finally, a Monte Carlo simulation of the binary decay which includes the detector geometry shows a quantitative consistency between singles and coincidence data, as shown in Fig. 1. This quantitative agreement between singles and coincidence demonstrates that all the events observed in singles result from binary decays, thus ruling out any sizeable amount of multifragmentation.

Footnotes and References

*Permanent address: Institute of Atomic Energy, P. R. China.

†Permanent address: Department of Chemistry, University of Maryland, College Park, Maryland 20742.

‡Permanent address: Nuclear Chemistry Division, Lawrence Livermore National Laboratory, Livermore, California 94550.

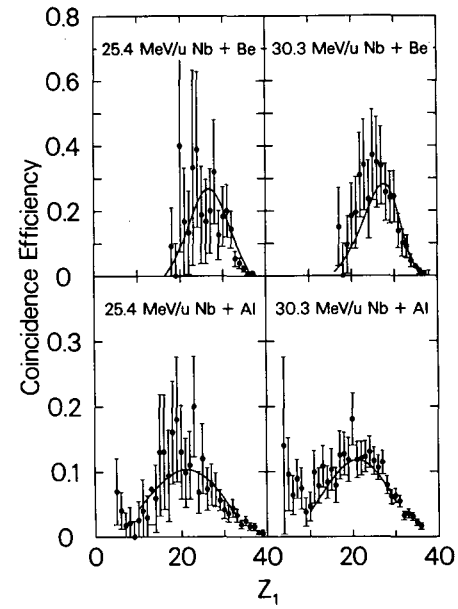

Fig. 1. Experimental coincidence/singles ratio compared to a Monte Carlo simulation.

XBL 8612-4837

Compound Nucleus Production of Complex Fragments at Bombarding Energies Between 12 and 18 MeV/nucleon

R.J. Charity, M.A. McMahan, R.J. McDonald, L.G. Moretto, G.J. Wozniak, D.G. Sarantites, L.G. Sobotka,* G. Guarino,† A. Pantaleo,† L. Fiore,† A. Gobbi,‡ and K. Hildenbrand‡*

In recent work at the Bevalac Low Energy Beamline, we have shown that all complex fragments with $Z > 13$ appear to be produced in the statistical decay of a compound nucleus formed in an incomplete fusion process. The energy covered in these experiments ranged from 25 to 50 MeV/nucleon in reactions with a rather asymmetric entrance channel (^{93}Nb + ^{9}Be, ^{27}Al; ^{139}La + ^{12}C). In other studies, we have observed and characterized complex fragment emission from compound nuclei at excitation energies near the threshold (50 to 100 MeV total excitation energy).

In order to establish a link between these two widely separated energy regions, we have undertaken a thorough study of complex fragment emission in the reverse kinematics reactions ^{93}Nb + ^{12}C, ^{27}Al at energies ranging between 12 and 18 MeV/nucleon. The Nb beams were provided by the GSI Unilac.

The singles data allowed us to generate invariant cross-section plots in the $v_{\parallel}, v_{\perp}$ plane for each Z

value. Such plots with their complete Coulomb circles progressively shrinking with increasing atomic number of the fragments give a most vivid evidence for binary compound nucleus decay (Fig. 1). The analysis shows that the source of the fragments has a velocity corresponding to that of the compound nucleus and that the fragments also have a $1/\sin\theta$ angular distribution. The velocity distributions of the fragments themselves arise mainly from the recoil after secondary emission of light particles. The absolute cross-sections as a function of Z value at the various energies, or alternatively the exitation functions for each Z value represent a crucial test for the compound nucleus hypothesis. Fig. 2 shows that the rapid increase of the cross-sections with excitation energy is indeed well reproduced by a compound nucleus calculation.

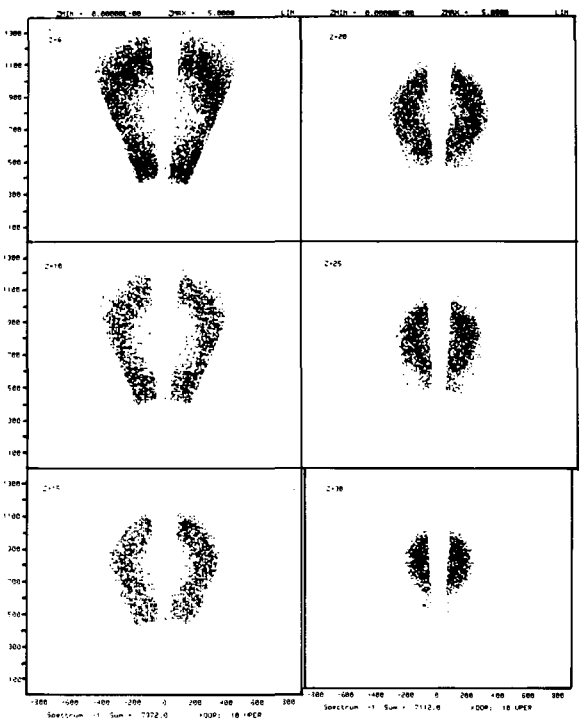

Fig. 1. Contours of invariant cross section in the $v_{\|}, v_{\perp}$ plane for complex fragments, ranging from Z = 6 to 30, emitted from a compound nucleus formed in the reaction 18 MeV/nucleon ^{93}Nb + ^{27}Al.

XBL 8612-4834

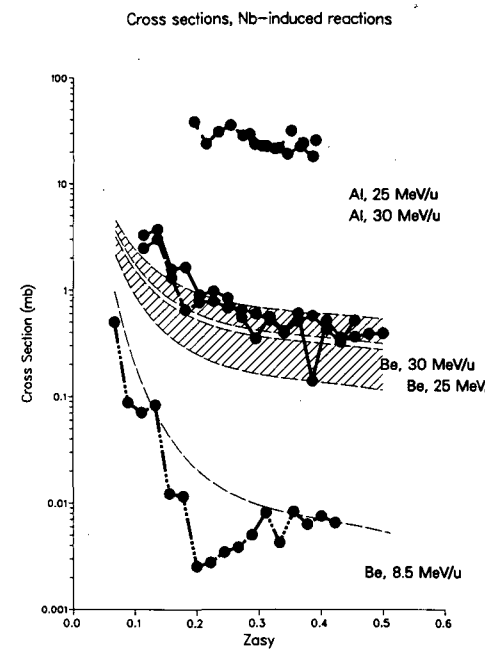

Fig. 2. Angle-integrated cross sections for the ^{93}Nb + ^{9}Be, ^{27}Al reactions at several bombarding energies, compared to a statistical model calculations (dashed lines) based on an approximation for rotating finite range barriers, and using the excitation energies extracted from the singles data. XBL 8612-4842

The coincidence data show that the distribution of the measured sum of the two atomic numbers can be accounted for quantitatively by complete fusion followed by binary decay, followed in turn by sequential light-particle emission. Similarly one finds that the two coincident fragments are mainly emitted back-to-back, the deviation from 180° being accounted for by sequential light-particle emission.

Finally a Monte Carlo evaluation of the coincidence efficiency shows that the coincidence data account fully for the singles, thus proving that in this Z range all events are binary.

Footnotes and References

*Department of Chemistry, Washington University, St. Louis, 63110.

†INFN, Bari, 70100, Italy.

‡Gesellschaft für Schwerionenforschung, 6100 Darmstadt, West Germany.

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

L.G. Sobotka,† G.J. Wozniak, R.J. McDonald, M.A. McMahan, R.J. Charity, L. G. Moretto, Z.H. Liu,‡ F.S. Stephens, R.M. Diamond, M.A. Deleplanque, and A.J. Pacheco§

The fraction of the total excitation energy imparted to the primary target-like fragment produced in the reaction 684 MeV ^{80}Kr + ^{174}Yb has been determined for one charge asymmetry in the exit channel. This fraction was deduced from the kinetic energy cost of evaporating neutrons from the target-like fragment and is approximately 0.5 for total kinetic energy losses as large as 160 MeV. This result is consistent with the predictions of nucleon exchange models and indicates that for some exit channels thermal equilibrium has not been reached for energy losses corresponding to a sizable fraction of the maximum kinetic energy relaxation.

Footnotes and References

*Condensed from Phys. Lett. B **175**, 27 (1986).

†Permanent address: Department of Chemistry, Washington University, St. Louis, MO 63130.

‡Permanent address: Institute of Atomic Energy, Beijing, P.R. China.

§Permanent address: Comision National de Energia Atomica, Buenos Aires, Argentina.

Impact Parameter Selection as the Cause of a Sharp Velocity Source in Complex Fragment Emission

R.J. Charity, M.A. McMahan, D.R. Bowman, R.J. McDonald, G.J. Wozniak, and L.G. Moretto

In a series of reactions such as ^{93}Nb + ^{9}Be, ^{12}C, ^{27}Al at a variety of energies, we have found that complex fragments are emitted by a common source with a very well-defined velocity, independent of the fragment atomic number and characteristic of an incomplete fusion process (see other contributions to this annual report). Some of these velocities plotted versus the fragment atomic number are shown in Fig. 1. The sharpness of the source velocity is puzzling in view of the expected continuum of mass transfers as a function of impact parameter, which would lead to a continuum of source velocities ranging from the projectile velocity to that of the compound nucleus. We believe that we have found an explanation for this puzzle in terms of both a massive transfer model and of the dependence of complex fragment emission upon compound nucleus excitation energy and angular momentum.

In the massive transfer model, the mass transfer corresponds to the occluded part of the lighter partner going to the heavier partner. Starting from central collisions, (b + r < R) as the impact parameter increases so does the partial cross section and the angular momentum, while the excitation energy remains constant. When the lighter partner begins sticking out (b + r > R) the partial cross-section continues to increase, but the excitation energy starts decreasing sharply.

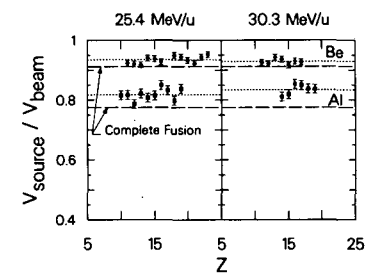

Fig. 1. A plot of the ratio of the source velocity to the beam velocity as a function of the atomic number of the complex fragment. Data are shown for four reactions 25.4 MeV/nucleon and 30.3 MeV/nucleon ^{93}Nb + ^{9}Be, ^{27}Al. The heavy dashed line denotes the velocity ratio corresponding to complete fusion and the dotted line to that of the data.

XBL 8612-4839

Since complex fragment emission is associated with high barriers (20–30 MeV), its competition with the most probable decay channels (n, p, α, etc.) decreases dramatically with decreasing excitation energy. The combination of these factors leads to a cross-section versus impact parameter plot that is rather sharply peaked, as shown in Fig. 2.

The initial rise at small impact parameters is due to the rise of the geometric cross-section and of the angular momentum of the fusion product, while the decrease at larger impact parameters is due to the rapid drop in excitation energy. Fig. 2 shows calculations carried out for a variety of emitted fragments. The maximum of the distribution is surprisingly constant for a range of Z values in agreement with the experimental findings. It should be pointed out that the sharpness of the peak depends very much upon the mass asymmetry in the entrance channel, being much more pronounced in very asymmetric systems. This confirms preliminary findings for large nearly symmetric systems.

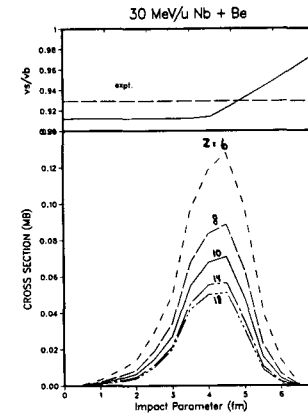

Fig. 2. The upper portion of this figure shows the ratio of the source velocity to the beam velocity as a function of the impact parameter of the collision for the massive transfer model (solid line) and the data (dashed line) for the 30 MeV/nucleon Nb + Be reaction. In the lower portion, the calculated cross section for emission of various complex fragments (Z = 6, highest curve, to Z = 18, lowest curve) as a function of impact parameter is shown.

XBL 8612-4841

K-Shell Ionization in 7.5- and 8.6-MeV/nucleon U+U Collisions at Very Small Impact Parameters*

J.D. Molitoris,† *Ch. Stoller,*‡ *R. Anholt,*† *W.E. Meyerhof,*† *D.W. Spooner,*†
R.J. McDonald, L.G. Sobotka,§ *G.J. Wozniak, L.G. Moretto, M.A. McMahan,*
*E. Morenzoni,*** *M. Nessi,*†† *and W. Wolfli*††

K-vacancy production probabilities in elastic 7.5- and 8.6-MeV/nucleon U+U collisions are reported for impact parameters less then 15 fm. In 7.5-MeV/nucleon U+U collisions the ionization probability rises above the trend indicated by larger impact parameter measurements, increasing to 1.8 vacancies per collision at the smallest impact parameter. The measured probabilities for 8.6 MeV/nucleon collisions increase to a maximum value of slightly less that 2 vacancies per collision at the smallest impact parameters. The data is compared to previous results and existing theory.

Footnotes and References

*Condensed from Z. Phys. D - Atoms, Molecules and Clusters **2**, 91 (1986).

†Permanent address: Department of Physics, Stanford University, Standford, California

‡Permanent address: Physics Department, San Jose State University, San Jose, CA 95192

§Permanent address: Department of Chemistry, Washington University, St. Louis, MO 63130

**Permanent address: Swiss Institute for Nuclear Research, CH-5234 Villigen, Switzerland.

††Permanent address: Laboratorium für Kernsphysik, Eidg. Technische Hochschule, Zurich, Switzerland.

Experimental Studies of Heavy Ion Radioactivities*

P.B. Price† and S.W. Barwick†

We survey the experimental status of the new field of heavy-ion radioactivity. Since the discovery by Rose and Jones of ^{14}C emission from ^{223}Ra, a group at Orsay has seen ^{14}C emission from ^{226}Ra and we and a Dubna group have discovered six more cases of ^{14}C or ^{24}Ne emission and have set stringent upper limits on branching ratios for seven other cases. In addition to a discussion of experimental techniques and results, we summarize the status of the various theoretical models.

Footnotes and References

*Condensed from Volume II, Chapter 4, *Charged Particle Emission from Nuclei*, edited by D.N. Poenaru and M. Ivascu, CRC Press, to appear in 1987.

†Also at Space Sciences Laboratory and Department of Physics, UCB.

Spontaneous Highly Asymmetric Binary Fragmentation of Heavy Nuclei*

P.B. Price† and S.W. Barwick†

We summarize the results of our studies of heavy ion radioactivities using plastic and glass track detectors. We have found or set stringent upper limits on branching ratios for six ^{14}C-emitting nuclides in the region around radium, three ^{24}Ne-emitters, and two ^{34}Si-emitters. The overall systematics are in reasonable accord with the highly asymmetric fission models of Poenaru *et al.*,[1] and Shi and Świątecki.[2] The preference for emission from even-even compared with odd-A nuclides is much greater for heavy-ion emission than for alpha emission. Searches for emission of ^{28}Mg and ^{34}Si ions from transuranium nuclides in collaboration with Ken Moody and Ken Hulet at Livermore are discussed.

Footnotes and References

*Condensed from the Proceedings of the International Heavy Ion School-Seminar, held at Dubna, September 23-30, 1986.

† Also at Space Sciences Laboratory and Department of Physics, UCB.

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Fission Mechanisms of 0.2 TeV Uranium Beams

L. F. Canto, R. Donangelo,* L. F. Oliveira,* and J. O. Rasmussen*

In this paper we examine first the contributions of various reaction mechanisms to "clean" fission of ^{238}U projectiles incident on nuclear emulsion at E/A · 1 GeV. "Clean" fission designates events in which fission occurs but no other charged particle tracks are observed.[1,2] The reaction mechanisms we know about are able to account for only about half of the observed cross section for clean fission. Evidently, charged-particle emission is more strongly suppressed in grazing collisions than our modified soft spheres model can account for. Also examined are the mechanisms for F_1 type events in which fission is accompanied by a small-angle singly or doubly charged particle. We developed a new Monte Carlo code yielding angular and linear momentum distributions following hot-spot nucleon emission or following a nucleon-nucleon quasielastic collision in the grazing passage of the heavy nuclei. Further under-

standing awaits resolution of descrepancies in data analysis, to see whether clean fission is mainly from low or high excitation energies.

Footnotes and References

*Universidade Federal do Rio de Janeiro, C.P. 68525, 21944 Rio de Janeiro–RJ, Brazil

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Subthreshold Pion Production in the Reaction $^{139}La + ^{139}La \rightarrow \pi^- + X$

J. Miller, W. Benenson, J. Bercovitz, G. Claesson, O. Hashimoto,† T. Kobayashi,† G. Krebs, G. Landaud,‡ S. Nagamiya,† G. Roche, L. Schroeder, I. Tanihata,† H. van der Plicht,* J. Winfield,* O. Yamakawa†*

Bevalac experiment 738H measured the cross-section for production of charged pions and light fragments at several energies below the NN $\rightarrow$ NNπ threshold. Center of mass angles between 30 and 90 degrees were surveyed. Associated multiplicity for charged particles was recorded in a 110-element scintillator array. Fig. 1 shows the π^- spectra at beam energies of 138, 183 and 246 MeV/nucleon for $\Theta_{CM} = 90°$. The solid line is a fit to data for the same system at 800 MeV/nucleon beam energy.[1] All of the spectra are well fit by an exponential function of the form $\frac{d^3\sigma}{dp^3} \propto e^{-T/T_0}$ with slope parameters T_0 of 14(5), 21(2), 25(1) and 55 MeV, respectively.

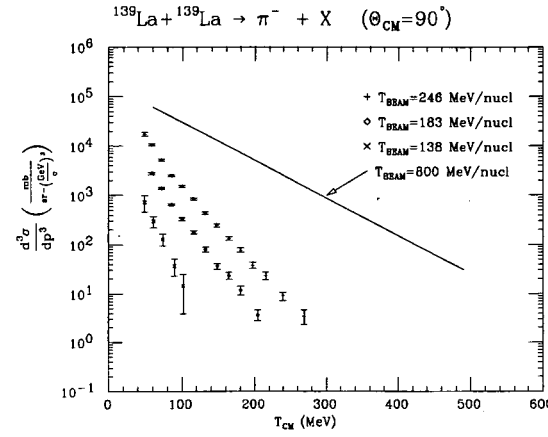

Fig. 1. Results from experiment 738H showing variant cross section vs pion kinetic energy for $^{139}La + ^{139}La \rightarrow \pi^- + X$ at $\Theta_{CM} = 90°$ for three different beam energies below the NN $\rightarrow$ NNπ threshold. The solid line is a fit to data at 800 MeV/nucleon, reported by Hayashi, *et al.*

XBL 8611-4574

Footnotes and References

* Michigan State University Cyclotron Laboratory

† INS/University of Tokyo

‡ Université de Clermont II

1. S. Hayashi, private communication

Dependence of Heavy-Ion Neutron Transfer on Distance and Spin*

J.O. Rasmussen, M.A. Stoyer, M.W. Guidry,† L.F. Canto,‡ and R. Donangelo‡

We review the "slope anomaly" data for 2-neutron transfer between heavy ions. Where one or both partners are deformed, the 2-neutron transfer always shows about the same dependence on distance-of-closest-approach D as does 1-neutron transfer. Where both partners are spherical, the 2-neutron

transfer falls off as the square of the 1-n transfer with one known exception $^{208}Pb(^{64}Ni,^{62}Ni)^{210}Pb$. We propose that the enhancement of 2-n transfer comes from the pairing attraction between the neutrons and that the enhancement requires availability of high-ℓ orbitals to form a tight wave packet in angle. A simple model is derived for numerical estimation. Prospects for testing Coriolis antipairing by heavy ion 2-n transfer are re-examined.

Footnotes and References

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†University of Tennessee, Knoxville, Tennessee 37916 and Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830.

‡Instituto de Fisica, Universidade Federal do Rio de Janeiro, Rio de Janeiro, Brazil.

Pion Production in High Energy Nucleus-Nucleus Collisions*

*D. Bangert,† R. Bock,‡ R. Brockmann,‡ A. Dacal,§ C. Guerra,§ J.W. Harris, G. Odyniec, M.E. Ortiz,§ H.G. Pugh, W. Rauch,** R.E. Renfordt,†† A. Sandoval,‡ D. Schall,†† L.S. Schroeder, R. Stock,** H. Ströbele,‡ J.P. Sullivan,‡‡ M.L. Tincknell, K.L. Wolf‡‡*

Negative pion production in collisions of $^{139}La + ^{139}La$ was studied in the Bevalac Streamer Chamber at incident laboratory energies of 530, 740, 990, 1200, and 1350 MeV/nucleon. Minimum bias, semi-central, and central trigger configurations were employed at each incident energy. In a geometric model these triggers correspond to impact parameters $b < b_{max}$, $b < 0.73\, b_{max}$, and $b < 0.24\, b_{max}$, respectively. Extrapolation to zero impact parameter as done previously[1] with the lighter Ar + KCl system is difficult for the heavy system due to the presence of a larger number and variety of nuclear fragments. Only after implementation of a 384 element scintillator array, covering angles $\theta_{lab} < 18^{\circ}$, was this extrapolation possible. It provided position, charge, and time-of-flight information allowing extraction of the total projectile spectator charge and, by subtraction, the number of participant protons in each event. The negative pion multiplicities were determined by scanning and measuring tracks on film. The participant and pion information were then correlated event-by-event. The observed negative pion multiplicity $< n_{\pi^-} >$ is found to be proportional to the participant nucleon number A at each incident energy, with the same proportionality constant as observed[1] for Ar + KCl at the same incident energies. The constancy of $< n_\pi >/A$, both as the mass of the interacting nuclei is changed from Ar + KCl to La + La and as the interaction volume is changed by varying the trigger conditions, demonstrates that pion production is a bulk nuclear matter probe rather than a surface probe. An $A^{2/3}$ dependence of $< n_\pi >$ is strictly ruled out by these data. The potential energy stored in the "fireball" at the moment of maximum compression, extracted by a process similar to that used in refs. 1 and 2, is shown in Fig. 1(a), where E^{pot}/A is the increase of potential energy per participant nucleon expended in going from initial ground state nuclear density ρ_0 to the density ρ reached at each of the incident energies. In dynamical models this density ρ (E_{cm}/A) is a monotonically increasing function of E_{cm}/A. Note that the fraction of initial c.m. energy that is transformed into potential energy rises from 13% at 125 MeV/nucleon to 33% at 380 MeV/nucleon. This corresponds to an extremely "stiff" nuclear matter equation of state compared to that used in nuclear matter calculations at T=O. Brown and coworkers[3] have recently argued that a significant fraction of the apparent stiffness of the EOS in nuclear collisions should result from the high relative baryon velocities, characteristic of high densities and temperatures in the fireball. The

temperatures reached in the fireball can be determined from our data, if we assume that all the c.m. energy that does not go into compression goes into thermal energy. The corresponding temperatures, extracted using a thermal model[4] are displayed in Fig. 1(b). They increase monotonically from 55 to 80 MeV over the energy range of the present experiment and up to 95 MeV for Ar + KCl. A similar result has recently been reported by Hahn and Stöcker.[5] In summary, we have investigated pion production for La + La and found a linear dependence both on the participant nucleon number, which reflects fireball size, and on the incident energy. The relative pion abundance, $< n_\pi >/A$, is the same for 140 + 140 and 40 + 40 collisions over the Bevalac energy range. This A-scaling of the pion multiplicity contradicts intuitive arguments concerning size-dependent absorption losses. Estimates of the fireball temperatures and the potential part of the compressional energy were presented. A very stiff nuclear matter equation of state is predicted from nucleus-nucleus collisions.

Footnotes and References

*Condensed from LBL-22003(rev) August 1986.

†University of Marburg, Marburg, West Germany

‡Gesellschaft für Schwerionenforschung, Darmstadt, West Germany

§Instituto de Física, UNAM, 21 D.F., México

**Fachbereich Physik, University of Frankfurt, Frankfurt, West Germany

††University of Heidelberg, Heidelberg, West Germany

‡‡Texas A&M University, College Station, Texas 77843

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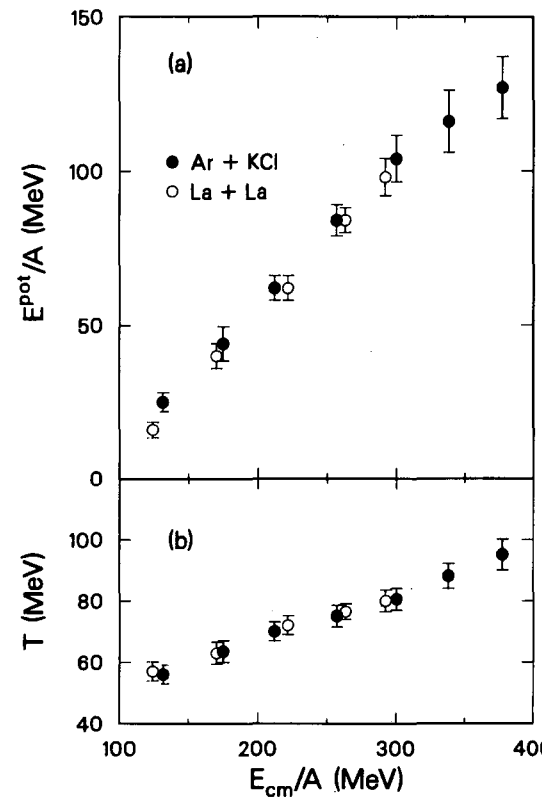

Fig. 1. a) The potential energy and b) the fireball temperatures as a function of c.m. energy as derived from the pion multiplicity data and the thermal model.[4] XCG 867-7343B

Subthreshold Production of K^- Mesons in Relativistic Nuclear Collisions*

E. Barasch, A. Shor, S. Abachi, J. Carroll, P. Fisher, K. Ganezer, G. Igo, T. Mulera, V. Perez-Mendez, and S. Trentalange

Collective effects in nuclear collsions may be studied by measuring the yield of particles whose production threshold is significantly higher than the energy available in the first N+N collision. By choosing to detect particles heavier than the pion (e.g., K^+, K^-) one may study collective effects at much higher incident energies, where the dynamics of the collision process may differ significantly from that ocurring at around 100 MeV. Measurements of the subthreshold production of K^- at 0 degrees in 2.1 GeV/nucleon Si+S collisions show several striking features:

– The yield is large, about 20 times that predicted on the basis of internal motion and about 5 times that calculated from secondary and tertiary processes.

– The yield is approximately exponential ($\exp -E_c m/90$ MeV).

– The yield extends to quite large cm energies (rapidities larger than that of the incident nucleons).

These results suggest that processes involving large numbers of nucleons are important even in systems as light as Si+Si, and are intriguing enough to warrant a systematic investigation of the production mechanism.

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The Production of Unusual Particles in Relativistic Nuclear Collisions

S. Abachi, A. Shor, E. Barasch, J. Carroll, P. Fisher, K. Ganezer, G. Igo, T. Mulera, V. Perez-Mendez, and S. Trentalange

Few sensitive searches have been made for the production of unusual particles in relativistic nuclear collisions, even though it has been suggested[1] that this environment could even lead to the creation of free fractional charge. By "unusual particles" we mean both known particles whose production is hindered by kinematics or other mechanisms, as well as objects previously unobserved. We have made a search for long-lived unusual particles produced at 0 degreees in the reaction 2.1 GeV/nucleon Si + Si at six secondary rigidities. No evidence for such production was found, although we could not rule out the interpretation of one event as being an antiproton. Upper limits on the yields for charges $-1/3, -2/3, -1, -4/3$, and -2 have been established, and the results from all rigidities combined to yield upper limits of less than 1 particle per 10^4 to 10^7 collisions in the mass range 0.1<M<5.0 GeV, and fewer than one antiproton per 4×10^7 collisions.

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Multiplicity and Transverse Energy Flux in ^{16}O + Pb at 200 GeV Per Nucleon

A. Bamberger, D. Bangert,† J. Bartke,‡ H. Bialkowska,§ R. Bock,** R. Brockmann,** C. De Marzo,†† M. De Palma,†† I. Derado,‡‡ V. Eckardt,‡‡ C. Favuzzi,†† J. Fendt,‡‡ D. Ferenc,§§ H. Fessler,‡‡ P. Freund,‡‡ M. Gazdzicki,***,††† H.J. Gebauer,‡‡ K. Geissler,† C. Guerra,** J.W. Harris, W. Heck,‡‡‡ T. Humanic,** K. Kadija,§§ R. Keidel,§§§ M. Kowalski,‡ S. Margetis,**** E. Nappi,†† G. Odyniec, G. Paic,§§ A.D. Panagiotou,****,‡ A. Petridis,**** J. Pfennig,‡‡‡ F. Posa,†† K.P. Pretzl,‡‡ H.G. Pugh, F. Puhlhofer,§§§ G. Rai, A. Ranieri,†† R. Renfordt,‡‡‡ D. Rohrich,§§§ K. Runge,* A. Sandoval,** D. Schall,*** N. Schmitz,‡‡ L.S. Schroeder, G. Selvaggi,†† P. Seyboth,‡‡ J. Seyerlein,‡‡ E. Skrzypczak,††† P. Spinelli,†† R. Stock,‡,‡‡‡ H. Ströbele,‡,** A. Thomas,‡‡‡ M. Tincknell, L. Teitelbaum, G. Vesztergombi,‡‡,†††† D. Vranic,**,§§ S. Wenig‡‡‡ and M. Wensveen***

First results from ultrarelativistic ^{16}O + Pb collisions at 200 GeV/nucleon are presented. The transverse energy E_T in average central collisions is ≈75 GeV for the interval $2.2 \leq y \leq 3.8$. A 16-fold convolution of the inelastic p + Au transverse energy spectrum, also measured at 200 GeV, reproduces the mean E_T of ^{16}O + Pb. The amount of nuclear stopping power appears to be high. Fig. 1 shows the differential transverse energy distribution in the midrapidity regime. The data points with E_T <50 GeV were obtained from events in the calorimeters and accompanying streamer chamber pictures; the points with E_T >50 GeV were obtained from calorimeter data only. The dashed curve shows the prediction of the HIJET program. The solid curve shows the result of convoluting 16 central p-Pb collision events, studied in the same experiment. The conclusions from the experiment are that the nuclear stopping power is high, that transverse energy densities of the order of 3 GeV/fm^3 are produced in average central collisions, and that a class of events with high E_T occurs which is not predicted by models such as HIJET, based on soft hadronic processes.

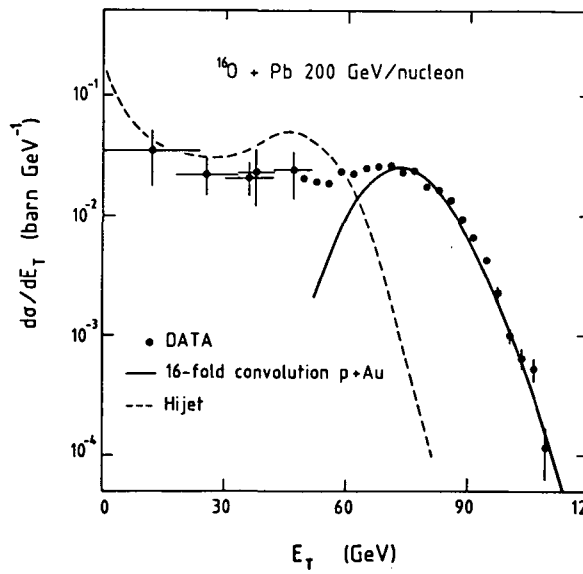

Fig. 1. Transverse energy distribution for 200 GeV per nucleon ^{16}O + Pb for the midrapidity region $2.2 \leq y \leq 3.8$. The solid curve is a 16-fold convolution of the E_T distribution for inelastic p + Au collisions at 200 GeV. The dashed curve is a prediction of the HIJET simulation code. XBL874-1792

Footnotes and References

*Fakultät für Physik, Universität Freiburg, D-7800 Freiburg, Germany

†CERN, CH-1211 Geneva 23, Switzerland

‡Institute of Nuclear Physics, PL-30055 Cracow, Poland

§Institute of Nuclear Studies, PL-00681 Warszawa, Poland

**Gesellschaft für Schwerionenforschung, D-6100 Darmstadt 11, Germany

††Dipartimento di Fisica, Universita di Bari, and INFN, Bari Italy

‡‡Max-Planck-Institut für Physik, D-8000 München, Germany

§§Rudjer Boskovic Institute, 41001 Zagreb, Yugoslavia

***Institut für Hochenergiephysik, Universität Heidelberg, D-6900 Heidelberg 1

†††Institute of Experimental Physics, University of Warsaw, Warszawa, Poland

‡‡‡Fachbereich Physik, Universität Frankfurt, D-6000 Frankfurt, Germany

§§§Fachbereich Physik, Universität Marburg, D-3550 Marburg, Germany

****Physics Department, University of Athens, 157-71 Athens, Greece

††††On leave of absence from Central Research Institute für Physics, Budapest, Hungary

Nuclear Collective Flow as a Function of Projectile Energy and Mass

K.G.R. Doss, H.Å. Gustafsson, H.H. Gutbrod, K.H. Kampert, B. Kolb, H. Löhner, B. Ludewigt, A.M. Poskanzer, H.G. Ritter, H.R. Schmidt and H. Wieman

The dependence of collective nuclear flow on multiplicity and beam energy for Ca + Ca, Nb + Nb, and Au + Au collisions has been measured with the Plastic Ball detector at the Bevalac. Event by event the data are analyzed with the transverse momentum method and a new quantitative measure of the flow effect is extracted. Fig. 1 shows the energy dependence of the flow quantity as a function of beam energy. It is expected that comparison of the present systematic results with model calculations will lead to a more precise determination of the nuclear matter equation of state.

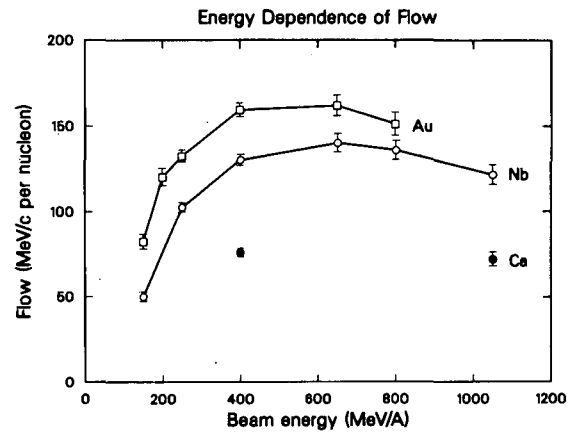

Fig. 1. Flow for minimum bias events as a function of beam energy. XCG 864-7173

Footnotes and References

*Condensed from Phys. Rev. Lett. **57**, 302 (1986)

Study of Medium-Heavy Fragment Production and Flow in Central Collisions of Heavy Nuclei

G. Claesson, K.G.R. Doss,† R. Ferguson,‡ A. Gavron,§ H-A Gustafsson,† H.H. Gutbrod,* J.W. Harris,† B.V. Jacak,§ K-H Kampert,* B. Kolb,* F. Lefebvres,** A.M. Poskanzer,† H-G Ritter,† H-R Schmidt,*L. Teitelbaum,† M.L. Tincknell,† S. Weiss,† H. Wieman,† and J.B. Wilhelmy§*

Understanding the decomposition of highly excited nuclear matter is still an important goal of nucleus-nucleus reaction studies. In pursuit of understanding the reaction dynamics and deexcitation processes, the LBL/GSI Plastic Ball detector system[1] was upgraded to measure light and medium-heavy fragments over a large solid angle in 200 MeV/nucleon Au + Au and Au + Fe reactions.

Computer-controlled high voltage modules were implemented to enable online gain-matching. With the gains reduced for the forward Ball modules, the energy loss spectrum was extended to enable the simultaneous measurement of all produced nuclei from hydrogen to neon. This allowed an estimate of the total charged particle multiplicity and hence the impact parameter. By choosing subsets of the data corresponding to peripheral or central collisions, the assumptions inherent in various models of nuclear fragmentation can be tested. Multiplicity and mass distributions were accumulated. The results from these distributions can be summarized as follows. Most peripheral collisions result in the production of only few fragments, which are emitted at small angles with energies close to that of the projectile. For central collisions, however, three to four fragments are produced in the average event. These fragments appear at lower energies and larger angles than in peripheral collisions. The multiplicity distributions show that central collisions are very violent with break-up of the entire system into primarily small pieces of $1<Z<6$. Conversely, in peripheral collisions a large projectile remnant, $24<Z<79$, is always observed. From the energy spectra it was found that the central collisions produce fragments with larger perpendicular momenta than peripheral ones. Midrapidity fragments from the region where the projectile and target overlap exhibit large perpendicular momenta, in contrast to fragments observed at the projectile rapidity, which result from the gentler mechanism of projectile breakup.

In order to study the flow of the fragments, the transverse momentum analysis technique of Danielewicz and Odyniec[2] was employed to determine the reaction plane of each event. The vector difference of the transverse momentum components of particles going forward and those going backwards is used together with the beam axis to define the reaction plane. Although the rapidity dependence of the correlation is more pronounced for central collisions, midrapidity fragments are always less correlated with the reaction plane than projectile-like fragments. In the limit of complete thermalization, azimuthally symmetric emission of midrapidity particles is expected. The observed correlations can be a result of collective flow of nuclear matter.[3] This should be more important for central rather than peripheral collisions. If the correlations are a result of collective motion, the random thermal motion generated in such energetic collisions should lessen the effect. For a system at given temperature, the heavier ejectiles have lower thermal velocities. The observations thus far suggest that collisions at small impact parameters result in complete breakup of both nuclei, but that large dynamical effects remain. The fragmenting system is highly excited, but retains some memory of the early part of the collision when the potential degrees of freedom are excited.

Footnotes and References

*GSI

†LBL

‡ORNL

§LANL

**Present address: Univ. of Caen, 14032 Caen, France.

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Evidence for Multiparticle Correlations in High Energy Heavy Ion Interactions

P. Beckmann, K.G.R. Doss, H.Å. Gustafsson, H.H. Gutbrod, K.H. Kampert, B. Kolb, H. Löhner, B. Ludewigt, A.M. Poskanzer, H.G. Ritter, H.R. Schmidt, T. Siemiarczuk and H. Wieman

A new approach to studying azimuthal multiparticle corralations in heavy ion interactions has been developed. The exclusive observable

$$W = \sum_i \vec{p}_{ti} / \sum_i |\vec{p}_{ti}|$$

where p_{ti} is the transverse momentum of i-th charged particle is used to define correlation functions of the type

$$R(W) = \frac{D(W) - B(W)}{D(W) + B(W)}$$

where D(W) is the experimental distribution of W and B(W) is the reference distribution corresponding to uncorrelated emission of particles. The reference distribution is constructed from the data by applying the random flight theory.

Strong many particle correlations are found in heavy ion reactions measured with the Plastic Ball. Energy, mass and multiplicity dependence of the correlations have been examined.

Footnotes and References

*Condensed from P. Beckmann *et al*, Preprint GSI-86-40

On-Line Isotope Separation of Projectile Fragments Produced in Relativistic Heavy-Ion Reactions*

Y. Nojiri,† K. Matsuta,† T. Minamisono,† K. Sugimoto,† K. Takeyama,† H. Hamagaki,‡ S. Nagamiya,‡ K. Omata,‡ Y. Shida,‡ I. Tanihata,§ T. Kobayashi,†† S. Matsuki,‡‡ S. Shimoura,‡‡ J. R. Alonso, G. Krebs, T. J. M. Symons

Radioactive isotopes have played an important role in research, not only in nuclear structure but also in fundamental interactions. In preparing β-radioactive nuclei for these investigations, on-line isotope separators connected directly with the beam line enable us to separate an isotope quickly.

In the present experiment, short lived β-emitting ^{20}F and ^{21}F were produced through projectile fragmentation of ^{22}Ne beam of ≈200 MeV/nucleon. Produced isotopes were analyzed and transferred to the experimental area using Beam44 at the Bevalac and stopped in the thin catcher by controlling the energy before stopping using a set of variable wedge absorbers made of thick plastic. Beta rays from the nuclei were observed by two sets of plastic scintillation counter telescopes and time spectrum was obtained as shown in Fig. 1.

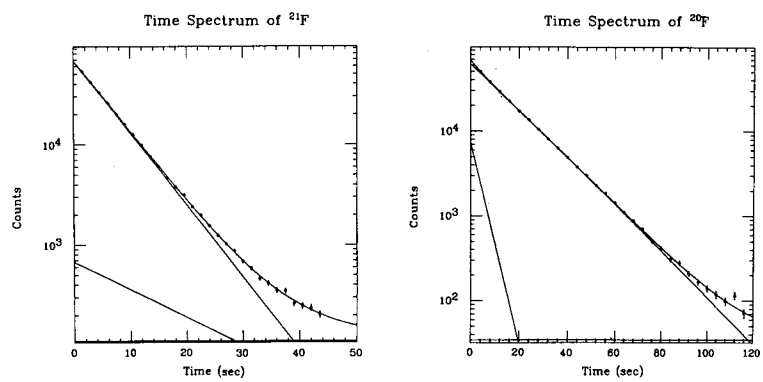

Fig. 1. Typical β-ray time spectra of ^{21}F and ^{20}F. The theoretical lines best fitted to the data consist of three components that are also separately shown, respectively. XBL 871-98

tion consisting of two exponential decays and constant background. The deduced half lives of ^{20}F and ^{21}F were 11.03±0.06 and 4.21±0.03 sec, respectively, which are consistent with the previous values[1,2] within the errors.

In the near future, the apparatus will be used for magnetic moment measurements of β-radioactive nuclei in the f shell.[3] For these experiments, a tilted foil technique[4] to polarize the nuclei and an NMR technique[5] will be combined with the separator. This will open up new applications of the technique to much wider varieties of studies using β-radioactive nuclei.

Footnotes and References

*Condensed from LBL-22406

†Faculty of Science, Osaka University, Toyonaka, Osaka 560, Japan

‡Institute for Nuclear Study (INS), The University of Tokyo, Tanashi, Tokyo 188, Japan

§RIKEN, Wako, Saitama 351-01, Japan

††National Laboratory for High Energy Physics, Tsukuba, Ibaraki 305, Japan

‡‡Faculty of Science, Kyoto University, Kyoto 606, Japan

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A Search for Stable Quarks Produced by the Tevatron

*H. S. Matis, R. W. Bland,† D. H. Calloway,† S. Dickson,† A. A. Hahn,‡ C. L. Hodges,† M. A. Lindgren,† H. G. Pugh, M. L. Savage,† G. L. Shaw,‡ R. Slansky,§ A. B. Steiner†, R. Tokarek***

The signature of a quark produced at an accelerator is very different from that of a typical hadron. De Rujula *et al.*[1] argued that after a quark is produced it would capture nucleons as it passes through a detector. Since a bare quark could have a net color charge, its interaction with matter could be significantly stronger then a typical hadron. Therefore, its signature could have been missed in previous experiments.[2]

In the first run, four steel cylinders filled with mercury were centered in a primary proton beam line which ran at 800 GeV/c and which had an integrated intensity of 1.0 $\times 10^{15}$ protons on target. Each cylinder contained about 1.5 liters of mercury. Since a quarked mercury atom is attracted to its neighbors by its image charge,[2] these atoms do not evaporate when the mercury is heated. When the mercury is gently heated, the residue should contain the quarked atoms. The residual charge of the tested mercury is shown in Fig. 1a.

From these data, an upper limit at 90% confidence level for quark production can be set at 2 $\times 10^{-10}$ quarks per incident proton for the third tank and 2 $\times 10^{-11}$ for the fourth tank.

Liquid nitrogen tanks were used to stop any produced quarks in the second run of this experiment. In this run, the 800 GeV/c proton beam struck a 10 cm thick lead target. A quark, produced in the interaction, could stop in one of the four tanks. Once it stopped it would be attracted to one of two electrically charged gold plated glass fibers which were in each tank. After the exposure the gold was carefully dissolved in a small bead of mercury. Approximately 213 micrograms of material have been processed so far. The results are shown in Fig. 1b, and are consistent with all drops containing only integer charges.

From this data, an upper limit for quark production of 1.0 $\times 10^{-10}$ quarks per proton interaction at the 90% confidence level can be set.

Footnotes and References

*Condensed from LBL-22279.

†Physics and Astronomy Department, San Francisco State University, San Francisco, CA 94132.

‡Physics Department, University of California at Irvine, Irvine, CA 92717

§Los Alamos National Laboratory, Los Alamos, NM 87545

**Fermi National Accelerator Laboratory, Batavia, IL 60510

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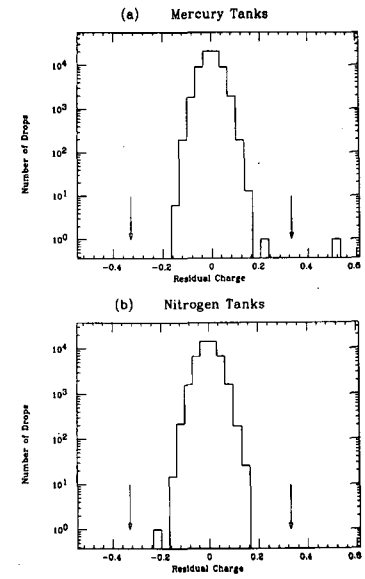

Fig. 1. This figure shows a histogram of residual charge for drops which passed all acceptance tests. The two arrows show the expected position for residual charge for any drop which contains a net fractional charge. a. Data from the distilled mercury samples. b. Data from the liquid nitrogen run.

XBL 869-3274

Measurement of Interaction Cross Sections Using He, Li, Be, B, and C Isotope Beams and Radii of Light p-shell Nuclei

I. Tanihata, H. Hamagaki, O. Hashimoto, Y. Shida, O. Yamakawa, T. Kobayashi, K. Sugimoto and N. Takahashi

It has been shown that nuclear radii can be determined from a measurement of interaction cross sections of high-energy heavy-ion collisions.[1,2] In particular, the use of unstable nuclear beams provides a unique tool for determining nuclear radii of unstable nuclei.

The secondary beams of ^{4,6,8}He, $^{6-9,11}$Li, $^{7,9-12,14}$Be, $^{8,13-15}$B, and ^{10,12}C were produced through the projectile fragmentation of 800 MeV per nucleon ^{11}B and ^{20}Ne accelerated at the Bevalac. The energy of the secondary beams was 790 MeV/nucleon at the target. The interaction cross sections (σ_I) were measured using Be, C, and Al targets by a transmission experiment with a large acceptance spectrometer. The experimental procedures were the same as reported in the previous papers.[1,2]

The root-mean-square (*rms*) radii of nucleon matter distribution[3] have been determined using a Glauber-type calculation.[2] The obtained *rms* radii are shown in Fig. 1 as a function of the neutron number (N). It is seen that the radii of Li and Be isotopes show similar behavior with N. The radii of nuclei with N=6 and 8 ($p_{3/2}$ and $p_{1/2}$ closed, respectively), except ^{8}He and ^{11}Li, are close to the prediction of a Hartree-Fock calculation based on spherical nucleus.[4] A large increase of the *rms* radius is seen

at N=7. It is considered that the increase of radius is due to a deformation of ^{11}B (or admixture of sd-shell components).[4] The nucleus ^{11}Li, with the neutron number of p-shell closure in the naive shell model, shows a considerably larger radius than neighboring nuclei. It suggests the existence of a large deformation and/or of a long tail in the matter distribution due to the weakly bound nucleons. Further increase of the radius in ^{11}Li from that of ^{11}B may therefore suggest that N=8 is not a neutron magic number for Li isotopes.

Appreciable differences of radii are observed between pairs of isobars with different isospin, ^{6}He-^{6}Li, ^{8}He-^{8}Li, and ^{9}Li-^{9}Be. The larger radii of the neutron-rich isotopes ^{6}He and ^{8}He, which have only two protons, suggest the existence of thick neutron skins. On the other hand, pairs of mirror nuclei (the same isospin isobars) ^{7}Li-^{7}Be, ^{8}Li-^{8}B, and ^{10}Be-^{10}C show equal radii. It indicates that the difference of the Coulomb interaction does not affect the nuclear radius in visible size for light p-shell nuclei.

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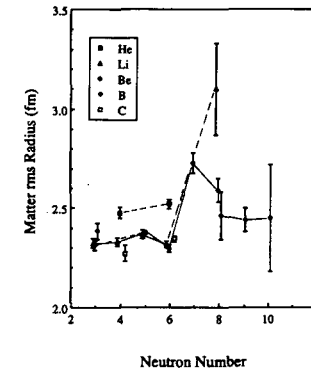

Fig. 1. Root-mean-square radii of nucleon distributions determined from the interaction cross section of 790 MeV/nucleon heavy-ion collisions. Radioactive nuclear beams have been used to obtain the radii of beta-unstable nuclei. XBL 871-97

Probing Nuclear Matter with Dileptons*

L.S. Schroeder

Dileptons have a long and distinguished history in particle physics, e.g., the discovery of the J/ψ and its impact on QCD. In nuclear science dileptons are now being employed to study many interesting features associated with pA and AA collisions at intermediate and high energies. Examples of dileptons at both the quark and hadron levels is shown in Fig. 1. The review of dileptons briefly describes what is known experimentally about e^+e^- and $\mu^+\mu^-$ production, and then outlines dilepton program at high energies (AGS/SPS) as probes of the quark-gluon plasma. In addition, the program developing at the Bevalac with the Dilepton Spectrometer (DLS) to extend the study of the nuclear matter equation of state at high temperature and density was discussed.

*Condensed from LBL-21974, and an invited talk presented at the VIII International Seminar on High Energy Physics Problems, Relativistic Nuclear Physics and Quantum Chromodynamics, held at Dubna, USSR, June 19–24, 1986.

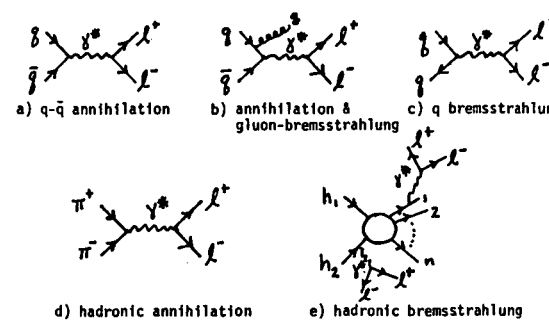

Fig. 1. Examples of processes yielding dileptons (e^+e^- or $\mu^+\mu^-$) in hadron-nucleus and nucleus-nucleus collisions. XBL 8611-4549

Muon Catalyzed Fusion at Low Temperatures*

*J. Bistirlich, H. Bossy,† W.H. Breunlich,‡ M. Cargnelli,‡ K.M. Crowe, H. Daniel,† F.J. Hartmann,† M. Justice, P. Kammel,‡ J. Kurck, J. Marton,‡ N. Naegele,† W. Neumann,† P. Pawlek,‡ C. Petitjean,§ G. Schmidt,† A. Scrinzi‡, R.H. Sherman,** T. von Egidy†, J. Werner‡, J. Zmeskal‡*

Muon catalyzed fusion, the process whereby a negative muon acts as a catalyst for the nuclear reaction

$$d + t + \mu^- \longrightarrow \alpha + n + \mu^- + 17.6 \text{ MeV},$$

has attracted renewed interest recently due to a resonance mechanism, which dramatically increases the rates. Basic information concerning the main $d\mu t$ fusion cycle as well as the competing $d\mu d$ and $t\mu t$ fusion branches was attained in our experiments at the Swiss Institute for Nuclear Research. The cycle rate, λ_c, which is a measure of the average rate at which the muon induces fusions, was observed to peak in liquid DT at 145 μsec^{-1} corresponding to 113 fusions per muon. A strong nonlinear density dependence in the resonant $d\mu t$ formation rate was revealed. The DT sticking factor, ω_s, which gives the probability that the μ^- becomes attached to the product He nucleus and which ultimately limits the maximum attainable yield, was measured with independent techniques and found to be (0.45±0.05)% in the liquid. Experiments in low density mixtures showed striking epithermal behavior indicating the presence of nonthermalized μt atoms and pointing to the possibility of achieving yields of over 200 fusions per muon at optimal conditions.

Footnotes and References

*Condensed from LBL-21174, LBL-21366, and invited paper presented at the International Symposium on Muon Catalyzed Fusion, Tokyo 1986, to be published.

†Physik Department, Technische Universität München D-8046 Garching, West Germany

‡Oesterreichische Akademie der Wissenschaften A-1900 Vienna, Austria

§Swiss Institute for Nuclear Research CH-5234 Villigen/Switzerland

**Materials Science and Technology Los Alamos National Laboratory Los Alamos, New Mexico 87545

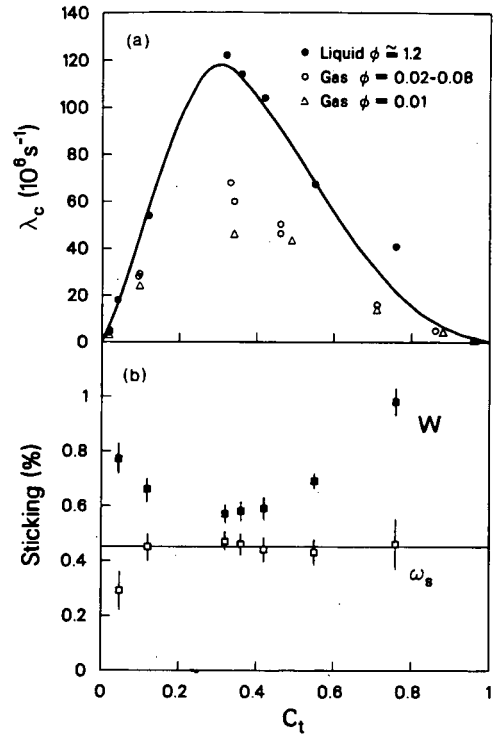

Fig. 1. a) Normalized DT cycle rates λ_c vs tritium concentration showing pronounced density effects. b) Raw sticking W and corrected DT sticking ω_s (from liquid data). XCG 865-7224

The Role of Pions and Hyperons in Neutron Stars and Supernovae*

N. K. Glendenning

We have calculated the equation of state of neutron stars in a relativistically covariant field theory of interacting hadrons. In particular we studied the role of hyperons and pions. These particles soften the equation of state considerably. As a consequence the limiting mass of neutron stars is reduced by the hyperons by about one half a solar mass or about 25 percent (see Fig. 1). This is a very significant reduction because all theories of neutron star matter that respect nuclear matter properties and take into account beta stability have predicted neutron star masses in a narrow range of half a solar mass. Therefore, theories of star matter that neglect the hyperons and predict star masses that fall within the range of 1.4 to 2 solar masses, would likely fall in the unacceptable range below 1.4 solar masses if they were included. (Since observed masses are as large as 1.4 solar masses, the limiting mass of theory must be at least this large.) Pions soften the equation of state at intermediate density. In calculations of star collapse, it is found that a crucial element in obtaining scenarios that lead to a successful supernova explosion is that the parameterized equation of state be soft at high density. In these cases the collapsing matter attains a rather high density, the domain where the pion condensate and hyperons become important components, before the shock wave is detonated, which expels the mantle and leaves the core to subside into a neutron star. We hypothesize that the physical origin of the parameterized softness in the supernova calculations is due to pions and hyperons, whose softening effects are exploited so effectively by gravity in arranging neutron star structure, as shown in Fig. 1.

Footnotes and References

*Condensed from LBL 22041; accepted by Z. Phys. A.

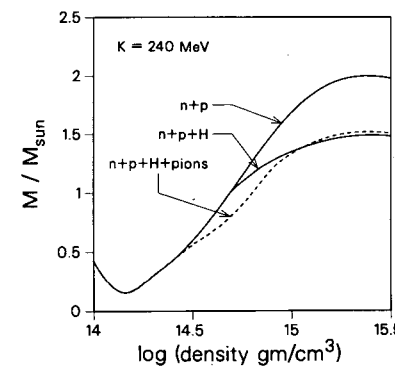

Fig. 1. Neutron star masses as a function of central energy density for the three cases, 1.) neutron and proton, 2.) hyperons in addition, 3.) pions in addition. In all cases leptons are present to complete beta equilibrium. The compression modulus of the corresponding nuclear matter is K=240 MeV.

XBL 868-3137

Soliton Matter as a Model of Dense Nuclear Matter*

N. K. Glendenning and B. Banerjee†

Topological soliton models of nucleon structure are able to account for nucleon properties at the 30% level. It is interesting to investigate how the internal structure is effected by the presence of other nucleons as in dense matter. We employ the hybrid soliton model consisting of quarks deeply bound to a topological meson configuration of the chiral sigma model. For simplicity we place the solitons (nucleons) on a crystal lattice. The levels of the isolated solitons spread into bands as the lattice separation is reduced, and at a density of about three times normal density, the filled ground state band intersects a higher empty band (see Fig. 1). At this density the matter would cease to be a color insulator and would become increasingly color conducting. This is a somewhat different picture of quark liberation in dense matter. Instead of the nucleons dissolving into quark matter, the basic nucleon structure remains (the topological field). Only the quarks, rather than being confined to a single site, are free to migrate throughout the matter.

Footnotes and References

*Condensed from Phys. Rev. **C34**, 1072 (1986).

†Tata Institute for Fundamental Research, Bombay, India

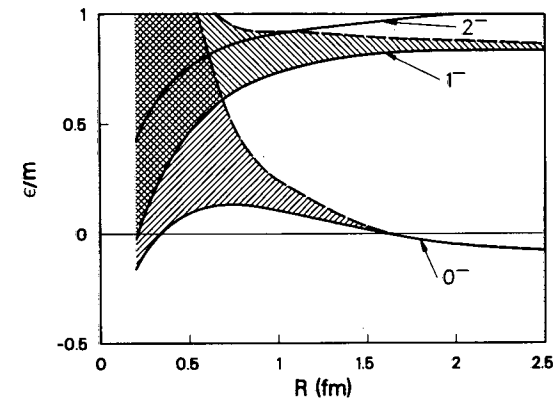

Fig. 1. Bands are shown for several levels as a function of lattice spacing. XCG 8510-473

Hyperons in Neutron Stars*

N. K. Glendenning

Generalized beta equilibrium in neutron stars is discussed in the framework of relativistic nuclear field theory, which includes nucleons, deltas, hyperons and leptons. The possibility of condensation of additional mesons beyond those that have non-vanishing source currents in the normal state of matter is examined. It is shown that in charge-neutral neutron star matter, pion condensation and the growth of hyperon populations precludes the possibility of other mesons, such as the kaon, condensing. The equation of state is calculated and the equations of star structure solved. The cores of neutron stars are found to be dominated by hyperons, as shown in Fig. 1, and the hyperon populations integrated over the volume of the star amount to 15-20 percent of the baryon population.

Footnotes and References

*Condensed from Z. Phys A. **326** (1986).

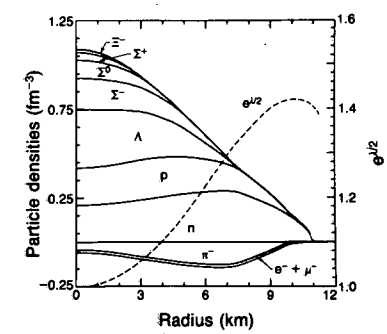

Fig. 1. Proper number in neutron stars at the limiting mass in an onion skin depiction (distance between curves denotes population). XBL 8311-3417

PART III: THEORY

Neutron Star Masses as a Constraint on the Nuclear Compression Modulus*

N. K. Glendenning

There is currently a controversy over the nuclear compression modulus, with Brown and Osnes claiming that it is much smaller than the value deduced from the giant monopole resonance in heavy nuclei. Neutron star masses can be used to shed some light on this matter. We have solved a relativistically covariant field theory of nuclear matter in the mean field approximation, for both symmetric nuclear matter and neutron star matter, involving a generalized beta equilibrium between nucleons, hyperons, isobars and leptons, and in two limiting cases in which pions condense at an effective mass equal to the vacuum value and in which they do not condense because of an assumed effective mass which is too large compared to the electron chemical potential. The parameters of the theory were fitted to the bulk properties of nuclear matter except that the compressibility was treated as unknown. The mass curves of neutron stars were calculated for various assumed values of the compressibility. Since masses as large as 1.4 solar masses have been observed, theory must possess a maximum mass at least this large. From Fig. 1 we see that values of the compression modulus less than about 200 MeV are incompatible with observed neutron star masses.

Footnotes and References

*Condensed from Phys. Rev. Lett. **57**, 1120 (1986).

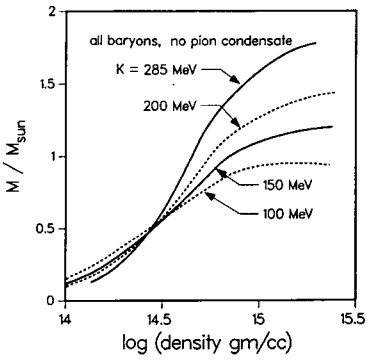

Fig. 1. The masses of neutron stars as a function of the case in which free pions condense.

XBL 865-2032

Finite Temperature Metastable State

N. K. Glendenning

The non-linearity of nuclear field theory admits of additional solutions besides the normal state of matter. One of these is an abnormal state, characterized by low baryon effective masses, abundant baryon-antibaryon pairs, and high entropy. Over a narrow range in temperature, matter can exist in the abnormal state at zero pressure. Fig. 1 shows one isotherm for which the pressure has a zero pressure point on the abnormal branch. This is a hot metastable state, for which there is a barrier against decay because the field configuration is different from the normal state, the baryon masses are far removed from their vacuum masses, and there is an abundance of pairs also far removed from their vacuum masses and a correspondingly high entropy.

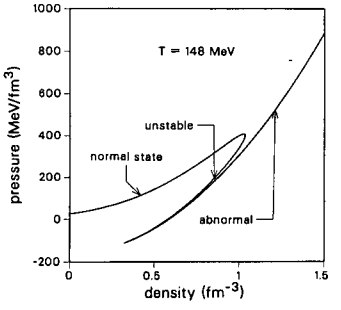

Fig. 1. Pressure as a function of density on the isotherm T=148 MeV, showing details of the normal, abnormal and unstable solution. Note that on the unstable solution the pressure is zero at a density of about $0.6 fm^{-3}$.

XBL 8610-3761

The abundance of baryon-antibaryon pairs is the glue that holds this matter together. The signals associated with this novel state are quite unusual. A fragment of such matter will cool by emitting a spectrum of black-body radiation, consisting principally of photons, lepton pairs and pions, rather than by baryon emission, because they are far removed from their vacuum masses. If produced at the upper end of its temperature range, a large fraction of the original energy is radiated in this way. The baryons and light elements produced in the eventual decay will account for only a fraction of the collision energy.

Footnotes and References

*Condensed from Phys. Lett. B **185**, 275 (1987).

Pion Interferometry Predictions for Relativistic Heavy-Ion Collisions Using the Intranuclear Cascade Model*

T. Humanic

Cugnon's [1] intranuclear CASCADE model was used to obtain pion source parameter prediction which could then be directly compared to experiments. Pions generated by CASCADE model were required to pass cuts typical of the experimental acceptances. These pions were then symmetrized using the expression of Yano and Koonin.[2] The pions were analyzed in the same fashion as the experimental data to give the source parameter predictions for R, λ, and τ. The source parameters were studied as a function of the minimum allowed pion momentum (k_{min}), where a variation of R was found, and is thought to be due to selecting pions produced at different times in the collision by the momentum cut. The parameters were also studied as a function of impact parameter (b), where the expected variation of R and τ was found. See Fig. 1 where the dependences are displaced for a 4π acceptance. The predictions agreed rather well with the experiments. Comparisons with the data of Zajc *et al.*, [3] give agreement at the 1σ level for R and τ, but cannot explain the values of λ. Comparisons with the data of Beavis *et al.*,[4] give agreement at the 1σ level for all the parameters.

Footnotes and References

*Condensed from T. Humanic, Phys. Rev. C **34** 191 (1986).

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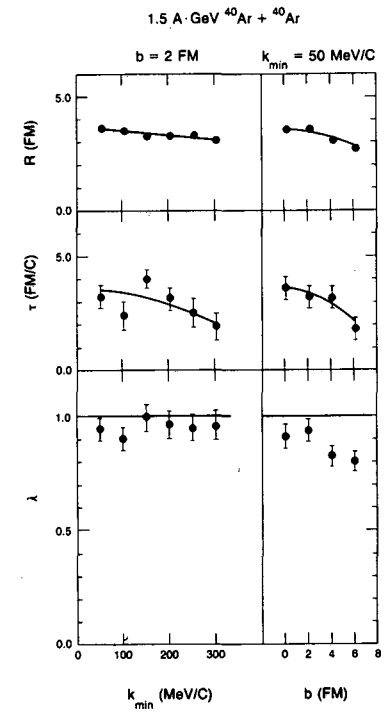

Fig. 1. Dependence of pion source parameters on k_{min} and b for the reaction 1.5 GeV/nucleon ^{40}Ar + ^{40}Ar. The lines are drawn to guide the eye.

XBL-849-10800

New Developments in Favored Alpha Decay for N<126*

J.O. Rasmussen

New on-line techniques are reviving interest in alpha decay as they provide information on decay rates and relative phases of S- and D-waves in alpha decay of very short-lived isotopes below the neutron closed-shell of 126. A Belgian group[1] has perfected a technique of low temperature orientation of recoil product nuclei in cooled magnetized iron host material. They have applied this so-called KOOL technique to several light Po, At, and Fr alpha emitters with half lives in the seconds to minutes regime.

We expect the alpha decay to be predominantly S-wave, but it cannot be entirely so or there would be no anisotropy. A small D-wave admixture should be considered. (Still higher L-values are allowed by the selection rules, but it seems likely that their contributions are negligible.) Thus, it is the interference of S and D waves that gives the observed anisotropy. A striking feature is that the anisotropy changes sign, emission preferring to be perpendicular to the spin axis for $N < 117$ and emission preferring the parallel direction for $N > 117$. We note that all the favored decays of actinides for which directional correlation information has been measured give alpha decay preferring the parallel direction ($\delta > 0$).

In this paper I attempt an interpretation based purely on nuclear shapes and shape changes, along the lines of Radi *et al.*[2] to avoid the complication of the microscopic shell model alpha decay calculations, extracting the alpha amplitudes on the surface directly from the shape changes in going from alpha daughter to parent.

The Po, At, and Fr isotopes of the new orientation experiments are in a region where weak oblate deformation is indicated. We simply conclude that the negative anisotropies of At isotopes with N<117 indicate that the oblate deformation increases with addition of an alpha particle to the corresponding Bi daughters. The positive anisotropies of the At and Fr isotopes with N>117 and of the 13/2+ Po-199m indicate that the oblate deformation decreases with addition of an alpha particle to the daughters.

The full paper also discusses the systematics of alpha reduced widths in the region below 126 neutrons.

Footnotes and References

*Condensed from invited talk at Anaheim ACS Meeting, September, 1986.

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Δ-excitations and Shell-Model Information in Heavy-Ion, Charge-Exchange Reactions*

P.A. Deutchman,[†] *K.M. Maung,*[‡] *J.W. Norbury,*[‡]
J.O. Rasmussen and L.W. Townsend[§]

We calculate total cross sections for coherent pion production using localized plane-wave approximations for the shell-structure of valence nucleons that are excited to Δ-particles in the intermediate state in the (^{12}C,^{12}B) and (^{12}C,^{12}N) charge-exchange, heavy-ion reactions. We find comparable agreement to projectile downshift data for ^{12}C(^{12}C,^{12}B)^{12}N. Then we improve the formalism by replacing the localized plane wave bound states with harmonic oscillator states which are imbedded in a multipole expansion approach and calculate pion differential cross sections to test for the sensitivity of the spectra to the single-particle mass parameter.

Footnotes and References

*Accepted for Phys. Rev. C (Rapid communications).

†Physics Department, University of Idaho, Moscow, Idaho 83843.

‡Physics Department, Old Dominion University, Norfolk, Virginia 23508.

§NASA Langley Research Center, Hampton, Virginia 23665.

Thermal Energy Partition in Complex Fragment Emission Inferred from Velocity Distributions

L.G. Moretto, R.J. Charity, M.A. McMahan, R.J. McDonald, G.J. Wozniak, D. G. Sarantites, L.G. Sobotka,* G. Guarino,† A. Pantaleo,† L. Fiore,† A. Gobbi,‡ and K. Hildenbrand‡*

The analysis of the velocity distributions of fragments produced in the reaction $^{12}C + {}^{93}Nb$ at 18 Mev/nucleon has revealed the surprising fact shown in Fig. 1. These velocity distributions become wider with decreasing charge of the fragments. More specifically the width σ is inversely proportional to $\sqrt{Z}$ as shown by the line. It has occurred to us that this simple observation proves that the excitation energy of the primary fragments is approximately proportional to their mass, as expected in the binary decay of an excited compound nucleus.

Let us assume that indeed the excitation energy E_x of the fragment of mass A is

$$E_x = kA.$$

As this fragment decays, it emits an average number **n** of particles of mass **m** and velocity **v**. The average recoil velocity **V** of the fragment for the emission of one of these particles is

$$\mathbf{V} = \frac{\mathbf{m}}{\mathbf{A}}\mathbf{v}.$$

The width of the recoil velocity after the random emission of **n** particles is

$$\sigma = \sqrt{\mathbf{n}}\,\frac{\mathbf{m}}{\mathbf{A}}\mathbf{v}.$$

But the mean number of evaporated particles **n** is proportional to the excitation energy and thus to the mass of the fragment

$$\mathbf{n} = \frac{E_x}{B^*} = \frac{kA}{B^*}$$

where B^* is the average amount of energy removed by the evaporated particle. Finally,

$$\sigma = \frac{\sqrt{k}}{\sqrt{B^*}}\sqrt{A}\,\frac{\mathbf{m}\mathbf{v}}{A} = \frac{\sqrt{k}}{\sqrt{B^*}}\frac{\mathbf{m}}{\sqrt{A}}\mathbf{v}.$$

The observed inverse proportionality with Z reflect the fact that Z and A are approximately proportional to each other. We take this evidence as a further indication that the fragments arise from the thermal emission of a hot compound nucleus.

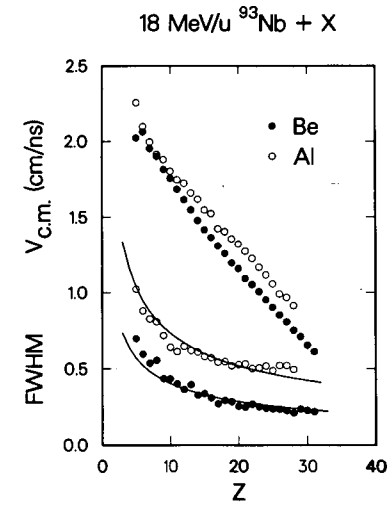

Fig. 1. A plot of the mean c.m. velocity (upper) and FWHM as a function of the Z value of the detected complex fragment for the reactions 18 MeV/nucleon $^{93}Nb + {}^{9}Be$, ^{27}Al. XBL 8612-4838

Footnotes and References

*Department of Chemistry, Washington University, St. Louis, 63110.

†INFN, 70100, Bari, Italy.

‡Gesellschaft für Schwerionenforschung, 6100 Darmstadt, West Germany.

PROSPECT: An Improved Beta-Delayed Particle Emission Simulation Code

J. Gilat, J.M. Nitschke and P.A. Wilmarth*

The Fortran code PROSPECT (adapted from an earlier version that originated at CERN and GSI) calculates β-delayed proton (and alpha-particle) spectra and branching ratios in the framework of the statistical model, as formulated by Hornshøj *et al.*[1] In this model, the intensity $I_p(E_p)$ of protons with an energy E_p is given by

$$I_p(E_p) = \sum_i \sum_f I_\beta(E) \frac{\Gamma_p^{if}(E_p)}{\Gamma^i}$$

Here i and f denote states in the intermediate and final nuclei of the β-delayed particle emission process, and E is the excitation energy in the intermediate nucleus

$$E = B_p + E_f + \frac{A}{A-1} E_p$$

The beta decay intensity to this excitation energy is given by

$$I_\beta(E) = \frac{f(Z, Q-E) S_\beta(E)}{\int_0^Q f(Z, Q-E) S_\beta(E) dE}$$

where f(Z,Q-E) is the statistical rate function for nucleus of charge Z and beta decay energy Q, and $S_\beta(E)$ is the beta strength function proportional to the squares of the matrix elements of the decay. The total width of each intermediate state is taken as the sum of its gamma width and partial proton widths to all available final states,

$$\Gamma^i = \Gamma_\gamma^i + \sum_f \Gamma_p^{if}(E_p)$$

with

$$\Gamma_\gamma^i = \int_0^E S_\gamma(E_\gamma) \frac{\rho_i(E - E_\gamma)}{\rho_i(E)} dE$$

and

$$\Gamma_p^{if}(E_p) = T_{if}(E_p)/2\pi\rho_i(E)$$

where $S_\gamma(E_\gamma)$ is the strength function for the emission of a photon of energy E_γ, $T_{if}(E_p)$ are the optical model generated proton transmission coefficients connecting the intermediate and final states, and $\rho_i(E)$ denotes the density of levels in the intermediate nucleus at excitation energy E.

In a previous modification, first suggested by Hardy,[2] the original Gilbert and Cameron level density formula was replaced by a back-shifted Fermi gas prescription, and the gamma width calculation was modified to include the effects of the giant dipole resonance and normalized to experimental photoabsorption cross sections.

Further improvements of the code completed during the last year include:

1.) Provision for the incorporation of externally generated beta strength functions $S_\beta(E)$, obtained, for example, from independent shell or RPA model calculations.[3] 2.) Replacement of the original statistical rate function routine by a more recent and accurate version,[4] and separation of the calculated proton spectra into parts associated with β^+ and EC decay, respectively. 3.) Provision for user-originated variation of the level density parameter. 4.) Incorporation of an additional set of optical model parameters, more appropriate for the calculation of transmission coefficients below the Coulomb barrier.[5] 5.) Improved tabular and graphic output.

Footnotes and References

*On leave from the Soreq Nuclear Research Center, Yavne, Israel

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Microscopic Model of Nucleus-Nucleus Collisions*

B.G. Harvey

The collision of two nuclei is treated as a collection of collisions between the nucleons of the projectile and those of the target nucleus. The primary projectile fragments contain only those nucleons that did not undergo a collision. The inclusive and coincidence cross sections result from the decay of the excited primary fragments.

Footnotes and References

*Condensed from LBL-21452 and a talk presented at the Heavy Ion Conference in the Fermi Energy Domain, Caen, France, May 12–16, 1986; published in Journal de Physique **47** 29 (1986).

Derivation of the Window Formula with Linear Response Theory

T. Døssing and J. Randrup*

It has long been known that the simple wall formula for the mean energy dissipation rate results when general linear response theory for one-body nuclear dynamics is applied to a suitably irregular mononucleus; that approach also yields expressions for the effects of symmetries. In the present study, the same general linear response theory is employed to derive the rate of energy dissipation in a binary one-body potential well whose two parts are connected by a small "window" and are in slow relative motion, a dinucleus. Under suitable randomization assumptions, the "completed wall-and-window formula" is obtained, including the contribution from the change in the mass asymmetry; and again expressions for the effects of symmetries are obtained. Thus the linear response theory yields the standard results for both mononuclei and dinuclei and therefore provides a well-founded basis from which to approach the dynamics of nuclei with intermediate shapes, such as are believed to occur in quasi-fission reactions.

Footnotes and References

*The Niels Bohr Institute, University of Copenhagen, Blegdamsvej 17, DK-2100 Copenhagen Ø Denmark

Fermi Jets from Hot Nuclei

*J. Randrup and R. Vandenbosch**

At relatively low temperatures, the nucleus consists of nearly independent nucleons in the one-body mean field. As a consequence, the nucleons exchanged between two reacting nuclei are expected to propagate nearly undisturbed through the receptor nucleus and, under suitable kinematical conditions, they may emerge from the back side as prompt ejectiles having very specific directional and spectral characteristics. We have examined this "Fermi-jet" effect based on the nucleon-exchange transport (NET) model which is known to provide a good reproduction of a broad range of other reaction observables. We incorporate the effect of the time-dependent nuclear temperature, as calculated with the NET model. This novel feature substantially enhances the emission of jet nucleons originating in the small reaction partner which grows quite hot (up to temperatures of 5-6 MeV in cases of practical interest). The occurence of direct two-body nucleon-nucleon collisions during the propagation is also considered.

*University of Washington, Seattle, WA

FREESCO: Statistical Event Generator for Nuclear Collisions*

G. Fái † *and J. Randrup*

This paper describes FREESCO, the numerical code which generates complete multifragment events in nucleus-nucleus collisions at beam energies from a few tens of MeV per nucleon to a few GeV per nucleon. The code represents an implementation of a statistical explosion-evaporation model describing the microcanonical disassembly of excited sources into pions, nucleons and complex nuclear fragments.

The model, and its present numerical implementation, are intended to provide a simple, well-defined reference against which to judge both more refined and specific models and the experimental data; in addition it may be valuable as a simulator of actual experiments involving complex detection systems whose responses are not easily understood.

Footnotes and References

*Condensed from Comp. Phys. Comm. **42**, 385 (1986)

†Department of Physics, Kent State University Kent, Ohio 44242

Microcanonical Simulation of Nuclear Disassembly*

S.E. Koonin and J. Randrup

The advent of detailed measurements of collisions between fast atomic nuclei has made it possible to study the violent disassembly of small, highly excited nuclear systems. In concert with this experimental development, the demand for refined theoretical tools has grown. A statistical approach, or "counting phase space", is a natural response of any physicist faced with a complicated system. If the system under study is sufficiently complicated, and our specification of its state not too detailed (e.g., restricted to one- or few-body observables), then a statistical hypothesis is often a remarkably economical and accurate description.

We have formulated a model for the disassembly of a highly excited finite nuclear source into interacting nuclear fragments. Thus, we imagine A nucleons with total energy E confined within a spherical volume Ω, as might approximate the "freeze-out" stage of a heavy-ion collision. The model can be viewed as a transition-state model of the disassembly of a hot nuclear system. Its basic assumption is that the evolution of the system from a structureless source to an assembly of interacting nuclear fragments can be considered as effectively occuring at a certain transition "state", in which all the matter is confined within a spherical volume Ω. The probability of the different possible final states can then be determined by considering the appropriate statistical weights of all the various configurations of the confined multifragment system. [As in other transition-state models, it is unlikely that the dynamical "decisions" are all taken at the same point in time, but it may nevertheless be a useful approximation.] Monte-Carlo sampling of the exact microcanonical and canonical ensemble provides many-fragment configurations at the effective freeze-out stage.

The effect of including the interaction between the fragments is found to besignificant. An elaboration of the model includes a vapor of nucleons and displays a liquid-gas phase transition between a collection of complex nuclei and a gas of very light fragments, with a critical temperature of around 16 MeV.

Footnotes and References

*Condensed from LBL-21165 (1986).

†W.K. Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, CA 91125

Quantitative Analysis of the Relation between Entropy and Nucleosynthesis in Central Ca + Ca and Nb + Nb Collisions*

*L.P. Csernai,†‡ G. Fái,§ D. Hahn, J.I. Kapusta,‡ J. Randrup, and H. Stöcker***

The final states of central Ca + Ca and Nb + Nb collisions at 400 and 1050 and at 400 and 650 MeV per nucleon, respectively, are studied with two independently developed statistical models, namely the classical microcanonical model and the quantum-statistical grand canonical model. It is shown that these models are in agreement with each other for these systems. Furthermore, it is demonstrated that there is essentially a one-to-one relationship between the observed relative abundances of the light fragments p, d, t, ^{3}He and α and the entropy per nucleon, for break-up temperatures greater than 30 MeV. Entropy values of 3.5 – 4 are deduced from high-multiplicity selected fragment yield data reported by the GSI-LBL Plastic Ball Group.

Footnotes and References

*Condensed from Phys. Rev. **C35**, 1297 (1987).

†On leave from the Central Research Institute for Physics, Budapest, Hungary. Present address: NSCL, Michigan State University, East Lansing, MI 48824.

‡School of Physics and Astronomy, University of Minnesota Minneapolis, Minnesota 55455

§Department of Physics, Kent State University Kent, Ohio 44242; On leave from Roland Eötvös University, Budapest, Hungary.

**Permanent address: Institut für Theoretische Physik, Johann Wolfgang Goethe Universität, Frankfurt am Main, West Germany.

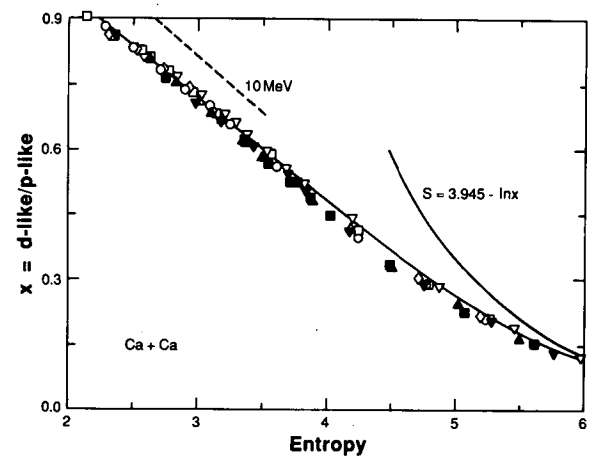

Fig. 1. Plot of x defined by (4) versus entropy per nucleon. The dashed curve has been calculated with the QSM at T = 10 MeV, and the solid curve with the quantum-statistical model at T = 30–90 MeV. The symbols indicate the results of the microcanonical event generator *FREESCO* as follows: ▽: T = 30 MeV, □: T = 45 MeV, ◇: T = 60 MeV, ○: T = 75 MeV, N: T = 90 MeV, H: T = 105 MeV, ■: T = 120 MeV. Also shown is the simple approximation S = 3.945 - ln$x$, which is seen to be accurate only at high entropies where the fraction of composite fragments is small. XBL 8611-4690

Tangential Friction in Nuclear Reactions Studied with the Time-Dependent Hartree-Fock Model*

F. H. Jørgensen,† T. Døssing,† B. S. Nilsson,† and J. Randrup

This study compares the time-dependent Hartree-Fock (TDHF) model to the nucleon-exhange transport (NET) model with respect to the tangential friction in damped nuclear reactions. The TDHF calculation is performed for the symmetric reaction 280 MeV ^{40}Ca + ^{40}Ca at a specified impact parameter and the evolution of the orbital angular momentum L is inferred from the time dependence of the density distribution of nucleons. Subsequently, the NET equation for the mean orbital angular momentum is solved in the environment provided by the TDHF evolution. The important quantities, namely

the center separation R and the window area σ_{eff} are quite well determined.

There is a good overall agreement with the TDHF results, showing that the main part of the angular momentum loss in TDHF can be interpreted as nucleon-exchange window friction. The more detailed behavior of the TDHF results indicates that additional variables play a role. In particular, the initial "undershoot" by L can be understood as a consequence of the finite relaxation time for the sharing of angular momentum within a single nucleus, and the deviations at the late stages suggest that symmetries of the potential prevent some orbitals from participating in the exchange.

Footnotes and References

*Condensed from LBL-22900, Phys. Lett. in press.

†The Niels Bohr Institute, University of Copenhagen Blegdamsvej 17, DK-2100 Copenhagen Ø, Denmark

Dynamical Hindrance to Compound-Nucleus Formation* in Heavy-Ion Reactions

J.P. Blocki, H. Feldmeier, and W.J. Świątecki

This extensive survey of the extra energy above the Coulomb barrier required to form a compound nucleus, calculated using the dynamical model of a liquid drop with one-body dissipation, has now been published. Some puzzling features of the results for very asymmetric systems are being studied further.

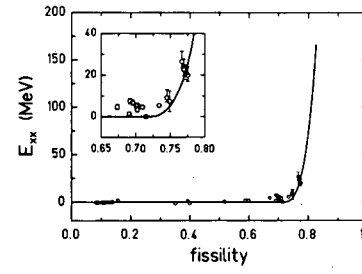

Fig. 1. The curve illustrates the calculated "extra-push" energy, inhibiting the fusion of heavy systems. Experimental measurements confirm semi-quantitatively this prediction. XBL-8611-4623

Footnotes and References

*Condensed from Nucl. Phys. **A459**, 145 (1986).

Calculated Fission Properties of the Heaviest Elements*

P. Möller, J.R. Nix, and W.J. Świątecki

Experimental results on the fission properties of nuclei close to ^{264}Fm show sudden and large changes with a change of only one or two neutrons or protons. The nucleus ^{258}Fm, for instance, undergoes symmetric fission with a half-life of about 0.4 ms and a kinetic energy peaked at about 235 MeV, whereas ^{256}Fm undergoes asymmetric fission with a half-life of about 3 h and a kinetic energy peaked at about 200 MeV. Qualitatively, these sudden changes have been postulated to be due to the emergence of fragment shells in symmetric fission products close to ^{132}Sn. Here we present a quantitative calculation that shows where high-kinetic-energy symmetric fission occurs and why it is associated with a sudden and large decrease in fission half-lives. We base our study on calculations of potential-energy surfaces in the macroscopic-microscopic model and a semi-empirical model for the nuclear inertia. For the macroscopic part we use a Yukawa-plus-exponential (finite-range) model and for the microscopic part a folded-Yukawa

(diffuse-surface) single-particle potential. We use the three-quadratic-surface parameterization to generate the shapes for which the potential-energy surfaces are calculated. The use of this parameterization and the use of the finite-range macroscopic model allows for the study of two touching spheres and similar shapes. Since these shapes are thought to correspond to the scission shapes for the high-kinetic-energy events it is of crucial importance that a continuous sequence of shapes leading from the nuclear ground state to these configurations can be studied within the framework of the model.

We present the results of the calculations in terms of potential-energy surfaces and fission half-lives for heavy even nuclei. The surfaces are displayed in the form of contour diagrams as functions of two moments of the shape. They clearly show the appearance of a second fission valley that leads to scission configurations close to two touching spheres, for fissioning systems in the vicinity of ^{264}Fm. Fission through this new valley leads to much shorter fission half-lives than fission through the old valley. The reason is that the inertia associated with motion in the new valley is much smaller than in the old valley. The large decrease in the inertia is also the reason for the unexpectedly short half-life for ^{258}Fm.

Another noteworthy feature is the appearance in some cases (where the fission fragments are close to magic nuclei) of molecular configurations in the form of two stiff, spherical pieces held together by the nuclear proximity attraction. An example is illustrated in Fig. 1.

Footnotes and References

*Condensed from preprint LA-UR-86-3266, September 12, 1986, to appear in Nuclear Physics.

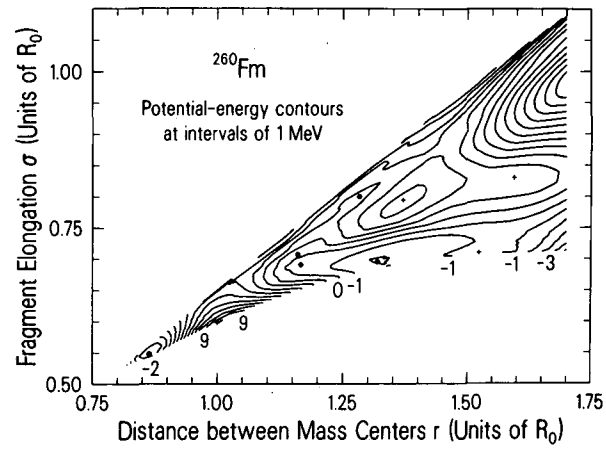

Fig. 1. The potential-energy landscape for the fission of ^{260}Fm. The dot at $\sigma = 0.7$, r=1.263 corresponds to a metastable molecular configuration in the shape of two slightly overlapping spheres.

XBL 8611-4622

Nuclear Mass Formula with a Finite-Range Droplet Model and a Folded-Yukawa Single-Particle Potential

P. Möller, W.D. Myers, W.J. Świątecki, and J. Treiner

We calculate ground-state masses for 4678 nuclei ranging from ^{16}O to ^{318}122 by use of a macroscopic-microscopic model, which incorporates several new features. For the macroscopic model we use the finite-range droplet model which we introduced in 1984. The microscopic contribution is taken from a calculation based on a folded-Yukawa single-particle potential. To estimate the parameters of the macroscopic model we use an approach that starts by defining the *error* of a mass formula in a rigorous way, which leads naturally to the use of the *maximum-likelihood* method to derive a set of equations for estimating the parameters and error of the theoretical model. By considering 1593 experimental masses from ^{16}O to ^{263}106 we estimate the error of the theoretical model to be 0.769 MeV. The model gives a good account of the isospin dependence even far away from stability and the values of the model parameters are very insensitive to details of the adjustment procedure.

Estimates of the Influence of Nuclear Deformations and Shell Effects on the Lifetimes of Exotic Radioactivities*

Y.-J. Shi† and W.J. Świątecki

The analysis[1] of the spontaneous decay of heavy elements by the emission of C, Ne, etc. has been refined further by the inclusion of nuclear deformation and shell effects. Fig. 1 shows a comparison of empirical and theoretical Gamow penetrability factors for 8 such decays and 7 lower limits. A byproduct has been the development of a tentative scheme for estimating the attenuation of the shell effects of two nuclei caused by their interaction during contact and fusion.

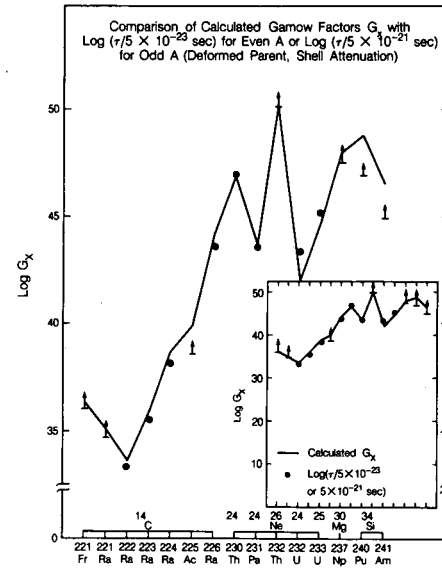

Fig. 1. Empirical Gamow factors (deduced from observed lifetimes divided by a characteristic pre-exponential oscillation period) compared with theoretical estimates. XBL 867-11186

Footnotes and References

*Condensed from LBL-21383, March, 1986, to appear in Nucl. Phys. 1986.

†Permanent address: Institute of Atomic Energy, P.O. Box 275, Beijing, China.

1. Y.-J. Shi and W.J. Świątecki, Phys. Rev. Lett. **54**, 300 (1985); Nucl. Phys. **A438**, 450 (1985).

New Fission Valley for ^{258}Fm and Nuclei Beyond*

P. Möller, J.R. Nix, and W.J. Świątecki

Macroscopic-microscopic calculations of the potential-energy landscape for the fission of several heavy elements have revealed a new valley, corresponding to a sequence of relatively compact configurations where the fragment shell effects dominate the division. These findings can be correlated with a number of fission properties of the isotopes of Fm and neighboring elements.

Footnotes and References

*Condensed from preprint LA-UR-86-3182, presented by P. Möller at the International School-Seminar on Heavy Ion Physics, Dubna, USSR, September 23-30, 1986.

Reconstruction of the Potential Energy of Deformation of ^{152}Dy from the Energy Levels of its Superdeformed Rotational Band

W.J. Świątecki

A general method is devised which, under certain assumptions, converts the trend of the rotational energy levels of an imperfect rotor into a differential equation for the rotor's potential energy, considered as a function of its (variable) moment of inertia. The differential equation can always be solved by quadratures and in certain cases has useful analytic solutions. The method is applied to the superdeformed band in ^{152}Dy and makes possible a semi-quantitative reconstruction of the potential energy of deformation. The result confirms the expectation that a shell effect of a few MeV, associated with a spheroidal shape with a 2:1 ratio of axes, determines the properties of the superdeformed system which, at the higher spins, rotates as a centrifugally solidified nucleus.

Footnotes and References

*Condensed from LBL-22539; to be submitted to Nuclear Physics.

The Superdeformed Band in ^{152}Dy as Evidence for the Centrifugal Solidification of a Rotating Nucleus*

W.J. Świątecki

The sequence of 19 rotational levels in the superdeformed band in ^{1562}Dy leads to moments of inertia that are smooth to within (1/20)th of a percent when plotted as a function of the angular momentum in the range I=24 to I=60. A careful analysis of the small deviations of the rotational spectrum from that of a rigid rotor suggests that the ^{152}Dy is driven by the centrifugal force from the regime of shapes where a fluid-like behaviour is manifested, to the regime where (due to shell effects) the nucleus behaves like a solid, resisting further elongation with the same universal elastic modulus that accounts quantitatively for the energies of the giant quadrupole resonances of nuclei throughout the periodic table.

Footnotes and References

*Condensed from LBL-28539; to be submitted to Phys. Rev. Lett.

The 88-Inch Cyclotron ECR Source

C. M. Lyneis and D. J. Clark

The 88-Inch Cyclotron began regular operation with the ECR (Electron Cyclotron Resonance) source in January 1985. Since then about 80% of the cyclotron operating schedule has been with the ECR source. A schematic drawing of the source is shown in Fig. 1. The operating experience with the Cyclotron+ECR has been highly successful in terms of reliability, stability, production of high charge state currents, and range of ions which can be produced. The performance of the system has steadily improved as a result of better source performance, better stability and tuning of the injection line, and better cyclotron tuning. The ECR source now produces 14 μA of O^{7+}, 1 μA of O^{8+}, 72 μA of Ar^{9+}, 1.4 μA of Ar^{14+}, 5 μA of I^{25+}, and .009 μA of I^{30+}. Metal ions from Mg, K, and Ca are produced in the ECR using an oven to inject vapor into the plasma chamber. Operation with the oven is quite stable and frequently requires no adjustment during runs lasting several days. Beams of F, Si, S, and Ti have been produced using various compounds with gas feed, or solids with the oven feed. The present beam intensities available from the ECR Source are shown in Tables I and II. The overall transmission from source analyzing magnet to cyclotron external beam is typically 2 to 10% with a maximum of 17%. As a result of the improved source performance and transmission a wide variety of new beams can be produced. For example, a 32.5 MeV/nucleon $^{16}O^{8+}$ beam and $^{48}Ca^{11+}$ beams with energies from 200 to 350 MeV have been used for nuclear physics experiments. A 1.08 GeV $^{36}Ar^{18+}$ beam was used to test the response of various scintillator materials to intermediate energy heavy ions.

Footnotes and References

1. C. M. Lyneis, *Recent Developments of the LBL ECR Ion Source*, Proceedings of the 7th ECR Ion Source Workshop, Jülich, H. Beuscher Editor, (1986)

2. C. M. Lyneis, *Operational Performance of the LBL 88-Inch Cyclotron with an ECR Source*, Proc. 11th Int'l Conf. on Cyclotrons and their Applications, Tokyo, Oct. 1986.

3. D.J. Clark and C.M. Lyneis, *Operation of the LBL ECR Source Injection System,* Proc. 11th Int'l Conf. on Cyclotrons and their Applications, Tokyo, Oct. 1986.

4. David J. Clark, *The LBL 88-Inch Cyclotron Operating with an ECR Source*, Proc. Xth National Conference on Particle Accelerators, Dubna, Oct. 1986.

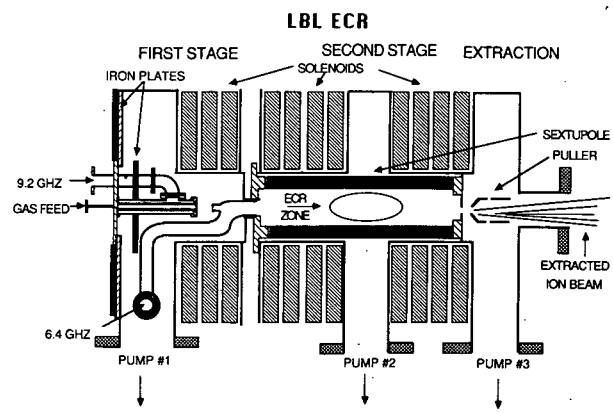

Fig. 1. Schematic drawing of the ECR Source.

XBL 867-2602A

Table I

Currents for the LBL ECR: Hydrogen through Silicon

CS	^{1}H	^{3}He	^{12}C	^{14}N	^{16}O	^{19}F	^{20}Ne	^{24}Mg	^{28}Si
1+	300	300	27	82	118				
2+		200	37	117	143	43	51	32	20
3+			*	106	152	55	63	34	33
4+			31	110	*	53	78	28	69
5+			6.5	93	96	37	58	44	72
6+				19	82	17	45	34	47
7+					14	11	21	18	30
8+					0.95	1	11	8	17
9+						0.05	1.1	6.3	7
10+							0.04	2.2	2.7
11+								0.1	0.5
12+									0.2

All currents in eμA measured at 10 kV extraction voltage.

*Indicates not measured because a mixture of two ions with identical charge to mass ratios were present.

Natural isotopic abundance source feeds were used except for ^{3}He and $^{22}Ne^{10+}$.

PART IV: INSTRUMENTATION AND METHODS

Table II

Currents for the LBL ECR: Sulfur through Xenon

CS	^{32}S	^{39}K	^{40}Ar	^{40}Ca	^{48}Ti	^{84}Kr	^{127}I	^{129}Xe
3+	10	4	38	23				
4+	*	4.5	82	24				
5+	20	5	*	*				
6+	*	8.5	60	37		9		
7+	63	11	66	38	2.4	12		
8+	*	18	106	36	*	22		
9+	36	37	72	31	12	25		4.1
10+	*	22	*	*	10	22	4.2	4.7
11+	5	12	18	22	8	19	4.9	5.1
12+	*	2.4	13	11	*	*	5.7	5.2
13+	0.4		5	3.2	1	21	7.5	5.2
14+	*		1.4	1.1		*	8.5	5
15+	0.001		*	*		16	11	4.3
16+			0.03	0.03		8	*	4.6
17+						7	12	4.3
18+						*	15	4.4
19+						2	15	4.8
20+						0.9	14	4.8
21+						*	*	4
22+						0.1	11	3.5
23+							10	3.1
24+							8.3	2.7
25+							5.6	2
26+							2.1	1.1
27+							0.83	0.34
28+							0.2	
29+							0.05	
30+							0.009	

All currents in eμA measured at 10 kV extraction voltage.

*Indicates not measured because a mixture of two ions with identical charge to mass ratios were present.

A New System for Observing the Decays of Very Proton-Rich Nuclei

M. Hotchkis, F. Blönnigen, T. Lang, D. Moltz, J. Reiff, X. Xu, and J. Cerny

Very proton-rich nuclei may decay by beta-delayed proton or two-proton emission, or by the ground state emission of one or two protons. Since the lifetimes of the latter two decay modes may be very short, and the production cross-sections are always very low, we have constructed a recoil catcher system capable of high detection efficiency in the half-life range 100 μs to 100 ms. As shown in the figure, both target and Al catcher foils are inclined at 20° to the beam direction; this ensures the maximum possible catching efficiency while minimizing the recoil-range effect on the proton energy resolution. The wheel turns continuously, carrying the activities out of the beam and passing them between two detector telescopes. The beam is pulsed to avoid irradiating the foil frames and the detector electronics are only active when the beam is off. This system has been tested with known beta-delayed proton emitters and the overall efficiency compares favorably with our He-jet transport system.

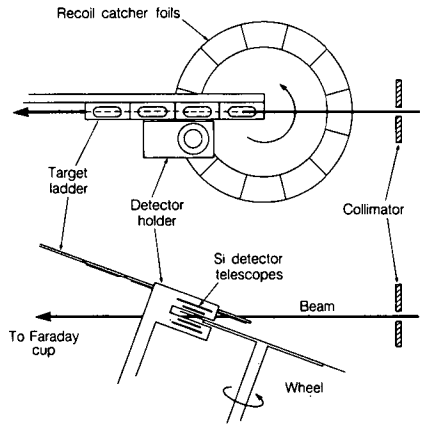

Fig. 1. Schematic of the set-up showing views from the side and from above. XBL 869-9247

Improvements to the Helium-Jet Coupled On-Line Mass Separator RAMA

D. Moltz, F. Blönnigen, T. Lang, W. Knoll, M. Hotchkis, J. Reiff and J. Cerny

In the past year many changes have been implemented to improve the overall efficiency of the helium-jet coupled on-line mass separator RAMA while retaining the essential feature of a very fast system. Although changes have been made to improve the overall reliability and operating characteristics of the helium-jet chamber, the primary improvements have been made to the ion source region. The entire skimmer-ion source region has been placed at the full 20 kV accelerating potential, thus permitting the skimmer-plasma distance to be reduced from 12 cm to <2 cm. This reduced skimmer-plasma distance should give a yield increase of ~40 strictly due to geometric considerations. Recent tests with ^{153}Er alpha activity have demonstrated that the overall yield has increased only a factor of five to 0.05%. One reason that the expected geometric increase has not been realized could be the very high thermal gradient not present in the former system. This thermal gradient could cause the activity-bearing aerosols to explode before they reach the plasma region. Since all of the current tests have utilized a modern version of the hollow-cathode ion source used in prior experiments, much work remains in developing other ion source technologies with greater efficiencies which retain the very short ion source holdup times (3-4 ms). More details of this ion source region redesign may be found elsewhere.[1] Although much development work remains, RAMA can be operated at a known level as a very effective tool for studying exotic nuclei far

from beta stability.

Footnotes and References

1. F. B. Blönnigen *et al.*, to be published in Nucl. Instr. Meth. as part of the Proceedings of the Electromagnetic Isotope Separators-11 Conference, Los Alamos, NM, August 18-22, 1986.

Phosphate Glasses for Identification of Heavy Ions*

P.B. Price,† L.M. Cook,‡ and A. Marker‡

Recent work by one of us (PBP) has shown that certain types of phosphate glass are as sensitive to charged particles as are plastic track detectors.[1] Using Bevalac beams we have studied the track-recording properties of more than 25 types of glass based on the P_2O_5 glass-forming network, a single arsenic-based glass, and several glasses in which fluorine largely replaces oxygen. We selected these glasses because of their commercial availability and because of the low bond strength of P-O, As-O, and Al-F, the hope being to extend the range of applicability to the detection of particles of low ionization rate. Four of them, VG-13, BG-24, LgSK-2 and UG-5 (Schott designation) are more sensitive than Cronar polyester and comparable in sensitivity to Lexan and other polycarbonates. The sensitivity of each of these types can be tuned by proper choice of an etchant. One of us (PBP) is using several of these glass types in accelerator experiments at Fermilab, TRISTAN, and the Bevalac, and in searches for heavy ion radioactivity involving emission of monoenergetic ^{28}Mg and ^{34}Si ions. The charge standard resolution of VG-13, BG-24, and UG-5 is about four times better than that of the best plastic detectors, and the sensitivity to thermal and other environmental effects is much lower or zero.

Footnotes and References

*A preliminary account of this work was published in Nature, **325**, 137 (1987).

†Also at Space Sciences Laboratory and Department of Physics, UCB

‡Schott Glass Technologies

1. P.B. Price, H.-S. Park, G. Gerbier, J. Drach, and M.H. Salamon, Nucl. Instr. Meth., **B21**, 60 (1987).

Systematics of Annealing of Tracks of Relativistic Nuclei in Phosphate Glass Detectors*

P.B. Price,† H.-S. Park,† G. Gerbier,† and M.H. Salamon†

For use in long-term studies of charged particles in nature, it is essential to know the dependence of track stability on various environmental conditions. We have determined the rate of decrease of track-etch rate as functions of storage time and temperature and of ionization rate in VG-13 and UG-5 phosphate glass detectors. We find that the fractional rate of reduction of reduced track etch rate, $s - 1$ (where $s = v_T/v_G$), depends on time t and temperature T as $At^{-n}\exp(-E/T)$, independent of ionization rate. Extrapolating to a storage time of two years, we conclude that, as long as the detector temperature is held below 0 °C, the thermally-induced reduction in apparent charge at uranium is less than ~0.1 charge unit.

Footnotes and References

*Condensed from a paper to be published in Nucl. Instr. Meth., 1987.

†Also at Space Sciences Laboratory and Department of Physics, UCB

VG-13: a Nuclear-Track-Recording Glass Detector with Uniquely High Resolution*

P.B. Price,† H.-S. Park,† G. Gerbier,† J. Drach,† and M.H. Salamon†

We have found that tracks of minimum ionizing nuclei as light as La can be revealed in VG-13, a phosphate glass, by etching it in fluoboric acid. (The sensitivity can be decreased by using HNO_3, HF, or NaOH.) Study of its response to U, Au, and La ions at temperatures from -77°C to $+20^\circ$C shows that the temperature dependence of the response is one to two orders of magnitude smaller than for track-recording plastic detectors. Ionic charge states corresponding to fully stripped ions, ions with one electron, and ions with two electrons are resolved with standard deviations ranging from ~0.1 to 0.25 charge unit for a single etchpit, or a standard deviation decreasing as $1/\sqrt{n}$ for n etchpits. This charge resolution for heavy nuclei exceeds that of any other detector, making possible searches for fractionally charged nuclei in high-energy nucleus-nucleus collisions. With Bevalac beams we are studying the isotopic resolution of VG-13, preparatory to a balloon flight scheduled for August 1987, with the goal of measuring the isotopic composition of iron and nickel in the cosmic rays.

Footnotes and References

*Condensed from a paper accepted for publication in Nucl. Instr. Meth., 1986.

†Also at Space Sciences Laboratory and Department of Physics, UCB.

The Preparation of Nuclear Targets by the Evaporation of Acetate-organic Solutions in the Presence of Ammonia Gas

S.-Y. Cai, A. Ghiorso, and D. C. Hoffman*

Chemical methods have been developed in order to prepare isotopic targets for bombardment by accelerator-produced ions. Three systems were investigated and compared: nitrate, chloride, and acetate-organic solutions. The best method was found to be the metallic acetate-organic solution when evaporated onto the substrate in the presence of ammonia gas. The targets obtained by this method are uniform and adherent. The hydroxide forms fine crystals which give a deposit of high quality for thicknesses from a few micrograms/cm^2 to several mg/cm^2. In addition, the process is simple and fast. A report giving details of the procedure is in preparation.

Footnotes and References

*Institute of Atomic Energy, PO Box 275(66), Beijing, China

Design of an Intermediate Energy Heavy-ion Multiplicity Array

W.L. Kehoe, A. Moroni,† G.J. Wozniak, J. Walton, D.R. Bowman, R.J. Charity, R.J. McDonald, M.A. McMahan, L.G. Moretto, A.C. Mignerey,* and I. Iori†*

After several successful Bevalac experiments to investigate the production of complex fragments at intermediate energies,[1,2] the Moretto/Wozniak group of LBL and the Mignerey group at the University of Maryland began conceptual designs for a heavy-ion multiplicity array in the summer of 1985. The Istituto Nazionale Di Fisica Nucleare (INFN), Milano, Italy, joined this collaboration in the winter of 1985. Originally it was hoped that by utilizing reverse kinematics, a small number of scintillators could be configured into a wall forward of the target to study the transition from binary decay to multibody breakup

or multifragmentation of a very hot system. While the scientific goal of this project has not changed, the design of the multiplicity array has evolved to meet the experimental requirements of the project.

The present design consists of an array of 48 large-area detector telescopes. Each telescope consist of three detectors: a 300 μm Si, a 5 mm Si(Li) and a 7.6 cm plastic detector. The geometry of the array, shown in Fig. 1, is a 7 × 7 wall placed at a minimum distance of 45 cm from the target, which can arc in two dimensions, so that the center of each telescope is perpendicular to the target. The beam passes through an empty telescope position in the center of the array. To detect multibody events in the array with good efficiency, the telescopes are designed for close packing and with a 64% active area. The front face of each telescope is 55 mm × 57 mm, with an active area of 44.8 mm × 44.8 mm. The silicon detectors are position sensitive. This is achieved by charge division using 15 implanted boron strips in the 300 μm Si detector and Pd-Au strips on the 5 mm Si(Li) detector. The Si and Si(Li) detectors are rotated 90° relative to each other to determine both the x and y position of charged particles traversing the telescope. Heavy ions with $Z<20$ and $E/A \geq 20$ MeV/nucleon will punch through the 300 μm Si, while heavy ions with $Z>16$ and $E/A \leq 100$ MeV/nucleon will stop in the 5mm Si(Li), to be identified using the ΔE-E technique. Except for high-energy protons, the remaining particles will stop in the 7.6 cm plastic and be identified using both the 300 μm Si and 5 mm Si(Li) as ΔEs. The large dynamic range of these three stage telescopes will allow for the identification of both the heavy and light components from multibody events.

Fabrication and construction of the array has already begun at LBL and the INFN. The plastic scintillators are being supplied by Bicron Corporation, and both types of silicon detectors are being fabricated in the silicon detector laboratory at LBL. An experiment using a partial array (5 × 3) will be performed in February 1987 at the LBL Bevalac. The complete array should be finished by the end of the 1987 fiscal year.

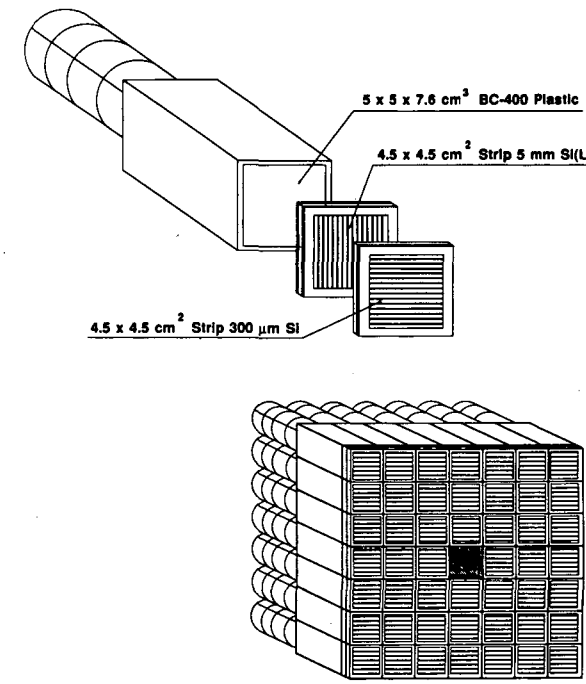

Fig. 1. Sketch of an individual Si-Si-Pl telescope showing modular design and the 7 × 7 array.
XBL 8612-4835

Footnotes and References

*Permanent address: Department of Chemistry, University of Maryland, College Park, Maryland, 20742.

†Permanent address: INFN and Department of Physics, University of Milano, Via Celoria 16, 20133, Milano, Italty.

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Large-area 5 mm Thick Si(Li) Detectors Designed for Close Packing

W.L. Kehoe, A. Moroni,† G.J. Wozniak, J. Walton*

Large-area 5 mm thick Si(Li) detectors have been fabricated in the silicon detector laboratory at the LBL for use as the second element in a three-stage telescope, which is part of a intermediate energy heavy-ion multiplicity array designed by the LBL/University of Maryland/INFN collaboration. The outer dimensions of each device are 50.8 mm × 50.8 mm, with a active area of 44.8 mm × 44.8 mm. The intrinsic region of the device has a thickness of 4.85±0.10 mm and a surface nonuniformity of $\leq$2%. The Li dead layer on the back of the device has a thickness in the range 30–50 μm. Heavy-ions with Z > 16 and E/A$\leq$100 MeV/nucleon will be stopped in this device.

Two types of 5 mm thick Si(Li) devices are being fabricated. The first type has a continuous layer of Pd, with a sheet resistance between 4–5 kΩ, and is position sensitive. This device has recently been successfully adapted for use in a newly designed compact four telescope gas(ΔE)-Si(E) detector. The second type has 15-2.42 mm Au strips separated by 14-0.61 mm Pd strips, where position is determined by charge division between the strips. This gives the the device a sheet resistance of ~7.5 kΩ and a 100 Ω resistance between each strip adequate for position resolution. It is these latter devices that will be used in the telescopes for the multiplicity array.

To maximize the active area of the multiplicity array, it was neccessary to design a package for close packing. This has been achieved by designing each element of the telescope as a separate modular package, taking advantage of the dead layer around the intrinsic region and the square geometry of the device. A key element in this design is the use of small M-F and F-F connector pins that carry the signal from one modular package to the next. The front face of each package is 55 mm × 57 mm, thereby giving the array a 64% active area. A front and cross sectional elevation of the package for the 5 mm thick Si(Li) device is shown in Fig. 1.

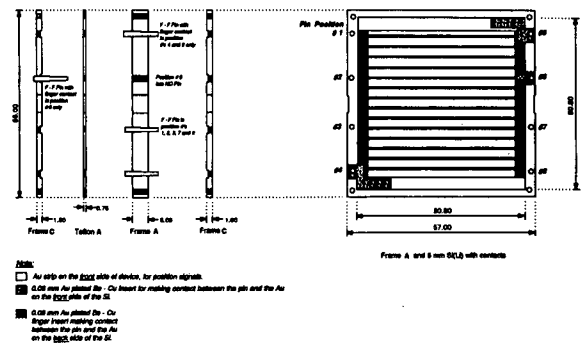

Fig. 1. Cross sectional elevation of the package for the 5 mm thick Si(Li) detector showing the positons of the F-F pins, and a front elevation showing the how the contacts are made to the detector.

XBL 8612-4836

Footnotes and References

*Permanent address: Department of Chemistry, University of Maryland, College Park, Maryland, 20742.

†Permanent address: INFN and Department of Physics, University of Milano, Via Celoria 16, 20133, Milano, Italy.

Using a Cyclotron plus ECR Source for Detector Evaluation and Calibration*

M.A. McMahan, G.J. Wozniak, C.M. Lyneis, D.R. Bowman, R.J. Charity, Z.H. Liu,† L.G. Moretto, W.L. Kehoe,‡ A.C. Mignerey,‡ and M.N. Namboodiri§

We have utilized the combination of the ECR source and the 88-Inch Cyclotron to produce and accelerate a series of ions as heavy as Kr for a study of the response of scintillators to heavy ions. Using this technique, all ions that are produced in the source with a given charge to mass (q/A) ratio, are accelerated together in the cyclotron. Different ion species are extracted by adjusting the resonant frequency of the cyclotron a few kHz, in effect using it as a mass analyzer. The extracted beams are then run directly into a detector. This provides a quick way to study the response of detectors to heavy ions. In one two hour period, over seventeen ion species ranging from $^{4}He^{+1}$ to $^{84}Kr^{+21}$ were observed for q/A = 1/4. The presence of many of these species was due to impurities in the ECR source. Fig. 1 shows a composite spectrum of these ion species taken with a plastic scintillator.

Using this technique, we have studied the response of several organic and inorganic scintillators to heavy ions in the energy range 8–30 MeV/nucleon. Scintillating materials are becoming increasingly important as heavy ion detectors in the energy range 20–100 MeV/nucleon, where silicon detectors cannot be made thick enough to stop intermediate-mass fragments. The response of scintillators to intermediate-mass fragments, however, has not been well studied. With these measurements, we have greatly increased the data available on both the energy and ion dependence for plastic, CsI, BGO, and glass scintillators.

Footnotes and References

*Condensed from LBL-21538, accepted for publication by Nucl. Instr. and Methods.

†Permanent address: Institute of Atomic Energy, Beijing, P. R. China.

‡Permanent address: Department of Chemistry, University of Maryland, College Park, MD 20742.

§Nuclear Chemistry Division, Lawrence Livermore National Laboratory, Livermore, CA 94550.

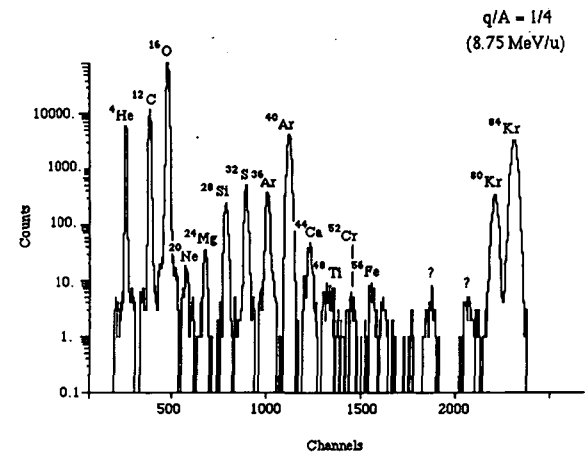

Fig. 1. Composite spectrum of some of the beams observed at q/A = 1/4 (8.75 MeV/nucleon).

XBL 865-2109

Quad Delay Gate Generator*

R.J. McDonald, M.R. Maier,† D.A. Landis, and G.J. Wozniak

Among the most common needs for nuclear physics experiments is the "delay gate" function, that is, the ability to delay a logic signal for some period of time and then regenerate a logic signal of preset width to be used in other parts of the logic circuitry. Since detectors have different response times, from fractions of nanoseconds to several microseconds, and because one typically wants to require a coincidence between different detectors, each channel of electronics will require a delay gate generator to adjust the relative timing between detectors. Even for the cases where all the detectors are fast, different transit times from the experimental area to the counting area can cause these signals to differ in time by tens of nanoseconds. In order to align these signals for fast coincidences, not only must the delay gate generator have a range on the order of tens of nanoseconds, but it must be stable at the level of a fraction of a nanosecond for periods of several days. Furthermore, ADC and TDC strobes and computer interrupt signals often require delays 1000 times longer.

A quad delay gate generator has been designed and packaged in a single-width NIM module (see Fig. 1). Both the delay times and gate widths may be set continuously from 25 ns to 120 μsec. In normal operation, the gate follows the delay time unless a "stop" pulse cuts it short. Alternatively, the module may be operated in a bipolar mode, where the delay time is set by the input "start" pulse and reset by the input "stop" pulse. Modes and coarse time ranges are set via an octal DIP switch on the front panel. Fine adjustments of the delay and gate width are made via two twenty-turn potentiometers. Stability over a several day period was measured at ~250 ps on the 120 ns full-scale range. LEDs give a visual indication of both the input rate and the dead time.

Footnotes and References

*Condensed from LBL-21929.

†Permanent address: National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, MI. 48824.

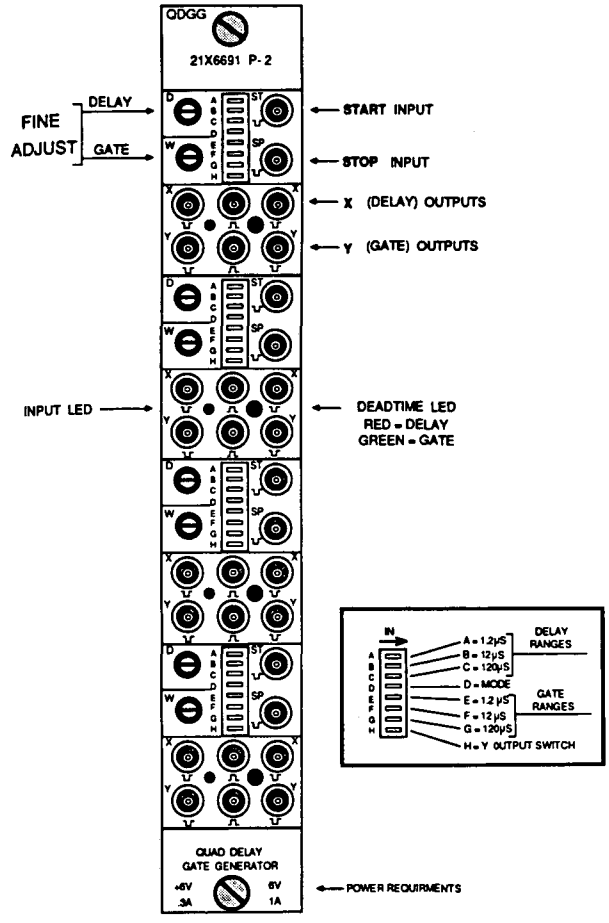

Fig. 1. Illustration of the front panel and description of the controls and connectors. The eight DIP switches labelled A-H select the delay and gate time ranges (see insert). XBL 8612-4840

Fast Dual Scale-Down Module*

R.J. McDonald, D.A. Landis, and G.J. Wozniak

Experiments in nuclear physics often involve the measurement of several classes of events which occur at significantly different rates. A simple example involves data which consists of "singles" and "coincidences" from two or more detectors. It is not uncommon for these data rates to differ by a factor of 100. The total volume of data collected may be reduced by taking all of the coincidence data plus a sample of the singles data. A preset fraction of the singles can be selected by using a scale-down module. In the example above, one may only want to take 1% of the singles data to obtain comparable statistics for both singles and coincidence data. Such scale-down modules have been constructed before, but they utilized slow TTL logic and provided limited scale-down ranges. Thus, a new and faster module was needed to work with the negative NIM logic signals and provide a larger range of scale-down factors.

Two fast NIM logic scale-down units have been packaged in a single-width NIM module as shown in Fig. 1. Each unit accepts pulses of width > 50 ns up to a rate of 15 Mhz and provides two negative NIM and one TTL output pulses at a rate $1/N^{th}$ of the input rate where N is an integer between 1 and 255. The time difference between the input and output signals is ~10 ns and remains constant regardless of the scale-down factor. The scale-down factor "N" is set via an octal DIP switch. Following each output pulse, an internal counter is set to "N" and each input pulse causes the counter to decrease by one until it reaches "1". At the time of the trailing edge of this pulse, a gate is opened and the next input is passed through to the output. In this way, the timing of the input signals is preserved regardless of the scale-down factor. This is critical because one does not want the logic circuit timing to change when the scale-down factor is changed. Also, since the scale-down module acts as a gate, the width of the output pulses is equal to the width of the input pulse. LEDs attached to the input and output pulses give a visual indication of the relative rates.

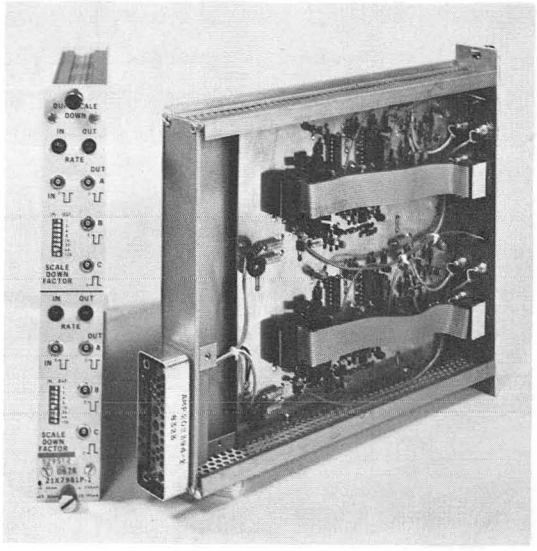

Fig. 1. Picture of the dual scale-down module from the front (left picture) and from the back and side (right picture). One cover has been removed to show construction details. CBB 864-3029

Footnotes and References

*Condensed from LBL-21930.

Quad Nanosecond Delay Module*

R.J. McDonald, J.B. Hunter, and G.J. Wozniak

The Nuclear Science Division's Electronics Pool contains many quad constant-fraction timing discriminators (CFTD) which require external cable delays. For a "fraction" setting of 40%, these CFTDs require a cable delay of about 60% of the risetime of the input of the pulse. For signals with very short risetimes (<6 ns), a short external cable may be attached directly to the CFTD. However, for longer risetimes (10–100 ns), the external delay cables become long and tend to be inconvenient. In addition, changing the delay time to optimize the timing resolution is awkward with external cables. Electronics setups, which require a large number of CFTDs, can be simplified by having four nanosecond delay units built into a single width NIM module which can be placed next the CFTD.

We call this module, shown in Fig. 1, the Quad Nanosecond Delay. In our design, four toggle switches can be used to vary the delay between 0 and 60 ns in 4 ns increments. The maximum cable length of 60 ns and the 4 ns increments are dictated by both the physical amount of cable one can fit in a single width NIM module and the number of switches that can be placed on the front panel. In addition, degradation of the signal amplitude and shape limits the maximum practical delay to about 60 ns. The insertion delay (the amount of delay with all switches in the "out" position) is ~1.7 ns. The accuracy of the delays is ~1%, as is the unit-to-unit variation. Design work for the PC board and silkscreening of the front panel were done with the MacDraw program on the Apple Macintosh computer and printed with the Laserwriter printer.

Footnotes and References

*Condensed from LBL-21298.

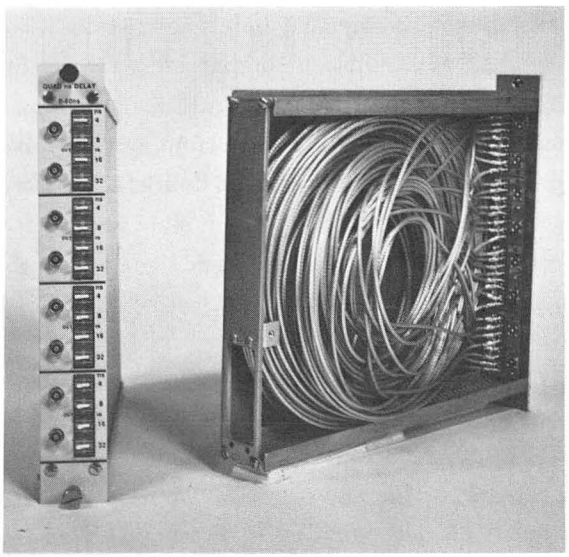

Fig. 1. Picture of the Quad Nanosecond Delay module from the front (left picture) and from the side (right picture). One cover is removed to show construction details. CBB 864-3027

Calculated Uncertainties of Absolute γ-ray Intensities and Decay Branching Ratios Derived from Decay Schemes*

E. Browne

Accurate values for absolute radiation intensities, i.e, the percentages of various types of radiations emitted in a nuclear transformation, are frequently required. For example, they are the basic quantities from which transition probabilities may be derived for testing nuclear models; and these intensities, together with their corresponding energies, are often used in applications of radioactivity to other fields for calculating average radiation energies emitted per disintegration. Hence it is important to report absolute radiation intensities and their uncertainties accurately. The concurrent determination of decay branching ratios is of course mandatory.

It generally requires elaborate calibrated detector systems and delicate measuring techniques to determine absolute radiation intensities. For short-lived isotopes and for isotopes which decay through more than one mode, e.g. β^- and electron capture, the experimental difficulties may be even greater. Chemical and isotopic purities of the source are also important, especially for a beta emitter, for which it is difficult to remove contributions from possible impurities from the continuous-energy beta spectrum. Consequently, most of the known absolute radiation intensities have been derived from *relative* intensities (i.e., intensities measured relative to that for a nominal transition for each radiation type) and from the knowledge of the isotope's decay scheme (which often includes assumptions based on nuclear-structure theory). A set of radiations, usually γ rays which represent the full disintegration intensity of the isotope, provides the *normalizing factor* between the relative and absolute scales. It is important to choose this set carefully, because the accuracy of the resulting absolute radiation intensities is of course affected by the relative intensities and assumptions for the set. This paper presents analytical methods for calculating uncertainties of absolute γ-ray intensities and decay branching ratios derived from decay schemes. The equations have been derived with standard mathematical error-propagating techniques, using first-order approximations in Taylor series expansions of absolute γ-ray intensities.

Footnotes and References

*Condensed from E. Browne, Nuclear Instruments and Methods in Physics Research **A249**, 461 (1986), North-Holland, Amsterdam.

Multiple Scattering of Heavy Ions in Target Foils at 210 MeV per Nucleon

K.G.R. Doss, H.A. Gustafsson, H.H. Gutbrod, K.H. Kampert, B. Kolb, H. Löhner, B. Ludewigt, A.M. Poskanzer, H.G. Ritter, H. Wieman

The deflection of heavy ions due to multiple Coulomb scattering in absorber foils is of interest in many different applications. The scattering angle of 210 MeV per nucleon Au^{35+} projectiles in a 250 mg/cm^2 Au foil and a 178 g/cm^2 Fe foil has been measured at the Bevalac with the upgraded Plastic Ball detector described in ref. 1. The detection system consisted of two position sensitive gas counters in front of the target to track the incoming beam particles and another gas counter 7 m downstream of the target that covered an angular range of up to 2 degrees. With those detectors the scattering angle of heavy ions could be measured with an accuracy of 0.06 degrees (FWHM).

The multiple scattering can be calculated in the standard Moliere or NWS theory[2] by assuming a mean projectile charge of 55, a reasonable choice since most of the projectiles are completely stripped

in the target foils.[3] The results of the model calculations agree well with the measured distributions. This confirms the validity of the theory even for high energies.

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2. J. Moliere, Z. F. Naturf. **3a** (1948) and J.B. Marion and B.A. Zimmermannn, Nucl. Instr. and Meth. **51**, 93 (1967).

3. H. Gould *et al*, Phys. Rev. Lett. **52**, 180 (1984).

Initial DLS Hodoscope Performance

C. Naudet, J. Carroll, G. Claesson, T. Hallmon,‡ G. Igo,* P.N. Kirk,† G. Krebs, E. Lallier, G. Landaud,§ L. Madansky,‡ D. Miller,** H. Matis, H. Pugh, G. Roche, L. Schroeder, Z. Wang, and A. Yegnesworen***

Last spring the left arm of the Di-Lepton spectrometer[1] (DLS) was tested at the Bevalac with an 800 MeV/nucleon Ne beam. In order to produce fast triggering and additional particle identification information, a large solid angle hodoscope system was used. This consisted of two sets of 16 scintillation segments covering an angular range of 10° to 60° in theta and 15° in phi. The segments were calibrated both in dE/dx and TOF by minimum ionizing electrons detected by the DLS Čerenkov apparatus. Particle identification may be deduced by dE/dx and TOF measurements alone. However, when combined with the momentum information produced by the DLS drift chambers a direct calculation of the mass is possible. In Fig. 1 we show the mass distribution obtained for 800 MeV/nucleon Ne-Al collisions. A clear separation and identification of positive pions and protons is found.

Footnotes and References

*Department of Physics, University of California at Los Angeles, Los Angeles, CA 90024.

†Department of Physics, Louisiana State University, Baton Rouge, LA 70803.

‡Department of Physics, Johns Hopkins University Baltimore, MD 21218.

§Laboratoire de Physique Corpusculaire, Université de Clérmont-Ferrand, France.

**Department of Physics, Northwestern University, Evanston, IL 60201.

1. Electron pair Production Study using the Di-Lepton Spectrometer, proposal 780H to the Bevalac, G. Roche spokesman.

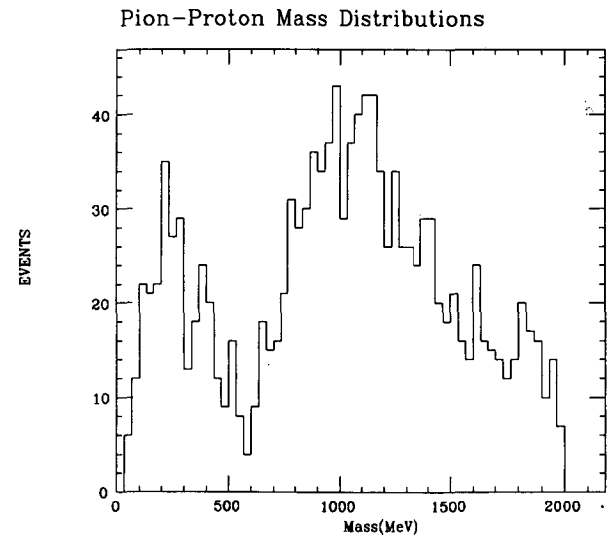

Fig. 1. Pion and Proton mass distributions. A clear separation between the pions and protons is shown.

XBL 8611-4637

A Fast Megapixel CCD Image Acquisition and Processing System for Streamer Chambers

S.I. Chase, T. Dinh, M. Fahmie, J.W. Harris, L. Teitelbaum, and M.L. Tincknell

A new system for acquisition and online analysis of Streamer Chamber pictures utilizes two large array Charge Coupled Device (CCD) cameras which take pictures electronically to replace or supplement traditional film cameras. These pictures are digitized and stored as arrays in computer random-access memory. The pictures can then be displayed, recorded on magnetic tape, and analyzed by computer program to extract pertinent physics information. This system was used as the Supervision System for experiment NA35 at CERN in November 1986. It consists of four major component subsystems:

- the imaging system consisting of two CCD cameras with readout and interface electronics;
- a fast coprocessor residing on the host computer and providing the system with data acquisition control, data buffering, and significant high-speed computing power for full-frame image processing operations;
- a high resolution color display;
- the host computer, a DEC VAXstation II (MicroVAXII) with a 1024×1024 black and white display console with windowing and graphics capability, controlled by software designed and written by our group at LBL.

In the NA35 experiment at CERN the system provided direct online displays of the Streamer Chamber, quantitative Streamer Chamber performance measures, and track multiplicity and angular distributions. Online correlations between track multiplicity, luminous intensity, and energy deposited in the downstream calorimetry of NA35 were also plotted. Both summary data and full pictures were recorded for offline analysis.

The system is being extended for future use at the Bevalac and at CERN. In the coming year the addition of a third CCD camera and a large-scale picture recording device such as a 2 Gbyte optical disk are planned. The image analysis software will be significantly augmented to extract more sophisticated information including automated track matching between views, 3-dimensional stereoscopic reconstruction of the particle momenta, and particle identification by ionization measurement. Even modest success in this program will dramatically extend the power of Streamer Chambers as a tool for high energy physics.

A Beam Counter for Ultra-Relativistic Heavy Ion Experiments

H.R. Schmidt, R. Albrecht,* G. Claesson,* B. Kolb,* H.H. Gutbrod,* M. Doss, A.M. Poskanzer, H.G. Ritter*

The upcoming ultra-relativistic heavy-ion experiment WA80 at CERN requires a beam counter with good Z identification, high count rate capability, good time resolution and low mass of the active parts. Čerenkov counters meet these requirements. Using quartz glass as a radiator, light guide and window of the photomultiplier enables one to transmit the Čerenkov signal without sizable absorption. Total internal reflection technique (TIR) yields very high light collection efficiencies.

A prototype TIR quartz counter was built with the following design: A 1 cm thick piece of quartz with a 2 cm x 5 cm front face and a hole of 1 cm diameter in the center serves as a light guide. The radiator is a 2 cm x 3 cm x 1 mm quartz plate that covers the hole. The ratio of 1:10 in thickness between the radiator and the light guide ensures that light produced by particles passing through the light guide

can be discriminated by pulse hight from light produced by beam particles in the thin radiator. The quartz is viewed from both sides by two XP2020Q PMT's (AMPEREX) with quartz windows. A silicon oil of high viscosity (DC200 from Dow Corning) has been used as an optical interface between the different quartz pieces.

The detector has been tested at the Bevalac with a 2.1 GeV per nucleon Ne beam with an intensity of 7×10^5 particles per second. The two areas resulting from the thin and thick parts of the counter are widely separated and peaks from different charges passing through the thin radiator (Z= 10, 9, 8 and 7) have been clearly identified.

Footnotes and References

*GSI Darmstadt

Performance and Calibration of the WA80 Calorimeters

R. Albrecht, T. C. Awes,† C. Baktash,† P. Beckmann,‡ F. Berger,‡ R. Bock,* G. Claesson,* L. Dragon,‡ R. L. Ferguson,† A. Franz, S. Garpman,§ R. Glasow,‡ H. A. Gustafsson,§ H. H. Gutbrod,* J. W. Johnson,† K. H. Kampert,‡ B. W. Kolb,* P. Kristiansson, I. Y. Lee,† H. Löhner,‡ I. Lund,* F. E. Obenshain,† A. Oskarsson,§ I. Otterlund,§ T. Peitzmann,‡ S. Persson,§ F. Plasil,† A. M. Poskanzer, M. Purschke,‡ H. G. Ritter, R. Santo,‡ H. R. Schmidt,* T. Siemiarczuk,* K. Soderstrom,§ S. P. Sorensen,† E. Stenlund,§ G. R. Young†*

WA80 is a collaborative experiment being carried out at CERN. The primary physics goals of the experiment are to search for indications of formation of a quark-gluon plasma, to determine nuclear stopping power and to survey and compare nucleus-nucleus and proton-nucleus collisions. Two calorimeters have been built for this experiment. The wall calorimeter is one of the main detector systems of the experiment. It is a joint venture of LBL, ORNL, LUND university, and GSI of Darmstadt. The zero-degree calorimeter is primarily a trigger calorimeter of ORNL design and construction.

Wall Calorimeter

The wall calorimeter has been designed to provide calorimetric coverage of the mid-rapidity participant region. In addition it is also to be used as a specialized trigger, capable of selecting events with a high associated transverse energy, Et. The wall calorimeter is a lead-scintillator electromagnetic, and a steel-scintillator hadronic, sampling calorimeter. It consists of thirty 20cm x 120cm stacks with each stack subdivided into six 20cm x 20cm towers with separate readout.

Prior to installation some stacks have been tested at the CERN PS and in September all towers have been calibrated with electrons and pions at the CERN SPS. The energy resolutions can be expressed as

$$\sigma/\sqrt{(E)} = 46(pions)\%$$

$$\sigma/\sqrt{(E)} = 17(electrons)\%$$

in good agreement with the design values.

Zero Degree Calorimeter

This trigger calorimeter was designed to provide: (1) near-total containment of 200GeV/c protons; (2) excellent energy resolution; and (3) high count-rate capability. It is a uranium-scintillator sampling calorimeter which uses a fast wavelength shifter readout and active photomultiplier bases for high rate capability. It was completed and tested in August 1986 with 135 GeV/c pions in the H3 beamline of the SPS.

Footnotes and References

*GSI, Darmstadt, West Germany

†Oak Ridge National Laboratory, Oak Ridge, Tennessee

‡University of Munster, Munster, West Germany

§University of Lund, Lund, Sweden

Relativistic Heavy Ion Facilities—Worldwide*

L.S. Schroeder

A review of relativistic heavy ion facilities which exist, are in a construction phase, or are on the drawings as proposals was presented at the 2nd Conference on the Intersections between Particle and Nuclear Physics (May 1986, Lake Louise, Canada). These facilities, shown in Fig. 1, span the energy range from fixed target machines in the 1–2 GeV/nucleon regime, up to heavy ion colliders of 100 GeV/nucleon. General features of these machines and the central physics issues addressed by each was described, along with a sample of the detectors used to extract the interesting physics.

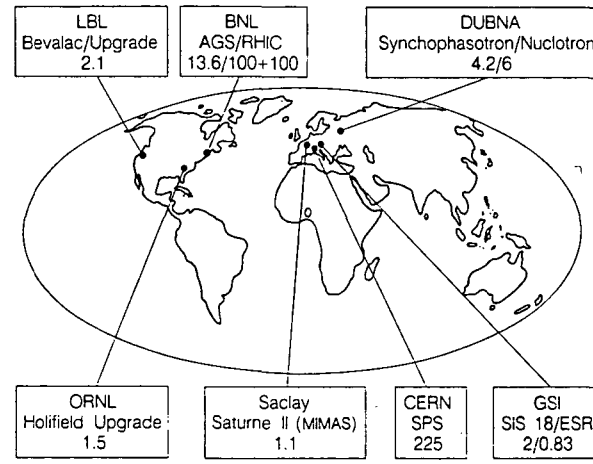

Fig. 1. Location of the seven relativistic (E > 1 GeV/nucleon) heavy ion facilities.

XBL 865-11123

Footnotes and References

*Condensed from LBL-21673, and an invited talk given at the 2nd Conference on the Intersections Between Particle and Nuclear Physics, held at Lake Louise, Canada (May 25–31, 1986).

PART V: APPENDICES

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Accepted at Nucl. Phys. A June 1986.

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Nuclear Science Seminars

October 7,1985	Dr. N.K. Glendenning LBL	Soliton Matter as a Model of Dense Nuclear Matter
October 9, 1985 Wednesday	Dr. K. Aleklett Studsvik, Sweden	Fragmentation of ^{197}Au by 35 AMeV ^{84}Kr
October 14, 1985	Prof. A. Rinat University of Maryland and Weizmann Institute	Deep Inelastic Scattering of Electrons and Hadrons from Nuclei: The Question of y Scaling
October 21, 1985	Dr. I Tanihata LBL	Nuclear Science Accelerator Initiative: Physics Opportunities (discussion)
November 8, 1985 Friday	Dr. K. Johnson LASL	Measurement of Free NP Elastic Scattering Spin Correlation Parameters Between 500 and 800 MeV
November 11, 1985	Dr. E. Norman LBL, and	Experiments with Radioactive Beams
	Dr. Y. Karant LBL	4π High Resolution Experiments
November 18, 1985	Dr. S. Bjørnholm Neils Bohr Institute	The Nuclear Quantum Fluid
November 20, 1985 Wednesday	Prof. R. Coussement Leuven University Belgium	Level Mixing Resonances–a New Method to Measure the Quadrupole Interaction
November 25, 1985	Graduate Students	
December 2, 1985	Harvey Gould LBL	New QED Experiments
December 4, 1985 Wednesday	Prof. T. Minamisono Osaka University Japan	Beta-Ray Angular Distribution from Aligned ^{12}B and ^{12}N and the Validity of G-parity Conservation
December 9, 1985	Dr. M.A. Nagarajan Daresbury	Heavy Ion Reactions Near the Coulomb Barrier
December 16, 1985	Dr. M.J.A. de Voigt KVI-Groningen The Netherlands	Possible Crystallization of Cooled Proton Beams
January 20, 1986	Holiday	
February 12, 1986 Wednesday	Prof. T. Minamisono Osaka University Japan	Hyperfine Interactions of Interstitial Light Ions in bcc Metals

February 17, 1986	Holiday	
February 20, 1986 Thursday	Prof. Hiroshi Toki Tokyo University	Chiral Bag plus Skyrmion Hybrid Metropolitan Model for Nucleons
February 24, 1986	Graduate Students	
February 28, 1986 Friday	Dr. Paul Cottle Yale University	Negative Parity States and Enhanced Electric Dipole Decay in Rn and Ra
March 5, 1986 Wednesday	Dr. Alex Brown MSU, National Cyclotron Laboratory	Large basis shell model calculations for M1 and GT transistors
March 10, 1986	Dr. Hammaren ORNL	Present Status of Number and Spins Projected for Nuclear Structures and Models
March 17, 1986	Dr. Jerzy Bartke	Relativistic Heavy-ion Research at Dubna
March 31, 1986	Dr. Zeev Vager Weizmann Institute Rehovet, Israel	Stereo Chemistry with Coulomb Explosions
April 17, 1986 Thursday	Dr. B. Shivakumar Yale University	Equilibration in Orbiting Reactions
April 28, 1986	Dr. Tord Bengtsson Neils Bohr Institute	Nuclear Structure Calculation at Very High Spin
May 5, 1986	Graduate Students	
May 12, 1986	Dr. Dieter Gross Hahn Meitner Institute	Decay of Very Hot Nuclei
May 13, 1986 Tuesday	Dr. P. van Baal SUNY	QCD on a Torus: A Bridge Between Analytical and Numerical Results
May 19, 1986	Graduate Students	
May 26, 1986	Holiday	
June 2, 1986	Helmut Koch Karlsruhe and CERN	The Crystal Barrel Experiment at LEAR
June 9, 1986	Prof. H.A. Weidenmuller Max-Planck Institute Heidelberg	Chaos in Atomic Nuclei
July 7, 1986	Dr. Peter Möller Lund, Sweden	Calculation of Stability Properties of Heavy Elements
July 14, 1986	Prof. P. Armbruster GSI	Heavy Element Research at GSI

July 28, 1986	Dr. H. Muhry University of Basel Switzerland	Effects of the Vacuum Polarization on the Sub-Coulomb ^{12}C- ^{12}C- Scattering
August 4, 1986	Dr. Barry Berman George Washington University	Channeling Radiation
August 7, 1986 Thursday	Walter Greiner University of Frankfurt	Positron Lines: Vacuum Decay, New Particles, or ??
August 11, 1986	Dr. U. Mosel University of Giessen West Germany	Production of Pions and High-Energy Gammas in Heavy-Ion Reactions
August 25, 1986	Dr. K. Takahashi LLNL	Beta Decay of Nuclei Near and Far from Stability
September 1, 1986	Holiday	
September 4, 1986	Dr. David Fields Michigan State University	Intermediate Mass Fragment Emission in ^{32}S Induced Reactions on Ag at 720 MeV
September 8, 1986	Prof. J. Rafelski University of Cape Town, South Africa	Probing the Vacuum with Heavy Ions
September 22, 1986	Dr. Richard Muller LBL	Geomagnetic Reversals from Impacts
September 29, 1986	Dr. Harvey Gould LBL	Results from the Uranium Lamb Shift Experiment

88-Inch Cyclotron Seminars

October 4, 1985	M.J. Murphy Lockheed, Palo Alto	Decay of Projectiles into Complex Fragments
October 11, 1985	C. Mathis and Y. Yano LBL, U.C.B.	Cyclotron and Generator Produced Radionuclides and Radio-Pharmaceuticals for Medical Studies with PET
October 18, 1985	P. J. Countryman Stanford University	Measurement of the Neutron Decay of ^{238}U from the Giant Resonance Region
October 25, 1985	M. H. Prior LBL	Atomic Physics with Slow, Highly Charged Ions
November 1, 1985	F. Blønnigen Institute Laue-Langevin	Precise Q-Beta Measurements of Neutron-Rich Nuclei with A=95-99
November 8, 1985	D. Di Gregorio CNEA, Buenos Aires	(1) The 20 MV Tandem at Buenos Aires (2) Sub-barrier Fusion of Oxygen-16 with the Sm Isotopes
November 15, 1985	M.-A. Deleplanque LBL	Physics with the High Energy Resolution Array
December 6, 1985	J. Wilczynski LBL	Evidence for Molecular Structure in ^{24}Mg from the ^{12}C(^{24}Mg, ^{12}C ^{12}C) ^{12}C Reaction
December 13, 1985	J. Garnett U.C. Berkeley	The Unsolved Problem of ^{35}Ar Beta Decay
December 19, 1985	M.J.A. de Voigt KVI- Groningen	Superdeformed States in High Spin Nuclei
January 10, 1986	P. McMahon LBL	Using the ECR Source to Test the Response of Scintillators to Heavy Ions
January 17, 1986	B. Harvey LBL	Calculations of Fragment Yields: Prospects and Problems
January 24, 1986	W.A. Kolasinski Aerospace Corp.	Upset of Microcircuits by Heavy Ions
January 31, 1986	C. Lyneis LBL	The LBL ECR Ion Source: Status and Future Possibilities
February 14, 1986	D. Moltz LBL	Recoil Atom Mass Analyzer (RAMA): Past, Present, Future
February 21, 1986	F. Ajzenberg-Selove University of Pennsylvania	(t,^{3}He) Reactions and Astrophysics
February 28, 1986	K. Lesko LBL	Neutrino Oscillation Experiment at LAMPF

March 7, 1986	K. Gregorich LBL	Physics and Chemistry of the Heaviest Elements: New and Proposed Techniques
March 14, 1986	E. Plagnol Orsay	Searching for the Limiting Excitation Energy a Nucleus Can Sustain
March 21, 1986	S. Gazes LBL	Partition of Excitation Energy in Peripheral Heavy Ion Collisions
March 28, 1986	K.M. Yu LBL, U.C. Berkeley	Structural Characterization of Semiconductor Contacts Using Heavy-Ion RBS
April 4, 1986	D. Pelte University of Heidelberg	Multiple Heavy-Fragment Breakup Reactions
April 11, 1986	E. Norman LBL	A Passage to India
April 18, 1986	R. Belshe LBL	Computing for Users at the Cyclotron and HILAC
April 25, 1986	J. Engelage U.C. Berkeley, SSL M. Webb U.C. Davis	^{12}C Fragmentation at HISS:Excitation Spectra and Channel Populations
April 17, 1986	B. Shivakumar Yale University	Equilibration in Orbiting Reactions
May 2, 1986	A. Harmon University of Virginia	Orbiting in Heavy-Ion Collisions
May 9, 1986	J.M. Nitschke LBL	Study of Beta-Delayed Proton Decay with OASIS
May 16, 1986	F. S. Goulding LBL LBL-UCSB	^{76}Ge Double-Beta Decay Experiment
May 23, 1986	C.D. Goodman Indiana University	Nuclear Structure Studies with Charge-Exchange Reactions
June 13, 1986	D. Hinde Australian National University	Time Scale of Fusion-Fission Reactions
July 18, 1986	K. Lesko LBL	Report on the Erice Cosmic Ray Conference
August 15, 1986	D. Moltz LBL	Report on the Dubrovnik Symmetries and Structure Conference
August 22, 1986	K. Holinde Julich	Charge Symmetry Breaking in n-p Interactions

August 29, 1986	R. Charity LBL	Complex Fragment Production in Intermediate Energy Reactions
September 3, 1986	S. S. Dasgupta Burdwan University, India	Alpha-Induced Deuteron Interactions
September 5, 1986	J. Wouters Catholic University, Louvain	Particle Emission from On-Line Separated Isotopes
September 12, 1986	H. E. Conzett LBL	Production of Polarized Protons Anti-Protons in Storage Rings
September 19, 1986	E. Norman LBL	(1) Improved Tests of the Exponential Decay Law (2) Searches for Supermassive X-Minus Particles in Iron
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