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**RESEARCH AT THE BNL
TANDEM VAN DE GRAAFF FACILITY — 1980**

March 1, 1981

DEPARTMENT OF PHYSICS

**BROOKHAVEN NATIONAL LABORATORY
ASSOCIATED UNIVERSITIES, INC.**

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RESEARCH AT THE BNL TANDEM VAN DE GRAAFF FACILITY — 1980

March 1, 1981

BROOKHAVEN NATIONAL LABORATORY
UPTON, NEW YORK 11973

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March 1, 1981

Dear Colleague:

The Executive Committee of the Tandem Users Group has urged us to provide a periodic description of the scientific program at the BNL MP Tandem Facility. To this end we have put together the enclosed package for limited circulation to our outside users and other interested parties. The material, which covers the last three years, is taken from a report submitted to DOE for the purpose of a program review. It was put together in January-February 1981. We have included in this report only one appendix-- a publication list. This list of publications is divided into BNL, BNL-Outside User Cooperative, and Outside User only.

Portions of the cover letter addressed to the program reviewers follow on the next page. The composition of the report and the reasons for some of its peculiarities are explained in the cover letter. Other peculiarities are due to the decision to issue this report on a limited budget.

Yours sincerely,

A handwritten signature in dark ink, appearing to read "E. K. Warburton". The signature is fluid and cursive, with the first letters of the first and last names being capitalized and prominent.

E. K. Warburton

Dear Reviewer:

Following the instructions set forth for this review package by the DOE, the main burden of describing the facility and the research program is in the Field Task Proposals (FTP) to be found in Sec. IV. For bureaucratic reasons there are three of these for the BNL Tandem van de Graaff research facility, namely, Heavy Ion Operations, Heavy Ion Research, and Light Ion Research. From the scientific point of view this split is artificial: the three FTPs together describe an integrated research program. The FTPs contain narrative material divided chronologically into three sections which describe research (1) for fiscal year (FY - from October 1 to October 1) 1980 and expected in the remainder of FY 81, (2) expected in FY 82, and (3) expected in FY 83. We call to the reader's attention that DOE regulations preclude the use of figures in FTP submissions. The two research FTPs also contain a complete publication list (BNL and Outsider Users combined) for the period January 1, 1980, to the present. There is also some budget information at the end of the FTPs as well as in Appendix 1. Because there is no coverage in the FTP of past years and no integrated description of the facility, we have included a section (Sec. III) of this package which gives a description of the BNL MP Tandem Facility, how research is organized at the Facility and some feeling for past achievements.

The description of the present facility (Sec. IIID) is intended to assist you in your assessment of our past achievements and future plans. The upgrade planned for this spring is outlined here as well as in the FTP because it is a major change in our facility. It is important to realize that the BNL MP Facility after this upgrade (1981) will be far superior to the original installation as dedicated in 1970. For instance, the maximum energy for a typical heavy ion beam (Iodine) is now some three times higher and after the upgrade will be about four times higher.

The description of the Outside User program (Sec. IIIC) is included because it was requested by DOE and also because it is such an important part of our total program (50%) and because we are proud of it.

As regards publications, we originally planned to include reprints of all publications for the last three years. We collected them and ended up with 154 articles and letters. Together they made an unwieldy pile, so we selected some 20% of the more meritorious for present inclusion. To this end, Appendix 3 contains selected articles, cover pages for the remaining articles, and all letters, BNL and Outside Users. Appendix 2 contains a complete list of all publications. Both appendices cover the period from January 1, 1978, to January 1, 1981.

Happy reading.

Yours sincerely,

E. K. Warburton

II. Personnel

A complete list of personnel now associated with the Tandem Van de Graaff Research Group is given below as is a list of Operations personnel and visitors whose work relates to this report. Note that the three members of the Operations group also are engaged in research. Within the overall group, subgroups of individuals combine into smaller research teams to carry out their mutual research interests. These smaller research teams do not have a formal, long-term character, although considerable continuity with respect to permanent staff within these subgroups inevitably results. It is a definite policy of the Research Group to encourage participation by young members of the staff in a wide variety of experiments. It is indeed possible, and often happens, for younger staff members, either individually or jointly, to initiate their own research program and obtain scheduled beam time to carry it out with no affiliations with any senior staff members. Long-term associations with single senior staff members are not encouraged. Research collaborations with staff members from other institutions occur with reasonable regularity, often a valuable by-product of the outside user program (although not in any way a necessary condition for the Outside Users). A final important component in the overall research program has been the Summer Visitor Program. This program, conducted by the Laboratory almost since its inception, has sought to bring for short periods scientists to BNL from other institutions, both domestic and foreign. The value of this program to all is difficult to overestimate. For several such visitors, the opportunity to become intimately acquainted with BNL facilities and staff has served as the germinal component in

the development of an Outside User program. Similarly, such contacts have also inspired collaborative research which has been carried out at other institutions. Such opportunities have enabled the participating BNL staff to make use of unique facilities at these other institutions and have contributed in an important way to the overall research program.

Operations Group

Peter Thieberger (Group Leader)
Craig Thorn
Harvey Wegner

In addition-
17 FTE^a Engineers, Technicians,
Operators, and Secretary

Research Group

Ernest Warburton (Group Leader)
David Alburger
Jean Barrette
Cyrus Baktash

Research Group (cont.)

Peter Bond
Chellis Chasman
Michael Collins^b
Edward der Mateosian^c
Ole Hansen^d
Dag Horn^d
Ottmar Kistner
Andres Kreiner
Micheal Levine^e
Kim Lister^d
John Clness
Andrew Sendorfi
Andrew Sunyar

In addition-
3.5 FTE^a Technicians & Secretary

Footnotes:

^a Full time equivalent

^b Arrived June, 1980

^c Arrived January 1981

^d Terminated Fall, 1980

^e On sabbatical leave, 1980

Traditionally the Tandem Research group partially supports visitors for periods of a month to a year. In the past two years these partially supported visitors have been:

1979

J.-P. Coffin, CRN Strasbourg
A. Filevich, AEC Buenos Aires
C. Fontenla, Cidadi U.
G. Goldring, Weizmann Institute
O. Hansen, Niels Bohr Institute
K. Nagatani, Texas A&M
R. Schuch, Heidelberg U.
D. Schwalm, GSI
J.-C. Sens, CRN Strasbourg
Sir D. Wilkinson, U. of Sussex
G. Young, ORNL

1980

L. Engstrom, U. of Lund
G. Garcia Bermudez, AEC Buenos Aires
G. Goldring, Weizmann Institute
T. Lonnroth, Finland
C. Maguire, Vanderbilt U.
A. Nathan, U. of Illinois
R. Schuch, Heidelberg U.
Sir D. Wilkinson, U. of Sussex
A. Xenoulis, NRC Democritos

An extensive list of Outside Users at the BNL facility that receive no (or very minimal) financial support from BNL appears in the FTP section on Users.

The more frequent in-house users not supported by the Facility are:

R. Casten Physics
A. Goland Physics
D. Gregory Physics
A. Hanson Physics
P. Haustein Chemistry

B. Johnson Physics
K. Jones Physics
S. Katcoff Chemistry
M. Pick Energy & Environment
M. Varma Safety/Environmental Prot. Div.

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III. The Research Program at the BNL Van de Graaff Accelerators

A. INTRODUCTION

The research program which forms the topic of this report is carried out almost completely at the BNL Tandem Van de Graaff Facility. The Facility itself consists of two in-line Emperor (MP) accelerators which can be operated together in a three-stage mode to provide high energy beams of heavy ions or alternatively, as separate accelerators when the highest possible energy beams of heavy ions are not required for the experiment. A wide variety of energetic heavy-ion beams of high beam quality, with precise and easily variable energy and with high reliability is provided by the Facility which is described in IIID below. A small part of the research program utilizes the BNL 3.5-MV Van de Graaff whose major support now derives from programs in material, chemical, and medical sciences.

The Facility is a national one. Beam time is shared on an approximately equal basis between the local staff and Outside Users from the physics community. Much of the laboratory equipment has been designed, built, and installed by the local scientific staff. Care is taken in its maintenance so that the Outside User community finds it easily useable in the implementation of its own research programs: All of the many problems concerned with ensuring continuity in the daily operation of the Facility for both in-house and Outside User programs are administered by members of the local scientific and technical staff. The Outside User Program is described more fully in Sec. IIIC.

The BNL research programs are described in Sec. IIIB. In that section an attempt is made to give an historical perspective to our

activities; to highlight very briefly representative examples of work accomplished in the last ten years; and to give some feeling of the scientific motivation for the work and its impact upon general understanding and progress in nuclear physics. The enclosed FTPs provide a thorough albeit brief description of current research.

B. ACHIEVEMENTS

The BNL MP Tandem Van de Graaff Facility was dedicated in 1970. Since then the research effort at the Tandem has covered a broad range of problems in nuclear and atomic physics with greatest emphasis on physics arising from the acceleration of heavy ions. Important developments in heavy-ion physics at BNL include fundamental discoveries about the reaction mechanism in heavy-ion quasielastic reactions, early achievements in the study of high-spin states in nuclei from $A = 20$ to $A = 214$, production of many new exotic nuclei far off the line of stability, pioneering efforts in the measurement of lifetimes via Doppler shift techniques, an exhaustive study of Coulomb excitation of sd-shell nuclei, the radiative capture of $^{12}\text{C} + ^{12}\text{C}$ and $^{12}\text{C} + ^{16}\text{O}$, the uncovering of new intermediate structure in quasi-molecular systems such as $^{12}\text{C} + ^{12}\text{C}$ and $^{12}\text{C} + ^{16}\text{O}$. Other highlights involve early studies of total fusion cross-sections, of evaporation residues after fusion, of transfer induced fission, and of the quasi-molecular behavior seen in the backward angle elastic and inelastic excitation functions and angular distributions for the highly asymmetric systems $^{16}\text{O} + ^{28}\text{Si}$ and $^{12}\text{C} + ^{28}\text{Si}$. Results obtained in the study of highly-excited atoms and of heavy-ion channeling in solids and recently in the study of the chemical structure of negative molecules have expanded the heavy-ion physics program beyond nuclear physics.

In the realm of light-ion physics the major contribution has been in beta decay studies. For example, the search for the existence of second-class currents was primarily investigated at BNL as was the possible extraction of fundamental information on the structure of the

nucleus from accurate determinations of the Fermi matrix element in beta decay.

The two largest efforts in terms of manpower and Tandem running time over the last 10 years have been in the areas of heavy-ion quasielastic reactions and in the study of high-spin states in the region $A = 140-170$. Research efforts in these areas and others are briefly summarized below. In what follows specific references are made only for post-1977 research. The aim of this section is to give an historical perspective to the present (and near-future) activities which are summarized in the enclosed FTPs.

Quasielastic Reactions. The investigation of interactions between heavy ions on grazing trajectories, specifically reactions involving small changes in mass, charge or energy, has been a strong focus of the research program at BNL. Elastic and inelastic scattering and particle transfer reactions have been studied in depth with particular emphasis on reaction mechanism studies. Recently this emphasis has shifted to the use of these reactions to obtain information about nuclear structure. Most of these studies have dealt with discrete final states in nuclei, thus the high quality, high energy beams from the Tandem Facility and the availability of the high resolution QDDD spectrometer have been crucial to the success of the program.

Elastic scattering studies have determined the potentials which govern the interaction between heavy ions for projectiles with $A < 20$ on a wide range of targets. In addition to the standard study of such potentials, a high resolution experiment showed the strong influence of Coulomb excitation upon elastic scattering from deformed nuclei.

The startling phenomenon of large back-angle elastic scattering cross sections for certain heavy ions was discovered, and the large oscillatory structure in angular distributions and in excitation functions at 180° for many heavy ion systems have been systematically studied. Kinematic problems make standard experimental techniques impossible, thus the QDDD spectrometer and the multitude of isotopic beams available from the tandems have been instrumental in these studies. The excitation function measurements at 180° have been obtained by reversing the reaction, i.e. the heavy partner incident on a light target, with the recoils detected at 0° in the laboratory. Since the initial discovery of the back angle phenomenon for ^{12}C and ^{16}O on ^{28}Si , systems from $^{12}\text{C} + ^{19}\text{F}$ (see FTP) to $^{16}\text{O} + ^{58}\text{Ni}$ (Kubono et al., 1979) have been extensively studied. Both the gross and fine structure in the excitation functions at $\sim 180^\circ$ have been measured (Barrette, et al., 1979), angular distributions near 180° have been investigated, and the out-of-phase behavior of the excitation functions at 90° and 180° has been demonstrated for several systems (Kubono, et al., 1979). A comparison of alpha transfer reactions between systems which show anomalous back angle cross sections have also been investigated (Gelbke, et al., 1978; Paul, et al., 1980).

Inelastic scattering has been used to determine transition and static quadrupole moments (LeVine, et al., 1981) as well as to provide the first measure of spin flip probability in reactions between heavy ions (Dünnweber, et al., 1979). Excitation function measurements of gamma rays from inelastic scattering in $^{12}\text{C} + ^{12}\text{C}$ scattering have shown gross structure oscillations which have been attributed to molecular resonance behavior (Cormier, et al., 1978). Correlations

were observed between the inelastic scattering excitation function for $^{12}\text{C} + ^{16}\text{O}$ and the fusion excitation function (Jachymski, et al., 1978).

Transfer reactions induced by heavy ions have concentrated on studies of the reaction mechanism and have been highlighted by the first observation of oscillations in angular distributions; a demonstration of the transition with energy of angular distributions, from bell-shaped behavior to oscillatory behavior; evidence for the sensitivity of transferred $L = 1$ reactions to the reaction mechanism with subsequent analysis of specific cases, some of which showed anomalous behavior (Bond, et al., 1979); and proof of the dramatic shape changes which occur in certain angular distributions due to interferences between multistep routes. An understanding of the reaction mechanism, obtained from a BNL collaboration between experimentalists and theorists, has led to a study of expected polarizations in heavy-ion-induced transfer reactions (Bond, 1980) and more recently to the use of specific heavy-ion-induced reactions to obtain strong preferential population of high spin single particle states. These latter studies have concentrated on the use of single neutron transfer to selectively populate high spin states in both near-spherical ($N \geq 82$) and well-deformed nuclei, some of which were previously studied at BNL by gamma-ray spectroscopy following heavy-ion fusion-evaporation reactions. The information obtained in heavy-ion-induced transfer has proven to be complementary to that obtained by gamma-ray spectroscopy.

Partly because of bombarding energy limitations the deep inelastic scattering process has not been widely studied but one

important result which was found for light systems was the strong anisotropy of discrete gamma rays in coincidence with deep inelastic fragments, a result contrary to what was observed for continuum gamma rays.

In the quasi-elastic program the upgrading of the accelerator to higher energies will expand the possible experiments considerably. For elastic and inelastic scattering higher energies will mean that the nearly unexplored region of very heavy ion scattering can be studied. The transfer program will likely grow rapidly as not only the list of possible targets expands but studies of selective, more massive transfer will be possible.

High-Spin Spectroscopy The yrast (and near-yrast) spectra exhibited by nuclei in the light rare-earth region ($A \approx 150-170$) provide an especially rich variety of examples which illuminate the role played by the different nuclear degrees of freedom in response to angular momentum-induced stresses. This is so because this mass region spans a range which includes nuclei with essentially spherical ground states near the semimagic ^{146}Gd nucleus ($Z = 64$, $N = 82$), through a region of transitional nuclei to the familiar class of nuclei with stable, nonspherical shapes. Work in this region commenced at BNL in the early 70's and has continued ever since.

For nuclei just above ^{146}Gd the nuclear spectra are dominated by single particle aspects of nuclear motion. Here the large angular momenta are generated by summed contributions from individual particles. The discrete yrast spectra are, in general, irregular because of orbital rearrangements of individual particles. Yrast isomers at $J \sim 40$ are a common occurrence in this region and are

interpreted as shell-model isomers. Examples include the 11^- isomers in $N = 86$ nuclei, identified at BNL in ^{156}Yb (6 nsec) (Lister, et al., 1978) and ^{154}Er (40 nsec) (Baktash, et al., 1979). This particular state is interpreted as the aligned $(h_{9/2} \otimes i_{13/2})_{11^-}$ configuration since its excitation energy is virtually constant across the $N = 86$ isotones (see Fig. 1).

Side feeding patterns into the yrast sequence in near-spherical or weakly oblate nuclei such as ^{154}Er differ markedly from those observed in the region of strongly deformed, prolate rare-earth nuclei where side feeding enters at all levels of the rotational bands. In the former case, the side feeding tends to concentrate at specific points in the yrast sequence and a significant fraction of the reaction strength proceeds through discrete states at very high spin. This has made it possible to establish discrete levels to $J=36$ at excitations near 13 MeV. As an example, the deexcitation scheme for ^{154}Er as observed with the $(^{16}\text{O}, 4n)$ reactions at 100 MeV bombarding energy is shown in Fig. 2 (see FTP and Baktash, et al., 1979).

The general systematics of high spin states in the $N = 86$ isotones are shown in Fig. 1 (see FTP). One striking feature of the level structures of the ^{150}Gd , ^{152}Dy and ^{154}Er isotones is a sequence of three quadrupole transitions beginning at $J^\pi = 21^-$ (19^- in ^{154}Er) and terminating at $J^\pi = 27^-$ (25^-). The (decreasing) energy spacings within these quasiband structures follow closely the predominantly $[(\pi f_{7/2})^2]_{0+, 2+, 4+, 6+}$ spacings in their respective $N = 84$ isotopes (see Fig. 2 and FTP).

At the upper end of the mass region under discussion, nuclei exhibit large prolate deformations in their ground states and the

Fig. 1. Systematics of the yrast states in the near-spherical $N = 86$ nuclei. Many features of the data such as 11^- isomeric states in ^{152}Dy , ^{154}Er and ^{156}Yb , and the high spin multiplet in ^{150}Gd , ^{152}Dy , and ^{154}Er are evidence of predominance of shell model configurations in their structure.

yrast sequence consists of states which belong to rotational bands. The phenomenon of "back-bending" has been demonstrated to be a common occurrence and is attributed to the crossing of the ground state band by an excited 2-quasiparticle ($i_{13/2}$ neutrons) band. Other quasiparticle excitations lead to side bands. Association of specific configurations with particular observed bands was made through a comparison of the experimental data with theoretical calculations of quasiparticle energies as a function of rotational frequency. A detailed knowledge of the band structure of the neighboring odd mass nuclei is important for understanding the band structure of even-even nuclei, thus complementary studies of level structure in odd mass nuclei have been made. The rich band structure observed in deformed nuclei is illustrated by the deexcitation scheme (see Fig. 3 and Kistner, et al., 1978) of ^{164}Er . Experimental results for this nucleus were a catalyst for theoretical attempts, largely successful, to describe quasiparticle motion in rotating, deformed potentials. Similar results in other nuclei (^{166}Yb , ^{176}Hf , etc.) have helped to establish the influence of Coriolis and centrifugal forces under extreme conditions.

Other examples of fusion-evaporation spectroscopy include a series of studies of high-spin states in $A = 20-63$ nuclei which (1) showed that heavy-ion fusion-evaporation reactions behave similarly for light ($A < 100$) and heavy ($A > 100$) nuclei and (2) delineated thoroughly the high-spin states of this region with pioneering applications of gamma-ray spectroscopy techniques.

Extensive high-spin investigations have also been made for heavier nuclei ($A = 190-220$) and doubly-odd nuclei near $A = 84$ (See

Fig. 3. Yrast and near-yrast rotational structures in the deformed nucleus ^{164}Er . Note the regularity of level spacings in this nucleus in contrast to those in ^{154}Er .

FTP). Altogether the program of spectroscopy of high-spin states via gamma-ray spectroscopy following heavy-ion fusion-evaporation is extremely varied and encompasses nuclei from $A = 21$ to 214.

Fusion Reactions. The study of fusion reactions has been carried on at the Tandem Facility by many groups of outside and inside users. The more recent work was done with the MIT-BNL energy mass separator and has included the study of the dynamic influence of valence particles in the complete fusion of massive (Ni+Ni) nuclei (Beckerman, et al., 1980) and the beginning of a systematic study of the excitation function for the heavy-ion-induced fusion of systems in the trans-lead region (Schier, et al., 1981). This latter work has already led to the discovery of the new alpha emitter ^{199}Rn (DiRienzo, et al., 1980) and will provide systematic data on the influence of the Coulomb barrier and the competition between evaporation and fission in the fusion leading to very heavy systems.

Earlier fusion studies at the Tandem Facility had concentrated on the understanding of evaporation residue distributions and on the determination of fusion barrier parameters for heavy ions. More recently work has been done on the fusion of medium-light systems to determine the saturation value of the evaporation residue cross section and to study the possible presence of a low critical angular momentum at high bombarding energy (see FTP).

Atomic Physics. The tandem accelerators at Brookhaven have shown themselves to be exceedingly versatile and unique machines for accelerator-based atomic physics research. The use of the accelerators in the 3-stage mode coupled with a great variety of beams available from the terminal ion source gives an unmatched range of

high energy heavy ions with reasonable intensities. Furthermore, the use of the accelerators in the unique 4-stage mode, where ions are first accelerated and then decelerated, has recently given access to the very interesting realm of low-velocity highly ionized beams. The combination of the two acceleration modes gives the atomic physicist an unequalled opportunity to control the experiment by choosing both the charge state and velocity of the ion to be used.

The BNL atomic physics program began about three years ago and is now exploiting these capabilities in a rather extensive program that also involves collaborators from many outside institutions. The areas of interest are mainly in beam-foil spectroscopy, ion-atom collisions, and electron impact excitation and ionization of heavy ion beams (see Heavy Ion FTP). A unique experiment designed to measure the $2s_{1/2}$ - $p_{1/2}$ Lamb Shift splitting in hydrogenic chlorine (being conducted by a Bell Lab-Rutgers collaboration) makes use of the excellent beam optics of these accelerators. In this experiment an intense laser beam is used to induce resonant transitions in a tightly focussed beam of Cl^{+16} ions.

Because of the richness of atomic phenomena, the fields described above require the most advanced heavy-ion accelerator facility possible. The upgrading of the BNL facility to give higher energies and thus more highly-ionized atoms is obviously of great importance for future atomic physics experiments employing either the 3-stage or the 4-stage accel-decel modes of operation.

Some further results . Other highlights of the first 10 years include a study of the Coulomb excitation of the low-lying levels of sd-shell nuclei which gave B(E2) and static quadrupole moment and

simultaneously lifetimes from gamma-ray Doppler shift line shapes. This study allowed for the first time a complete comparison of the two methods of measuring $2^+ \rightarrow 0^+$ lifetimes and gave a relative set of accurate $B(E2)$ -values from $A = 20$ to 37 . It was also the definitive publication on the extraction of $Q(2^+)$ -values from gamma-ray line shapes via the re-orientation effect in Coulomb excitation (Schwalm, et al., 1977).

The first observation of beta decay of six of the eight $T_Z = 5/2$ nuclei from ^{21}O to ^{35}P was accomplished at the BNL Tandems. These were found by observation of gamma rays following heavy-ion fusion-evaporation reactions. As well as determining masses for the $T_Z = 5/2$ nuclei, these studies added valuable new spectroscopic information on the final $T_Z = 3/2$ nuclei (see FTP and Alburger, et al., 1981). A complete list of radioisotopes which were observed first at the BNL Tandem Van de Graaff Facility is given in Table I.

Studies of high-energy gamma rays following the heavy-ion complete fusion reactions $^{12}\text{C}(^{12}\text{C}, \gamma)^{24}\text{Mg}$ (Sandorfi, et al., 1978) and $^{12}\text{C}(^{16}\text{O}, \gamma)^{28}\text{Si}$ (see FTP) have revealed a new class of resonant states. These are uncorrelated with features of other heavy-ion reactions or of electromagnetic strength functions, and exhibit both fusion and gamma-ray partial widths that are significantly enhanced over statistical predictions. These radiative capture measurements suggest a new and unusual form of intermediate structure, namely highly-clustered configurations built on the ground-state bands of the fused nuclei (see FTP).

Table I. Beta Radioactivity First Observed at the BNL Tandem Facility

	Isotope	Half-Life	Year	Research Team
1.	^{44}V	90 msec	1971	Cerny, Goosman, Alburger
2.	^{33}Si	6.3 sec	1972	Goosman, Alburger
3.	^{35}P	48 sec	1972	Goosman, Alburger
4.	^{31}Al	0.644 sec	1973	Goosman, Alburger
5.	^{29}Mg	1.20 sec	1973	Goosman, Davids, Alburger
6.	^{23}F	2.23 sec	1974	Goosman, Alburger
7.	^{14}B	16.1 msec	1974	Alburger, Goosman
8.	^{34}Si	2.77 sec	1977	Nathan, Alburger
9.	^{55}V	6.54 sec	1977	Nathan, Alburger, Olness, Warburton
10.	^{12}Be	24.4 msec	1978	Alburger, Balamuth, Lind, Mulligan, Young, Zurmühle, Middleton (research done at University of Pennsylvania)
11.	^{70}Br	80.2 msec	1978	Alburger
12.	^{80}Y	33.8 sec	1980	Haustein, Lister, Alburger, Olness
13.	^{79}Sr	2.30 min	1980	Haustein, Lister, Alburger, Olness
14.	^{81}Y	72.0 sec	1980	Lister, Alburger, Haustein, Olness
15.	^{21}O	3.42 sec	1980	Alburger, Lister, Olness, Millener
16.	^{82}Y	9.5 sec	1980	Lister, Alburger, Haustein, Olness

C. THE OUTSIDE USER PROGRAM

Research by Outside Users at the Tandem Facility is conducted by scientists drawn from universities and other laboratories. An active Outside Users program, affording research opportunities for a diverse range of scientific interests, is maintained: in the last few years, about 50% of the beam time has been used by a changing group of approximately 80 physicists including about 15 graduate students per year. The attached list of users' home institutions (Table II) indicates a strong representation of Northeastern universities, but other areas are represented as well. The scope and success of the user program is best appreciated by inspecting the Publication List (Appendix 1).

Scientists from a number of institutions have participated in a Summer Visitors Program which Brookhaven has sponsored for many years. This program provides partial financial support to physicists who come to BNL for periods on the order of 6 weeks in the summer. The Tandem Laboratory and Nuclear Theory Group have each had 6 to 8 visitors on this basis each summer.

Brookhaven has a 25-year history of providing high quality working and living conditions for accelerator users. Housing is available on site, and transportation through Islip and New York airports is convenient. It has been the policy of the Tandem Laboratory that essentially all capital equipment items such as modular electronics, spectrometers, scattering chambers and the data-collection computer are shared by all inside and Outside Users. Technician assistance is provided to all users to facilitate daily experimental setup as well as installation of major pieces of

Table II. List of Affiliations of Outside Users of the BNL Tandem for 1978-80

Argonne National Laboratory	SUNY, Albany
University of Arizona	SUNY, Stony Brook
Aarhus University, Denmark	New York University
Bell Laboratories	Oak Ridge National Laboratory
University of Bergen, Norway	Ohio University
University of California, Berkeley	Panametrics, Inc.
CEN, France	University of Pennsylvania
City College of CUNY, New York	University of Pittsburgh
CNEA, Buenos Aires, Argentina	Princeton Plasma Physics Laboratory
CRNS, France	Princeton University
GSI, Darmstadt, Germany	University of Rochester
University of Heidelberg, Germany	Rutgers University
University of Illinois	University of Sao Paulo, Brazil
Johns Hopkins University	University of Seattle
Kansas State University	Smithsonian Astrophysical Observatory
University of Lowell, Massachusetts	Stanford University
University of Lund, Sweden	University of Sussex, England
Massachusetts Institute of Technology	Tennessee Technological University
University of Mexico	University of Tennessee
Michigan State University	University of Texas
University of Michigan	University of Toledo, Ohio
University of Minnesota	Vanderbilt University
MPI, Heidelberg, Germany	University of Virginia
University of Munich, Germany	University of Washington, Seattle
Technical University, Munich, Germany	Weizmann Institute, Israel
Niels Bohr Institute, Denmark	Williams College
University of Notre Dame	Yale University
NRC, Greece	

experimental equipment. The Brookhaven scientific staff frequently collaborates with outsiders, and also provides aid to outsiders to enable independent use of the many locally developed and constructed experimental instruments. As a result of these policies, it is generally possible for users to bring little or no equipment to BNL. However, for particular projects it is also possible for users to install major pieces of equipment. Some notable examples are the EMS spectrometer of MIT, the Bell-Rutgers laser for Lamb shift measurements, and an x-ray spectrometer from SUNY-Stony Brook. Users who install and then use large equipment for long periods of time are encouraged to invite participation of BNL and other outside groups in the use of such equipment. The BNL physicist who serves as Liaison to the Program Advisory Committee also represents the users in scheduling meetings and is responsible for the smooth operation of their programs.

The Tandem Users Group, which was founded in the early days of the project, meets periodically at BNL and at APS meetings. Approximately 400 scientists presently receive copies of the Tandem Newsletter. The Users Group elects an Executive Committee which discusses matters regarding the Users Program, the existing facility and directions for growth and improvement. In this way users have an active role in determining the experimental facilities to be built.

The present members of the Executive Committee of the Tandem Users Group are:

F. Becchetti (University of Michigan)	L. L. Lee, Jr. (SUNY, Stony Brook)
P. Braun-Munzinger (SUNY, Stony Brook)	D. E. Murnick (Bell Labs)
T. M. Cormier (University of Rochester)	P. D. Parker (Yale University)
H. T. Fortune (University of Pennsylvania)	S. G. Steadman, Chairman (MIT)
T. H. Kruse (Rutgers)	

As a rule the experimental time requested by Outside Users significantly exceeds that which is available. In order to set priorities, requests by Outside Users are reviewed by a Program Advisory Committee 3 to 4 times a year. Members of this committee are selected from the scientific community in consultation with the Tandem Users Executive Committee, and terms are for approximately three years. The present members are:

J. Alexander (SUNY, Stony Brook)
B. F. Bayman (University of Minnesota)
H. G. Berry (ANL)
J. L. C. Ford, Jr. (ORNL)
L. Grodzins (MIT)
W. Henning (ANL)
A. E. Litherland (University of Toronto)
L. Riedinger (University of Tennessee)

The Chairman of the Committee is Arthur Schwarzschild, Chairman of the Physics Department, and Ottmar Kistner serves as the BNL Liaison member.

Graduate Student Training. The BNL facility, which is in close proximity to a large university community in the Northeast, has been a training ground for many students. The excitement engendered by working at an advanced facility appears not only to attract newcomers to the field but to act as a positive influence for keeping them in the field.

During the past eight years more than 30 students from 6 universities have done all or significant parts of their graduate thesis research at the BNL tandems (Table III). Many more have participated in the research program (Table IV). A test of the success of graduate student programs at this user facility lies in an

Table III. Graduate students who have done all or significant parts of their graduate thesis research at the BNL tandem. The first degree was awarded in 1975.

Name	Affiliation as Student	Degree	Present Affiliation
D. Abriola	SUNY, Stony Brook	Ph.D. Candidate	
M. Al-Kofahi	MIT	Ph.D. Candidate	
M. Anderson	Univ. of Michigan	M.S.	
M. Cobern	Yale	Ph.D.	Oil industry
T. Cormier	MIT	Ph.D.	Univ. of Rochester
S. B. DiCenzo	Yale	Ph.D.	Bell Labs, Murray Hill
A. Dilmanian	MIT	Ph.D.	Washington Univ., St. Louis
A. deRienzo	MIT	M.S.	West Point Military Academy
C. Flaum	Univ. of Rochester	Ph.D.	Schlumberger Well Services
W. Freeman	SUNY, Stony Brook	Ph.D.	Argonne National Lab
M. Fritts	Yale	Ph.D.	Naval Research Lab
S. Gazes	MIT	Ph.D. Candidate	
R. Goldstein	MIT	Ph.D.	Retina Foundation
D. Grogan	MIT	M.S.	U. S. Army
D. L. Hanson	Yale	Ph.D.	Los Alamos Scientific Lab
J. W. Harris	SUNY, Stony Brook	Ph.D.	Lawrence Berkeley Lab
D. Horn	MIT	Ph.D.	Brookhaven National Lab
O. Ila	MIT	M.S. Candidate	
C. Jachcinski	SUNY, Stony Brook	Ph.D.	Argonne National Lab
J. Karp	MIT	Ph.D.	SUNY, Stony Brook
A. Lazzarini	MIT	Ph.D.	Univ. Washington, Seattle
R. Ledoux	MIT	Ph.D. Candidate	
M. Neuhausen	MIT	M.S.	Operations Research
A. Mignerey	Univ. of Rochester	Ph.D.	Univ. of Maryland
A. Nathan	Princeton	Ph.D.	Univ. of Illinois
D. Perlman	MIT	Ph.D.	Harvard Univ.
H. Sang	MIT	M.S.	Xerox Corp.
W. Thoms	MIT	M.S.	Operations Research
K. Van Bibber	MIT	Ph.D.	Stanford Univ.
H. Wilschut	SUNY, Stony Brook	Ph.D. Candidate	
C. Wu	Univ. of Rochester	Ph.D. Candidate	
G. Young	MIT	Ph.D.	Oak Ridge (Wigner Fellow)

Table IV. Students who have worked at the BNL
tandem as members of users groups

<u>Name</u>	<u>Affiliation</u>
G. Bartouni	MIT
G. Berkowitz	SUNY, Stony Brook
P. Boisseau	MIT
B. A. Brown	SUNY, Stony Brook
E. Dafni	SUNY, Stony Brook
F. d'Amato	MIT
P. Fields	Tennessee Tech. University
M. Gai	SUNY, Stony Brook
D. Ganett	MIT
U. Garg	SUNY, Stony Brook
D. Gregorio	ORNL
M. Harakeh	SUNY, Stony Brook
N. E. Geacintov	NYU
D. F. Geesaman	SUNY, Stony Brook
D. E. Gustafson	University of Virginia
J. Hall	Kansas State University
K. Johnson	University of Michigan
L. Medsker	University of Pennsylvania
F. Milder	University of Michigan
J. Molitoris	MIT
J. Nemeth	SUNY, Stony Brook
C. Ordonez	MIT
D. Pisano	Yale
M. Rafailovich	SUNY, Stony Brook
A. Ratkowski	NYU
K. Rubin	MIT
R. Shroy	SUNY, Stony Brook
T. P. Sjoreen	SUNY, Stony Brook
A. Smith	MIT
P. Stwertka	University of Rochester
R. Valicenti	MIT
R. Won-yusoff	MIT

examination of the careers of Ph.D. graduates whose thesis work was done at the BNL tandems (see Table III). More than two-thirds of the Ph.D.s have stayed in nuclear physics and are distinguishing themselves in the field. Within the past year alone, of 4 new Ph.D.s, 3 have stayed in nuclear physics. In contrast, less than a quarter of U.S. experimental nuclear physics Ph.D.s in recent years have stayed in the field; the rest have moved into other branches of physics or other sciences. Several factors can be cited which we believe contribute to this high retention rate in nuclear physics for doctorates trained at BNL. First of all, the research experience at the BNL tandems is lively and challenging. Students enjoy coming to a well-equipped facility to do exciting physics, often not possible elsewhere, and where each may still take some responsibility for the success of the run. In lengthy contacts with the personnel and the guests at BNL, the students get to know and be known by a wide group of scientists. If a student is good, he finds encouragement to stay in the field not only from his thesis supervisor but also from the outside scientists who often solidify their opinion with a job offer.

D. THE BNL MP TANDEM VAN DE GRAAFF FACILITY

The Brookhaven Tandem Facility has two upgraded model MP accelerators (MP6 and MP7). A large variety of isotopic ion beams is provided at energies higher than available at any other tandem facility operating at present and with good intensities and excellent beam qualities characteristic of the best electrostatic accelerators. The terminal voltage obtainable for experiments on MP7 is now 14.4 MV and that on MP6 for three-stage operation, -8.5 MV. Figure 4 shows on a Periodic Table, all the elements that have been accelerated to date and the maximum energies as a function of the atomic number can be seen in Figs. 5 and 6.

The tandems have been used on a twenty-four hour, seven-day week basis until the recent introduction of alternate weekend shutdowns due to budgetary constraints. The following compilation gives an indication of the reliability and performance of these machines.

Utilization of Total Available Time 1975-1980

Accelerator Development and Testing	7%
Scheduled Maintenance	8%
Unscheduled Maintenance	4%
Standby, Holidays, Snowdays, etc.	6%
Beam Used in Research	75%

The superior performance of the tandems has been achieved through years of gradual improvements involving original BNL developments, many of which have been adopted elsewhere. Commercially available improvements have also been installed and redundant systems and components have been incorporated to improve reliability.

Some of the developments pioneered at Brookhaven are described below:

Fig. 5. Performance curve for present Tandem Facility and anticipated upgrade when single stripping is used. Solid lines are for maximum charge state and dashed for 10% intensity.

Fig. 6. Performance curve for present Tandem Facility and anticipated upgrade when double stripping is used. Solid lines are for maximum charge state and dashed for 10% intensity.

Terminal Ion Source Installation. A complete terminal ion source system, originally designed and constructed using an off-axis duoplasmatron source, has been recently improved and modified for the use of a Middleton-type sputter ion source. A novel feature of the system is double electrostatic beam inflection to allow the use of the accelerator as a normal tandem when not used as a negative ion injector.

Improved Accelerator Tube Performance After the installation of the stainless steel electrode HVEC upgraded tubes, a breakthrough in accelerator tube performance was achieved at BNL by combining the inclined field suppression scheme with magnetic suppression. The success of this arrangement provides stable and prolonged operation at high voltages with complete absence of vacuum discharges. Other improvements which have led to better accelerator tube performance include the design of a special inclined field pattern, since adopted by the manufacturer, the introduction of magnetically suppressed limiting apertures in the dead section between tubes and improved spark-gap protection of the tube insulators.

Column Connection and Resistor Improvements. The stability of the electrostatic generator has been substantially improved by replacing all spring-loaded column connections by solid electrical connections and by installing many new connecting rods to improve the electrostatic configuration. The original voltage-dividing resistors were replaced by an improved version developed by the manufacturer, and independent resistor strings for tubes and column have been implemented. Additional protection against damage caused by over voltages was found necessary and was successfully developed and

implemented at BNL. Further developments have led to a different and far superior resistor module which has now been installed in both accelerators. This new arrangement has proven to be stable and reliable at 14 MV terminal voltage. Since resistor-related problems have recently limited the MP7 voltage, it appears that higher voltages will become available in the near future.

Gas Prestripping of Molecular Beams. Often the most advantageous negative beams that can be obtained from the sputter ion source are molecular rather than atomic ions and when such molecules break up in a stripper foil, the Coulomb repulsion of the components leads to beam quality impairment. It was found that the beam quality is restored if such beams are sent through a volume of low pressure gas before reaching the foil to gently dissociate the molecules before they become highly charged.

Dual Foil Stripping. The energies for heavy ions have been increased over those attainable with one stripper in the high voltage terminal by locating a second foil stripper downstream of the terminal. The high ion velocities at this point lead to more effective stripping, and the higher charge states obtained produce an energy increment (equivalent to about 1 MV terminal increment) during acceleration to ground potential.

Experimental Facilities

The major experimental apparatus is listed below:

- a. QDDD Magnetic Spectrometer
- b. Time-of-Flight Spectrometer
- c. General Purpose Scattering Chambers (2)
- d. High Energy Gamma-Ray Spectrometer
- e. Total Energy Sum Spectrometer
- f. Gamma-Ray Goniometers (2)
- g. Energy Mass Separator
- h. Automated Recoil Distance Chamber (Plunger)

- i. Radioactivity Transfer Systems ("Rabbit" and He-jet)
- j. Mechanical Beam Chopper (for msec activities)
- k. UV Spectrometers (2)

Plans for the Tandem Facility

The completed developments described above and in the attached FTP (Operations) have led to continuously expanding capabilities in terms of available beams, attainable energies, stability, reliability, etc. For instance, ^{16}O beam energies have been increased by more than 40%, Cl energies have been doubled, and I energies have been tripled over the last several years.

This expansion of capabilities continues at present. The proposed improvements described in the attached FTP will lead to a three-stage performance comparable to the performance of a 20-MV tandem (see Figs. 5 and 6). Aside from being essential for research at BNL, the accelerator development program has made and continues to make significant contributions to electrostatic accelerator technology.

Brookhaven has at present the electrostatic accelerator system which has achieved the highest operating terminal voltage in the USA. With the planned improvements this facility will continue to be among the 3 or 4 largest in the world.

The Cyclotron Addition. During the past four years there has been a major effort of the BNL nuclear physics experimental group to design a post-accelerator to increase the energies of the tandem beams. The effort has been motivated by the needs of the present research program which finds itself increasingly working at the energy limits of the available beams. The requirements for the energy range

of a booster are twofold: (1) It must be possible to extend the present programs in a continuous progression upwards as the needs are modified by research demands. This continuity of research program implies that the lowest energies of the booster should approximate the highest from the tandems. (2) The range of energies available from the booster should enable a research capability that spans the exciting and unexplored region where the beam energy is comparable to the Fermi energy, where the velocity of sound in nuclear matter is reached and some compression of nuclear matter is to be expected. After considerable evaluation it was decided that the machine energy requirements are best fulfilled by a variable energy cyclotron which would provide beams of energies starting from the uppermost tandem capability and extending to 150 MeV/A for oxygen beams and 20 MeV/A for uranium beams, approximately 15 times presently available tandem energies.

In 1978 our first proposal was made for a superconducting cyclotron. This proposal was not recommended by NSAC which instead funded MSU. The proposal, however, made us very much aware of the disadvantages associated with superconducting machines. Although their size is small, minimizing building and construction costs, their accessibility for diagnostic probes, and for repair is poor. The very important orbit separation is small making single turn extraction (a condition for good energy resolution) difficult. At about this time the SREL (Space Radiation Effects Laboratory) synchrocyclotron was decommissioned. It was noted that the $H\rho$ -product of this cyclotron was 50 kgauss-meters, the same as our proposed superconducting cyclotron magnet. It was arranged to disassemble the magnet,

transport it to Long Island, and have it stored at BNL and a program was begun to design a variable energy cyclotron based upon the SREL magnet. It was believed, correctly, that the availability of the SREL magnet would allow the building of a warm cyclotron at approximately the same cost as a superconducting one. The lower field strength of the warm magnet would obviate many of the difficulties noted for the superconducting one.

The general scheme of the variable energy isochronous cyclotron post-accelerator facility is that beams from the tandem are bunched and transported to the cyclotron center. There they are stripped to higher charge state and, after acceleration, extracted and returned to the tandem experimental areas. In order to make a detailed conceptual design considerable manpower was directed to this project: four and a half man years of effort was taken from the experimental and tandem operations nuclear physics group, and more than two from the theoretical nuclear physics group together with a complement of several man years of professional engineering and consultants from both within BNL and outside. Significant innovative techniques, most important of which is a novel pole tip design, have led to the design of a cyclotron with a very unusual dynamic range in energy and mass at low power cost and have contributed to the art of cyclotron design.

A proposal was submitted to DOE in January 1980 with a cost estimate of ~11M (January 1981 dollars). NSAC deferred action on the proposal largely for budgetary reasons. The proposal was resubmitted in January 1981.

TANDEM VAN DE GRAAFF FACILITY OPERATIONS

Preamble

The BNL Tandem Facility is at present the world's most powerful electrostatic accelerator facility in routine operation for research. Its versatility, precision, high energies, and large variety of beams, make it a very important physics research tool. The Facility includes two MP Tandem Van de Graaff accelerators, the additional apparatus required for their operation and maintenance, and the major pieces of equipment used in the experimental effort (on-line computer, magnetic spectrometer, etc.). The operation and improvement of the machines together with the development of experimental equipment is the primary aim of the operations group. The research staff also contributes towards this goal. Extensive accelerator improvements implemented over the past years and being continued at present led to beam energies not surpassed by any other tandem now operating. Several of these improvements are original BNL developments which have been adopted by other laboratories and industrial manufacturers. The operations group has also been working towards the adaptation of the Space Radiation Effects Laboratory (SREL) cyclotron as a post-accelerator. This machine would effectively increase the tandem beam energy range by about a factor of 15, opening important new areas of research.

I. Accelerator Performance and Improvements

- A. Accelerator Operations and Performance
- B. Four-Stage Mode of Operation
- C. Improvements to MP-6
 - 1. Pelletron Charging System
 - 2. Large Diameter Stainless Steel Acceleration Tubes
 - 3. Two-Stage Double Foil Stripping
- D. Improvements to MP-7
 - 1. 16MV Extended Acceleration Tube
 - 2. Special Tube Extension for Four-Stage Operation
 - 3. New Column Spark Gaps
- E. General Improvements for Both MP-6 and MP-7
 - 1. Mercury Diffusion Pumps Replaced
 - 2. High Voltage Terminal Shields
 - 3. Improved Resistors for Tube and Column

II. Improvements on Experimental Facilities

- A. Sigma Computer Improvements
- B. QDDD Spectrometer Improvements
- C. Cyclotron Booster Studies

I. Accelerator Performance and Improvements

A. Accelerator Operations and Performance

During this period both accelerators continued operating with extremely high reliability. Reliable operation of MP7 at terminal voltages in excess of 13 MV was routinely obtained and the maximum terminal voltage reached was 14.1 MV. Alternate weekend shut-downs due to budgetary constraints caused a 14percent direct loss of available beam time and, as expected, some reliability degradation and additional loss of time due to voltage conditioning requirements. Also, the number of operators had to be reduced by one, leading to a reduction in the midnight crew size from two to one operator (the presence of one experimenter is required to satisfy the two-man rule). This reduction in manpower causes unavoidable delays especially if both accelerators have to be operated independently. It will also have an impact on completion times of upgrade, repair and maintenance work. Very serious scheduling problems are anticipated during vacation periods and in case of sick leave.

During calendar year 1980 beams from MP7 (two-stage and three-stage) were delivered for experiments during 70percent of the time, while 10percent was used for scheduled maintenance and development, 3percent for unscheduled maintenance, 6percent for conditioning after holidays and snowdays, and 11percent for alternate weekend shut-downs. With the acceleration of 170 and ^{92}Zr the total number of beam species accelerated to date increased to 60.

B. Four-Stage Mode of Operation

A new and unique four-stage accel-decel mode of producing fully stripped very slow heavy ions was successfully tested and will soon be used in important atomic physics experiments of fundamental as well as applied interest. In this mode of operation beams accelerated by MP6 in the normal tandem mode are then further accelerated to the negative MP7 terminal where they are stripped and then decelerated towards ground potential. Very low energies can be achieved in principle but at present the vertical deflection due to the inclined accelerating field sets a lower limit for these energies. About 1 nA of fully stripped ^{32}S beam at 10 MeV was obtained and this beam will be adequate for the first experiments.

C. Improvements to MP-6

1. Pelletron Charging System

A three-chain pelletron charging system was installed to replace the old MP6 charging belt. This new charging system led to improved stability and reliability at high voltages. Also, an insulated drive shaft system was installed in this accelerator to provide power to the terminal and to the dead sections. The power in the dead sections is necessary to operate vacuum ion pumps which will further improve the vacuum and thus lead to better heavy ion transmission and to improved acceleration tube performance under high gradient conditions. Similar systems are being installed in MP7 and should be completed by the end of this period.

2. Large Diameter Stainless Steel Acceleration Tubes

The 8 inch MP6 acceleration tubes were replaced by standard 14 inch stainless steel electrode HVEC tubes which provide improved transmission, better vacuum and increased voltage holding capabilities.

3. Two Stage Double Foil Stripping

A foil stripper was installed in the dead-section following the MP6 terminal to provide double stripping capabilities for two-stage operation.

D. Improvements to MP-7

1. 16MV Extended Acceleration Tube

During the last months of the this period major MP7 modifications will be initiated that should lead to a very substantial increase of 2 and 3 stage beam energies. A similar modification recently completed at the Strasbourg Centre de Recherches Nucleaires (CEN) tandem led to 16 MV operation. With our three-stage capability this would be roughly equivalent to a single 18 or 19 MV tandem.

The number of glass insulators in each of the eight acceleration tube sections will be increased from 72 to at least 88. The extended tube sections will thus protrude into the present field-free regions which will be modified appropriately. The present acceleration tubes will be completely disassembled at the factory, the electrodes and glass-insulators will be refurbished or replaced as needed and new ones will be added. The modifications to be performed in the field-free regions will include new dead-section boxes, modified tube supports, new ball-valve assemblies, tube shields, aperture supports, stripper and vacuum pump modifications. The acceleration tube voltage gradient at 16 MV terminal voltage will be 45.5 kv/inch while at present it is 48.6 kv/inch when operating at 14 MV.

2. Special Tube Extension for Four-Stage Operation

An additional modification being contemplated at present is the further extension of the last tube section to 96 insulators to incorporate a number of straight electrodes which should substantially improve the above mentioned four-stage production of fully stripped very slow heavy ion beams.

3. New Column Spark Gaps

The MP7 column was provided with additional spark protection in a manner similar to the one we have previously adopted for the acceleration tubes. In addition to better protection for the column, which is desirable at the higher voltages that will be reached in the future, this modification also provides added protection for resistors and acceleration tubes.

E. General Improvements for Both MP-6 and MP-7

1. Mercury Diffusion Pumps Replaced

The four old mercury-diffusion pumps located at both ends of each accelerator have been replaced by combined cryo-pump ion-pump systems. This modification improves vacuum, reliability, and cost savings in terms of electrical power and liquid nitrogen consumption.

2. High Voltage Terminal Shields

High voltage terminal shields are being installed in both accelerators to replace the present horizontal bar structure. This modification will lead to an improvement of the electrostatic configuration and to better shielding for the components located in the high voltage terminal.

3. Improved Resistors for Tube and Column

All resistive voltage dividers in both accelerators have now been protected with a BNL designed arrangement consisting of parallel plate shields, spark gaps and inductors. This modification seems to have solved the previously experienced problems due to overvoltage induced resistor damage.

II. Improvements on Experimental Facilities

A. Sigma Computer Improvements

During a major study and search for a new computer system it was decided to upgrade the Sigma system instead of replacing it as was planned for FY 1982. The upgrade consists of replacing the current one-half megabyte of memory with one megabyte of new memory, adding an additional I/O processor, and adding a second CPU. For considerably less money and manpower, the upgraded system will approach a level of performance that a new system would provide. There will be no software conversion costs or delays. All of the current data collection systems can continue to be used. It is anticipated that the upgrade will be completed early in 1981.

The decision to upgrade the Sigma system also resulted in a change of plans with respect to the high-density tape drives. The present tape drives in use are 800 byte/in., while the new drives provide 800, 1600, or 6250 bytes/in. density. With the new plan, two of the high density units are being interfaced to the Sigma computer instead of being installed directly in the data collection station which will provide more flexibility and versatility on the main system.

A 16-bit microprocessor is being added to the new data collection station. It will be used when special gating or arithmetic calculations must be done to the data on-line. Since the system is independent of the main computer, more of the data collection load will be removed from the main computer.

An initial implementation of a CAMAC data collection system is being added to the data collection interfaces. This will provide some CAMAC capabilities and provide the experience necessary for future expansion.

Several software improvements were added to the system. These include a Pascal compiler, cross assemblers for new microprocessors, a program to accomplish gating on very large spectra (e.g. sixteen million channels), and programs for handling data sorting for new complex experiments.

B. QDDD Spectrometer Improvements

The scattering chamber motions--target height and angle and the angle of two arms--have been motorized so that they can be remotely positioned and sensed. This makes it much easier to control these functions and to accurately set and reposition them. In addition, the control of the target height makes it possible to move the target during an experiment to better dissipate the heat produced by the beam and therefore extend the life of volatile targets.

A new scattering chamber has been fabricated for particle-gamma coincidence measurements using the QDDD as a large solid angle (15 msr) particle detector with very good energy resolution. The chamber is a small diameter thin walled aluminum can so that a Ge(Li) detector can be mounted close to the target. The spectrometer is coupled to the chamber through a very flexible bellows so that central scattering angles from about 45 to 30 degrees can be observed with the full solid angle. Because of the high energy resolution for both the particles and gammas this facility has been very useful in investigations of detailed nuclear structure in the rare earth nuclei.

An extension to the existing focal plane box was fabricated to allow more working room around the new 150 cm long focal plane detector. This new volume is pumped by two cryopumps which have been modified to allow the cold surface to project into the space to be pumped so that extremely high pumping speeds can be obtained (>10,000 l/sec). To allow the cryopumps to be regenerated, remotely activated covers have been built to seal the cryopump heads from the focal plane box. In addition to providing lower ultimate pressures, in spite of the gas load due to leaking detector windows, the cryopumps reduce the time required to pump the focal plane box down to operating pressure.

A new gas handling system has been completed to purify and recirculate the filling gas for the proportional counters used in the focal plane. This system removes electronegative gases (O_2 , F_2 , Cl_2) and water from the detector gases which are light hydrocarbons up to hexane. In order to simplify the use of this somewhat complicated system, it is controlled by a microprocessor.

C. Cyclotron Booster Studies

The Tandem Operations Group continued its support of the booster cyclotron design and development. The voltage and performance upgrade of the tandem facility extends the heavy mass performance of the cyclotron to higher energies and the vacuum and ion source improvements increase the beam current available for cyclotron injection and the number of isotopic ion beams that are operationally available for immediate use with the cyclotron booster accelerator (60 different isotopes at present). Extensive tests with three-stage accelerated ^{197}Au and other lighter ions were made in regard to stripper foil lifetimes, transmission efficiency, charge state distribution and other operational parameters that are all involved with the cyclotron booster design.

HEAVY ION PHYSICS WITH THE TANDEM VAN DE GRAAFF FACILITY

Preamble

Heavy ion physics deals with the ways in which nuclear matter in large aggregates interacts with other such aggregates. Nucleons, individually or in clusters, within such interacting aggregates, experience an environment vastly different with respect to energy, angular momentum and perhaps density from that of stable nuclear systems. To understand the transfer of matter, energy, and angular momentum between these aggregates, to describe the ultimate disposition of these quantities among the reaction residues, and to understand the reaction and accommodation of specific residual nuclear systems to abnormal inputs of these quantities are the aims of the program. Individual aspects of the program deal with heavy-ion direct reaction mechanisms, transfer, elastic and inelastic scattering with resonance structure, high angular momentum state spectroscopy via both compound nucleus reactions and heavy projectile Coulomb excitation, fission and fusion phenomena, general and nuclear physics, as well as investigations in atomic and molecular physics. Complementary light-ion research uses α -particle, deuteron, and proton projectiles. The experimental pursuit of these objectives in nuclear physics is made possible by the many energetic heavy ion beams and sophisticated analytic tools available at the Tandem Accelerator Facility and involves resident staff and the outside user community with about equal division of accelerator beam time.

I. Properties and Structure of Nuclear States

A. Gamma-Ray Studies of High Spin States Produced via Heavy Ion Fusion-Evaporation Reactions

1. High-Spin States in ^{46}Ti and ^{46}V
2. Search for High-Spin States Using Inverted $^{51}\text{V} + \text{Li}$ Reactions
3. High-Spin States in Odd-Odd Br Nuclei
4. High-Spin Structure of ^{75}Br
5. Yrast Properties of ^{74}Kr
6. Yrast Properties of Sr Isotopes
7. Investigation of High-Spin States Near the $N = 82$ Shell Closure

a. The $N = 86$ Isotones

- i. ^{150}Gd
- ii. ^{154}Er
- iii. ^{156}Yb
- iv. General Systematics

b. The $N = 85$ Isotones

- i. ^{149}Gd
- ii. ^{153}Er

c. The $N = 84$ Isotones

- i. ^{148}Gd
- ii. ^{152}Er

d. Transitional $N = 87$ Isotones

- i. ^{154}Ho
- ii. ^{157}Yb

e. Transitional $N = 88$ Isotones

- i. ^{157}Tm

8. Rotational $N = 94-96$ Nuclei

- a. $^{166}, ^{167}, ^{168}\text{Hf}$
- b. ^{166}Yb
- c. ^{170}Hf

9. Gamma-Gamma Energy Correlations in ^{176}W and ^{182}Os

10. Odd-Odd Tl Isotopes

11. High-Spin States for Nuclei with $Z = 83, 85$ and $N < 126$

- a. $^{197}, ^{198}\text{Bi}$ and $^{201}, ^{203}\text{At}$
- b. ^{205}At

12. $Z = 86$ Systematics

- a. $^{204}, ^{206}, ^{208}\text{Rn}$
- b. ^{214}Rn

B. Coulomb Excitation

1. Coulomb Excitation Study of Medium-Mass Transitional Nuclei

- a. The Projectile Coulomb Excitation of ^{72}Ge
- b. Multiple Coulomb Excitation of ^{104}Rn and ^{110}Pd

2. Coulomb Excitation of the Os-Isotopes

3. Coulomb Excitation of Deformed Nuclei

- a. ^{166}Er
- b. ^{248}Cm

C. Lifetimes and Moments

1. Electromagnetic Transitions in ^{14}C and ^{14}N
2. Lifetimes of (sd)-Shell Nuclei via the Recoil Distance Technique
3. Static Quadrupole Moments of 2^+ States
4. Static Quadrupole Moments for the 2^+ States of $^{54,56,58}\text{Fe}$
5. Attenuated Gamma-Ray Anisotropies from Nuclei Recoiling Through Gas
6. Precession Measurements of Gamma-Ray Anisotropies Following Nuclear Recoil Through Multiple-Tilted Foils

D. Radiative Capture of Heavy Ion Systems

1. The General Program
2. The Gamma Decay of a Quasi-molecular $^{12}\text{C} + ^{12}\text{C}$ Resonance to the Ground State of ^{24}Mg
3. Fusion Resonances in $^{12}\text{C}(^{16}\text{O},\gamma)^{28}\text{Si}$
4. The $^{13}\text{C}(^{12}\text{C},\gamma)^{25}\text{Mg}$ Reaction
5. The $^{10}\text{B}(^6\text{Li},\gamma)^{16}\text{O}$ Reaction
6. Progress Toward $^{12}\text{C}(^{12}\text{C},\gamma)^{24}\text{Mg}$ EMS Studies
7. A Study of $^{16}\text{O} + ^8\text{Be}$ Resonances in ^{24}Mg

II. Direct Reactions

A. The General Program

B. Elastic Scattering

1. Back Angle Excitation Function of $^{12}\text{C} + ^{19}\text{F}$
2. $^{86}\text{Kr} + ^{208}\text{Pb}$

C. Transfer Reactions

1. Single Neutron Transfer to High Spin States
 - a. Ni and Co Isotopes
 - b. Nd Isotopes
 - c. Sm Isotopes
 - d. Er Isotopes
2. Two-Proton Pickup Reaction to ^{196}Os
3. Transfer Reactions to Continuum States Induced by 100 MeV ^{18}O on ^{27}Al
4. Polarization in Heavy-Ion Induced Transfer Reactions

III. Nuclei Off the Line of Stability

- A. Beta Decay of ^{18}N
- B. Beta Decay of ^{21}O
- C. Identification and Decay of ^{79}Sr , ^{80}Y , ^{81}Y and ^{82}Y
- D. Half-Life of ^{32}Si

IV. Fusion-Evaporation, Deep Inelastic, and Fission Reaction Mechanisms

A. Light Heavy-Ion Systems

1. Exit Channel Competitions: $p2n, dn, t$, etc.
2. ${}^6\text{Li}$ Evaporation in the Reaction ${}^{18}\text{O} + {}^{28}\text{Si}$ at $E_{\text{cm}}=60$ MeV
3. Deep Inelastic Cross Sections in the Reaction ${}^{16}\text{O}({}^{16}\text{O}, {}^{16}\text{O}^*){}^{16}\text{O}^*$ at $E_{\text{cm}}=32.5$ MeV
4. Complete Fusion of ${}^{28}\text{Si} + {}^{28}\text{Si}$
5. The Reaction ${}^{28}\text{Si} + {}^{28}\text{Si}$ at 160 MeV

B. Evaporation Residues from Heavy Compound Nuclei

1. Excitation Functions of Evaporation Residues from ${}^{37}\text{Cl} + {}^{175}\text{Lu}$, ${}^{181}\text{Ta}$, ${}^{186}\text{W}$, and ${}^{198}\text{Pt}$
2. A new Isotope ${}^{188}\text{Rn}$ and Evidence for the Isomeric State ${}^{198\text{m}}\text{Rn}$
3. Possible Entrance Channel Effects in the Formation of ${}^{204}\text{Rn}$ by ${}^{35}\text{Cl} + {}^{169}\text{Tm}$, ${}^{48}\text{Ti} + {}^{156}\text{Gd}$ and ${}^{65}\text{Cu} + {}^{139}\text{La}$

V. Atomic Physics

- ##### A. Molecular Structure by Coulomb Explosion
- ##### B. Atomic Physics with Heavy-Ion Beams

1. Beam Foil Spectroscopy
2. Ion-Atom Collisions
3. Excitation and Ionization of Heavy Ions by Electrons

C. Energy Loss of Heavy Ions in Single Crystals

VI. Instruments

- ##### A. General Purpose NaI Total Energy Spectrometer
- ##### B. Multiple Event 2D Image Intensifier Scintillation Detector
- ##### C. High Mass Product Bending Magnet for MP6

VII. Post-Accelerator Development

- ##### A. Design of Magnetic Field for the 500 cm Cyclotron

VIII. Outside User Program

I. Properties and Structure of Nuclear States

A. Gamma-Ray Studies of High Spin States Produced via Heavy Ion Fusion-Evaporation Reactions

Heavy-ion collisions which result in fusion leave the compound nucleus in highly excited states of large angular momentum. Particle evaporation cools the nucleus to within a few MeV of the yrast line. The residual nuclei at this point still contain many MeV of excitation energy and large angular momentum and the manner in which these residual nuclei dispose of this excess energy to accommodate the stresses introduced by such large angular momenta contains the physics of high spin spectroscopy. Experimentally, this topic is pursued by studies of the gamma-ray spectra which deexcite the nucleus and remove angular momentum efficiently. Near the yrast line, most of the remaining excitation energy is involved in generating the angular momentum. Level densities are also quite low so the discrete gamma-ray spectra in this region contain extractable information about the responses of the nuclear structure to this large angular momentum.

1. High-Spin States in ^{46}Ti and ^{46}V

The $^{40}\text{Ca}(^9\text{Be}, 2\text{pn})^{46}\text{Ti}$ and $^{40}\text{Ca}(^9\text{Be}, \text{p}2\text{n})^{46}\text{V}$ reactions were investigated in order to study the high-spin states of ^{46}Ti and ^{46}V . Measurements of excitation functions, angular distributions, and gamma-gamma coincidence spectra were completed, in addition to recoil distance and Doppler shift attenuation measurements of lifetimes. The data on ^{46}Ti disclose an even-parity yrast band based on the $J^\pi = 0^+$ ground state with the spin sequence 0-2-4-6-8-10-11-12, interconnected by strong E2 transitions. A quasirotational band ($\Delta J = 1$) based on the 3059-keV $J^\pi = 3^-$ state is seen up to the $J^\pi = 10^-$ member. The lowering of the 11^+ state below the 12^+ state, as well as other features of the decay scheme, are rather well-predicted by the empirical $(1f_{7/2})^n$ model.

The new data on ^{46}V resolve previous experimental ambiguities for states of $E_x \leq 2$ MeV, and determine a $\Delta J = 2$ sequence of states at excitation energies (in keV) of 802 ($J^\pi = 3^+$), 1225(5^+), 1604(7^+) and 3903(9^+). A comparison of ^{46}Ti with the cross-conjugate nucleus ^{50}Cr (based on the $(1f_{7/2})^n$ model) confirms a very nice matching of even-parity states up to the $J^\pi = 12^+$ member, including the inversion of the 11^+ and 12^+ levels. A similar comparison for ^{46}V - ^{50}Mn , although at least qualitatively correct, is less satisfying with respect to level energies and E2 rates. Additional confirmatory data on ^{46}V and an extension of data on ^{50}Mn is planned. (A. R. Poletti, E. K. Warburton, and J. W. Olness)

2. Search for High-Spin States Using Inverted $^{51}\text{V}+\text{Li}$ Reactions

A search for states of relatively high spin, formed in reactions of ^{51}V projectiles with ^7Li , was made via vacuum recoil and particle-gamma-ray coincidence techniques to complement previous BNL-SUNY work in which beams of $^6,^7\text{Li}$ were used to bombard a ^{51}V target. The center-of-mass energy was the same as that attained with the 25-MeV Li beams used previously. Evaporation residues recoiled in vacuum for a flight time of about 600 psec and were stopped by a Ta foil. An EAE particle detector telescope was positioned just downstream from this stopper foil. The function of the telescope was to detect and identify light charged particles whose range exceeded the stopper foil thickness. Gamma radiation was detected using Ge(Li) detectors placed at 0° and 120° relative to the beam direction. All possible combinations of gamma-ray and gamma-particle coincidences were recorded event-by-event.

As expected, the gamma-gamma coincidence spectra were dominated by gamma rays from ^{52}Cr and ^{53}Cr , resulting from $\alpha, 2n$ and α, n evaporations, respectively. All of the transitions in ^{52}Cr observed previously were also observed in the 0^0 gamma-ray spectra that were in coincidence with low energy portions of the alpha particle energy spectrum and in addition, five new transitions were also observed. It was found that a plot of relative gamma-ray intensity versus alpha particle energy was useful in ordering the gamma rays. On the average, more energy is available for excitation of the ^{52}Cr evaporation residues when the emitted alpha particles have lower energy and the intensities of gamma rays deexciting levels of highest excitation fall off fastest with increasing alpha particle energy. The data analysis is continuing in order to better determine the gamma-ray intensity dependence on emitted alpha-particle and proton energies. (R. L. Kozub, J. Lin, J. F. Mateja (Tenn. Tech. U.); C. J. Lister, E. K. Warburton (BNL))

3. High-Spin States in Odd-Odd Br Nuclei

The nuclei in this region are moderately deformed, and the influence of the $g_{9/2}$ orbit gives rise to important Coriolis effects. In the particular case of doubly-odd nuclei, the yrast states are expected to involve the $\pi g_{9/2} \times \nu g_{9/2}$ configuration that has been previously identified in ^{76}Br . The 4^+ member of the multiplet lies lowest and becomes the head of a Coriolis distorted band which has been successfully described by a two-noninteracting-quasiparticle-plus-rotor model. This model also predicts the occurrence of a change of phase in the level staggering above the $J^\pi = 9^+$ state, obtained by the maximum alignment of the valence proton and neutron.

The systematic study of Br isotopes was continued with the $^{60}\text{Ni} + ^{16}\text{O}$ (50 MeV) reaction that was used to populate high-spin states in ^{74}Br . The main feature of the data is the identification of a $\Delta J = 1$ band built on a $J = (4)$ isomeric state and observed up to $J = (11)$, which shows a change of phase in the level staggering above the $J = (9)$ state. If the identification of this state with the 9^+ member of the $\pi g_{9/2} \times \nu g_{9/2}$ band is shown to be correct, this change of phase provides the first direct confirmation of this phenomena in the Br isotopes.

The ^{72}Br isotope was also studied by means of the $^{58}\text{Ni} + ^{16}\text{O}$ (50 MeV) reaction. The data consist of gamma-gamma coincidence and angular distribution measurements, which are being analyzed. Future experiments will be dedicated to the study of the electromagnetic properties of the $\Delta J = 1$ band found in ^{76}Br which will provide a more stringent test of the above mentioned model. (G. Garcia Bermudez, A.J. Kreiner, M.A. J. Mariscotti, C. Baktash, E. der Mateosian, P. Thieberger)

4. High Spin Structure of ^{75}Br

The (N, Z) dependence of the nuclear deformation in the Br region was investigated via the high spin states of ^{75}Br which were studied through the $^{62}\text{Ni}(^{16}\text{O}, 2n p)$ reaction. Both positive and negative-parity bands were established up to spin $(25/2)$. A new low-lying isomeric $9/2^+$ state ($T_{1/2} = 39 \pm 4$ nsec) of $\pi g_{9/2}$

parentage was found, thereby solving the longstanding problem of its location. The structure was interpreted with the one-quasiparticle-plus-rotor model concluding that the quadrupole deformation for ^{75}Br is larger than in any other known odd Br isotopes. (A. J. Kreiner, M. A. J. Mariscotti, C. Baktash, E. der Mateosian, and P. Thieberger)

5. Yrast Properties of ^{74}Kr

Recent experimental studies have revealed an island of isomerism in the $N = 82$ region. The relative abundance of isomerism in this region is due to the proximity of the nearly doubly magic nucleus ^{146}Gd and because the yrast structures are mainly simple shell-model configurations. Calculations have predicted a non-collective structure for some parts of the yrast line in almost all the nuclei in the $A = 40$ -80 region. Calculations with the cranking-plus-Strutinsky formalism have been able to reproduce the yrast structure in $N = 82$ nuclei with reasonable success and predict yrast isomers to be relatively abundant in the $40 \leq A \leq 80$ region. Since some of these nuclei are away from the shell closures (in contrast to the $N = 82$ nuclei), a verification of these predictions is important. Consequently, a study of the high spin states in ^{74}Kr will be undertaken in order to search for the predicted isomers. (C. Baktash)

6. Yrast Properties of Sr Isotopes

The nuclear structure considerations for ^{74}Kr described above also pertain to isotopes of Sr ($Z = 38$). A systematic study of the high-spin structure of the Sr isotopes, including side-bands, would also provide an important test of the application of the Interacting Boson Model (IBA) to systems of neutrons and protons. Strontium is two protons shy of the major-shell closure at $Z = 40$ and at a minor-shell closure with the $p_{1/2}$ shell left unfilled. Fusion-evaporation reactions like $^{40}\text{Ca}(^{40}\text{Ca}, 2p)^{78}\text{Sr}$, $^{64}\text{Ni}(^{26}\text{Mg}, 2p)^{88}\text{Sr}$, and $^{48}\text{Ca}(^{44}\text{Ca}, 2p)^{90}\text{Sr}$ should allow the study of high-spin structure of Sr isotopes across a whole neutron major shell, i.e., $N = 40$ to 52. This study would provide a stringent test for the IBA or any other applicable nuclear model. (C. Baktash, J. W. Olness, and E. K. Warburton)

7. Investigation of High-Spin States Near the $N = 82$ Shell Closure

In the past few years, two parallel developments have helped generate an intense interest in the spectroscopy of nuclei in the region of $N = 82$ and $Z = 64$. One development has been the confirmation of the existence of a large energy gap in the single particle spectrum at $Z = 64$. Consequently, ^{146}Gd (82 neutrons, 64 protons) may be considered as a doubly closed nucleus, forming a region

of shell- model nuclei analogous to that near ^{208}Pb . Therefore, ^{146}Gd and its neighboring nuclei provide a fertile ground for the study of single-particle shell structure and effective two-body interactions. Moreover, accessibility of these nuclei through a variety of light and heavy ion fusion-evaporation reactions (in contrast to the Pb region) makes such studies feasible.

The second development has been the discovery of an island of isomerism in this same region, followed by a detailed spectroscopic study of a few $N = 86$ nuclei to very high spin states ($J \sim 36$). These studies were prompted by Bohr and Mottelson's suggestion that at very high angular momenta (e.g., $J = 50$ in the rare earth region) nuclei are driven towards oblate shapes, giving rise to yrast traps deexcited by $L = 3$ transitions. However, yrast isomers discovered thus far occur primarily in a narrow region around magic nuclei ^{146}Gd and ^{208}Pb , and for spin $J < 40$. These isomers are a consequence of microscopic shell structure. Similarly, the experimental fact that the high-spin states in the $N = 82$ nuclei are populated with unusually high intensities (compared to the deformed nuclei) in fusion-evaporation reactions, may be attributed to the absence of parallel collective bands in these near spherical nuclei.

A systematic and detailed spectroscopic study of these nuclei to very high spin in the $N=82$ region was begun in order to explore the important role of shell structure in this region. This systematic study will help elucidate some of the more important aspects of shell model structure at high angular momenta.

At present, the studies include the systematics of $N = 84$ ($^{148}\text{Gd}, ^{152}\text{Er}$), $N = 85$ ($^{149}\text{Gd}, ^{151}\text{Dy}, ^{153}\text{Er}$), and $N = 86$ ($^{150}\text{Gd}, ^{154}\text{Er}, ^{156}\text{Yb}$) nuclei. The maximum angular momentum generated by two- and four-valence neutrons in these nuclei are $\sim 12\hbar$ and $\sim 20\hbar$, respectively. Therefore, systematics of the even-even $N = 84$ and $N = 86$ nuclei above these limiting spins will provide valuable information about the excitation of protons in the region of $Z = 64$ shell closure. Equally important is the information obtained about the neutron excitations by comparing the spectra of the ($Z = 84, 85$ and 86) isotopic chains.

a. The $N = 86$ Isotones

A systematic study of the $N = 86$ isotones to very high spin states is near completion. A summary of the results is given in the following subsections.

1. ^{150}Gd

The yrast states of ^{150}Gd have been studied up to spin $J = 36$. To establish their parities, a linear polarization measurement was made using the $^{124}\text{Sn}(^{30}\text{Si}, 4n)$ reaction at 135 MeV. Previous assignments (based on angular distribution measurements) for states up to $J^\pi = 27^-$ were confirmed. The parity of the higher-lying states was tentatively assigned as $30(+)$, $32(+)$ and $34(+)$ respectively. Interestingly, the excitation energy of these states are suggestive of a simple $(v^4)_{20+} \times [(h_{11/2})^2]_{10+} \times [(d_{5/2})^2]_{0+, 2+, 4+}$ shell model configuration pattern.

11. ^{154}Er

The yrast states of ^{154}Er were previously studied to a probable spin of $J = 36$. The presence of an unobserved transition, Δ , below the 40-nsec isomeric state has prevented exact determination of the spins and energies of the sequence of high-lying levels feeding this state. (A tentative $J^\pi = 10^-$ has been suggested for this state on the basis of $N = 86$ systematics and plausibility arguments.) A recoil shadow coincidence experiment, employing the $^{32}\text{S}(150\text{ MeV}) + ^{126}\text{Te}$ reaction was carried out in order to remove this ambiguity. No coincident low-energy gamma ray ($E > 30\text{ keV}$) was found. The data are now being analyzed for weak transitions (e.g. $7^- \rightarrow 5^-$) from the levels fed by the isomeric state.

The lifetimes of the sequence of states feeding the isomeric state were also measured using the recoil distance method in conjunction with a delayed coincidence technique that took advantage of the delayed transitions for the removal of spurious gamma rays from other competing channels. Preliminary results indicate the presence of a 460-psec lifetime at $J^\pi = (19)^-$.

When the previous data are combined with the new data, the level scheme is extended to a probable spin of $J=38$ and excitation energy $E \sim 13.4\text{ MeV}$. The continuation of the quasi-ground band has also been established to $J^\pi = 20^+$, which is the highest spin state (with positive parity) that can be formed from 4 valence neutrons.

111. ^{156}Yb

The high-spin states in ^{156}Yb were investigated by means of the reaction $^{144}\text{Sm}(^{16}\text{O}, 4n)$ at 70-120 MeV, and $^{113}\text{In}(^{46}\text{Ti}, p2n)$ at 190-210 MeV. Because of several competing reactions, particle-gamma, gamma-gamma and x-gamma coincidence measurements were necessary in order to identify transitions from ^{156}Yb . Measurements of gamma-ray excitation functions, linear polarization, lifetimes, and angular distribution were also made. A 6.1-nsec isomer was found at 3.027-MeV excitation energy with $J^\pi = 11^-$. Energy level assignments were established up to $J^\pi = 17^-$. From the 17^- state to the 25^- state, similar transition intensities leave some doubt on the correct level ordering. Above $J^\pi = 25^-$ the observed population of states falls rapidly. Candidates for levels with spin up to $J = 30$ were found in this work, but their population was too weak to extract structural information.

iv. General Systematics

The level schemes of ^{150}Gd , ^{152}Dy (studied by Khoo, *et al.*), ^{154}Er and ^{156}Yb exhibit interesting systematic trends which include (i) a smooth decrease of the excitation energy of the 2^+ to 8^+ states with increasing proton number, (ii) the presence of low-lying negative parity 3^- to 9^- states whose excitation energy increases with increasing proton number, and (iii) the regular occurrence of close lying 10^+ and 11^- states fed by cascades extending to 16^+ and 17^- , respectively. By extending the extreme single particle approach of Kleinheinz, these features may be described as $(f_{7/2})^2$ or $(f_{7/2}h_{9/2})$ neutron configurations coupled to: (i) the ground state, (ii) a 3^- octupole phonon, and (iii) to $[(i_{13/2})^2]_{10^-}$ or $(i_{13/2}h_{9/2})_{11^-}$ configurations. The near equality of the transition energies, however, may indicate admixtures of some quadrupole vibrations in the wave functions.

Since maximal alignment of 4 neutrons in this region cannot generate more than 20 h units of angular momentum, proton excitation becomes necessary for states with $J > 20$. Interestingly, in ^{150}Gd , ^{152}Dy (^{154}Er), a sequence of transitions starting with $J^\pi = 21^-(19^-)$, decreasing in energy establishes a quasiband structure up to $J^\pi = 27^-(25^-)$. Moreover, the energy spacings within these structures closely resemble the $[(f_{7/2})^2]_{0^+, 2^+, 4^+, 6^+}$ energy spacings of their corresponding $N = 84$ isotopes. Both the lifetime of the 21^- state in ^{152}Dy ($T_{1/2} = 14$ nsec) and 19^- state in ^{154}Er ($T_{1/2} = 460$ psec) indicate transition rates of ~ 1 Wu for the analogous $21^- \rightarrow 19^-$ and $19^- \rightarrow 17^-$ transitions in the respective nuclei. Such correlations are suggestive of coupling a $(\nu f_{7/2})^2$ two-neutron structure to bandheads composed of $[(\pi h_{11/2})^2]_{8^+, 10^+} \otimes (\nu g_{7/2} \nu i_{13/2})_{11^-}$ aligned shell-model configurations. The presence of readily recognizable $(j)^2$ configurations in this region suggest that even at spins up to 30, relatively pure and near-spherical shell model states are the dominant mode of excitation. (C. Baktash, E. der Mateosian, D. Horn, O. C. Kistner, C. J. Lister, A. W. Sunyar)

b. The $N = 85$ Isotones

The interpretation of the high-spin yrast states in the $N = 86$ nuclei is strongly connected with the knowledge of the quasiparticle states in the neighboring odd- A nuclei. Therefore, in conjunction with the systematic study of $N = 86$ isotones, investigation of the odd- A $N = 85$ nuclei was initiated. The results for ^{151}Dy have been published.

1. ^{149}Gd

High spin yrast states in ^{149}Gd were populated by means of the $^{124}\text{Sn}(^{30}\text{Si}, 5n)$ reaction at 135 MeV beam energy. An extensive set of data in the form of gamma-gamma coincidence, gamma-ray singles, angular distributions, linear polarizations and pulsed beam timing correlations was accumulated and is being analyzed to establish a decay scheme for this nucleus. (C. Baktash, E. der Mateosian, D. Horn, O. C. Kistner, C. J. Lister, and A. W. Sunyar)

11. ^{153}Er

The $^{144}\text{Sm}(^{12}\text{C}, 4n)$ reaction was used to study the high-spin single-particle states in ^{153}Er . A delayed coincidence technique, utilizing 4 NaI detectors, was used to time the various transitions. In addition to the previously known ($T_{1/2} = 380$ nsec) isomeric state (whose excitation energy was established at 2.759 MeV), a second isomer ($T_{1/2} = 270 \pm 20$ nsec) was located at 5.183 MeV. A sequence of transitions depopulating this isomeric state was found to bypass the lower isomer and directly feed into the $J^\pi = 21/2^-$ state at 2.759 MeV. Cascades of transitions proceeding between these two isomeric states were found to be highly fragmented. While the structure and the low-lying states up to the $J^\pi = 21/2^-$ state closely resembles those in ^{149}Gd and ^{151}Dy isotones, little similarity was found in the deexcitation pattern of the upper isomeric state. The systematics of the low-lying states in the $N = 85$ odd- A nuclei studied so far supports the simple shell model structure interpretation first suggested by Kleinheinz *et al.* for the ^{151}Dy case. (D. Horn, C. J. Lister, C. Baktash (BNL); G. R. Young (ORNL))

c. The N = 84 Isotones

The investigation of ^{148}Gd and ^{152}Er was undertaken to extend these studies down to N = 84 (two valence neutrons).

i. ^{148}Gd

The reaction $^{122}\text{Sn}(^{30}\text{Si}, 4n)$ at 133-MeV was used to populate high spin states in ^{148}Gd . In addition to some known transitions which deexcite the previously established states with $J = 18$, at least 15 new transitions were assigned to this nucleus. Preliminary analysis of the data indicates that these transitions originate from states above the known $J^\pi = 18^+$ state. (E. der Mateosian, C. Baktash, D. Horn, O. C. Kistner, C. J. Lister, A. W. Sunyar)

ii. ^{152}Er

The yrast levels of this nucleus were studied by means of the $^{144}\text{Sm}(^{12}\text{C}, 4n)$ reaction at beam energies in the range of 65-95 MeV. The coincidence data were taken in conjunction with the ^{153}Er study at 82 MeV which is less than the optimum energy for the $4n$ channel. Therefore, the yrast sequence of even-spin even-parity states was studied only to the $J^\pi = 16^+$ state. The resulting level structure closely resembles that of nearby N = 84 isotones. The $J^\pi = 0^+, 2^+, 4^+, 6^+$ sequence is largely due to the valence $(f_{7/2})^2$ configurations, and the $J^\pi = 8^+$ level is due to promotion of one or two neutrons to an $h_{9/2}$ orbital. The sequence of $J^\pi = 10^+, 12^+, 16^+$ and 18^+ may be simply explained as a result of coupling the low-lying states to the $[(h_{11/2})^2]_{0^+}$ proton configuration. (D. Horn, C. J. Lister, C. Baktash(BNL); G. R. Young (ORNL))

d. Transitional N = 87 Isotones

i. ^{154}Ho

Continuing analysis of data from a series of experiments which assigned over 30 gamma rays to the nucleus ^{154}Ho (N = 87) resulted in a tentative decay scheme which consists of about 20 transitions. Work on this nucleus is continuing in order to establish the relationship of this decay scheme to two previously known isomers with half-lives of 3.2 and 12 min. One very interesting feature of the level scheme is an apparent transition from a rotational band at low excitation energies to a sequence of shell-model states at higher energies. (A. Filevich, C. Baktash, E. der Mateosian, O. C. Kistner, A. W. Sunyar)

ii. ^{157}Yb

The N = 87 nucleus, ^{157}Yb , exhibits a cascade of five stretched quadrupole transitions feeding a $J^\pi = 13/2^+$ isomer of 45-nsec half-life. It is interesting that this cascade is itself fed from a series of five transitions, each of which is within 7 keV of 680 keV. Angular distribution measurements indicate that at least the three most intense of these transitions are quadrupole in nature. The state feeding this cascade is 6.728 MeV in excitation and has $J = 51/2 \pm 1$. (C. Baktash, E. der Mateosian, D. Horn, O. C. Kistner, C. J. Lister, A. W. Sunyar)

e. Transitional N = 88 Isotones

The analysis of the level structure of ^{158}Yb , produced by bombarding ^{144}Sm with 100 MeV ^{18}O projectiles, is continuing. Most of the unresolved problems in constructing the deexcitation scheme have been overcome. Alternative deexcitation paths from a spin 11 state of the odd-spin side band to the ground state band were identified, as well as an additional gamma-ray sequence which is probably associated with a second side band in this nucleus. The analysis was hampered by problems of low side band intensity in this reaction and several degeneracies in transition energies.

It was also possible to observe the favored sequence of the $113/2$ neutron band in neighboring ^{159}Yb . Scientists at other laboratories had previously observed five transitions of this band implying a spin $33/2^+$ state. Three additional transitions were identified here and extends the band to the $45/2^+$ state. (E. der Mateosian, O. C. Kistner, A. W. Sunyar)

1. ^{157}Tm

The nucleus ^{157}Tm was observed to have a collective band of stretched quadrupole transitions extending to an excitation of 3.7 MeV and to $J^\pi=35/2^-$ assuming a ground-state spin of $11/2$. No backbend was observed in this nucleus whereas its isotone, ^{155}Ho , undergoes a sharp drop in transition energies. (D. Horn, C. Baktash, E. der Mateosian, O. C. Kistner, C. J. Lister, A. W. Sunyar)

8. Rotational N = 94-96 Nuclei

a. $^{166}, ^{167}, ^{168}\text{Hf}$

A series of experiments concerned with the investigation of the high-spin structure of light Hf isotopes was begun by means of heavy-ion induced compound nucleus reactions. Backbending phenomena, aligned bands in the odd mass and even-even isotopes as well as systematic features of side band structure can be interpreted in terms of quasiparticle configurations. Theoretical calculations, those of the Copenhagen and Lund groups, for example, show that the energies of such configurations often cross each other as the frequency with which the deformed field rotates is increased. In order to make comparisons with such calculations, detailed information is needed about the high-spin band structure in these nuclei. Such experiments can provide important information about both neutron and proton quasiparticle structure in this region and thereby test the theoretical ideas.

^{166}Hf , ^{167}Hf and ^{168}Hf have been produced by bombardment of $^{154}, ^{155}, ^{156}\text{Gd}$ with 95-114 MeV ^{16}O and bombardment of ^{122}Sn with 215-MeV ^{48}Ti . Although the latter projectile-target combination is more favorable with respect to angular-momentum, the maximum available energy of 215 MeV was too low for optimum yield and these measurements were temporarily abandoned. High resolution

gamma-gamma coincidence measurements, gamma-ray angular distribution measurements and gamma-ray excitation function measurements were performed with the ^{160}O reaction. Preliminary analysis of these data show a number of interesting features of the deexcitation schemes of these Hf isotopes.

The even-spin, even-parity yrast sequences in the ^{166}Hf and ^{168}Hf ground state bands cross the S-band at spin 14, where the backbends occur. In ^{166}Hf , the ground state band continuation is observed to a probable spin 20. An odd-spin band which feeds the ground state band at the 6^+ , 8^+ and 10^+ states is observed from spin 7 to spin 21 in ^{166}Hf . The parity of this side band was not determined. Other band-like sequences of gamma-rays were isolated, but the connections to either the ground state or odd-spin band were not identified. In the case of ^{168}Hf , the rotational frequency at which the crossing of the ground state band and S-band occurs is identical to that observed for ^{166}Yb .

These new experimental data for ^{167}Hf considerably extend the earlier work of a Stockholm group. Both the favored and unfavored branches of the $113/2$ neutron band are observed. The favored branch appears to backbend at the $41/2^+$ level and is observed for three additional transitions. Similarly, the $h9/2$ neutron band, built upon the $5/2^-$ state, is also extended by observation of three additional transitions. Analysis of these data is continuing. (C. Baktash, D. Horn, O. C. Kistner, E. der Mateosian, and A. W. Sunyar)

b. ^{166}Yb

Progress was made in the study of the high-spin band structure of ^{166}Yb initiated in FY 1979. This work is an interesting extension of the previously reported study of the high-spin band structure in the isotone, ^{164}Er , a nucleus which has received much theoretical attention because of the richness of its band structure. The similarity of ^{166}Yb to ^{164}Er is indeed striking. The ground-state band, the Coriolis decoupled even-spin, even-parity yrast band, and odd-parity even and odd spin yrast bands are reproduced essentially identically up to spins and parities 20^+ , 24^+ , 24^- and 23^- , respectively. The gamma band in the case of ^{166}Yb is much more weakly populated, only the odd spin part of which is observed at all up to a spin of 13 or possibly 15. The observed $7^+ \rightarrow 5^+$ transition does not agree with that reported in the literature. Of particular interest is an even spin band of unknown parity, the lower levels of which deexcite to the odd spin members of the gamma band. In ^{166}Yb this band is observed down to spin 6, one level lower than in ^{164}Er , thereby upsetting a previously suggested assignment to a negative parity $K = 8$ band. A low moment of inertia $K = 7$ negative parity band built on a pair of proton orbitals seen in ^{164}Er was thus far not observed in this nucleus. Analysis of these data is continuing. (C. Baktash, E. der Mateosian, D. Horn, O. C. Kistner, and A. W. Sunyar)

c. ^{170}Hf

In an effort to observe multiple band structure in ^{170}Hf , 79-MeV ^{12}C ions were used to bombard a ^{162}Dy target. In addition to gamma-gamma coincidences between two Ge(Li) detectors, a multiplicity signal from a "halo" of 12 NaI detectors was also collected. This allowed identification of those events associated with a large number of gamma rays, and consequently, with large angular momentum. Angular distributions of the gamma rays were measured in a separate experiment. The ground state band was extended to $J^\pi = 26^+$. Four cascades each of 4-6 transitions were seen feeding into the ground band, one through a previously observed isomer of 23 nsec and spin 8^+ . Further analysis is in progress. (C. Baktash, D. Horn, C. J. Lister (BNL); G. R. Young (ORNL))

9. Gamma-Gamma Energy Correlations in ^{176}W and ^{182}Os

Atomic nuclei provide unique quantum mechanical systems capable of sustaining very high angular momentum. Although, on the basis of the liquid-drop model, nuclei can carry as much as 70 $\hbar$ angular momentum in the mass 150 region, the highest states studied in discrete gamma-ray spectroscopy so far do not exceed spins 30 and 40 in deformed and spherical nuclei, respectively. Study of the states above spin ~ 40 will shed some light on the behavior of nuclear systems under extreme conditions of high-angular momentum. Specifically, it would provide some insight into the question of competition and interplay between collective and single-particle degrees of freedom. Transitions deexciting these high-spin states form a continuum, and have been investigated through multiplicity distribution, angular correlations, multipolarity, and spectral shape studies. One of the nuclear properties obtained from these measurements is the effective moment of inertia. However, this parameter does not reflect the nuclear shape, nor the degree of collectivity or the loss of pairing which are related to the true collective moment of inertia. The collective moment of inertia can be obtained from analysis of the structure of the gamma-gamma energy correlation of gamma-gamma coincidence data. To optimize such studies, detectors with both good resolution and peak-to-Compton ratio are needed. The Compton-suppression spectrometer satisfies both these requirements. A measurement of the gamma-gamma energy correlation in ^{176}W and ^{182}Os utilizing two such detectors is scheduled. These nuclei are among the heaviest deformed nuclei in the rare earth region and provide an excellent opportunity to study the interaction of high- j orbitals, such as neutron $j_{15/2}$ and proton $i_{13/2}$ with rotational motion. (C. Baktash (BNL); L. Y. Lee (ORNL); J. X. Saladin (Univ. of Pittsburgh))

10. Odd-Odd Tl Isotopes

The odd-odd staggering in $\pi h_{9/2} \otimes \nu i_{13/2}$ states was studied via the energy levels of ^{200}Tl , populated through the $^{198}\text{Pt}(^{6}\text{Li}, 4n)$ reaction at 30-40 MeV. In-beam gamma-ray spectroscopy techniques revealed an almost completely new level scheme confirming the $\pi h_{9/2} \times \nu i_{13/2}$ two-quasiparticle band which in this case is built on a $J^\pi = 7^-$ isomeric state ($T_{1/2} = 4.8 \pm 0.2$ nsec) in contrast to $J^\pi = 8^-$ for all the lighter doubly-odd Tl isotopes studied to date. The systematic variation of the odd-even staggering present in these bands strongly suggests that the mechanism behind this phenomenon is an interaction of the particles with the core rather than among the valence particles themselves.

Calculations of the yrast spectrum of the $\pi h_{9/2} \times \nu i_{13/2}$ two-quasiparticle structure in odd-odd Tl isotopes as a function of neutron number indicate the occurrence of level crossings which in the Tl case lead to the prediction of increasingly longer lifetimes for the band heads. A search for nsec, μ sec and msec isomerism was undertaken for the very neutron deficient Tl nuclei with $A = 190$ and 188 . Two new isomeric states of $T_{1/2} = 0.8$ and 40 msec have been found in ^{190}Tl and ^{188}Tl respectively, suggesting that the predicted level crossing is taking place. The detailed in-beam spectroscopy for ^{190}Tl was done and similar work for $^{188}, ^{186}\text{Tl}$ is planned since the knowledge of these bands is very important to assess the role played by the residual proton-neutron interaction. (A. J. Kreiner, C. Baktash, G. Garcia Bermudez, E. der Mateosian, P. Thieberger (BNL); M. A. J. Mariscotti (CNEA, Argentina))

11. High Spin States for Nuclei with $Z = 83, 85$ and $N < 126$

a. $^{197}, ^{199}\text{Bi}$ and $^{201}, ^{203}\text{At}$

An experimental study of high-spin level structures in Bi ($Z = 83$) and At ($Z = 85$) isotopes in the neutron deficient region below $N = 126$ was undertaken to investigate the onset of collectivity as a function of neutron number. The yrast levels in Bi and At nuclei, which are comprised mainly of spherical valence proton states near the $N = 126$ closed shell, gradually begin to mix with neutron-hole excitations of the Pb core as the neutron number decreases. Studies of the $^{205}, ^{207}, ^{209}, ^{213}\text{At}$ isotopes were completed and compared with the $N = 126$, ^{211}At proton levels. The neutron-hole proton-particle interactions yield multiplets with the $J_{\text{max}}-1$ states lying lowest in the multiplets and thus determining many of the yrast levels as seen in several Bi isotopes. As the neutron number decreases from $N = 126$, these interactions will eventually involve the co-existence of significant collectivity in the core. The interaction for a $(\pi h_{11/2})^{-1}$ proton-hole configuration can most easily induce a potential energy surface with a softness to deformation that results in a depressed energy and a $J = 1$ band built on the $11/2^-$ deformed (prolate) state. The proton particle states $(\pi h_{9/2}, \pi f_{7/2}, \pi i_{13/2})$ would manifest (prolate) deformations with $\Delta J = 2$ decoupled bands that should be first seen in the At isotopes. An oblate deformation would reverse the band structure.

The present experimental program involves gamma-ray spectroscopy for $^{197}, ^{199}\text{Bi}$ and $^{201}, ^{203}\text{At}$ via the $^{192}, ^{194}\text{Pt}(^{10}\text{B}, 5n)^{197}, ^{199}\text{Bi}$ and $^{192}, ^{194}\text{Pt}(^{14}\text{N}, 5n)^{201}, ^{203}\text{At}$ reactions. The following measurements involving Ge(Li) detectors are required to extract the high-spin level properties: 1) gamma excitation functions, 2) gamma-gamma coincidence, 3) gamma-angular distributions, 4) pulsed beam-gamma timing and possibly 5) perturbed angular distribution measurements. The latter two measurements would allow the determination of lifetimes and g-factors for isomers giving additional electromagnetic information. In this region, light-heavy ions are preferred in order to keep the Coulomb excitation from dominating the experiment. The rare ^{192}Pt target is thus an important part of these studies. An initial set of experiments have been carried out in $^{197}, ^{199}\text{Bi}$. Preliminary results have revealed strong yrast populations in each nucleus indicating that the reactions are populating previously unobserved high-spin states. (D. B. Fossan, T. Chapuran, K. Dybdal, W. Piel (SUNY); E. K. Warburton, D. Horn (BNL))

b. ^{205}At

As part of the program outlined above, the properties of high-spin states in ^{205}At have been studied with the $^{197}\text{Au}(^{12}\text{C},4n)^{205}\text{At}$ reaction. In beam measurements with Ge(Li) detectors of gamma-gamma coincidences, gamma-ray angular distributions, and pulsed-beam-gamma timing were made to determine a decay scheme, level energies, gamma-ray multipolarities, spin-parity assignments, and isomeric lifetimes. High spin states up to $27/2$ were identified as either proton excitations of the $(N = 126)$ ^{211}At nucleus coupled to the ^{202}Pb $Z = 82$ ground state or neutron excitations of ^{202}Pb coupled to the $(\pi h_{9/2})^3$ $9/2^-$ ground state of ^{211}At . The lifetime measurements of the $25/2^+$ 2062-keV state and an unobserved state above the $25/2$ 2339-keV state yielded mean lifetimes of 92 ± 2 nsec and ~ 3 usec, respectively. (T.P. Sjoreen, D.B. Fossan, U. Garg, A. Neskakis, A. R. Poletti (SUNY); E. K. Warburton (BNL))

12. $Z=86$ Systematics

Interest has in recent years been focussed on the regions of the $N=82$ and $Z=82$ shell closures where states of large angular momentum, formed by the alignment of valence neutrons in high- j orbitals, have been observed. Particularly the $N=86$ isotones and the $Z=86$ isotopes, with four valence nucleons in the $f_{7/2}$, $h_{9/2}$ and $i_{13/2}$ orbitals, have been fertile ground in the spectroscopy of discrete high spin states. Information concerning the degree of collectivity and amount of deformation in such particle-aligned states would be valuable, and it is especially in this respect that the systematic behavior of the (even) $Z=86$ isotopes is significant. The isotopes ^{210}Rn and ^{212}Rn have been investigated to a high spin. The present study extends the spectroscopy of the Rn isotopes to the neutron deficient region ($^{204,206,208}\text{Rn}$) where deformation is expected to gradually set in, and to the neutron rich ^{214}Rn which has two valence protons and exhibits a more pronounced shell structure. With the previously studied isotopes, this set forms the longest chain of isotopes investigated to high spins in the Pb region and provides valuable information for nuclear structure models. This is particularly the case in view of the parallel and complementary study of $N=86$ nuclei reported elsewhere in this review.

a. $^{204,206,208}\text{Rn}$

The $^{192,194,196}\text{Pt}(^{16}\text{O},4n)^{204,206,208}\text{Rn}$ and $^{197}\text{Au}(^{14}\text{N},5n)^{206}\text{Rn}$ reactions were used to investigate the product nuclei to about 4 MeV excitation energy and a spin of 15. The single and coincidence gamma-ray measurements were made with a DC beam, while a pulsed ^{16}O beam was used to search for isomeric states. Two isomers ($J=10$, $J=15$) were observed in each nucleus above the previously known $J^\pi=8^+$ levels. Systematic features of these isotopes include increasing lifetimes and decreasing excitation energy for the $J^\pi=8^+$ states as the closed neutron shell is approached. Compared to their respective $Z=84$ isotones ($^{202,204,206}\text{Po}$) Rn isotopes show less single particle structure for the $J^\pi=0^+, 2^+, 4^+, 6^+, 8^+$ multiplet. The $B(E2)$ values for the $8^+ \rightarrow 6^+$ transitions increase rapidly in Rn isotopes with decreasing neutron number. Therefore, while proton $(h_{9/2})^2$ configurations contribute predominantly to the structure of these levels, the systematics suggest a gradual onset of collectivity and larger admixtures of

other components for the lighter Rn isotopes. Another notable feature of the systematics is the presence of $J^\pi=9^-$ neutron hole states at 2200-2300 keV excitation energy. These states are analogous to those observed in the respective N=82 isotones ($^{200,202,204}\text{Pb}$) where they are very long-lived isomers. The series of isomeric states at ≈ 2400 -2600 keV excitation energy may be interpreted as proton $(f_{7/2} i_{13/2})_{10^-}$ configurations. The observed lifetimes indicate highly retarded M1 transitions to 9^- states, presumably due to a lack of overlap between the wave functions of proton 10^- and neutron 9^- states. Levels above $J=10$ states are somewhat difficult to interpret. The series of isomers at $E \approx 4$ MeV and $J=15$ are suggestive of the behavior observed for the corresponding polonium nuclei. However, a detailed discussion of their nature requires a more definitive determination of their excitation energies and spin values. One interesting feature of the present systematics is the gradual increase in the energy of proton $h_{9/2}$ configurations with decreasing neutron number. A similar pattern also exists for the N=86 nuclei. This apparent symmetry suggests deformation effects as the possible cause. (D. Horn, C. Baktash, C.J. Lister)

b. ^{214}Rn

The reaction $^{208}\text{Pb}(^{13}\text{C}, 3n)^{214}\text{Rn}$ was used to populate states up to a spin of ≈ 25 and excitation energy of ≈ 5 MeV. Excitation functions in the energy range of 75-95 MeV and use of alpha-gamma coincidence techniques allowed identification of the deexcitation gamma rays from this nucleus. Three isomeric states were found at 1622 keV ($J^\pi=8^+$, $T_{1/2}=40$ nsec), 3484 keV ($J^\pi=(16^+)$, $T_{1/2}=100$ nsec) and 4509 keV ($J^\pi=(20^+)$, $T_{1/2}=230$ nsec). Many of the features of the level scheme may be described in terms of simple shell model configurations built out of 2 valence neutrons and 4 valence protons. The low-lying states up to $J^\pi=8^+$ are formed from a neutron $(g_{9/2})^2$ multiplet. Similarly, the first 10^+ state may be due to the neutron $g_{9/2} i_{11/2}$ configuration. The spin and parity assignments for the higher-lying states are tentative, thus making configuration assignments premature. However, the position of two states with probable J^π of (17^-) and (20^+) in the level scheme are consistent with proton $[(h_{9/2})^3(i_{13/2})]_{17^-}$ and $[(h_{9/2})^2(i_{13/2})^2]_{20^+}$ configurations. Work is being continued to establish a more definitive spin-parity assignment for the high spin states and to carry out a shell-model calculation to interpret the result. (T. Lönnroth (Univ. of Jyväskylä, Finland); D. Horn, C. Baktash, C.J. Lister (BNL); G.R. Young (ORNL))

B. Coulomb Excitation

1. Coulomb Excitation Study of Medium-Mass Transitional Nuclei

Medium mass transitional nuclei (Ge-Cd) exhibit a coexistence of structures. The electromagnetic properties of the low-lying states were studied by Coulomb excitation of either the target or the projectile.

a. The Projectile Coulomb Excitation of ^{72}Ge

A beam of 270 MeV ^{72}Ge ions was Coulomb excited by a ^{208}Pb target. The reduced Doppler broadening effect allowed the use of three Ge(Li) detectors at 0° , 50° , and 90° and smaller target-to-detector distances. Moreover, the 0° Ge(Li) detector was provided with a rise-time sensing circuit (indicating the angle of incident photons with respect to the axis of detector) that allowed further reduction of the Doppler broadening effect by application of appropriate corrections. Excitation of the ground band and the 0_2^+ state band was observed up to the 6_1^+ and 4_2^+ members, respectively. Some of the important transitions were not observed so unique determination of the matrix elements is not possible. However, the observed yields can be reproduced by introducing a large static moment for the $Q(2_2^+)$ state, while $Q(2_1^+)$ was found to be close to zero. These results are consistent with calculations predicting shape coexistence in these nuclei. (D. Cline, C. Y. Wu, T. Czosnyka (U. of Rochester); C. Baktash (BNL); S. Steadman (MIT))

b. Multiple Coulomb Excitation of ^{104}Ru and ^{110}Pd

Thin targets of ^{104}Ru and ^{110}Pd were Coulomb excited by ^{58}Ni and ^{208}Pb projectiles at the BNL and Super HILAC facilities, respectively. In the case of the Ni beams, the deexcitation gamma rays were detected in two Ge(Li) detectors in coincidence with the backscattered particles. The gamma-ray yields are being analyzed to extract information about the reduced transition matrix elements between the low-lying states in these nuclei. The final analysis of ^{104}Ru awaits completion of additional lifetime measurements. In the case of ^{110}Pd , additional data obtained with ^{16}O at Upsala were found very helpful in the determination of the mixing ratios and the reduced matrix elements for the low-lying states. A preliminary level scheme has been suggested for the states up to J-10 in this nucleus and work is continuing to obtain model independent reduced matrix elements for the higher-lying states. While some models reproduce the $B(E2)$ -values for the ground band, no model has been found to adequately describe the excited bands, and in particular, a rotational band built on the 0_2^+ state which has large $B(E2)$ values. (L. Hasselgren, J. Srebrny, C. Y. Wu, D. Cline, T. Czosnyka (U. of Rochester); D. Habs, R. M. Diamond, H. Hubel, H. Korner, F. S. Stephens, U. Swilonsky (LBL); C. Baktash (BNL); G. R. Young (ORNL))

2. Coulomb Excitation of the Os-Isotopes

The Os-Pt nuclei span a region where a prolate to oblate shape transition takes place, and hence provide a crucial testing ground for the nuclear models that attempt to describe the collective degrees of freedom. While all models agree that these nuclei are to varying degrees triaxial, they differ on the question of the extent of the softness of their cores with respect to gamma-vibrations. Among various observables, the electromagnetic properties of the gamma band in these nuclei provide the most sensitive probe of the core softness. An early Coulomb excitation measurement on Pt nuclei using Xe ions from the LBL Super HILAC facility showed that the gamma-ray yields could be reproduced by assuming the $E2$ matrix elements corresponding to the rigid triaxial rotor model. The rigid triaxial cores are, however, contrary to most microscopic models.

The resolution of this discrepancy requires a set of model independent matrix elements, which in turn require additional data from Coulomb excitation of these nuclei by a variety of lighter projectiles. In collaboration with the University of Pittsburgh, the electromagnetic properties and the low-lying states in $^{188,190,192}\text{Os}$ were investigated using α , ^{16}O and ^{32}S projectiles. The gamma-ray yields (from particle-gamma coincidence measurements) were analyzed to extract the branching ratio and the spectroscopic quadrupole moment of the 2_2^+ states in these nuclei. The results are in better agreement with the microscopic models than the rigid triaxial rotor model. In addition, a ^{58}Ni beam from the BNL Tandem Facility was used to investigate the higher-lying states in $^{190,192}\text{Os}$. These data along with that using ^{40}Ca and ^{136}Xe ions are being analyzed to extract the E2 matrix elements for states up to 12^+ in the ground band, 10^+ in the gamma band and 6^+ in the $K^\pi = 4^+$ band. (C. Baktash (BNL); J. X. Saladin, J. J. O'Brien, J. G. Alessi (U. of Pittsburgh); C. Y. Wu, D. Cline, T. Czosnyka (U. of Rochester); S. Steadman (MIT))

3. Coulomb Excitation of Deformed Nuclei

a. ^{166}Er

Both a 231-MeV and a 190-MeV ^{58}Ni beam were used to Coulomb excite ^{166}Er . The deexcitation gamma rays were detected in two Ge(Li) detectors in coincidence with backscattered ions detected in a position-sensitive annular detector. The ground band was observed up to the spin 16^+ member and the gamma band to the spin 10^+ level. The gamma-ray yields have been analyzed to extract $B(E2)$ values for comparison with models. (H. Sang, S. Steadman, G. R. Young (MIT); C. Baktash (BNL); C. Y. Wu, J. Srebrny, D. Cline (U. of Rochester))

b. ^{248}Cm

This nucleus is the heaviest deformed nucleus accessible for Coulomb excitation, hence offering an interesting case for the study of the influence of collective rotations and high j orbitals at very high angular momentum. Recently, ^{248}Cm was Coulomb excited up to spin 28^+ at GSI, Darmstadt, and some of the level energies were found to deviate from the rotational model at spins about 22^+ . The E2 matrix elements for the ground rotational band have not been studied. In addition, the analysis of the data may be significantly affected by the negative parity band present in all actinide nuclei. This nucleus was Coulomb excited by 260-MeV ^{58}Ni in order to search for the negative parity band. In addition to the ground band (observed up to 14^+), some weaker transitions were also present in the gamma-ray spectrum. Analysis is continuing in order to place these new transitions in the decay scheme. (T. Czosnyka, L. Hasselgren, C. Y. Wu, D. Cline (U. of Rochester); C. Baktash (BNL))

C. Lifetimes and Moments

1. Electromagnetic Transitions in ^{14}C and ^{14}N

The measurements of the lifetimes of the $J^\pi=0^+$ 6590-keV and 3^- 6728-keV states in ^{14}C and the 3^- 5834-keV state in ^{14}N were completed using the recoil distance method. Gamma rays following the pn and 2n evaporation channels from the $^9\text{Be} + ^7\text{Li}$ reaction were detected at 0° to the beam. The experimental results are: $^{14}\text{C}(6590,0^+)$, $\tau = 3.7 \pm 0.9$ psec; $^{14}\text{C}(6728,3^-)$, $\tau = 96 \pm 15$ psec; $^{14}\text{N}(5834,3^-)$, $\tau = 12.9 \pm 1.9$ psec. Extensive shell-model calculations for both ^{14}C and ^{14}N were made on an SU(3) basis and were compared to these and other experimental results. (R.L. Kozub, J. Lin, J.F. Mateja (Tenn. Tech. Univ.); C.J. Lister, D.J. Millener, E.K. Warburton (BNL))

2. Lifetimes of (sd)-Shell Nuclei via the Recoil Distance Technique

The survey of gamma rays emitted in the bombardment of ^7Li targets by various light nuclei revealed the possibility of determining lifetimes of several nuclear states for which such determinations would be of current interest. A preliminary result of 2.8 ± 0.9 psec was obtained for the ^{21}F 1755-keV level with the BNL recoil distance apparatus. An intrinsic Ge detector--much less sensitive to neutron damage than the previously used Ge(Li) detectors--has also been purchased by Tennessee Technical University, and will be used in the BNL Compton-suppression spectrometer. These improvements should make possible the measurement of several lifetimes of current interest in ^{17}N and ^{21}F . (R.L. Kozub, J. Lin (Tenn. Tech. U.); E.K. Warburton, C.J. Lister, D.J. Millener (BNL))

3. Static Quadrupole Moments of 2^+ States

Measurements of the static quadrupole moments of the first excited 2^+ states of even-even nuclei exploit the reorientation effect in Coulomb excitation. Backward angle scattering in the center of mass system is studied by kinematic reversal; the recoiling target nucleus is observed at forward angles in the focal plane of the QDDD spectrometer. Since the focal plane detector allows unique identification of the recoil nucleus the technique is insensitive to target contaminants. The high energy resolution (250 keV) and the large sensitivity of the excitation probabilities to the quadrupole moment (~ 70 -85%/eb) make accurate determinations of Q_{2^+} possible even for states at excitation energies as high as 2 MeV. The latest application of this technique is described below in 4.

The next case under study is $Q(2^+)$ for the first excited state of ^{30}Si at 2.24 MeV and the feasibility of the measurement has been demonstrated.

4. Static Quadrupole Moments for the 2^+ States of $^{54,56,58}\text{Fe}$

This work which was begun in FY 1978 has now been completed. The static quadrupole moments of the first 2^+ excited states of ^{54}Fe , ^{56}Fe and ^{58}Fe were measured utilizing the reorientation effect in Coulomb excitation as described above. Results for $B(E2;0^+ \rightarrow 2^+)$ and $Q(2^+)$ -values were obtained by combining, for each Fe isotope, light (^{12}C or ^{16}O) and heavier (^{52}Cr or ^{40}Ca) heavy ion Coulomb excitation results. Scattered ^{12}C or ^{16}O ions or recoiling Fe ions were detected in the QDDD spectrometer. The results for the $B(E2;0^+ \rightarrow 2^+)$, $Q(2^+)$ pairs (in e^2fm^4 and $\text{e}\cdot\text{fm}^2$), are as follows: ^{54}Fe ; 676 ± 38 , -5 ± 14 , ^{56}Fe ; 1022 ± 55 , -19 ± 8 , ^{58}Fe ; 1234 ± 36 , -27.3 ± 5.0 . (M.J. Levine, E.K. Warburton (BNL); D. Schwalm (BNL and GSI, Darmstadt))

5. Attenuated Gamma-Ray Anisotropies from Nuclei Recoiling Through Gas

The measurement of magnetic moments of short-lived isomers in Mn isotopes described in last year's report was continued. This experiment makes use of the very large magnetic fields that exist at the nuclei of highly ionized atoms recoiling through gas following heavy ion induced compound nucleus reactions. The recoil velocity of $v/c = 0.06$ obtained with the ^{45}Sc bombardment of ^{12}C at 140 MeV together with a krypton gas recoil medium allows an ideal range of experimental parameters. A more complete set of data that measured the attenuation of gamma-ray anisotropies as a function of both pressure and distance was obtained with good statistical accuracy. Analysis of this data is now in progress. (C. Baktash, O.C. Kistner, C.J. Lister, J.W. Olness (BNL); G. Goldring (Weizmann Institute))

6. Precession Measurements of Gamma-Ray Anisotropies following Nuclear Recoil Through Multiple-Tilted Foils

A major disadvantage of the gas recoil attenuation technique for measuring nuclear moments described above is that it does not yield the sign of the magnetic moment. An alternative technique, largely developed at the Weizmann Institute of Science, makes use of the fact that ions recoiling into vacuum from a surface tilted away from the normal to the beam direction will be spin polarized along the tilt axis. The resulting polarized magnetic field at the nucleus will then give rise to a measurable rotation of the gamma-ray anisotropy where the sense of rotation determines the sign of the nuclear magnetic moment. However, because both nuclear and atomic spins precess about their resultant spin, the simple interpretation of a nuclear spin precessing about a fixed direction applies for short times only. For longer times, the anisotropy is attenuated, the measured precession begins to decrease, and the analysis becomes model dependent and very difficult. The best results are obtained when the interaction time is limited by interposing a recoil stopper at a sufficiently close distance to the polarizing foil. An experiment has been performed which overcomes this limitation by interposing a number of closely spaced foils between the target and the stopper. The atomic polarization is then reset periodically at the exit from each foil and the useful interaction time is accordingly extended. In the limit of a large number of foils the perturbed angular distribution resembles a simple precession independent of the nuclear spin and the distribution of the hyperfine fields. This

technique was demonstrated by precessing the 2^+ first excited states in Pd and Sn isotopes Coulomb excited with ^{32}S ions from the Weizmann Institute Pelletron electrostatic accelerator. Increases in the measured asymmetry parameter by as much as a factor of 5 were obtained when using sandwiches of up to 15 polarizing carbon foils as compared to the case for a single polarizing foil. Precession angles of greater than 30 mrad were measured.

Some difficulties with this technique still remain to be solved. The sandwiches of carbon foils used in the experiment deteriorated with exposure to the beam so that the observed effect would decrease with time. However, some foils lasted much longer than others. Though carbon foils have been the most effective for this purpose, it may be that some other material with more suitable physical properties may be found. (O.C. Kistner (BNL); E. Dafni, G. Goldring, M. Hass, Y. Niv, A. Zemel (Weizmann Institute))

D. Radiative Capture of Heavy Ion Systems

1. The General Program

Studies of compound nuclear de-excitation by emission of high-energy gamma rays (~ 20 MeV) following the fusion of two heavy ions have proven to be a very selective tool for investigating unusual structures at high excitation energies in the fused nuclei. For example, the recent work on the $^{12}\text{C}(^{12}\text{C},\gamma)^{24}\text{Mg}$ reaction, originally begun at BNL in 1977, has revealed narrow (~ 0.3 MeV) $J^\pi = 2^+$ structures that decay directly to the members of the ground state rotational band of ^{24}Mg , but are not correlated with the structure in the distribution of ground state E2 strength in ^{24}Mg or with previously identified features of the $^{12}\text{C} + ^{12}\text{C}$ system. Comparisons with Hauser-Feshbach calculations have shown these resonances to have both non-statistical ^{12}C and ground-state gamma-ray widths. These results suggest highly-clustered states built on the ground state band of the fused nucleus ^{24}Mg , however adequately detailed calculations are still lacking. The goal of the heavy-ion capture program at BNL is to locate and to study such phenomena.

These experiments require a spectrometer capable of detecting high-energy gamma rays with good resolution and high-count-rate stability. The new BNL NaI-spectrometer system used for these measurements maintains a resolution of 3.3% for 20 MeV gamma rays at rates above 200 kHz. The low cross sections encountered in heavy-ion capture (50 to 100 nb/sr) necessitate extraordinary beam currents (~ 2 particle-uA) and large blocks of running time. However, since for most of this work only modest bombarding energies have been required, this program has been aptly suited to MP6 which is generally available when three-stage energies are not required.

2. The Gamma Decay of a Quasi-Molecular $^{12}\text{C} + ^{12}\text{C}$ Resonance to the Ground State of ^{24}Mg

Recently, a giant resonance doorway state was proposed as the origin of the resonances observed in the $^{12}\text{C}(^{12}\text{C},\gamma)^{24}\text{Mg}$ reaction at center-of-mass (cm) energies between 5 and 11 MeV. In order to investigate this hypothesis a detailed search was made for the gamma decay of a known quasi-molecular $^{12}\text{C} + ^{12}\text{C}$ resonance (the $J^\pi = 2^+$ state at a cm energy of 5.60 MeV) to the low-lying states of ^{24}Mg . This is a sensitive test of the proposed mechanism since the resonance energy corresponds to a strong peak in the E2-strength function at 19.53 MeV in ^{24}Mg . The

cm energy region between 5.3 and 6.3 MeV was explored with a thin target. Decays to the ground state and to the first seven excited states of ^{24}Mg were observed. The 2^+ quasi-molecular resonance was present in the yield to the ground state at 5.60 MeV with the same width (0.13 MeV) as observed in elastic scattering. However, in contrast to the other radiative capture resonances, this structure was not resonant in any of the other gamma-ray yields. It appears to gamma decay only to the ground state of ^{24}Mg , and with a strength that is about a factor of 10 less than that of the previously measured capture resonances. Furthermore, a calculation using the measured ^{12}C width of this state and assuming statistical photon decay quantitatively accounts for the observed capture yield to the ground state. Wavefunctions built upon excited states of ^{24}Mg are unknown, and a similar analysis for the expected gamma decays to excited states is not possible. Nevertheless, the apparent absence of decays to levels other than the ground state remains a conundrum in light of the great similarity between the wavefunctions of the members of the ground state rotational band. The nature of the gamma-decay branches reflects an unusual and unexpected form of structure for the quasi-molecular state, and the very different non-statistical behavior of the other capture resonances remains an interesting puzzle. (A.M. Sandorfi (BNL); A.M. Nathan (U. of Illinois))

3. Fusion Resonances in $^{12}\text{C}(^{16}\text{O},\gamma)^{28}\text{Si}$

In order to investigate whether capture resonances occur in other nuclei a study was made of the $^{12}\text{C}(^{16}\text{O},\gamma)^{28}\text{Si}$ reaction. This measurement also served as a means of studying the effects of the structure of the fused nucleus upon heavy-ion capture. The combined Q-value and Coulomb barrier are 5 MeV higher than for $^{12}\text{C} + ^{12}\text{C}$ capture, which results in higher excitation energies in ^{28}Si , while the low-lying structure of ^{28}Si is consistent with the co-existence of both oblate and prolate intrinsic shapes, a situation very different from ^{24}Mg .

The cm energy region between 6.5 and 12.5 MeV in $^{12}\text{C} + ^{16}\text{O}$ was studied with a thin target. Transitions to the ground state and to the first nine excited states of ^{28}Si were observed, and the unique gain stability of the BNL spectrometer system under high count-rate operation proved crucial in identifying the final states of these gamma transitions. The three most striking features in the gamma-ray spectra are: (1) the extremely small cross sections for γ_0 decay, relative to the γ_1 and $\gamma_{2,3}$ transitions which appear with about the same cross section (30 to 50 nb/sr) as in the $^{12}\text{C}(^{12}\text{C},\gamma)$ reaction; (2) the existence of at least four relatively narrow (0.2 to 0.4 MeV) isolated resonances in the γ_1 excitation function; (3) the presence of a much stronger transition (200 to 300 nb/sr) to states at ~7 MeV excitation in ^{28}Si . Since the ground state of ^{28}Si is oblate while the incoming $^{12}\text{C} + ^{16}\text{O}$ channel is inherently prolate, the lack of significant γ_0 yield may be viewed as resulting from the inability to connect these two intrinsic shapes with a simple electromagnetic operator. The same argument can be made for the γ_1 yield since the wavefunctions of the ground and first-excited states of ^{28}Si look very much alike, although prolate impurities may be responsible for the interesting structure of the γ_1 excitation function. Resonances in the latter occur in the vicinity of the Coulomb barrier at cm energies of 7.4, 8.5, 9.2,

and 9.8 MeV and have not been observed in either scattering or reaction channels. The $^{12}\text{C} + ^{16}\text{O}$ system is known to have far fewer and more ill-defined "quasi-molecular" features than the $^{12}\text{C} + ^{12}\text{C}$ system, and the qualitatively similar behavior of their capture yields suggests that heavy-ion capture is more useful in the investigation of unusual structure in the fused nucleus than as a tool for studying heavy-ion reaction mechanisms. Angular distributions were measured and, although the spin assignments for the γ_1 resonances cannot be uniquely obtained, values of $J^\pi=2^+$ and 4^+ are completely consistent with the radiation patterns from the resonances at cm energies of 8.5, and 9.8 MeV, respectively. Some of these features are correlated in the $\gamma_{2,3}$ yield, but none appear in γ_0 . The γ_5 yield to the 6.69-MeV level in ^{28}Si also resonates at 8.5 MeV cm (25.3-MeV excitation). This $0^+ 6.69$ MeV final state is the lowest member of the prolate intrinsic shape of ^{28}Si , and the strong enhancement in this transition (about a factor of 5) over the γ_1 yield is consistent with the prolate nature of the entrance channel.

In addition to the new and unusual structures observed in $^{12}\text{C}(^{16}\text{O},\gamma)^{28}\text{Si}$, it is apparent from this study that heavy-ion capture can serve as a sensitive probe of prolate components in oblate nuclei. (M.T. Collins, A.M. Sandorfi)

4. The $^{13}\text{C}(^{12}\text{C},\gamma)^{25}\text{Mg}$ Reaction

The effects upon carbon + carbon radiative capture of non-identical particles in the entrance channel and of an extra odd neutron in the fused nucleus were investigated near the Coulomb barrier of the $^{13}\text{C} + ^{12}\text{C}$ system. High energy gamma rays to the ground and low-lying states of ^{25}Mg were evident at several energies, with cross sections comparable to $^{12}\text{C}(^{12}\text{C},\gamma)^{24}\text{Mg}$. No single transition appeared to dominate the spectra and a detailed excitation function has not yet been made. (A.M. Sandorfi)

5. The $^{10}\text{B}(^6\text{Li},\gamma)^{16}\text{O}$ Reaction

A search was made for heavy-ion capture to p-shell nuclei via the $^{10}\text{B}(^6\text{Li},\gamma)^{16}\text{O}$ reaction. This reaction has a Q-value (30.9 MeV) substantially larger than previously studied heavy-ion capture reactions, and thus capture near the Coulomb barrier reaches much higher excitation energies in the fused nucleus. No yield to the ground or low-lying states of ^{16}O was observed. A search was also made for decays to a high-lying state at 14.8 MeV in ^{16}O . Although strong transitions to this state were observed in $^{12}\text{C}(^{12}\text{C},\gamma)$ for the same initial excitation energy in ^{16}O , (see the Light Ion report) there was no evidence for such a transition in $^{10}\text{B}(^6\text{Li},\gamma)$. The extremely small probability for radiative capture in this system emphasizes the importance of the structure in the fused nucleus. (A.M. Sandorfi, M.T. Collins)

6. Progress Toward $^{12}\text{C}(^{12}\text{C},\gamma)^{24}\text{Mg}$ EMS Studies

Nuclear structure information essential to the understanding of the fusion resonances observed in heavy-ion radiative capture is contained in the gamma-decay branching ratios. In all previous experiments where only the high-energy gamma-ray has been detected, backgrounds have limited this information to transitions to the ground and first few excited levels in the fused nucleus. These backgrounds can be drastically reduced by detecting the fused nucleus, recoiling at $\sim 0^\circ$, in coincidence with the decay gamma rays.

Initial tests were made with the $^{12}\text{C}(^{12}\text{C}, ^{24}\text{Mg})$ reaction using the BNL Energy Mass Separator (EMS). After modifications to the beam transport diagnostics, vacuum, and collimating slits, the backgrounds due to low-energy tails on the incident beam were sufficiently reduced to enable EMS operation at the high beam currents typical of heavy-ion capture studies. A new EMS scattering chamber and fusion-product detector are presently being fabricated. Coincidence measurements are expected to begin soon. (A.M. Sandorfi, M.T. Collins (BNL); M. Beckereman, M. Salomaa (MIT))

7. A Study of $^{16}\text{O} + ^8\text{Be}$ Resonances in ^{24}Mg

Intermediate structure "doorway states" are frequently used to model resonances in heavy-ion reactions that are correlated in several decay channels. Following the recent suggestion that the E2 giant resonance may act as a "doorway" for the $^{12}\text{C}(^{12}\text{C}, \gamma)^{24}\text{Mg}$ resonances, a search was made for correlated structure in the $^{16}\text{O} + ^8\text{Be}$ channel, an ideal test since the Q-values and hence ^{24}Mg excitation energies reached through both channels are nearly identical. Since ^8Be exists as neither target nor projectile, the inverse reaction $^{24}\text{Mg}(e, ^{16}\text{O}, ^8\text{Be})e$ was studied using electrons from the Superconducting accelerator at Stanford University. Resonances were observed in the $^{16}\text{O} + ^8\text{Be}$ channel between 18 and 28 MeV excitation in ^{24}Mg with equivalent capture cross sections ten times those of the $^{12}\text{C} + ^{12}\text{C}$ structures. However, no correlations between these channels were observed. The $^{16}\text{O} + ^8\text{Be}$ yields were not consistent with statistical decays from giant resonances, and suggested unusual highly-clustered states in ^{24}Mg . (A.M. Sandorfi (BNL); J.R. Calarco, R.E. Rand, H.A. Schwettman (Stanford))

II. Direct Reactions

A. The General Program

This program, which in the past has emphasized the study of elastic and inelastic scattering and reaction mechanism studies of few nucleon transfer, has this year emphasized the study of selective population of high spin states in nuclei. Such selectivity is accomplished for large negative Q value reactions and requires beams not only of high quality but also of high energy in order to obtain large enough cross sections. The magnetic QDDD spectrometer plays an important analytic role in these studies for reasons of energy resolution and large solid angle. As an added tool in the study of these states, coincidence measurements between gamma rays and particles detected in the spectrometer have been made. Many of the studies have been made on nuclei previously studied by high spin gamma spectroscopy and have been shown to give complementary information needed in the interpretation of structure in those nuclei.

Work has continued on the surprising large yield of heavy ion elastic scattering at far backward angles. The program at BNL has been particularly successful because of the availability of high energy heavy ions beams and the QDDD spectrometer. Due to kinematic considerations, it is almost impossible to study these back angle reactions in the scattering of the lighter ions from the heavier targets--while by reversing the reaction the "back angle" cross section becomes a forward angle measurement in the laboratory. The spectrometer makes these measurements possible.

In this general area of research there has been and continues to be strong cooperation between BNL experimentalists and theorists, which has been important for the achievements of the program.

B. Elastic Scattering

1. Back Angle Excitation Function of $^{12}\text{C} + ^{19}\text{F}$

The 180° excitation function of $^{12}\text{C} + ^{19}\text{F}$ elastic scattering was studied by the technique of measuring recoils at 0° with the QDDD spectrometer. Previous measurements had shown large structures in such an excitation function only when the nuclei were alpha-like (i.e. ^{12}C , ^{16}O , ^{24}Mg , etc.) The measurements here provide the first case that in an odd mass system very large oscillations appear both in the elastic and inelastic excitation functions. Further theoretical and experimental investigations are in progress. (C.F. Maguire, G.L. Bomar, R.B. Piercey (Vanderbilt); P.D. Bond (BNL))

2. $^{86}\text{Kr} + ^{208}\text{Pb}$

In a collaborative experiment performed at GSI in Darmstadt, W. Germany, the first true elastic scattering measurement for massive heavy ions has been made. Previous experiments have had insufficient resolution to distinguish elastic from inelastic scattering or even from some transfer reactions. Preliminary analysis of the results indicates that the optical parameters derived in other experiments were incorrect and also show that very large differential cross sections for few nucleon transfer are present. Analysis is in progress. (O. Hansen, P.R. Christensen, F. Videback, S. Sorenson (Niels Bohr Institute); D. Schüll (GSI); F. Busch (Marburg); P.D. Bond (BNL))

C. Transfer Reactions

1. Single Neutron Transfer to High Spin States

A wide ranging study of the use of heavy ion induced transfer for spectroscopic studies of nuclei has begun. Specifically, the single neutron transfer reactions ($^{16}\text{O}, ^{15}\text{O}$) and ($^{12}\text{C}, ^{11}\text{C}$), which have large negative Q values, have been shown to be very selective in populating only high j states in nuclei. These Q values result in rather small cross sections which necessitate the use of high bombarding energies and a large solid angle, highly dispersive spectrometer like the QDDD. The kinematic conditions coupled with the selection rules for transfer give a strong enhancement of high spin states with $j_f = l_f + 1/2$ for the ($^{16}\text{O}, ^{15}\text{O}$) reaction while states with $j = l_f - 1/2$ are very strong with the ($^{12}\text{C}, ^{11}\text{C}$) reaction. This is an important feature as the equivalent light-ion reaction, ($^4\text{He}, ^3\text{He}$), does not clearly distinguish these states. Coincidence measurements with gamma rays for several isotopes were performed with a specially designed chamber in order to improve the effective energy resolution of the particle experiments. Some of the nuclei studied below were used to determine the reliability of the method while new states have been formed in others.

a. Ni and Co Isotopes

The $9/2^+$ neutron states in the $58,60,62\text{Ni}$ isotopes have been established in other experiments and for the reactions studied here are by far the strongest states which are populated by the $(^{16}\text{O},^{15}\text{O})$ reaction at 120 MeV. The states expected to be populated in ^{60}Co by the same reaction on ^{59}Co are the $\pi f_{7/2} \otimes \nu g_{9/2}$ configurations which are not known. The particle spectrum appears to show selectivity but requires additional measurements to sort out the closely spaced levels. (P.D. Bond, J. Barrette)

b. Nd Isotopes

The light Nd isotopes are near spherical (just past the $N=82$ closed shell) while the heavier isotopes become deformed. Both the $(^{16}\text{O},^{15}\text{O})$ and $(^{12}\text{C},^{11}\text{C})$ reactions were studied on four of these isotopes, $^{142},^{143},^{144},^{145}\text{Nd}$. A remarkably few number of levels are populated to any degree even in the resulting even-even final nuclei. In the odd nucleus ^{143}Nd only the known $f_{7/2}(\text{g.s.})$ and $i_{13/2}$ states at 1.27 and 2.81 MeV are populated strongly with the $(^{16}\text{O},^{15}\text{O})$ reaction while the $h_{9/2}$ states are populated with the $(^{12}\text{C},^{11}\text{C})$ reaction. In the final nucleus ^{144}Nd only a few states are observed, consistent with $(f_{7/2})^2$ and $(f_{7/2}i_{13/2})$ states for the $(^{16}\text{O},^{15}\text{O})$ reaction. However, gamma ray coincidence measurements are required to determine whether this conjecture is true. (P.D. Bond, J. Barrette)

c. Sm Isotopes

Features similar to those described for the Nd isotopes have also been observed in the Sm isotopes, i.e. the $f_{7/2}$ and $i_{13/2}$ states are strongly populated in the $(^{16}\text{O},^{15}\text{O})$ reaction while the $h_{9/2}$ states are strongly populated with the $(^{12}\text{C},^{11}\text{C})$ reaction. One neutron transfer to ^{147}Sm leading to the even-even nucleus ^{148}Sm , an apparently simple structure, is observed in the particle spectrum. The population of the $0^+, 2^+, 4^+$ and 6^+ states, however, is not consistent with an $(f_{7/2})^2$ configuration. A coincidence measurement with 150 ions detected in the QDDD spectrometer and gamma-rays in a $\text{Ge}(\text{Li})$ detector indicate that simple interpretations for structure of other states may also not be correct. Further measurements are being made. (P.D. Bond, J. Barrette, C.E. Thorn)

d. Er Isotopes

The transfer reactions $(^{16}\text{O},^{15}\text{O})$ and $(^{12}\text{C},^{11}\text{C})$ have also been studied on the deformed nuclei $^{166},^{168},^{170}\text{Er}$. As with Nd and Sm nuclei, only a few final states are populated in these deformed nuclei. New $13/2^+$ states belonging to the $9/2[624]$ Nilsson orbital, not previously observed, were found as were two new $9/2^-$ states. Arguments based on DWBA calculations were tested by performing a gamma ray coincidence measurement which provided added evidence that the assignments were correct for these nuclei. A particularly intriguing finding was a strong population of a broad group of states at -3.5 MeV in excitation in the odd Er isotopes. Preliminary evidence from the gamma-ray experiment is that this group might contain some $j_{15/2}$ states from the next higher shell. This conjecture is being tested by further measurements.

Data were also obtained for single neutron transfer from ^{167}Er to the even nucleus ^{168}Er . The spectrum is more complicated than for the odd nuclei although only a relatively small number of states are populated. In addition to the 4^+ and 6^+ in the ground state band, strong population is observed of states between 1.3 and 1.9 MeV in excitation. Another region above 2.5 MeV in excitation is also populated strongly. A preliminary gamma-ray coincidence measurement has been made in an attempt to simplify the data. (P.D. Bond, C. Baktash, J. Barrette, A.J. Kreiner and C.E. Thorn)

2. Two-proton Pickup Reaction to ^{196}Os

The nucleus ^{196}Os was studied for the first time with the 2 proton pickup reaction $^{198}\text{Pt}(^{18}\text{O}, ^{20}\text{Ne})^{196}\text{Os}$ at 120 MeV. Some evidence for population of the ground state and first 2^+ state has been found but with a very low cross section (mass excess is estimated to be -28.5 MeV). States at higher excitation are dominated by ^{20}Ne in its excited state at 1.63 MeV. A coincidence measurement between ^{20}Ne particles detected in the QDDD and gamma rays in a Ge(Li) detector was not successful because of a very low counting rate. Thus further studies of the spectroscopy of ^{196}Os will require some kind of breakthrough in experimental technique. (R.F. Casten, D. Warner, P.D. Bond, D. Horn)

3. Transfer Reactions to Continuum States Induced by 100 MeV ^{18}O on ^{27}Al

In order to understand the average properties of quasi-elastic transfer reactions at high energy the energy spectrum and the angular distribution between $\theta_{\text{lab}}=6^\circ$ and 50° were measured for all of the reaction products (^6Li to ^{20}Ne), produced in the reaction ^{18}O on ^{27}Al at 100 MeV. The mass and atomic number of all the light products with $6 \leq A \leq 20$ and $3 \leq Z \leq 10$ were obtained with the time-of-flight spectrometer. An ionization chamber was used to measure the specific energy loss. Few nucleon transfer reactions populating continuum states can be described in detail by an extension of a diffraction model for inelastic processes developed by M. Mermaz. The angular distribution is strongly forward peaked and the energy spectrum is characterized by a gaussian shape for nuclei formed by transfer of a few nucleons. The centroid of this gaussian is determined by the conditions of optimum Q value, whereas the width is related to the energy dependence of the level density in the nuclei involved. For larger mass transfer ($M \geq 6$ amu) the reaction products are more damped than predicted for a simple quasi-elastic process and the angular distributions become flatter and approach a $1/\sin \theta$ dependence. Both these phenomena are characteristic of completely relaxed or deep inelastic reactions. However, the kinetic energies of the ejectiles are still above the coulomb barrier and the relative yield of the various nuclides does not follow the Volkov systematic that is expected when thermal equilibrium is reached. Consequently, it appears that this energy is a transition region between quasi-elastic and deep inelastic reactions and these data allow a study of this region as a function of the transferred mass and observation angles (M. Mermaz (Saclay); J. Barrette, H.E. Wegner (BNL))

4. Polarization in Heavy-Ion Induced Transfer Reactions

Work was completed on a semiclassical analysis of expected polarizations in heavy ion induced transfer reactions. These polarizations are found to depend upon a few, easily estimated parameters. Explicit formulae were derived under the no-recoil approximation and comparisons of full recoil calculations to data were made. (P.D. Bond)

III. Nuclei Off the Line of Stability

A. Beta Decay of ^{18}N

An activity corresponding to ^{18}N was produced via the $^9\text{Be}(^{18}\text{O}, p2) ^{18}\text{N}$ reaction at $E(^{18}\text{O})=120$ MeV. The beryllium target foil served also as the entrance window to a helium-filled chamber in which the ^{18}N nuclei were stopped. Radioactive products were swept by a continuous helium flow through a capillary to a counting volume consisting of a 7.5 cm diam. coil wound from 4m of this tubing, positioned in front of a Ge(Li) detector. The transit time through the coil was $\sim 1/2$ sec, matched to the 0.63 sec half-life of ^{18}N , so that contaminant radioactivities of longer half-lives were effectively suppressed. An extensive series of measurements and calibrations were completed to determine the ^{18}N half-life, as well as gamma-intensities and subsequently beta-branching ratios.

In addition to a 64% beta-branch to the $J^\pi=1^-$ 4456-keV level (previously reported in 1964 as 100%) a 20% branch was observed to the 6880-keV level, for which a previous assignment of $J^\pi=0^-$ or 1^+ had been given. Weaker branches were also seen to levels (E_x in keV) at 5530(2^-), 6198(1^-), 6350(2^-), and 7771(2^-). This new information allows a definite assignment $J^\pi=0^-$ for the ^{18}N 6880-keV state, and establishes a $J^\pi=1^-$ assignment for the previously unknown ^{18}N ground state. The observed beta-transition strengths are in satisfactory accord with an extended shell-model description, although it is clear that in these calculations there is only a small overlap between the ^{18}N and the wavefunctions of the odd-parity ^{18}O states. (J.W. Olness, E.K. Warburton, D.E. Alburger, C.J. Lister, D.J. Millener)

B. Beta Decay of ^{21}O

Of the eight $T_z = +5/2$ nuclei from ^{21}O to ^{35}P five were discovered in the past decade at BNL and two were found elsewhere but also studied at BNL. Only in the case of ^{21}O had the radioactivity not yet been observed. The $^9\text{Be}(^{18}\text{O}, 2p\alpha) ^{21}\text{O}$ reaction was used to produce the ^{21}O activity which was studied with a gas transfer system of novel design. Thirteen gamma rays in the decay of ^{21}O were observed in singles and gamma-gamma coincidence measurements and lead to detailed information on the structure of ^{21}F energy levels. The half-life of the activity was found to be 3.42 ± 0.10 sec. A value for the ^{21}O mass excess was determined via beta-gamma coincidence measurements which is in agreement with more accurate reaction Q-values. Shell-model calculations were carried out and reproduce the main features of the ^{21}O decay scheme. (D.E. Alburger, C.J. Lister, J.W. Olness, D.J. Millener)

C. Identification and Decay of ^{79}Sr , ^{80}Y , ^{81}Y , and ^{82}Y

Measurements and analysis were completed on four new isotopes in the A-80 region recently discovered at the Brookhaven Tandem Facility. These activities included ^{79}Sr (2.1 min), ^{80}Y (34 sec), ^{81}Y (73 sec), and ^{82}Y (9.5 sec) and were produced in the reactions ^{58}Ni (^{24}Mg , 2pn) ^{79}Sr , ^{58}Ni (^{24}Mg , pn) ^{80}Y , ^{58}Ni (^{25}Mg , pn) ^{81}Y , and ^{60}Ni (^{24}Mg , pn) ^{82}Y , respectively. A helium-jet recoil transfer technique was used and the gamma and beta rays were measured with Ge(Li) and plastic detectors. Decay schemes were established and mass excesses determined. The mass excesses show progressively larger deviations from the predictions of currently available mass models for the more neutron-deficient Y isotopes near the N=Z line which may reflect the influence of nuclear deformation of these isotopes on the mass surface in the vicinity of N=Z=40. (C.J. Lister, P.E. Haustein, D.E. Alburger, J.W. Olness)

D. Half-Life of ^{32}Si

^{32}Si is produced by cosmic-ray spallation reactions on argon in the upper atmosphere, whereupon it drifts to the earth's surface and mixes with ocean water. As a tracer ^{32}Si is used in studies of ocean currents, glacier formation, and the recent history of cosmic-ray flux on meteorites. For such studies the half-life of ^{32}Si must be known, but was only known as an estimate of ~300 yr. A sample of ^{32}Si produced at the BNL 3.5-MV Van de Graaff in 1969 was used to determine the half-life by combining two separate measurements. At Brookhaven the specific activity (^{32}Si disintegrations per minute per gram of Si) was found by standard counting methods, while at the Argonne National Laboratory the ratio $^{32}\text{Si}/\text{Si}$ in part of the same sample was determined to be $(2.82 \pm 0.50) \times 10^{-8}$. This latter measurement used the Tandem Van de Graaff together with an Enge split-pole magnetic spectrograph as a mass spectrometer. By combining the BNL and Argonne results the ^{32}Si half-life was found to be 101 ± 18 yr, considerably shorter than previous estimates. This new value will strongly influence studies of cosmogenic ^{32}Si in terrestrial, meteoric, and lunar materials. (W. Kutschera, W. Henning, M. Paul, R.K. Smither, E.J. Stephenson, J.L. Yntema (ANL); D.E. Alburger, J.B. Cumming, G. Harbottle (BNL))

IV. Fusion-Evaporation, Deep Inelastic, and Fission Reaction Mechanisms

A. Light Heavy-Ion Systems

1. Exit Channel Competitions: p2n, dn, t, etc.

Previous studies of heavy-ion induced reactions at the NRC Democritos Tandem Accelerator (Athens, Greece: Xenoulis and collaborators) disclose interesting features on the competition between exit channels leading to the same final nucleus. For example, the production of the 417-keV state of ^{26}Al by ^{12}C (^{16}O , pn/d) $^{26}\text{Al}^*$ ($E_x=417$ keV) illustrates a strong increase in the ratio d/pn as the bombarding energy is lowered from 38 to 24 MeV. These data clearly establish that such competition must be accounted for explicitly in comparisons of experimental and calculated cross sections.

Because these studies were limited in energy and range of target-projectile combinations, an extension of this measurement was undertaken at BNL. Ions of ${}^6\text{Li}$, ${}^{12}\text{C}$, and ${}^{16}\text{O}$ were used to bombard a 1 mg/cm^2 ${}^{12}\text{C}$ target, which was prepared on a Ta foil thick enough to stop the heavy bombarding ions. Light particles (p,d,t, α) were detected by a ΔE -E telescope placed at 0° relative to the incident beam, and coincident gamma rays were detected in a Ge(Li) detector at 90° to the beam. Data were analyzed by setting gates on gamma rays signalling a given final nucleus: The relative intensities in the E vs ΔE map then establishes the relative cross sections for the p vs d exit channels, or for p2n vs dn vs t. Data were taken over a range of target-projectile combinations and energies so as to significantly extend the previous work. At the higher energies available at BNL, it is also possible to assess the $2p2n/2d/\alpha$ competitions.

The results are now being analyzed in detail and compared to Hauser-Feshbach calculations. (A.C. Xenoulis (N.R.C. Democritos); R. Kozub (Tenn. Tech. Univ.); C.J. Lister, J.W. Olness (BNL))

2. ${}^6\text{Li}$ Evaporation in the Reaction ${}^{18}\text{O} + {}^{28}\text{Si}$ at $E_{\text{cm}}=60\text{ MeV}$

The evaporation of ${}^6\text{Li}$ nuclei from compound nuclei was recently observed for the first time at the Hahn-Meitner Institute in Berlin in singles experiments. A coincidence experiment was performed between the ${}^6\text{Li}$ detected in a solid-state telescope and the fusion products detected in a time-of-flight spectrometer at small angles. The purpose of the present measurement was to determine whether the ${}^6\text{Li}$ evaporation products follow fusion or are from transfer reactions with light impurities in the target or other reaction mechanisms. The experiment was done with 100-MeV ${}^{18}\text{O}$ ions from the 14-MV tandem of the Weizmann Institute of Science. The results confirm that there are ${}^6\text{Li}$ nuclei evaporated from the compound system; however, these are a small fraction of the total ${}^6\text{Li}$ yield. The energy spectrum and angular distribution of the ${}^6\text{Li}$ in coincidence with the fusion products were measured and are being compared with the predictions of evaporation calculations. (M. Lehr, I. Tserruya, Z. Frankel, E. Duering (Weizmann Institute of Science); J. Barrette (BNL))

3. Deep Inelastic Cross Sections in the Reaction ${}^{16}\text{O}({}^{16}\text{O}, {}^{16}\text{O}^*){}^{16}\text{O}^*$ at $E_{\text{cm}}=32.5\text{ MeV}$

Time dependent Hartree-Fock (TDHF) calculations predict that in the reaction ${}^{16}\text{O} + {}^{16}\text{O}$ at $E_{\text{cm}}=34\text{ MeV}$, central collision will not lead to fusion but to strongly inelastic binary events distributed over the entire angular range. To test this prediction the inelastic events corresponding to the reaction ${}^{16}\text{O}({}^{16}\text{O}, {}^{16}\text{O}^*){}^{16}\text{O}^*$ at $E_{\text{cm}}=32.5\text{ MeV}$ has been measured. Both ${}^{16}\text{O}$ fragments were uniquely determined by measuring particle-particle coincidences between a gas telescope covering a small solid angle and a very large solid angle two dimensional gas counter. The relative time of flight between the two counters was recorded leading to a kinematically complete measurement for binary events.

The Q value spectrum has large peaks corresponding to the excitation of the first-excited states in ^{160}O near 7 MeV and to the mutual excitation of both ^{160}O final products.

Less than 1 mb/sr cross section is observed for all ^{160}O events with Q values larger than 16 MeV. This small yield is inconsistent with the TDHF prediction of more than 100 mb and can be due to the absence of the reaction mechanism predicted by TDHF but it can also be due to the predominance of particle transfer for reactions at small impact parameters or to the particle decay of the excited ^{160}O nuclei. A more detailed analysis of the data will be done to investigate this point. (I. Tserruya, Z. Frankel, H. Lehr, E. Duering, A. Breskin (Weizmann Institute of Science); J. Barrette (BNL))

4. Complete Fusion of $^{28}\text{Si} + ^{28}\text{Si}$

The fusion-evaporation cross section and evaporation residue mass distribution was measured for the system $^{28}\text{Si} + ^{28}\text{Si}$ in the range $70 \leq E_{\text{cm}} \leq 95$ MeV. The fusion products were detected with the time-of-flight spectrometer. These data complement similar data obtained for the system $^{28}\text{Si} + ^{27}\text{Al}$ and are part of a study of the limiting or critical angular momentum for the fusion of medium mass system at high energy. Over the energy range studied the fusion cross section decreases as the bombarding energy increases indicating the presence of a high critical angular momentum for fusion. This is consistent with the predictions of various macroscopic models of heavy ion interaction. The system $^{28}\text{Si} + ^{28}\text{Si}$ is one of the systems for which time-dependent-Hartree-Fock calculations have predicted the presence of a low critical angular momentum below which no fusion should occur. The measured mass distribution is consistent with evaporation calculations without the inclusion of any such low critical angular momentum. More precise evaporation calculations are needed in order to reach a definitive conclusion for a low critical angular momentum. (J. Barrette, H.E. Wegner, C.J. Lister (BNL); P. Braun-Munzinger (SUNY))

5. The Reaction $^{28}\text{Si} + ^{28}\text{Si}$ at 160 MeV

The mass, atomic number and energy of all nuclei produced in the reaction $^{28}\text{Si} + ^{28}\text{Si}$ at $E_{\text{lab}}=160$ MeV were measured at $\theta_{\text{lab}}=16^\circ$ with the time-of-flight spectrometer complemented by a gridded ionization chamber to measure the specific energy loss of the reaction products. Complete mass and charge separation was obtained up to $A=40$ and $Z=20$. One of the aims of the experiment was to compare the cross section for the production of neutron deficient isotopes in deep inelastic reactions with the cross section using more conventional quasi-elastic transfer reactions. It has been demonstrated that deep inelastic reactions can successfully produce neutron rich isotopes. The diffusion process encountered in deep inelastic reactions can also be useful in generating neutron deficient isotopes. All the nuclei with $T_z=-1$ in the region of ^{28}Si have been observed with a large cross section of more than 100 $\mu\text{b/sr}$. This result is encouraging and it is expected that by reducing the background from known sources in the spectrometer the limit of presently known neutron deficient isotopes in this mass region will be reached.

The complete identification of the nuclides following deep-inelastic reactions between identical nuclei also provides unique information on the average mass and charge evaporated by the fragments. These quantities are related to the excitation energy and angular momentum deposited into the fragment. The evaporation of particles from the fragments creates an observable shift of 0.5 to 1 mass units toward the neutron rich side of the valley of stability. The mass distribution of the various elements are also not symmetric and reflect the drift from the $N=Z$ line to the minimum of the valley of stability. The analysis of these data is almost completed and the energy dependence of these phenomena will be studied during the next year. (J. Barrette, H.E. Wegner)

B. Evaporation Residues from Heavy Compound Nuclei

Evaporation residues from heavy compound nuclei can only be identified and studied as individual isotopes if they are first separated from the beam and target recoil particles. This separation at zero degrees and other angles is accomplished with the Energy Mass Separator or EMS. The recoil compound nuclei or evaporation products are separated from the intense beam particles by their unique heavy mass, high charge state and low velocity. Once separated, they are identified by their alpha decay and their daughter products, and the corresponding alpha decay energies and half-lives. The reactions described below are the heaviest compound nuclei under study at the Tandem Van de Graaff Facility and generally require the highest possible heavy ion energies and intensities.

1. Excitation Functions of Evaporation Residue from $^{37}\text{Cl} + ^{175}\text{Lu}$, ^{181}Ta , ^{186}W , and ^{198}Pt

Measurements of the evaporation residues from the fusion of ^{37}Cl with ^{175}Lu , ^{181}Ta , ^{186}W , and ^{198}Pt leading to the compound nuclei ^{212}Ra , ^{218}Th , ^{223}Pa , and ^{235}Am have been carried out with the EMS and are being analyzed. Further measurements will be made in some cases to extend the excitation functions for the various residual nuclei to higher energies in order to establish where the fusion evaporation cross section is maximum and at what excitation it largely disappears. The total fusion cross section for the compound nuclei ^{212}Ra , ^{218}Th , ^{223}Pa , and ^{235}Am are approximately 100 μb , 10 μb , 1.0 μb , and less than 0.1 μb , respectively. As the observed evaporation residues become more and more proton rich, proton and alpha evaporations predominate over neutron evaporation, similar to observations in lighter proton-rich nuclei. It is not clear from the present data analysis that any protoactinium isotopes are being formed by neutron evaporation from the compound nucleus ^{223}Pa . The evaporation residues that might be daughters formed by alpha decay of parent Pa isotopes may actually be parents formed directly by prompt alpha particle evaporation in addition to neutron evaporation. Half-life measurements will be necessary for final confirmation of any new Pa isotopes. The first preliminary measurement with ^{198}Pt showed a few alpha particles from evaporation residues, however confirmation of the formation of the ^{235}Am compound nucleus is not possible without better statistics. (A.C. DiRienzo, H.A. Enge, S.E. Gazes, M.K. Salomaa, A. Sperduto (MIT); W. Schier (Univ. of Lowell); H.E. Wegner (BNL))

2. A New Isotope $^{199}_{86}\text{Rn}$ and Evidence for the Isomeric State $^{199m}_{86}\text{Rn}$

The $^{35}\text{Cl} + ^{169}\text{Tm} \rightarrow ^{204}\text{Rn}$ reaction was used to produce a new radon isotope and its isomeric state by 5 neutron-evaporation from the compound nucleus. Since the yield was less than 0.1 ub for the production of this new radon isotope, ^{199}Rn , a different reaction was investigated in the hope that the isotope could be made with a much better yield. The $^{40}\text{Ca} + ^{162}\text{Dy} \rightarrow ^{202}\text{Rn}$ reaction forms the desired ^{199}Rn isotope with only a 3-neutron evaporation as compared with 5-neutron evaporation from ^{204}Rn . Preliminary data have been analyzed for this reaction; however, it was found that most of the neutron evaporations were accompanied by proton or alpha particle evaporations, and the yield for the production of the new isotope was less than observed in the previous reaction and may actually be zero. However, the work is continuing because it is possible that the excitation function was not studied to high enough energy to provide an optimum yield. If reactions of ^{40}Ca with any Dy isotopes will form ^{199}Rn with much higher yield, it may be possible to form even lighter isotopes like $^{198,197}\text{Rn}$. (A.C. DiRienzo, H.A. Enge, S.B. Gazes, M.K. Salomaa, A. Sperduto (MIT); W. Schier (Univ. of Lowell); H.E. Wegner (BNL))

3. Possible Entrance Channel Effects in the Formation of ^{204}Rn by $^{35}\text{Cl} + ^{169}\text{Tm}$, $^{48}\text{Ti} + ^{156}\text{Gd}$ and $^{65}\text{Cu} + ^{139}\text{La}$

Since there is some evidence in all the measurements to date with the EMS that entrance channel effects may play a strong role in the formation of different evaporation residues, measurements of $^{35}\text{Cl} + ^{169}\text{Tm}$, $^{48}\text{Ti} + ^{156}\text{Gd}$ and $^{65}\text{Cu} + ^{139}\text{La}$, all of which form ^{204}Rn , were made to see if any such effects could be directly observed. For the more symmetric ^{65}Cu reaction compound nucleus formation at the Coulomb barrier corresponds to a ^{204}Rn excitation energy of 35 MeV, while for the more asymmetric $^{48}\text{Ti} + ^{156}\text{Gd}$ and $^{35}\text{Cl} + ^{169}\text{Tm}$ reactions it corresponds respectively to a ^{204}Rn excitation of 43 and 52 MeV. All of the evaporation residues for each reaction were studied over the maximum excitation range available within the energy limits of the three-stage tandem. Unfortunately, the maximum available ^{65}Cu energy does not provide an excitation energy that overlaps the ^{35}Cl excitation energy beyond the Coulomb barrier region. The overlap for the ^{48}Ti excitation region is also limited because of the limited ^{48}Ti energy range. In the limited overlapping regions the yields for the different residues corresponding to 3n, 4n, 3np and 4np evaporations share no common ratios between the three compound systems formed in these three reactions, although the compound nuclei are, in principle, identical in excitation in the overlap regions except for small differences in angular momentum. Comparisons of these data with evaporation calculations show little or no agreement for the relative yields of different evaporation residues. The energy range of these measurements will be extended and further calculation will be carried out in an attempt to understand these fusion-evaporation processes in more detail. (A.C. DiRienzo, H.A. Enge, S.B. Gazes, M.K. Salomaa, A. Sperduto (MIT); W. Schier (Univ. of Lowell); H.E. Wegner (BNL))

V. Atomic Physics

A. Molecular Structure by Coulomb Explosion

These studies are undertaken in an attempt to gain structural information on molecular ions by exploring the Coulomb explosion of the positive atomic fragments following the passage of a fast molecular ion through a thin carbon foil. The greatest merit of this novel technique is that it makes possible the study of molecular species largely inaccessible by more conventional methods.

The Coulomb explosion of $C_3, 4, 5$ and $CNO^{+,-}$ molecules were studied by the use of polycarbonate foils. These unusual molecular ions are produced by a sputtering process either in the terminal source of the MP6 injector accelerator or externally and then gas charge exchanged to positive in the stripper canal. When the molecules pass through a $1 \mu\text{g}/\text{cm}^2$ carbon foil, the molecular bond is broken and the neutral heavy ion constituents are instantly stripped to a charge distributed over several charge states. The mutual repulsion between the charged ions at molecular separations then disassembles the molecule in the form of a miniature explosion. The charged ion components of the molecule then travel a few centimeters to a polycarbonate foil where they are imbedded. This plastic sheet is subsequently electrochemically etched so that the impact points of the heavy ions can be observed under a microscope. Extensive microscopic analyses of C_3 , CNO^- and CNO^+ molecular explosion events have been made and 83 C_3 events, 87 NCO^- events and 33 NCO^+ events have been unambiguously identified and sorted for further study.

The spatial orientation of the three particle events varies from three particles at relative uniform spacings in a straight line or extreme obtuse triangle to extremely acute triangles. These triangle events have all been sorted into a two dimensional array where the longest side of a triangle, l , is plotted as a function of the ratio, R , of the altitude, d , to the longest side or d/l . These distributions can then be compared to theoretical models of the original molecule programmed through the Coulomb explosion taking into account the random orientation of the molecule, the charge state distributions of the heavy ion components of the molecule, multiple Coulomb scattering of the component ions, and the original wave function of the molecule.

The limited statistics of these first measurements indicate that the effective temperature of these sputtered molecules must be several thousand degrees Kelvin. However, better statistics and more detailed calculations will be necessary before any distinction can be made between triangle structure or an extremely flexible rod-like structure for the original molecule. (P. Thieberger, H.E. Wegner, (BNL); G. Goldring (Weizmann Institute))

B. Atomic Physics with Heavy-Ion Beams

1. Beam Foil Spectroscopy

The beam foil spectroscopy program is presently concentrating on research in two areas. First, studies are being conducted on radiation emitted in the range from 5-100 nm by elements of interest to the Magnetic Fusion Energy Program. Work has concentrated on the measurement of spectra for Zr since this may be present as a contaminant in the new TFTR device at Princeton and on gold to search for Pm-like resonance lines in Au XIX which may be useful for diagnostic

purposes. Second, a 2-m normal incidence spectrometer was loaned to the program by Oak Ridge National Laboratory for an experiment to measure the 2-electron Lamb shift in titanium. The spectrometer was placed in operation, and initial experiments to test the feasibility of the work will be carried out during this period.

2. Ion-Atom Collisions

Ion-atom collisions can be studied in a variety of ways. One of the most interesting and widely investigated topics has been the worldwide attempt to understand the mechanisms involved in the production of inner-shell vacancies during the collision of complex multi-electron systems. The only detailed theoretical calculations, the rotational coupling model, has assumed that the mechanism for K-vacancy production requires a vacancy in the $2p\sigma$ molecular orbital. The experimental observation of a sudden increase in K x-ray cross sections for nearly symmetric collisions as the $2p\sigma$ vacancies are introduced by appropriate choice of the projectile charge state has been taken as proof of this theoretical picture. However, an experiment has been performed which measures the charge state for the case of nearly symmetric collisions where the cross section should depend on the $2p\sigma$ vacancies and these values have been compared to the case of very asymmetric collisions where such a dependence is not expected. Surprisingly, the results were essentially the same for the two cases, thus showing that this type of experiment cannot be taken as an unambiguous test of the rotational coupling model, or it could be speculated that the mechanisms were indeed similar for the two cases. Many further experiments are suggested by this result. The accel-decel mode in which ions are first accelerated and then decelerated will be an invaluable aid in giving great flexibility in choosing charge state and velocity for further experiments to refine our ideas of these vacancy production mechanisms.

Work in the field of ion-atom collisions concentrated on the development of new experimental equipment and techniques, although collaborative experiments on double K-shell-to-K-shell processes were also undertaken. A 16-ring annular parallel plate avalanche detector and associated electronics was substantially fabricated and will soon undergo initial tests. This detector will be used in conjunction with single-collision gas jet and differentially-pumped gas cell targets for study of characteristic and noncharacteristic x rays. The scope of the experiments will be greatly expanded by the unique capability of the BNL Tandem Facility to produce highly-charged low-velocity ions which is accomplished by using the final stage of the second tandem to decelerate the ions when operating in a four-stage mode. Studies of charge state dependence and excitation curves for the various processes to be investigated will be feasible for the first time and cannot be done anywhere else in the world.

3. Excitation and Ionization of Heavy Ions by Electrons

Studies of the excitation and ionization of heavy ions by electrons give data essential to understanding many aspects of atomic structure and high temperature plasmas. These experiments, involving crossed or merged beams, are exceedingly difficult, a statement borne out by the fact that as yet no experiments of this nature have been attempted with a tandem. Work is continuing on the assembly and testing of equipment for study of electron impact excitation and ionization of heavy ions. Testing of the charge state deflectors is in progress, and design work for detection systems will begin in the near future. Much of the

apparatus will also be generally useful for the measurements on ion-atom collisions systems as well. It is expected that this work will develop into a very substantial field with measurements on the charge state distributions of the ions as well as elaborate electron spectroscopy measurement. (B. M. Johnson, D. C. Gregory, K. W. Jones (BNL); J. L. Cecchi (Princeton); P. Richard, J. Hall, T. J. Gray (Kansas State U.); T. H. Kruse (Rutgers); L. J. Curtis (U. of Toledo, Ohio); H. G. Berry, R. Brooks (ANL); R. Schuch (Heidelberg); I. Tserruya (Weizmann Inst.); H. Schmitt-Böcking (Frankfurt U.))

C. Energy Loss of Heavy Ions in Single Crystals

An ion can traverse a channel in a single crystal without experiencing any charge-changing collisions. This fact has been used to determine the charge state dependence of channeled heavy ion energy loss for a series of ions ranging from fluorine to chlorine along the $\langle 110 \rangle$ direction in a silicon crystal. Energy losses for both bare ions and ions partially clothed with bound electrons at $E/A = 3.1$ MeV/amu were measured.

These data are particularly interesting because the most stringent constraints to date are placed on the magnitude of terms of order Z^3 and higher in theories of energy loss of ions in matter. The accepted Bethe theory contains only Z^2 , but recent corrections to this theory contain Z^3 and Z^4 terms, for which little direct experimental evidence exists. The energy loss measured in this experiment shows a strict Z^2 scaling and agrees reasonably well with the Bethe theory without the need for Z^3 and Z^4 terms. The data for partially clothed ions were compared to a simple theory for the effect of bound electron screening on the energy loss and give reasonable agreement. (J.A. Golovchenko (Bell Labs); H. Knudsen, C.D. Moak (ORNL); A.N. Goland, J.S. Rosner, C.E. Thorn, H.E. Wegner (BNL))

VI. Instruments

A. General Purpose NaI Total Energy Spectrometer

Study of nuclear systems at very high angular momentum constitutes one of the most exciting and rapidly developing fields in nuclear physics today. At present, high-spin states are being studied by both discrete gamma-spectroscopy and continuum gamma-ray methods. The spectroscopy of high-spin states can only be extended by using more novel and powerful gamma-ray detection systems. The sum spectrometer is a particularly valuable tool for this purpose. It is a large volume NaI detector, which is capable of registering nearly the sum total of the gamma-ray energies emitted in a cascade. Provisions are made for the beam entrance and exit, as well as additional ports to accommodate the gamma-gamma coincidence experiments. When used in conjunction with a Ge(Li) detector, it forms a powerful filter to assist in the detection of weak gamma-rays emitted from the high-spin states. In connection with the proposed research projects at BNL, the following uses for the sum spectrometer may be envisioned:

1. To enhance the detection sensitivity of the high-spin states populated through Coulomb excitation or (HI,xn) reactions.
2. To detect the total energy of a cascade of delayed gamma-rays emitted from an isomeric state. This information will serve to determine the approximate energy and spin of the isomeric state when combined with a multiplicity filter.

3. To study the decay of the entry states and side feeding patterns in the residues of the compound nuclei formed in the (HI,xn) reactions.

4. To investigate the changes in the effective moment of inertia as a function of spin at very high angular momentum ($J > 40$) in deformed nuclei. (C. Baktash, E. K. Warburton)

B. Multiple Event 2D Image Intensifier Scintillation Detector

The experimental necessity of detecting simultaneous multiple low energy heavy ions from the Coulomb explosion of accelerated molecules has led to the modernization of a visually monitored phosphor detector system as originally used by Rutherford and collaborators. A thin monolayer phosphor scintillator coating is applied uniformly on the input fiber optic plate of a commercially available image intensifier. The image intensifier is a three-stage unit with a light gain of 85,000. In operation, the image intensifier is enclosed in a simple cylindrical aluminum shell and O-ring seal so that the input fiber optic plate is coupled conveniently into the vacuum system with the rest of the Coulomb explosion apparatus. A television camera equipped with a high sensitivity television tube views the output fiber optics with a magnification arranged to fill most of the vertical dimension of a conventional television monitor. A small photomultiplier tube adjacent to and off-axis from the camera lens provides fast trigger signals that are used by the logic of a television digitization system.

A commercially available television digitizing system is used to digitize the scintillation light images provided by the television camera. This unit has 64 K byte memory and two 8 inch floppy discs for system programs and data storage. The system digitizes the camera video signal continuously into 128 horizontal by 256 vertical pixals so that two stored frames utilize 32 K of memory. The intensity in each pixal is digitized to a 4 bit level. The system is programmed so that trigger pulses from the photomultiplier guarantee that all of the stored and analyzed events are single events within the television frame speed (i.e., one event in one thirtieth of a second). When the buffer store in memory is full, it is transferred onto the floppy disc which can then be read into a file of an XDS Sigma 7 computer for further analysis.

This new system has been used to study the Coulomb explosion of $C_n^-(n=1-6)$, C_3^+ , NCO^- , NCO^+ and the multiple scattering of carbon ions in carbon foils. The original etched polycarbonate detector system involved several weeks of work for the analysis of approximately 200 events. The electronic image intensifying system and TV digitizing system allows approximately 2000 events to be recorded and analyzed in final form in three hours. Similar systems based on the experience with this system are being planned at ANL and the Weizmann Institute where similar kinds of Coulomb explosion studies are being investigated. (H.E. Wegner, P. Thieberger)

C. High Mass Product Bending Magnet for MP6

One of the surplus SREL beam transport magnets was installed in the beam transport line between MP6 and MP7. With modified pole tips the magnet provides a 160° bend for heavy ions accelerated by MP6 corresponding to any energy-mass product of 1000. The high mass product allows direct testing of heavy ion beams suitable for injection into the cyclotron booster and also allows the molecular structure studies by Coulomb explosion to be extended up to molecules as complex as C_{12} . The Coulomb explosion study beam line in target room #1 was also moved to the high energy end of MP6 in order to utilize the new magnet. Additional small surplus magnets were installed in the line to replace a permanent magnet 5 degree bending capability that was awkward to adjust and also to allow for charge state separation of the Coulomb exploded ions. (P. Thieberger, H.E. Wegner)

VII. Post-Accelerator Development

Last year a cyclotron booster to the Tandem accelerators was designed and proposed to DOE for FY 1981 funding. The cyclotron design was based upon the use of the SREL synchro-cyclotron disassembled and stored at BNL. The proposal was reviewed by NSAC and given a deferred status to enable NSAC to have time to consider the effect of the required operating budget on the overall heavy ion program in the U.S.

The design of the cyclotron has continued at a reduced level this year largely because of the thoroughness of the earlier effort. However, several design aspects were reexamined in greater detail. In particular, the novel magnet pole tip design was refined and the effects of pole slant angle and valley shims better understood. Magnetic measurements were made on the iron used in the model magnet and iron from the actual SREL cyclotron to confirm the expectations that the model was giving a realistic picture of the SREL magnet. In addition, the 1/3 scale R.F. model was retested and measurements made of its Q and voltage distribution. Further measurements were made of the tuning panel range, and additional theoretical calculations were made. The results of the R.F. development confirm the earlier results as given in the submitted proposal. The buncher calculations have been redone taking into consideration the longitudinal emittance of the beam both from the source and from the tandem terminal gas stripping. New values for voltage and frequency of the rebuncher have been obtained which are somewhat different from those of the submitted proposal. However, the new values are well within the range of conventional technology and cause no change in the characteristics of the anticipated beams accelerated by the cyclotron. The tandem terminal voltage increase to ~16 MV expected this year should result in an increase in the energy of the cyclotron beams above mass 60. New charge states have been calculated for different beams and a conservative 20% increase in energy for all beams above mass 60 can be expected. The uranium beam will therefore be at 20 MeV/A rather than ~16 MeV/A as in the original proposal.

The machine and building costs have been reviewed prior to resubmission of the proposal for funding in FY 1983. Prices are up an average of 11.7%, raising the total cost to \$12.070M January 1981 dollars. (C. Chasman, C. Thorn)

A. Design of Magnetic Field for the 500 cm Cyclotron

Pole tips and trim coils were designed to provide the magnetic field for a 500 cm diameter heavy ion cyclotron using the magnet steel and main coils from the decommissioned SREL synchrocyclotron. This design is based on measurements with an 18" diameter scale model of the SREL magnet and on calculations with the magnetic field code TRIM. The pole tip configuration incorporates unique features with the result that highly desirable focussing, injection, and extraction properties are obtained for a broad range of beams (^{12}C to ^{238}U) and energies (dynamic range about 15 to 1) with very small power dissipation in the trim coils.

The magnetic field measurements were made with a Hall probe mounted on a three axis translator. A microprocessor system was fabricated to automate the field mapping procedure, and to transfer the data directly into the Sigma 7 computer for processing and analysis. Each complete scan of a pole tip required 30,000 points (41 radial x 46 aximuthal x 16 excitation points). Measurements of the response of trim coils were also made for several trim coil configurations. The measured field and trim field data were combined by the Sigma 7 computer to produce isochronized field maps for direct use by beam dynamics and ray tracing programs on the 7600 computer.

For conventional pole tips, with uniform gap, hills and valleys, all isochronism must be provided by the trim coils and their maximum power dissipation is then about one megawatt. The design developed in this study replaces the conventional solid hill poles with pole tips mounted over a small secondary gap which tapers radially from a maximum at the magnet edge to zero near the center. This "flying hill" geometry results in an effective channeling of magnetic flux from the center toward the edge of the magnet, without the usual increase in fringing, which produces a radially increasing field that is more nearly independent of power to a maximum of 70 kilowatts, the "flying hills" also produce a more nearly constant shape and magnitude for the flutter factor, eliminating the need for flutter coils and increasing the dynamic range of the cyclotron. A detailed design incorporating these hills has been prepared for converting the SREL synchrocyclotron into a variable energy heavy ion isochronous cyclotron.

VIII. Outside User Program

The Tandem Facility research time is shared approximately equally between BNL scientific staff and the outside user community. Outside user running time is allocated on the basis of recommendations from the Tandem Program Advisory Committee. Membership on this Committee is rotated, new members being chosen with the advice of the Executive Committee of the Tandem Users Discussion Group. The members of this Committee during the fiscal year 1980 were: John Alexander (SUNY, Stony Brook); Benjamin F. Bayman (U. of Minnesota); H. Gordon Berry (ANL); James L. Ford, Jr. (ORNL); Lee Grodzins (MIT); Walter Henning (ANL); Albert E. Litherland (U. of Toronto); Arthur Z. Schwarzschild (BNL), chairman; Ottmar C. Kistner (BNL), Secretary and Outside User Liaison.

During the fiscal year 1980 the Committee approved 25 new proposals for running at the BNL Tandem Facility. During this period 24 experiments were completed. The experimental questions addressed cover a broad range of heavy-ion topics--mostly nuclear physics, together with the physics of highly stripped atoms. Experiments utilizing compound nucleus reactions are taking a larger and larger fraction of the time, and this year have dominated over the study of direct reaction mechanisms. Of increasing importance for these experiments is the recently improved MIT-BNL Recoil Mass Spectrometer. These experiments, which are pushing to ever heavier compound systems, require the highest possible energies and the full range of beams that are available at the BNL Facility. One new proposal is noteworthy in that it promises to be a forerunner of a new group of atomic physics experiments. This experiment makes use of the unique capability of the BNL Facility to provide beams of fully stripped heavy ions at very low energy by operating in a four-stage accel-decel configuration. The QDDD spectrometer continues to be basic to many of the experiments, and the flexible data-taking capability provided by the on-line computer is vital to all of them. The Users Liaison Group supports the outside user so that these capabilities can be employed easily and fully.

A list, by title of approved experiments completed in FY 1980, follows:

#235. Energy dependence of quasielastic reactions of intermediate mass systems. T. M. Cormier, B. R. Fulton, and B. Herman (U. of Rochester).

#245. Resonances in the $^{16}\text{O}(^{16}\text{O}, ^{16}\text{O}(O_2+))^{16}\text{O}$ and $^{16}\text{O}(^{18}\text{O}, ^{16}\text{O}(O_2+))^{18}\text{O}$ reactions. W. Freeman, W. Piel, H. Wilschut, P. Paul (SUNY, Stony Brook).

#247. Supercluster transfer via heavy-ion induced reactions. J. Janecke, F. Becchetti, D. Overway (U. of Michigan); G. Kekelis (Williams College).

#253. Q-value dependence of heavy-ion scattering. J. Karp, R. Ledoux, S. Gazes, S. Steadman (MIT).

#255. Beam foil spectroscopy. J. L. Cecchi (Princeton Plasma Physics Laboratory); T. H. Kruse (Rutgers); K. W. Jones, B. M. Johnson, D. C. Gregory (BNL).

#257. $^{12}\text{C} + ^{12}\text{C}$ direct reaction cross sections. R. E. Malmin, J. J. Kolata, S. Tripathy (U. of Notre Dame).

#260. K-shell to K-shell electron transfer. T. J. Gray, J. M. Hall, P. Richard (Kansas State U.); B. M. Johnson, K. W. Jones, D. C. Gregory (BNL).

#261. Spins of $^{28}\text{Si} + ^{28}\text{Si}$ resonances. R. R. Betts, J. F. Petersen, S. B. DiCenzo (Yale U.); B. B. Back, K. L. Wolf (ANL).

#262. Beam foil spectroscopy. J. L. Cecchi (Princeton Plasma Physics Laboratory); T. H. Kruse (Rutgers); K. W. Jones, B. M. Johnson, D. C. Gregory (BNL).

#263. Complete fusion cross section measurements for $^{16}\text{O} + ^{181}\text{Ta}$ and $^{37}\text{Cl} + ^{160}\text{Gd}$. J. Ball, S. Steadman, S. Gazes, H. A. Enge (MIT).

#265. Half-lives of new isotopes and isomers, ^{199}Rn , $^{199\text{m}}\text{Rn}$, ^{172}Pt , ^{168}Os , $^{173\text{m}}\text{Ir}$ and $^{171\text{m}}\text{Ir}$. W. Schier (U. of Lowell); H. A. Enge, A. Sperduto, M. Salomaa, A. DiRienzo (MIT); H. E. Wagner (BNL).

#266. Sub-barrier fusion of massive nuclei. M. Beckerman, H. A. Enge, A. Sperduto, M. Salomaa, J. Ball, S. Gazes, J. Molitoris (MIT).

#269. Search for high spin states populated via reactions of ^{51}V with ^7Li . R. L. Kozub, J. Lin, J. F. Mateja, J. C. Wells (Tenn. Tech. U.); E. K. Warburton, C. J. Lister (BNL).

#271. Investigation of possible pre-equilibrium particle emission accompanying heavy-ion fusion. H. A. Enge, J. D. Molitoris, W. A. Schier, A. Sperduto, M. Salomaa, A. Di Rienzo (MIT).

#272. Fusion cross section measurements for $^{13}\text{C} + ^{14}\text{N}$ and $^{10}\text{B} + ^{17}\text{O}$. Y.-d. Chan, D. E. DiGregorio, J. L. C. Ford, J. Gomez del Campo, M. E. Ortiz, D. Shapira (ORNL).

#273. $^{12}\text{C}(^{24}\text{Mg}, \alpha)^{32}\text{S}$, $^{12}\text{C}(^{18}\text{Si}, \alpha)^{36}\text{Ar}$, and $^{12}\text{C}(^{32}\text{S}, \alpha)^{40}\text{Ca}$ excitation functions. E. Cosman, R. Ledoux, M. Beckerman, S. Steadman, M. Brodheim, G. Lavelle (MIT); A. Lazzarini (U. of Washington).

#274. Gamma-ray multiplicities of fission fragments from fusion fission. S. Steadman, J. Ball, S. Gazes, L. Grodzins (MIT).

#275. Gamma-ray multiplicity following alpha particle and neutron emission in the reaction (120-200 MeV) $^{37}\text{Cl} + ^{107}\text{Ag} \rightarrow ^{144}\text{Gd}$ using the recoil product selector (RPS) at 0 to 10° . L. Grodzins, H. Enge, J. Ball, S. Steadman (MIT).

#277. Sequential fission of light nuclei via molecular resonances. T. M. Cormier, P. M. Stwertka, B. Herman (U. of Rochester); H. E. Wegner (BNL).

#280. Coulomb excitation of ^{248}Cm using 260 MeV ^{58}Ni ions. D. Cline, T. Czosnyka, L. Hasselgren, C. Wu (U. of Rochester); R. M. Diamond, F. S. Stephens (LBL); E. V. Hulet (LLL); C. Baktash (BNL).

#281. Beam foil spectroscopy. J. L. Cecchi (Princeton Plasma Physics Lab); T. H. Kruse (Rutgers); K. W. Jones, B. M. Johnson, D. C. Gregory (BNL).

#282. Explicit investigation of the 19.7 MeV resonances in $^{16}\text{O} + ^{12}\text{C}$. H. W. Wilschut, T. R. Renner, R. Freifelder, P. Braun-Munzinger (SUNY, Stony Brook).

#284. Lifetime measurements using the RDM and $^{18}\text{O} + ^7\text{Li}$ reactions. R. L. Kozub, J. Lin, J. F. Mateja (Tenn. Tech. U.); E. K. Warburton, C. J. Lister (BNL).

#293. Investigation of the $\pi g_{9/2} \otimes \nu g_{9/2}$ system in the Rb isotopes. M. A. J. Mariscotti, G. Garcia Bermudez, A. J. Kreiner (CNEA, Argentina); C. Baktash, E. der Mateosian, P. Thieberger (BNL).

Thus far in FY 1981 there are 22 experiments which have been carried over from the previous year or have been newly approved for running. Following is a list of these experiments which are in various stages of completion or preparation:

#95. Lamb shift study of Cl^{16+} . D. E. Murnick, C. K. N. Patel, M. Leventhal, O. R. Wood II (Bell Laboratories); H. W. Kugel (Rutgers).

#264. A. New protactinium isotopes produced with the $^{37}\text{Cl} + ^{186}\text{W}$ reaction. B. New radon isotopes produced with the $^{40}\text{Ca} + ^{161,162,163,164}\text{Dy}$ reactions. H. A. Enge, A. Sperduto, M. Salomaa, A. DiRienzo (MIT); W. Schier (U. of Lowell); H. E. Wegner (BNL).

#276. Relativistic and QED effects in 2-electron titanium. H. G. Berry, R. Brooks, R. DeSerio (ANL); A. E. Livingston (Notre Dame); K. W. Jones, B. M. Johnson, D. C. Gregory (BNL).

#279. A. Clean up of $^{37}\text{Cl} + ^{186}\text{W}$ and $^{40}\text{Ca} + \text{Dy}$. B. Preliminary investigation of new reactions leading to more massive systems ($A_{\text{C.N.}} > 220$). H. A. Enge, T. DiRienzo, M. Salomaa, A. Sperduto (MIT); W. Schier (U. of Lowell); H. E. Wegner (BNL).

#283. Search for direct gamma transitions in $^{12}\text{C} + ^{12}\text{C}$ resonances. R. L. McGrath, T. Renner, D. Abriola, S. Y. Zhu (SUNY, Stony Brook).

#285. Search for level crossings in the $^{199}\text{Hg}/2 \otimes ^{213}\text{Po}/2$ system and associated isomerism in the lighter ($A \leq 190$) doubly odd Tl isotopes. A. J. Kreiner, M. A. J. Mariscotti (CNEA, Argentina); C. Baktash, E. der Mateosian, P. Thieberger (BNL).

#286. Study of gamma-gamma correlation in ^{176}W and ^{182}Os . J. X. Saladin (U. of Pittsburgh); I. Y. Lee (ORNL); C. Baktash (BNL).

#287. Backward angle cross sections for $^{28}\text{Si} + ^{12}\text{C}$ reaction products. D. Shapira, J. L. C. Ford, R. Novotny, K. A. Erb (ORNL).

#288. Near- and sub-barrier fusion of $^{58,64}\text{Ni} + ^{74}\text{Ge}$ and $^{74}\text{Ge} + ^{74}\text{Ge}$. M. Beckerman, M. Salomaa, H. Enge, A. Sperduto (MIT).

#289. High spin spectroscopy for $Z > 82$ neutron deficient transition region: search for collectivity in Bi and At isotopes. T. Chapuran, K. Dybal, D. Fossan, W. Piel (SUNY, Stony Brook); D. Horn, E. K. Warburton (BNL).

#290. Fine structure in $^{28}\text{Si} + ^{28}\text{Si}$ excitation functions. R. R. Betts, B. B. Back, B. Glagola, K. L. Wolf (ANL).

#291. Gamma-ray multiplicity of evaporation residues. M. Al-Kofahi, S. Steadman, S. Gazes, M. Salomaa (MIT).

#292. Pre-equilibrium light particle emission in deep-inelastic heavy-ion collisions. S. Gazes, S. Steadman, J. Karp (MIT).

#294. Beam-foil excitation of VUV spectra of Au XIX. L. J. Curtis (U. of Toledo, Ohio); K. W. Jones, B. M. Johnson, D. C. Gregory (BNL).

#295. $^{24}\text{Mg}(^{16}\text{O}, ^{12}\text{C})^{28}\text{Si}$ reactions at backward angles. S. J. Sanders (Yale); W. Henning, J. P. Schiffer, H. Ernst (ANL); J. Barrette (BNL).

#296. Nuclear structure in Ni-Ge and Ge-Ge complete fusion. M. Beckerman, M. Salomaa, H. Enge (MIT); A. DiRienzo (USMA, West Point).

#297. Spectroscopic studies of neutron-deficient Zr, Nb, and Mo isotopes, $A \leq 90$, via $^{58}\text{Ni} + ^{28}\text{Si}$ and $^{58}\text{Ni} + ^{32}\text{S}$ reactions. R. A. Naumann, R. Dewberry (Princeton); P. E. Haustein, J. W. Olness, D. E. Alburger (BNL).

#298. Development of BNL 4-stage tandem decelerator facility and its use for atomic physics experiments. R. Schuch (Heidelberg U.); H. Schmit-Böcking (Frankfurt U.); I. Tserruya (Weizmann Inst.); K. W. Jones, J. Barrette, B. M. Johnson, D. C. Gregory (BNL).

#299. Gamma-ray multiplicity of evaporation residues. M. Al-Kofahi, S. Steadman, M. Salomaa (MIT).

#300. Gamma-ray multiplicities of fission fragments from fusion-fission. S. Steadman, A. Smith, M. Al-Kofahi (MIT).

#301. Backward angle scattering at high energies for the systems $^{12}\text{C} + ^{28}\text{Si}$ and $^{16}\text{O} + ^{28}\text{Si}$. T. Renner, P. Braun-Munzinger (SUNY, Stony Brook); J. Barrette (BNL).

#302. Transfer-induced molecular resonances. J. Karp, R. McGrath, T. Renner, D. Abriola (SUNY, Stony Brook).

An important part of the outside user program is the Brookhaven Summer Visitors Program. This program affords invited scientists from other institutions the opportunity to perform experiments at the Tandem in collaboration with BNL scientists while resident at Brookhaven for a period of one month or longer. In addition to the valuable exchange of ideas and experimental techniques, this program can provide an excellent opportunity for prospective outside users to gain experience in carrying out experiments at the BNL Tandem.

A total of 77 scientists representing 24 outside institutions carried out experiments at the Tandem Facility in FY 1980. Their names and affiliations appear below.

J. Ball (MIT), F. Becchetti (U. Michigan), M. J. Bechara (MIT), M. Beckerman (MIT), R. Betts (ANL), P. Braun-Munzinger (SUNY, Stony Brook), W. Brandt (NYU), J. L. Cecchi (Princeton), Y.-d. Chan (ORNL), T. Chapuran (SUNY, Stony Brook), Y. Chen (MIT), D. Cline (U. Rochester), T. Cormier (U. Rochester), E. Cosman (MIT), T. Czosnyka (U. Rochester), S. B. DiCenzo (Yale), A. DiRienzo (MIT), K. Dybdal

(SUNY, Stony Brook), H. Enge (MIT), L. Engstrom (U. Lund, Sweden), D. Fields (Tenn. Tech. U.), J. L. C. Ford (ORNL), D. Fossan (SUNY, Stony Brook), W. Freeman (SUNY, Stony Brook), R. Freifelder (SUNY, Stony Brook), B. R. Fulton (U. of Rochester), D. Gannett (MIT), G. Garacia Bermudez (CNEA, Argentina), S. Gases (MIT), D. DiGregorio (ORNL), B. G. Goldring (WIS, Israel), J. Gomez del Campo (ORNL), T. Gray (Kansas State U.), L. Grodzins (MIT), J. Hall (Kansas State U.), L. Harwood (MSU), L. Hasselgren (U. of Rochester), B. Herman (U. of Rochester), O. Ila (MIT), K. Johnson (U. of Michigan), J. Karp (MIT), G. Kekelis (Williams), R. Kozub (Tenn. Tech. U.), A. J. Kreiner (CNEA, Argentina), T. H. Kruse (Rutgers), H. W. Kugel (Rutgers), R. LeDoux (MIT), M. Leventhal (Bell Laboratories), J. Lin (Tenn. Tech. U.), C. Maguire (Vanderbilt U.), M. A. J. Mariscotti (CNEA, Argentina), M. C. Mermaz (SPNBE/CEN Saclay, France), J. F. Mateja (Tenn. Tech. U.), J. Molitoris (MIT), D. E. Murnick (Bell Laboratories), M. Nai-Feng (MIT), A. Nathan (U. of Illinois), C. E. Ordonez (MIT), M. E. Ortiz (ORNL), D. Overway (U. of Michigan), C. K. N. Patel (Bell Laboratories), P. Paul (SUNY, Stony Brook), J. F. Peterson (Yale), W. F. Piel (SUNY, Stony Brook), T. Renner (SUNY, Stony Brook), P. Richard (Kansas State U.), W. Schier (U. of Lowell), D. Shapira (ORNL), A. Smith (MIT), A. Sperduto (MIT), S. Steadman (MIT), P. M. Stwertka (U. of Rochester), R. Valicenti (MIT), D. Wilkinson (U. of Sussex, England), H. Wilschut (SUNY, Stony Brook), O. R. Wood (Bell Laboratories), C. Wu (U. of Rochester), A. Xenoulis (NRC, Greece).

CHARGED PARTICLE RESEARCH - LIGHT IONS AND GENERAL NUCLEAR SCIENCE

Preamble

The Tandem Van de Graaff Facility furnishes high-energy beams of light ions ($A \leq 4$) of high quality. The 3.5-MV Van de Graaff is a useful adjunct to the Tandem since it provides low-energy, light-ion beams. These facilities complement the heavy-ion facility so that altogether a broad spectrum of research programs can be studied. The major emphasis is focused on obtaining information on properties of individual nuclear levels. Frequently, these studies are directed toward specific problems of fundamental nucleon interactions and weak interaction physics. Decay properties of short-lived off-stability nuclides produced by light-ion bombardments are studied in parallel with the heavy-ion produced species. Studies of specific residual nuclei produced by both light- and heavy-ion induced reactions permit exploration of the same system under vastly different conditions of energy and angular momentum. The 3.5-MV Van de Graaff has been valuable in the testing of equipment and targets and is indispensable for those experiments on fundamental interactions which are too time consuming for the Tandem Facility. It is also useful for applied studies such as the gamma-ray precision energy measurement program.

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I. Beta Decay and Weak Interactions

A. The General Program

There are several reasons for the increased activity in this general area at the present time. The most important is the stimulus of the predictive ability of the large-basis shell-model program developed by D. J. Millener of the Nuclear Theory Group. This program permits--for the first time--an omnibus comparison of first-forbidden decays as well as allowed beta-decay matrix elements in the light ($A \leq 40$) nuclei. A program to carry out this comparison is underway. A necessary complement to this theoretical study is an experimental program to search for new first-forbidden decays and to increase the accuracy of previous determinations.

Another motive for reexamining beta decay in $A = 10-40$ nuclei is that very rapid technological advances have taken place that allow the relatively easy extraction of interesting new spectroscopic information in cases not studied for 5 or more years.

General apparatus used in all the studies of beta-decay schemes outlined below include a rapid transit "rabbit" system to cycle the source from the target to the count position and large Ge(Li) gamma-ray detectors. For some studies an escape-suppression Ge(Li)-NaI(Tl) spectrometer was used. This system suppresses the general Compton background in a gamma-ray spectrum by an average factor of five.

One outcome of the increased accuracy in some of the determinations described below is the greater appreciation of the role of Coulomb effects which were largely obscured by the poor accuracy that previously prevailed. An example is the difference in the rates of the mirror decays $^{21}\text{F}(\beta^-)^{21}\text{Ne}$ and $^{21}\text{Mg}(\beta^+)^{21}\text{Na}$. The possibility of using such comparisons to investigate the Coulomb wave functions of the nucleus is encouraging.

B. Decay Schemes

1. ^{11}Be : A New Unique First-Forbidden Branch

Previous attempts at Brookhaven in 1971 to detect certain weak but interesting beta-ray branches in the decay of ^{11}Be , formed at the 3.5-MV Van de Graaff with the $^9\text{Be}(t,p)^{11}\text{Be}$ reaction, did not succeed because of insufficient statistical accuracy. By utilizing the recently installed "rabbit" target-transfer system new measurements on ^{11}Be revealed the unique first-forbidden beta-branch to the 4445-keV state of ^{11}B with a branching intensity of 0.050(6)% and $\log f_t =$

10.96(5). A weak gamma ray of 692 keV due to the $7978 \rightarrow 7286 \rightarrow 0$ cascade was also found. Most of the known $\log ft$ -values for unique first-forbidden beta transitions lie between 8.8 and 10.5, with only two cases larger than the new ^{11}Be value of 10.96. Theoretical calculations on this as well as on the various electromagnetic transitions in ^{11}B are under way. (D. H. Wilkinson (Univ. of Sussex); D. E. Alburger, D. J. Millener, E. K. Warburton (BNL))

2. ^{19}O : New Results

The escape-suppression $\text{Ge(Li)}\text{-NaI(Tl)}$ spectrometer was used to study the ^{19}F gamma rays following $^{19}\text{O}(\beta^-)^{19}\text{F}$ decay. Previous studies with NaI(Tl) spectroscopy (all prior to 1966) had established gamma decays to states at excitation energies [E_x in keV (with spin-parity J^π)] of 110(1/2⁻), 197(5/2⁺), 1554(3/2⁺) and 4367(7/2⁺). The new results, in addition to significantly improving the accuracy of the determination of gamma energies and beta branchings, disclosed new beta branches to states at 3906 keV(3/2⁺) and 1346 keV(5/2⁻). The latter is another non-unique, first-forbidden decay. The previously quoted branch to the 4367-keV state ($\log ft = 3.60$) is revised downward (to $\log ft = 4.4$), which is in better accord with shell-model predictions. (J. W. Olness, E. K. Warburton, D. E. Alburger)

3. ^{20}F : The Non-Unique First-Forbidden Branch

A very weak beta-ray branch from the $J^\pi = 2^+$ ^{20}F ground state to the $J^\pi = 2^-$ 4967-keV level was observed at BNL in 1966. In order to more precisely define the ft -value for this non-unique, first-forbidden decay, the activity was reinvestigated. ^{20}F activity was produced at the 3.5-MV Van de Graaff via the $^{19}\text{F(d,p)}^{20}\text{F}$ reaction. The 3333-keV gamma ray from the $^{20}\text{Ne } 4967 \rightarrow 1634$ transition was measured with an energy accuracy of ± 0.20 keV and an intensity accuracy of $\sim 4\%$, both representing improvements over the best previous values by a factor of 3.5. (D. E. Alburger, E. K. Warburton)

4. ^{21}F : A Reexamination

General studies of the nuclear structure of $A = 21$ nuclei were continued with a reinvestigation of the beta decay of ^{21}F ($T_{1/2} = 4.2$ sec). The activity was produced at the 3.5-MV Van de Graaff using the $^{19}\text{F(t,p)}^{21}\text{F}$ reaction. Eight new gamma-ray transitions were found and associated with four new beta-ray transitions to known excited states of ^{21}Ne at 3736, 3884, 4525, and 4685 keV. The decay to the 3884-keV level is another new non-unique first-forbidden branch and will be considered theoretically. The half-life and the branches to the first three states of ^{20}Ne were remeasured with significantly increased accuracy. From a

comparison of the results with shell-model calculations it was concluded that uncalculated Coulomb effects are a major block to the sensitivity of such comparisons. (E. K. Warburton, D. E. Alburger)

5. ^{24}Al : The Rotational Structure of ^{24}Mg

The positron decay of ^{24}Al has been studied with the Ge(Li)-NaI(Tl) escape-suppression spectrometer after formation via the $^{24}\text{Mg}(p,n)^{24}\text{Al}$ reaction using an 18-MeV proton beam from MP7. The number of ^{24}Mg gamma-ray transitions observed following ^{24}Al decay was increased from 19 to 44. Definite new positron branches were observed to ^{24}Mg levels at 10576, 10821, and 11314 keV. An enhanced E2 transition from the 4^+ 9301-keV level to the 2^+ 7349-keV level was sought for and found. A probable $8439 \rightarrow 7349$ $4^+ \rightarrow 2^+$ transition was also observed. These new results were made possible by the excellent background reduction brought about by the escape-suppression spectrometer. The beta decay results and the new gamma-ray transitions are discussed in terms of the band structure of ^{24}Mg . As an example, the new $9301 \rightarrow 7349$ $4^+ \rightarrow 2^+$ transition provides strong evidence for an excited 0^+ band built on the 0^+ level at 6.43 MeV in ^{24}Mg . (E. K. Warburton, C. J. Lister, D. E. Alburger, J. W. Olness)

6. ^{18}N and ^{21}O

Results for the beta decay of ^{18}N and ^{21}O have been reported under Heavy Ion Physics with the Tandem Van de Graaff Facility. The investigation of these decays is part of the general program outlined here of the investigation of nuclear structure in $A \leq 40$ nuclei via beta decay.

C. The Rank 0 Matrix Element in $J \rightarrow J$ Parity-Changing Beta Decay

There is high current interest in meson-exchange effects in the relativistic matrix element of γ_5 , operative in $J \rightarrow J$, parity changing beta decay or muon capture. The effects are predicted to be quite large, about 50%, and its experimental determination is considered to be of high importance. Attention has largely centered on the $0^- \rightarrow 0^+$ transition between the ^{16}N first-excited state and the ^{16}O ground state. However, this is a very difficult transition rate to determine either experimentally or theoretically (via a nuclear model).

A second approach to the determination of this matrix element has been proposed here at BNL. This approach concerns $J \rightarrow J$ ($J \neq 0$) transitions for which rank 1 and 2 operators can contribute to the beta decay rate as well as rank 0 (there are two rank 0 matrix elements with that of γ_5 usually the dominant one). The contribution of the rank 0 matrix element is then determined by one of two

means: (1) the rank 1 and 2 matrix elements are determined partly from shell-model calculations and partly from the analog E1 rate, leaving (by subtraction from the total rate) the rank 0 matrix element in a semi-empirical determination; (2) the beta-recoil angular correlation is measured, thus fixing the rank 0/rank 1 ratio for a transition with $2J \leq 2$, i.e., rank 2 not allowed. The case being pursued is $^{11}\text{Be}(\beta^-)^{11}\text{B}$ (1/2⁻ first-excited state) and the beta-recoil correlation is investigated by measuring the Doppler-shift of the subsequently emitted 2124-keV gamma ray as a function of beta energy using a beta-gamma coincidence matrix. Initial surveys showed the method to be capable of the required accuracy. Tests also showed that the beta source-detector geometry has an important role in determining the accuracy and consequently a new assembly was developed and is being fabricated. (E. K. Warburton, D. E. Alburger, D. J. Millener, D. H. Wilkinson (Univ. of Sussex))

D. Mass of the Neutrino

The rest mass of the beta-decay neutrino has been the subject of extensive speculation since the particle was first proposed. A long history of beta-decay shape measurements has established its mass at ≤ 50 eV, and it is commonly taken to be identically zero. The discovery that the μ neutrino is different from the e neutrino naturally raises the question of whether the neutrinos differ in mass. Recent theories allow for different neutrino masses as a result of imposed symmetry conditions and particle interactions.

New evidence for a neutrino mass may be implied by the neutrino oscillation experiment of Reines *et al.* and by the missing intensity in the solar neutrino experiment. In astrophysics there is considerable interest whether neutrino mass represents the missing mass of the universe and whether observed UV radiation is caused by the decay of a heavy neutrino into a light one.

A Russian group recently found the neutrino mass to be greater than 14 eV in a ^3H beta-spectrum measurement. This very important result depends critically upon knowing the final atomic state of the daughter atom, ^3He . To this end the far ultra-violet spectrum of photons emitted in the decay of ^3H bound in the same amino acid, and valine, used by the Russian group is being investigated. The hope is that enough atomic transitions will decay by photons (rather than by Auger electrons) that the final atomic states of the ^3He can be deduced. (C. Chasman)

II. Precision Gamma-Ray Energy Measurements

A. The General Program

There is a great need in both applied and basic nuclear research and technology for precise gamma-ray energy standards. The available resources at BNL make it a very efficient laboratory for such measurements. These resources include 1. a large pool of available gamma-ray detectors and associated electronics, 2. powerful and interactive computer facilities, 3. a well-developed expertise in analysis of gamma-ray spectra, and 4. three particle accelerators and a reactor all available for production of both off-line and on-line gamma-ray sources. A measurement program has been organized and is underway. Emphasis is on those sources most unique to BNL's production facilities. The accuracy aimed for is ~ 10 ppm (i.e., ~ 10 eV for a 1-MeV gamma-ray).

An example of the need for such measurements is in the search for and study of off-stability nuclides and their beta decay to gamma-emitting states of the daughter nucleus. Often the decaying bodies are produced very weakly so that beta-gamma and gamma-gamma coincidence measurements are difficult or impossible. In such cases gamma-ray energy measurements are often the sole means of identification of the activity, and the reliability of the identification is directly dependent on the precision of the energy measurements. Such a situation arose for ^{18}N beta decay (see Heavy Ion Research). Here the presence in the gamma spectrum of accurately known gamma rays from ^{20}F , ^{21}F , ^{16}N , and ^{15}C activities was of crucial importance in the energy measurement and subsequent identification of the $^{18}\text{N}(\beta^-)^{18}\text{O}$ gamma rays.

B. A Summary of Results to Date

1. Short-Lived Activities

In the precision energy measurement of a gamma ray emitted following a short-lived beta activity there are two main problems encountered when using Ge(Li) detectors that are not usually of consequence. First, when the mixed source technique is used, the counting rate and the fraction of counts due to the short-lived activity will decrease during the counting cycle and any count rate dependence of the system gain will lead to an error. Second, short lifetimes are usually accompanied by large beta-energies and the associated Doppler effects must be considered. As an example, the energy of the gamma ray from the first-excited state of ^{11}B was determined after formation via the beta-decay of 13.8-sec ^{11}Be . The result was 2124.473 ± 0.027 keV. (E. K. Waburton, D. E. Alburger)

2. ^{13}C

Precision energies of gamma-ray transitions connecting the bound levels of ^{13}C were determined by forming these states in the $^{10}\text{B}(\alpha, p)^{13}\text{C}$ or $^{12}\text{C}(d, p)^{13}\text{C}$ reactions at the 3.5-MV Van de Graaff. It was suggested that a long-lived gamma-ray energy standard emitting ^{13}C radiations of 3684 and 3854 keV, both of which were determined with an accuracy of ± 23 eV, could be made by mixing ^{10}B with an alpha-particle emitter. A source consisting of 80 mCi of ^{244}Cm plus ^{10}B was fabricated at Oak Ridge National Laboratory. Tests on its gamma-ray spectrum showed that this source will be very useful in extending the range of precision gamma rays into the region above 3.5 MeV. (E. K. Warburton, D. E. Alburger)

3. Other Results

Precision energy measurements were made this year on gamma-ray transitions in ^{11}B , ^{13}C , ^{19}F , ^{20}Ne , and ^{21}Ne . The ^{13}C results were from in-beam studies of $^{12}\text{C}(d, p)^{13}\text{C}$ and $^{10}\text{B}(\alpha, p)^{13}\text{C}$, the remainder were made following the beta decay studies reported elsewhere in this report.

III. Radiative Capture: High-Energy Gamma Transitions to Highly-Excited States

High-energy gamma rays have been observed from the $^{12}\text{C}(\alpha, \gamma)$ reaction de-populating states between 32 MeV and 39 MeV in ^{16}O . This work was performed with 33.75 MeV to 42.25 MeV alpha-particle beams obtained from the MP7 Tandem Van de Graaff. A narrow, unexpectedly strong gamma-ray peak, corresponding to decay to an unbound 6^+ state at 14.8 MeV in ^{16}O was observed with an angular distribution consistent with E2 radiation. Structure in the excitation function of this transition favors a resonant rather than direct capture mechanism.

Calculations indicate that a large overlap often exists between wave functions formed by applying the E2 operator to certain excited configurations and alpha-cluster states carrying the same $\text{SU}(3)$ quantum numbers. In ^{16}O these overlaps, for E2 excitations based on n-particle, n-hole states with maximal intrinsic deformation range from 0.81 to 0.87. In particular, the overlap between the E2 operator applied to the 14.8-MeV state of ^{16}O and a high-lying α -cluster state with SU_3 symmetry $(\lambda\mu) = (62)$ is predicted to be 0.82. This excitation promotes a particle from the 2p-2h 6^+ state through 2 major shells, and because of this large overlap some 30% of the E2 sum rule strength built on this 6^+ state is predicted to reside in an 8^+ state near the excitation energy of the observed concentration of yield. The remaining strength is predicted to be fragmented among lower spin components and is not expected to produce compact resonance structure.

The observed concentration of sum-rule strength together with the nature of the excitation, involving the promotion of a particle through 2 major shells, is characteristic of a Giant Quadrupole excitation. This represents the first possible example of a Giant Quadrupole Resonance (GQR) built on an excited state in any nucleus. Furthermore, the resonance is fundamentally different from that built on the ground state since the 6^+ parent state has a structure very different from the ground state.

Similar structures built on other states in ^{16}O , or in other nuclei may well occur. However, the likelihood of observing a compact GQR is closely tied to the structure of the parent state. Weaker transitions to other possible "parent" states are often hidden by large backgrounds. It is planned to further investigate such excitations by detecting the high-energy capture gamma rays in coincidence with the recoiling nucleus using the BNL energy mass separator. This will greatly reduce the background in the gamma-ray spectrum due to other processes, such as the tail from the 15.11-MeV line resulting from $^{12}\text{C}(\ell, \ell')$ which plagues $^{12}\text{C}(\ell, \gamma)^{16}\text{O}$ capture. It should be possible to look for weaker alpha-particle capture transitions in ^{16}O as well as other nuclei. (A. M. Sandorfi, M. T. Collins, D. J. Millener)

IV. Parity Non-Conservation in Strong Interactions

The fundamental question of the conservation of parity in strong interactions has been investigated at a number of laboratories during the past 20 years. This is a problem of long-standing interest to BNL nuclear physicists. The most recent activity at BNL in this area was centered on problems in ^{21}Ne . The problem of most current interest is described below.

A. Parity Forbidden Alpha-Particle Emission in the Decay of ^{16}N

A sensitive test of parity non-conservation can be made in the beta decay of ^{16}N where a branch of 1% feeds a 2^- state of ^{16}O at 8.88 MeV. Although the $2^- \rightarrow 0^+$ alpha-particle emission from this state to ^{12}C is parity forbidden, a group from the Max-Planck-Institute at Mainz reported a very weak positive result. Since this is the only measurement on record, it is an important experiment to repeat. The problem is to make extremely thin, but sufficiently intense sources of ^{16}N after producing the activity in the $^{15}\text{N}(\text{d}, \text{p})^{16}\text{N}$ reaction. Tests showed that the helium-jet system will not deposit the ^{16}N gas on the tape. A special test box was set up to see if a surface nitriding scheme will work. Tests will continue. (D. E. Alburger, J. W. Olness)

V. General Nuclear Spectroscopy

A. ^{13}C

The studies on ^{13}C via $^{10}\text{B}(\alpha, p\gamma)^{13}\text{C}$ and $^{12}\text{C}(d, p\gamma)^{13}\text{C}$ (see IIA2 above) included accurate gamma-ray intensity measurements for all possible transitions between the bound states of ^{13}C . The branching ratios derived from these measurements were compared to the predictions of a large-basis shell-model calculation. (E. K. Warburton, D. E. Alburger, and D. J. Millener)

B. Reactions Induced in ^{36}S

Spectroscopic information on the neutron-rich nuclei ^{37}S and ^{38}S ($T_z = 5/2$ and 3 , respectively) has been difficult or impossible to obtain because of the inability to secure suitable target-projectile combinations for such studies. Recently Oak Ridge National Laboratory (ORNL) has produced a small quantity of highly enriched ^{36}S in order to investigate the $^{36}\text{S}(n, \gamma)^{37}\text{S}$ reaction. As a necessary extension of this work, a collaborative effort has been initiated between ORNL and BNL to produce ^{36}S targets suitable for study of deuteron- and triton-induced reactions. The $^{36}\text{S}(d, p)^{37}\text{S}$ reaction will be investigated at the Tandem Facility, using the QDDD magnetic spectrograph to determine excitation energies and spin/parity information necessary to interpret the (n, γ) data on ^{37}S . It is expected that similar targets can be employed at the 3.5-MV Van de Graaff to initiate an investigation of the $^{36}\text{S}(t, p)^{38}\text{S}$ reaction, leading to information on low-lying excited states of ^{38}S , about which nothing is currently known. Of first priority is the fabrication and testing of the targets. (J. W. Olness, E. K. Warburton, D. E. Alburger, C. Thorn (BNL); S. Raman (ORNL))

C. The Strengths of Electric Monopole Transitions

The decay rate of a nuclear electric monopole transition is a sensitive measure of the properties of the wave functions describing the initial and final states. Several such transitions have been measured with the BNL magnetic pair spectrometer, notably those in ^{58}Ni and ^{54}Fe . This program of measuring matrix elements of EO transitions is continuing in medium-weight nuclei such as ^{32}S that can be excited in p, p' reactions with the MP6 Tandem Van de Graaff. (D. E. Alburger, E. K. Warburton)

Appendix

PUBLICATION LIST

The following is a publication list of the Brookhaven Tandem Van de Graaff Research Group for the period from January 1978 - January 1981. The publications are ordered first by year; within each year by BNL, BNL-Outside User Collaborative, or Outside User; and for each of these into letters, articles, abstracts and invited talks (for BNL and Collaborative only).

1980

BNL - Letters

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