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ANNUAL PROGRESS REPORT
for Period Ending December 31, 1978**

P. H. Stelson, Director

JUNE 1979

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1. Holifield Heavy-Ion Research Facility

PHASE I PROJECT STATUS

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J. A. Martin	R. C. Juras ³
J. A. Biggerstaff	B. Lieberman ¹
C. M. Jones	C. A. Ludemann
R. S. Lord	J. E. Mann
R. L. Robinson	G. S. McNeilly ²
J. K. Bair	W. T. Milner
R. M. Beckers ¹	S. W. Mosko
T. P. Cleary ²	J. A. Murray ¹
D. L. Haynes ¹	R. O. Sayer ²
E. D. Hudson	N. F. Ziegler

In the 18-month period since the last annual report, good progress has been made in all areas associated with bringing the new 25-MV tandem electrostatic accelerator into operation in the latter part of 1979.

A view of the accelerator tower early in this period is shown in Fig. 1.1. At this time the tower height had reached 138 ft above the ground floor, the height required for installation of the main pressure vessel to proceed. In August, after the interior scaffolding had been cleared from the tower, the sections of the pressure vessel were lifted into the tower and welded in place. All 14 sections of the vessel were placed in position in about three weeks. A lift of one of the sections is shown in Fig. 1.2. Final welding on the pressure vessel was completed in November, and the vessel was successfully tested for pressure and vacuum in December.

With completion of the pressure vessel, construction on the tower resumed in early 1978 (see Fig. 1.3). Full height was reached in June, and the project took occupancy of the building in November. The present appearance of the facility is shown in Fig. 1.4.

The storage and handling facility for the SF₆ insulating gas was completed in early 1978, and receipt of gas began in March. The final shipment of gas was received in October to bring the total amount stored on site to 280,000 lb.

Fig. 1.1. Appearance of the Heavy-Ion Facility construction site in July 1977. The structural steel outline of the injector room can be seen in the foreground.

Construction of the 25-MV tandem accelerator at the National Electrostatics Corporation plant continued during this period. Operation in air of the column and injector, using the computer-based control system, was successfully demonstrated in September 1978. A view of the 500-kV injector platform is shown in Fig. 1.5. Following these tests, the column structure was disassembled and prepared for shipment to Oak Ridge, the first truckload arriving in November. Hoisting of column components into the tower is illustrated in Fig. 1.6, and the start of reassembly of the column inside the pressure vessel is shown in Fig. 1.7.

ORNL-PHOTO 3847-77

Fig. 1.2. One section of the pressure vessel being lifted into the tower.

ORNL-PHOTO 4876-78

Fig. 1.4. View of the completed building.

ORNL-PHOTO 1199-78

Fig. 1.3. The completed pressure vessel inside the tower. The main area of ORNL can be seen in the background.

ORNL-PHOTO 0235-78

Fig. 1.5. The 500-kV injector platform with surrounding ground shield.

Fig. 1.6. An 11-ft-diam column bulkhead being lifted into the tower.

Fig. 1.7. Beginning of column assembly inside pressure vessel.

The conversion of ORIC to serve as an energy booster for beams from the 25 MV-tandem is now essentially complete. Installation of the inflection magnet inside the dee-stem resonator back plate was accomplished during a shutdown in the second quarter of 1978. Some additional modifications to allow easy interchange of the ion source and foil holder mechanisms will be made during a two-month shutdown beginning in December.

A number of other activities related to bringing the facility into operation in late 1979 are discussed in the following sections.

1. UCC-ND Engineering Division.
2. UCC-ND Computer Sciences Division.
3. Instrumentation and Controls Division.

EXPERIMENTAL FACILITIES

R. L. Robinson	N. R. Johnson
J. L. C. Ford	R. W. Miles
C. D. Goodman	R. L. Mlekodaj ¹
M. L. Halbert	F. E. Obenshain
J. W. Johnson	F. Plasil

Development of the experimental facilities has, to a first approximation and within the constraints of funding, followed the recommendations made by the Users Group in late 1976. The proposed experimental layout of the Holifield Heavy-Ion Research Facility as developed from their recommendations is shown in Fig. 1.8. Major pieces of existing apparatus are the 30-in.-diam scattering chamber on beam line 51, the broad-range magnetic spectrometer (BL 52), the time-of-flight system (BL 53), UNISOR (BL 62), a chemistry facility for study of transactinide nuclei (BL 68-69), and a gamma-ray spectrometer (BL 41).

A 1.6-m-diam multipurpose scattering chamber and the basic elements for a gamma-ray spectrometer system, to be placed on beam line 23, have been designed, and fabrication is in progress. Design is complete and components received for beam lines 23, 31, 33, and 35, which are funded as part of the project. The mount for the split-pole spectrometer has been designed. It is planned to relocate this spectrometer, which is currently at the EN tandem accelerator, on beam line 33. Design work is under way for the section of beam line 31 that will link the tandem to the new scattering chamber and to UNISOR.

Fig. 1.8. Proposed experimental layout for the HHIRF.

Calculations for a recoil mass spectrometer were made by Harald Enge and co-workers at the Massachusetts Institute of Technology. A solution for a working system was much more difficult to obtain than anticipated because of unexpected complexities of the second-order corrections. Work on this system will be delayed pending resolution of the design problems.

A program was initiated to upgrade the vacuum of existing beam lines and apparatus. During the past year the 30-in.-diam scattering chamber was overhauled, and the majority of the diffusion pump stations and about 60 ft of vacuum lines were refurbished.

1. UNISOR.

DATA ACQUISITION

J. A. Biggerstaff D. C. Hensley
W. T. Milner R. O. Sayer¹

The first elements of the new data acquisition system, shown schematically in Fig. 1.9, have been received. Most of this equipment is manufactured by Interdata, Inc. The figure does not show the CAMAC

branch and serial highway drivers or the highways and crates which are being installed in both the tandem and the cyclotron counting rooms. Each computer shown will have two branch drivers connected via a single highway to one of the counting rooms. The dual branch drivers are intended to provide multiplexed direct memory access transactions (DMA) to two different CAMAC addresses or a DMA transaction on one channel and program-controlled single-action transactions on the other channel.

The equipment on hand and on order is sufficient to service a single on-line user, support off-line data processing, and, most important, support software development. Initial software development efforts are concentrated in five areas:

1. generation of FORTRAN-callable CAMAC routines for users who wish to write their own software,
2. routines for (multiplexed) "singles" acquisition at high data rates,
3. sorting into large (greater than 10^7 word) arrays in nearly real time for event rates of several kilohertz,
4. list-mode acquisition routines and off-line sorting routines,
5. interactive graphics routines.

ORNL-DWG 78-18533

Fig. 1.9. First elements of the data acquisition system. LSU, loader storage unit; PASLA, programmable asynchronous line adapter; BSELCH, buffered selector channel; EDMA, extended direct memory access.

Procurement has been initiated for additional equipment to expand the system. Major items to be added include the following:

1. A third computer with peripherals. A branch highway will be extended from this computer to both of the counting rooms to provide facilities for experiment setup and calibration. Each CAMAC crate will be connected to this highway as well as to the "private" highway. Users will share the third computer while setting up and calibrating and will switch to the private highway for on-line acquisition. This switching will be effected completely by software.
2. Memory expansion for all three computers and additional mass storage.
3. Alphanumeric/graphic terminals and printer/plotters.
4. CAMAC data acquisition modules.

In order to overcome some of the intrinsic limitations of CAMAC, it is necessary to provide local intelligence at the front end of the system to provide for digital filtering to remove uninteresting events and to gather good events from multiple CAMAC addresses and process them so that the computer DMA channel can read from a fixed CAMAC address. The speed required of such a device dictates that it be constructed from "bit-slice" components rather than using commercial microprocessors, but, on the other hand, a rather low level of intelligence is required. Such a device, called an event handler, has been developed, and we have accumulated several months of satisfactory experience with it (see following section).

1. UCC-ND Computer Sciences Division.

CAMAC EVENT HANDLER

D. C. Hensley

An "event handler" (EH) module has been developed which is a fast, programmable data acquisition interface linked to and through CAMAC. The special features of this interface make it a powerful tool in implementing data acquisition systems for experiments in nuclear physics. The name "event handler" has been chosen because the primary function of the interface is to handle the equipment and information associated with experimental events.

The EH is divided into two components: a processor and an auxiliary controller. The auxiliary controller can

drive or respond to the CAMAC crate, and this feature allows one to load and verify a program all from the host computer. The processor is driven by a 10-MHz clock, has a 20-bit-wide by 256-word-deep random access memory, uses a 3-bit op-code, and has a basic cycle time of about 0.4 μ sec. Two 24-bit data registers are available to bit-checking instructions, and the processor can check the status of six front-panel inputs and can drive six front-panel outputs. The data output of the EH has been made to resemble that of a 24-bit-wide FIFO (first in, first out buffer). The EH has a genuine subroutine capability, which is valuable if a given protocol is used in several different parts of a program. If the protocol is long or involved, program space can be reduced, and system debugging may be greatly simplified.

Our experience with the device indicates that it is nicely tailored for many experiments, especially in the following applications:

Setting up. The EH can readily execute any data acquisition sequence and display various converted parameters on a local light-emitting diode display or on a slave multichannel analyzer.

General parameter list. The simplest (most straightforward) application is to have the EH read and transmit a prescribed list of modules. It can do this with an average speed of about 2 μ sec per word. It can then clear the modules and wait for the next event.

Selective parameter list. The most common aspect of multiparameter experiments is that few of the parameters within a given event will be relevant (i.e., meaningfully nonzero). In this case, communications overhead can be greatly reduced, since the EH can transmit only those parameters which are relevant.

"Crash" mode. Because there is a relatively long digitizing time associated with many analog-to-digital converters (ADCs), especially CAMAC ADCs, it is often desirable to accept an event and start the ADCs digitizing and then, after deciding that the event is in fact not wanted, to stop and clear (crash) the ADCs and to start over.

In-crate tester. Since it can request any CAMAC function, the EH can be used as a device to drive a CAMAC module that needs testing. This is very useful, particularly when the host computer is too busy to act as a testing instrument.

The following is a list of some of the experiments that have been run with this system; all of these experiments exceeded the capability of our previous hardware:

1. two heavy-ion telescopes and eight slave light-ion telescopes with ten time-to-amplitude converters,

2. a heavy-ion telescope and six slave neutron time-of-flight detectors with neutron-gamma discrimination,
3. two Ge(Li) detectors, six slave light-ion telescopes, and seven slave small NaI detectors,
4. a conversion electron spectrometer, an x-ray Si(Li) detector, three large NaI detectors, and seven slave small NaI detectors,
5. three large NaI detectors and 14 slave small NaI detectors.

The basic result has been that not only can these experiments be implemented (even easily) but the flexibility of the current event handler (CAMAC) system has allowed one to optimize critical aspects of the experiment, particularly the reduction of dead time and the characterization of the event.

In addition to this, 24-bit, fast (less than 2 μ sec) data transmitters and receivers were designed and implemented, and the experimental electronics may now be positioned far from the computer (i.e., next to the apparatus) with an overall gain in data acquisition throughput.

The event handler satisfies nicely an apparent lack in current data acquisition equipment. This CAMAC-based programmable interface is much faster than CAMAC microprocessor systems and is better geared for a wide variety of experiments in nuclear physics. Because it is programmable and already linked to CAMAC, it is much more adaptable and versatile than hard-wire logic for event managing, particularly if event managing includes the manipulation of CAMAC modules. Because it is essentially totally independent of the host computer, the EH can be immediately implemented into any system possessing a CAMAC interface. We anticipate that many of the multiparameter experiments at the Holifield Heavy-Ion Research Facility will be built around the event handler.

USERS ACTIVITIES

R. L. Robinson

Meetings of the HHIRF Users Group were held October 3, 1977, and September 28-29, 1978, at ORNL. Current membership of the Users Group is 318, and a total of 530 have requested information on the project. Current information is distributed through a newsletter published every four months. Those who have served on the executive committee are:

1977-78: H. Enge (Massachusetts Institute of Technology)

D. Fossan (State University of New York at Stony Brook)

P. Richard (Kansas State University)

1978-79: D. Cline (University of Rochester)

C. Moak (Oak Ridge National Laboratory)

C. Britt (Los Alamos Scientific Laboratory)

John Rasmussen was chairman in 1977 and Harald Enge in 1978.

ORNL has agreed to underwrite construction of a building which is to meet some of the needs of the users while at ORNL. Vanderbilt University had previously committed \$100,000 to help support construction of this building. Present plans are for the building, which will be known as the Heavy-Ion Institute, to have four areas: (1) office space and (2) living areas for users who are here for a short time, (3) rest areas for users during long experimental runs, and (4) a commons area with kitchen facilities where the users can interact in a relaxed, informal atmosphere. Funding is scheduled for fiscal year 1979; a preliminary completion date is October 1980. This building is to be located near HHIRF.

PHASE II STUDIES

J. B. Ball	L. B. Maddox ³
J. K. Ballou ¹	J. A. Martin
R. M. Beckers ²	W. T. Milner
J. D. Bell ³	S. W. Mosko
J. A. Biggerstaff	R. A. Michelotti ¹
E. D. Hudson	J. A. Murray ²
R. S. Lord	R. L. Robinson
C. A. Ludemann	R. O. Sayer ³
G. S. McNeilly ³	J. A. Steed ²
T. A. Welton	

At the time of writing the last annual report, we were confidently proposing a new and improved version of the $K = 400$ separated-sector cyclotron, a product of several years evolution. The project was not included in the budget for FY 1979. We decided that an additional year's inflation added to the cost estimate (bringing it to about \$30 million) would price the project out of competition with other projects promising comparable or better performance for less money, so we decided to develop a new plan.

The decision was made to switch to a cyclotron with a superconducting magnet à la Michigan State/Chalk River and to reduce the size of facility additions as much as possible. With this change we reluctantly gave up the advantages of external stripping, easy beam injection and extraction, well-separated turns, easy beam diagnostics, and the use of the ORIC as an

alternate injector. Compensating advantages gained with the new design are higher beam energy, lower cost, lower power usage, and less required space.

The preliminary parameters of the new cyclotron lead to specific energies of 150 MeV/A for light ions and about 40 MeV/A for $A = 238$ ions. The energy performance of the new cyclotron is compared with other facilities in Fig. 1.10.

Fig. 1.10. Ion energy at 10^{11} particles/sec from Phase II compared with other facilities.

Giving up the ORIC as an alternate injector offered the possibility of planning the new Phase II facility around the idea of using all of the existing experiment areas for Phase II beams. The new arrangement provided multiple beams (beam splitting), and the conversion could be done sequentially in a way to minimize the impact of the new project on the Phase I experimental program. Figure 1.11 shows the proposed Phase II facility layout.

The preliminary cost estimate for the project (for FY 1980) is about \$18 million, including allowances for cost escalation. The cost in 1978 dollars would be approximately \$13.5 million.

A preliminary study was published in March 1978 and presented to the 1978 Facilities Subcommittee of the Nuclear Science Advisory Committee of DOE/NSF (NUSAC) on March 13. The report "Recommendations for FY 1980 Facility Funding" was issued by NUSAC on April 20. The recommendation did not include funding of HHIRF Phase II in FY 1980 but urged submission of a more complete proposal at a later time with improved performance parameters.

In response to the NUSAC report, we have reviewed a number of other possibilities for booster accelerators, including two-stage arrangements such as a $K = 600/100$ combination, and concluded that the increased energy performance did not warrant the added cost and complexity. We also studied the possibility of using the 2500-ton magnet of the 600-MeV synchrocyclotron of the Space Radiation Effects Laboratory (now shut down). The contemplated conversion would have used a superconducting coil system with weak-spiral pole tips and with valley coils to adjust valley fields to optimize the injection path. This study showed the possibility of 250 MeV/A for light ions and perhaps 50 MeV/A for uranium, but the modest increase in performance over our March design did not seem worth the increased size and technical complexity of the cyclotron.

The most attractive plan that has developed from recent studies is to follow the $K = 1200$ cyclotron of the March proposal with a large superconducting ring cyclotron booster. The ring booster would be a six-sector separated-sector design to provide up to 600 MeV/A for light ions and 100 MeV/A for the heaviest ions without additional stripping. With stripping between stages, the ring booster would give 340-MeV/A uranium ions.

A proposal is now being prepared for a project similar to the March 1978 proposal to NUSAC, the $K = 1200$ cyclotron and associated rearrangement of HHIRF facilities. This plan is being developed to be consistent with adding a third stage to achieve much higher energies.

1. ORNL Fusion Energy Division.
2. UCC-ND Engineering Division.
3. UCC-ND Computer Sciences Division.

Fig. 1.11. The new Phase II arrangement of the HHIRF experiment areas utilizes essentially all of the existing beam transport equipment. Seven beam lines are provided, some with enough space for several experiments; all lines can be served by either the tandem or the tandem-booster. A beam-splitter system based on the use of rf deflectors and septum magnets provides for beam sharing between two or among all three of the principal beam lines.

NEGATIVE ION SOURCE DEVELOPMENT

G. D. Alton

The Modified Aarhus Geometry Source

The negative-ion source, discussed briefly in the previous annual progress report,¹ has been constructed and evaluated for use in acceptance testing of the 25-MV tandem accelerator. The source,² based in principle on the University of Aarhus design,^{3,4} produces ion beams by sputtering material from a spherical probe which is maintained at a negative potential (about -1000 V) relative to a cesium-rich space-charge-limited plasma discharge. The spherical probe is positioned a distance away from the exit aperture equivalent to its radius of curvature. Negative ions, sputtered from the surface, are accelerated by the difference in potential developed across the plasma sheath and are focused at the ion exit aperture (2 mm in diameter).

The relationships between negative-ion yield and oven temperature and sputter probe voltage have been established for a number of different elements.² Maximum ion currents occur at oven temperature of about 200°C and sputter probe voltages between -900 and -1200 V, depending on the cathode material.

Reproducible negative-ion currents of 175 $\mu\text{A H}^-$, 20 $\mu\text{A C}^-$, 8 $\mu\text{A P}^-$, 2.8 $\mu\text{A FeH}^-$, 56 $\mu\text{A Ni}^-$, 51 $\mu\text{A Cu}^-$, 8 $\mu\text{A Se}^-$, 36 $\mu\text{A Ag}^-$, and 55 $\mu\text{A Au}^-$ have been generated. In the case of H^- generation, hydrogen gas is introduced into the discharge, ionized, and ion-implanted into the cathode surface, and then negative ions are sputtered from the surface. The negative-ion yield in this case is sensitively dependent on the specific cathode material. Also, the maximum negative-ion yield occurs at extremely low voltages (about -80 V).

The source has been operated continuously for 80 hr and 384 hr, respectively, using silver and gold cathodes to observe the long-term operational stability and to get an idea of source lifetime. In both cases, the run time

was limited by the time necessary to completely erode away the cathode material. The source has demonstrated a surprising degree of stability and reliability while generating much higher negative-ion intensities from elemental materials than obtained from conventional sputter sources.

Axial-Geometry Positive- or Negative-Ion Source

An axial-geometry source,^{2,5} shown in Fig. 1.12, also has been evaluated in terms of its positive- as well as negative-ion capabilities. Transformation from the Aarhus-geometry source entails simple alterations to the ionization chamber. The hot filament is placed between the spherical sputter cathode and the ion extraction aperture; the discharge occurs principally along the axis of symmetry.

Two modes of source operation have been briefly investigated. In one mode, the source is operated with essentially no magnetic field other than that produced by the filament itself. In this mode, a small-diameter, but strongly eroded, wear pattern occurs on axis. The yield vs cathode position varies inversely with distance from the exit aperture.

When operated with a transverse magnetic field, the source demonstrates uniform cathode wear similar to the Aarhus-geometry source. The yield is maximized

whenever the cathode is positioned a distance away from the aperture equivalent to its radius of curvature.

Thus far, only two cathode materials have been investigated, carbon and gold, producing C^- and Au^- of 20 and 28 μA respectively. The source operates at considerably higher oven temperatures (about 250°C) than the Aarhus source as well as higher probe voltage (over 1000 V) for the materials tested to date.

The axial-geometry source may be converted to a positive-ion source by simply reversing the polarities of power supplies necessary for extraction and transport of the beam through the test facility. Source operational parameters are presently being determined which maximize the positive-ion yields from gaseous and high-vapor-pressure materials. Positive-ion currents of 10 μA Ar^+ , 150 μA P^+ , and 200 μA As^+ have been observed. A source such as this can be used as a means of producing positive ions for a charge-exchange negative-ion source.

1. G. D. Alton, *Phys. Div. Annu. Prog. Rep.* June 1977, ORNL-5306, p. 20.

2. G. D. Alton, *Proceedings of Fifth Conference on Application of Small Accelerators*, North Texas State University, Nov. 6-8, 1978 (to be published in *IEEE Trans. Nucl. Sci.*, 1979).

Fig. 1.12. Axial-geometry positive- or negative-ion source.

3. H. H. Andersen and P. Tykesson, *IEEE Trans. Nucl. Sci.* NS-22, 1632 (1975).

4. P. Tykesson, H. H. Andersen, and J. Heinemeier, *IEEE Trans. Nucl. Sci.* NS-23, 1104 (1976).

5. G. D. Alton, *Proceedings of the IEEE Particle Accelerator Conference, San Francisco, California, March 12-14, 1979* (to be published in *IEEE Trans. Nucl. Sci.*, 1979).

ANALYSIS OF ORIC MAGNETIC-FIELD MEASUREMENTS

T. P. Cleary¹

Analysis of the medium-to-high-field portion (from 12 to 20 kG) of the data obtained in an extensive remapping² of the ORIC magnetic field has been completed. This field region covers the present normal operating range of the cyclotron and the anticipated range when the cyclotron is operated in a coupled mode with the tandem.

The field was studied as a function of 23 variables — the currents: the main coil, ten trim coils, nine harmonic coils, and three valley coils. The data grid covered the entire median plane of the cyclotron from 0 to 38 in. in 1-in. steps and from 0 to 358° in 2° steps. For each radius, the data were Fourier-analyzed and each of the resultant coefficients parameterized in terms of the 23 variables. The first ten Fourier coefficients and every 3d up through the 48th harmonic were retained in the analysis. The parameters used in the description of each Fourier coefficient were determined by means of a nonlinear least-squares analysis of all the corresponding coefficients derived from the medium-to-high-field data. The nonlinear effects of the iron were taken into account by expressing the variation of each coefficient with respect to each current as a function of the average field at that radius. Thus, given a set of currents, the average field could be generated by means of iteration, while the higher coefficients could be directly calculated from the currents and this average field. The required data base consists of the parameters needed to construct each Fourier coefficient at each radius, and this procedure leads to a reduction in the overall data-base size by a factor of 100. Synthesis of the average field from this parameterization reproduces the absolute field to within about 10 G and the relative field to within 5 G. As an example, the differences between the measured and synthesized fields used for accelerating $^{20}\text{Ne}^{6+}$ ions to 165.4 MeV are shown in Figs. 1.13 and 1.14

1. UCC-ND Computer Sciences Division.

2. R. M. Beckers et al., "ORIC Magnetic-Field Measurements," *Phys. Div. Annu. Prog. Rep.* June 30, 1977, ORNL-5306, pp. 22-24.

Fig. 1.13. Radial plot of the difference between the average measured and synthesized fields for the same coil current settings. General level of the field is 16 kG.

Fig. 1.14. Azimuthal plot of the difference between the measured and synthesized fields at 30 in. Higher-frequency oscillations of the order of 25 G which result from the truncation of the Fourier series at the 48th harmonic have been removed for the purposes of this comparison.

ORIC OPERATIONS

S. W. Mosko	C. L. Haley
C. L. Viar	G. A. Palmer
R. S. Lord	S. N. Lane
J. W. Johnson	R. F. Joy
C. A. Ludemann	A. D. Higgins ¹
H. L. Dickerson	E. W. Sparks ²
H. D. Hackler	B. J. Castevens ³

ORIC operated on a 15-shift-per-week basis through 1977 and 1978 except for some periods of extended

shutdown for HHIRF injection line installation and for electric power curtailment. A three-month shutdown period from mid-April to mid-July 1978 was dedicated to installation of injection line optics and the main injection bending magnet (Fig. 1.15).

ORIC beam time distribution by particle is shown in Table 1.1. Beams of neon or heavier nuclei account for 44% of the total beam time. Our previous report of June 30, 1977, shows only 31% for this mass range. A survey of research time distribution shows that about 65% of ORIC beam time involves experimenter groups with one or more members from institutions other than ORNL. On a pro rata basis, approximately 40% of the accelerator time supported research of experimenters from outside ORNL. More than 50 individuals comprised this outside participation.

Machine operable time (Table 1.2) taken as a percentage of operable time plus unscheduled outage time gives a reliability factor of 73%. If ion source changing time is included with machine operable time rather than outage time, the reliability factor increases to 83%.

Table 1.1. ORIC beam time distribution by particle for period July 1, 1977, to December 31, 1978

Particle	Mass	Maximum energy ^a (MeV)	Total hours	Percent
Deuterons	2	24	40	1
Alphas	4	61	183	6
Lithium	6	93	152	5
Lithium	7	49	33	1
Boron	10	68	11	
Boron	11	68	63	2
Carbon	12	190	253	9
Nitrogen	14	183	200	7
Oxygen	16	205	715	24
Fluorine	19	175	15	
Neon	20	171	849	29
Neon	22	132	47	2
Sulfur	32	155	49	2
Argon	40	160	319	11
			2929	100

^aThe maximum energy listed is the highest value actually used and does not represent the maximum available.

Fig. 1.15. Installation of the ORIC beam injection line bending magnet in the ORIC des stem. The long tube contains magnet power and water leads which are excluded from the vacuum system.

Table 1.2. Time analysis of ORIC operation
for period July 1, 1977, to December 31, 1978

	Hours	Percent
Beam on target	2015	46
Beam adjustment	228	5
Target setup	83	2
Startup and shutdown	329	8
Machine research	279	6
Total time machine operable	2934	68
Source changes	398	9
Vacuum outage	12	
Rf outage	177	4
Power supply outage	174	4
Electrical component outage	35	1
Mechanical component outage	67	2
Water leak outage	222	5
Total unscheduled outage	1087	25
Scheduled maintenance	231	5
Scheduled engineering	95	2
Total time available ^a	4345	100

^aA large block of time (1310 hr) which was dedicated to major shutdowns for HHIRF equipment installation and power curtailment is not included in this table.

Several improvements to ORIC were implemented both during the long shutdowns and during periods of normal operation via equipment substitutions. All ten circular trimming coil power supplies have been upgraded for improved performance and reliability. Significant component changes include new higher-voltage water-cooled shunts, silicon pass transistors replacing germanium units, and solid-state regulator amplifiers replacing vacuum-tube circuitry. New regulating circuitry was also installed in the main field motor generator set.

The circular trimming coil power supplies and the harmonic coil power supplies are now permanently interfaced with the control computer. Machine setup is accomplished automatically, using the computer library of previous run data. The harmonic coil power supplies are referenced to sinusoidal algorithms in place of the former manually controlled sine potentiometer.

Some rf system improvements were required as a consequence of major modifications to the resonator during the spring 1977 shutdown. Tuning stability problems were encountered due to excessive friction in the rf trimmers support bearings. An ultralow-friction replacement featuring captive knife edges was designed and installed during the spring 1978 shutdown.

The experimental beam lines underwent a major improvement during the spring 1978 shutdown. Most effort went into improving vacuum seals and oil vapor traps. Substantial reduction in operating pressure was achieved, resulting in improved beam transmission between the cyclotron and most experiment stations.

A few changes in ion source hardware and operating techniques have evolved during this reporting period which are reducing operating costs and improving reliability. Unused parts related to now-abandoned plans for continuously rotatable cathodes were eliminated from the source head design to reduce fabrication costs and improve source head cooling. The newest source heads appear to have improved operating time between service intervals. Also, it was found that krypton may be substituted for much more expensive xenon arc support gas, which has been vital to obtaining good ion output with ions below mass 20.

1. Plant and Equipment Division.
2. Instrumentation and Controls Division.
3. UCC-ND Computer Sciences Division.

2. Nuclear Physics

GAMMA-RAY CONTINUUM SPECTRA FROM HEAVY-ION REACTIONS

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The continuum gamma-ray spectrum produced by a residual deformed nucleus following a heavy-ion-induced evaporation reaction is the most promising source of experimental information on the nuclear structure of yrast and near-yrast states at very high spin (greater than $40\hbar$).³ For a typical deformed rare-earth residue, the high-spin nuclear structure information is contained in a well-localized bump of gamma radiation between a few hundred keV and about 1.5 MeV, known as the yrast continuum. The radiation in this region (at least for $E_\gamma \geq 500$ keV) is dominated by stretched $E2$ transitions, as indicated by measurements of angular correlations⁴ and conversion coefficients.⁵ Underlying this is a continuum of statistical transitions (i.e., non-collective transitions that carry away excitation energy but little spin).

Spectrum Shape, Moment of Inertia, and Gamma-Ray Multiplicity for ¹⁶⁴Yb

Continuum spectra obtained from 2×3 in. NaI detectors were taken in coincidence with a seven-detector NaI array during bombardment of ¹⁵⁰Nd by 130- and 115-MeV ²⁰Ne. By considering only those events in which a given minimum number of detectors in this array fired, the upper spin region of population in the residue can be enhanced, and the low-multiplicity background arising from Coulomb excitation and other quasi-elastic reactions can be removed. The effect of this requirement can be taken into account in a well-defined way by a modification of the entry spin distribution.

We have attempted a detailed quantitative analysis of the yrast continuum by subtracting the underlying

statistical component in a way that makes ample allowance for our ignorance of its detailed shape. We describe the statistical spectral shape by the two-parameter empirical form

$$Y(E_\gamma) \propto E_\gamma^X \exp(-E_\gamma/T). \quad (1)$$

For a fixed value of the parameter X , the high-energy ($E_\gamma \geq 2$ MeV) continuum was fitted to Eq. (1). The fit was then subtracted from the experimental spectrum, and the remaining yrast spectrum was analyzed for the moment of inertia, $\mathcal{J}$, as a function of spin, I , with the assumption that

$$E_\gamma = \frac{\hbar^2}{2\mathcal{J}} (4I - 2), \quad (2)$$

and an entry spin distribution

$$P(I) \propto \frac{2I + 1}{1 + \exp [(I - I_{\max})/d]}. \quad (3)$$

where $d = 3.5$ was assumed, based on optical-model calculations, and $I_{\max}$ was fixed by requiring agreement with gamma multiplicity experiments.⁶ This process was repeated for several values of X . Uncertainties in $\mathcal{J}$ have been adjusted to span their full range of variation with X in the range 1-3.

In Fig. 2.1, results of the analysis for $\mathcal{J}$ vs I from the four-and-higher-fold data at 115 and 130 MeV are shown. The final nuclei which are predominant in a given spin region, as shown in Fig. 2.1b, were deduced using data from ref. 6. In the 130-MeV data, $\mathcal{J}$ is seen to be essentially constant between $I \approx 20$ and $I \approx 28$ and then to increase, reaching the rigid-sphere value at $I \approx 45$. This spin region is dominated by the $6n$ channel (¹⁶⁴Yb). The flattening of the $\mathcal{J}$ vs I curve in the 115-MeV data above $I = 35$ could be due to increasing contributions from the $5n$ channel (¹⁶⁵Yb).

Figure 2.2 shows experimental data on the mean and width of the gamma multiplicity distribution as a function of E_γ for 130-MeV ²⁰Ne + ¹⁵⁰Nd. The lines are

Fig. 2.1. Moment of inertia vs spin for 115- and 130-MeV $^{20}\text{Ne} + ^{150}\text{Nd}$. Results of the analysis at both energies are shown in a. In b these results are schematically reproduced along with an indication of the contributions of various final channels. The dashed line in a is for the ground band in ^{164}Yb deduced from discrete line spectra.

Fig. 2.2. Means and widths of the multiplicity distributions for 130-MeV $^{20}\text{Ne} + ^{150}\text{Nd}$. The solid lines are for $X = 2$, $d = 3.5$, and the dashed lines for $X = 2$, $d = 8$.

calculations based on parameters deduced from the analysis of the shapes of the continuum spectra for $X = 2$. Smaller or larger values of X give appreciably poorer accounts of these data. $X = 2$ also gives the best agreement with expected relative and absolute yields of statistical and yrast transitions and with average statistical transition energies.

Conversion Coefficients and Multipolarities for $^{164}, ^{165}\text{Yb}$

The experiment described above included a lens for detection of conversion electrons. The total conversion coefficient, α , of the gamma-ray continuum was determined as a function of gamma-ray energy from 0.5 to 2.5 MeV. The results are consistent with a mixture of $E1$ and $E2$ for $E_\gamma > 1.0$ MeV, with a smooth increase of the $E1$ fraction with E_γ up to about 1.5 MeV. At lower energy, in the upper half of the yrast region, α shows the expected dominance of $E2$ radiation, but for the lower half an increasing $M1$ contribution is found. Details have been published (ref. 5).

Angular Correlations and Multipolarities for ^{130}Ce

The dominance of stretched $E2$ transitions in the yrast cascade, although well established for deformed

rare earths, may not hold in other regions of the periodic table. In order to deduce moments of inertia from continuum spectra in these other regions, one must measure the multipolarity distribution. We have made such a measurement for ^{130}Ce by the method of high-order angular correlations from the reaction $^{96}\text{Zr}(^{40}\text{Ar}, 4n)$. Three 5-in.-diam NaI detectors in the horizontal plane detected the continuum gamma rays. Fourteen 2×3 in. NaI counters both in and out of plane were used to study the angular correlations. Preliminary results are consistent with stretched quadrupole for gamma rays between 0.4 and 1.5 MeV. Below 0.4 MeV the data suggest about 40% dipole contribution.

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A HIGH-SPIN ISOMER IN ^{148}Tb

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A persistent theme of nuclear research over the last several years has been the study of effects of large angular momentum on the structure of nuclei. One interesting manifestation of such effects might be the existence of isomeric yrast states at very high angular momentum. Recently Pedersen et al.⁵ reported the discovery of an island of isomers near $N = 82$ which decay via cascades of 8 to 20 gamma rays. We have found such an isomer in ^{148}Tb ($N = 83$). Several experiments were carried out for its discovery, identification, and characterization.

The initial experiment used ^{16}O beams of 128, 141, and 155 MeV from ORIC on ^{142}Nd . Evaporation residues escaping from the target were collected on a plastic-film annular catcher placed 20 cm downstream. Gamma rays emitted from the catcher between beam bursts were detected by two Ge(Li) detectors operated in coincidence with each other and a multiplicity array of 12 NaI counters. About 50 lines with $M \geq 10$ were observed at the highest bombarding energy. Of these, 13 to 16 were found to be in prompt coincidence with each other. These lines have $M \approx 13$, suggesting that the isomeric cascade is simple.

The second experiment, done with 155-MeV ^{16}O on ^{142}Nd , used an electron lens and a Ge(Li) detector view-

ing singles from a catcher foil 9 cm beyond the target. The energy difference between the conversion electrons and the corresponding gamma-ray lines was measured for ten transitions and found to be equal to the K binding of ^{148}Tb (see Fig. 2.3b). The isomer was thus formed by $\alpha p x n$ emission, probably not the most favorable reaction; the production cross section was on the order of 40–80 mb. The ratio of electron to gamma-ray yield gave the multipolarities for these ten transitions and led to an estimate of $J \approx 30$ for the isomer.

The excitation functions measured in the first experiment, when compared with the systematics of such reactions, indicated $x = 5$ or 6, that is, ^{148}Tb or ^{147}Tb . A low-lying 9^+ state in ^{148}Tb is known⁶ to decay ($T_{1/2} \approx 2.2$ min) to ^{148}Gd . Four of the known⁶ gamma rays in the latter nucleus were observed in our spectra with the same excitation function as for the isomeric cas-

Fig. 2.3. Conversion electron data for ten delayed transitions plotted as a function of the energy of the corresponding gamma ray. (a) Conversion coefficients with relative uncertainties. The absolute normalization is based on known E2 transitions in ^{148}Gd and ^{150}Dy , corrected for timing and detection-in-flight effects, with an uncertainty estimated to be less than 15%. (b) K binding energies deduced from the energy difference between gamma rays and K conversion electrons. The hypotheses that the transitions are in isotopes of gadolinium or dysprosium can both be rejected at the 99% confidence level. Chi-squared per degree of freedom for the terbium hypothesis is 1.2.

cade, demonstrating that the isomer is in ^{148}Tb ; this identification has been confirmed by very recent data from Singhal and Johns.⁷ In a short bombardment of ^{139}La by ^{16}O at 140 MeV, which would produce ^{148}Tb by $7n$ emission, at least 12 of the lines in the isomeric cascade were easily seen in both prompt and delayed singles spectra from the target.

The last experiment used a 151-MeV $^{32}\text{S}^{7+}$ beam (the first time a sulfur beam from ORIC has been used for nuclear research) on a ^{120}Sn target, giving ^{148}Tb by $p3n$ emission. Four Ge(Li) detectors were used in various prompt and delayed coincidence combinations to establish further details of the decay scheme as well as to discover what transitions feed the isomer. A three-point angular distribution of the prompts was also measured. At this writing the analysis of this rich store of data is incomplete, but it appears that enough information is available to characterize all levels below and some levels above the isomer and to give an accurate value of its half-life (about 0.5 μsec from a preliminary analysis).

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A SEARCH FOR ALPHA PARTICLE EMISSION BY YRAST ISOMERS

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An island of isomers near $N = 82$ in the light rare earth nuclei, first reported by Pederson et al.,⁴ has become a topic of considerable interest in recent years. These isomers are believed to be the yrast traps first predicted by Bohr and Mottelson.⁵ Many experimentalists have studied these isomers using gamma-ray multiplicity techniques with much success.^{6,7} We have undertaken an investigation of alpha-particle emission by these isomers to gain more information about the nature of the nuclear states involved.

We employ a trajectory- and energy-sensitive charged-particle detector to observe alpha decay in flight. The experimental configuration is shown schematically in Fig. 2.4. ^{16}O beams from ORIC are used to bombard thin ($100\text{--}800\ \mu\text{g}/\text{cm}^2$) ^{142}Nd targets, producing the compound system ^{158}Er . The excited compound system recoils from the target and cools by particle evaporation (about 10^{-21} sec). The "shadow" plate shields the detector from this prompt charged particle emission by making the beam line invisible for the first 3 cm (about 8 nsec) of flight. Any decays in flight with half-lives in the range of about 5–100 nsec are visible to the detector.

A $570\ \mu\text{g}/\text{cm}^2$ Mylar window allows particles to enter the detector, which consists of three sections inside a gas-filled chamber. The first element of the system, a position-sensitive wire proportional counter, yields the entry position (P_w) and partial energy loss (ΔE_w) of the charged particle. This is followed by an ion-chamber region providing an energy-loss signal (ΔE). Finally, the particle is stopped at the rear of the chamber in a solid-state position-sensitive detector recording the particle energy (E_p) and its position (P_p).

The three energy signals allow determination of the particle energy, and ΔE vs E comparison permits Z identification. The two position signals allow reconstruction of the particle's trajectory. This and the calculated recoil velocity permit derivation of the decay half-life. Also, trajectory information allows correction for the detector solid angle and Doppler broadening effects.

Our bombardments of ^{142}Nd yield two distinct groups of alpha particles. The first, having laboratory energies in the range 3–4.5 MeV, exhibits structure within this

Fig. 2.4. Schematic of the experimental configuration employed to study short-half-life alpha decay in flight.

range and shows a buildup with distance downstream from the target. The energy structure is broadened by transformation to the center of mass of a recoiling compound system. We conclude that these alpha particles result from decay at rest of rare earth nuclei deposited on the detector entrance window. They can be so deposited by recoil from a prior decay occurring at least 0.5 cm downstream from the target or by some mechanism which is not presently understood. Bombardment of a ^{120}Sn target showed no evidence for these alpha particles.

The second group of alpha particles is a continuum which falls off in yield from about 5 MeV to about 15 MeV and decreases rapidly with distance downstream from the target. A similar continuum appears for both ^{142}Nd and ^{120}Sn targets and to a smaller extent with a blank target frame and represents a background limitation in our present arrangement. If the continuum from ^{142}Nd were entirely due to decay in flight the cross section for production and subsequent α -decay of an isomer with a half-life of 10–50 ns would be about 25 μb . Detailed analysis of the data should establish a significantly lower upper limit. Combined with measured cross sections for the production of several isomers by this reaction, upper limits for the branching ratio for alpha decay of these isomers should be established. A possible source for this background is n, α reactions in the detector entrance window or in the methane gas volume near the position sensitive wire. Although no evidence for monoenergetic alpha groups appears above this background for 125, 135, and 145 ^{16}O bombardment of ^{142}Nd , the deposition of rare earth activity on the entrance window mentioned above is suggestive of the existence of a prior particle decay.

≈ 50 region. Most of these known isomers have low spin ($I \approx 8$) and involve the $g_{9/2}$ proton orbit. Recently, much higher-spin isomers ($I \approx 30$) have been observed in the lead region³ and in the vicinity of the 82-neutron shell.⁴ Theoretical calculations indicate⁵ that these isomeric nuclei have oblate shapes. Similar calculations also indicate that high-spin isomers may exist in the region around $N \approx 50$ and $Z \approx 50$. Therefore we have initiated a search for new isomers in this region with (HI, xn) reactions.

A beam of 81-MeV ^{20}Ne from ORIC was used to bombard lead-backed targets of ^{76}Ge and ^{78}Se . In the experiment, both γ -RF and γ - γ -RF coincidence data were taken using two Ge(Li) detectors. Lifetimes of isomers were derived from the γ -RF data, while the gamma rays deexciting and feeding the isomers were determined from the γ - γ -RF data. Since the neutron binding energy at the 50-neutron shell is quite large, several competing reaction channels via charged-particle emission led to a variety of final nuclei. We were able to identify and measure the decay properties of the known isomers $^{91,92,94}\text{Mo}$, ^{93}Tc , and $^{94,95}\text{Ru}$ and to study the prompt transitions in ^{91}Nb and ^{95}Tc . We found one new isomer having a half-life of about 5 nsec. From the excitation energy of the compound system and the systematics of the decay process, this isomer was placed in ^{94}Tc . The gamma-rays deexciting this isomer include 283-, 691-, and 1373-keV transitions. Additional transitions having energies of 167, 186, 607, and 1032 keV also appear to be associated with this new isomer. Prompt gamma-ray lines identified with this isomer have energies of 606, 620, 692, 882, and 1448 keV.

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SEARCH FOR ISOMERS IN THE $N \approx 50$ and $Z \approx 50$ REGION

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From reactions induced by light ions, there are known to be several isomers in the nuclei in the $N \approx 50$ and Z

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FUSION OF $^{16}\text{O} + ^{10}\text{B}$ AND THE LIQUID-DROP LIMIT

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The cross section for the fusion of $^{16}\text{O} + ^{10}\text{B}$ has been measured at nine bombarding energies, covering the

center-of-mass energy range (MeV) $16 \leq E_{c.m.} \leq 78$. Self-supported ^{10}B targets (98% enrichment) were used for eight different ^{16}O bombarding energies, and a gas-cell target was used for one measurement at $E_{^{10}\text{B}} = 67$ MeV (ref. 1).

Figure 2.5 shows the results for the fusion cross section (solid points) plotted vs $1/E_{c.m.}$. The open triangles are the results for $^{14}\text{N} + ^{12}\text{C}$ (refs. 2,3) and are shown for comparison. The thick solid line is the Glas-Mosel fit to the fusion data (excluding the highest-energy point), with parameters $V_c = 2.5$ MeV and $r_c = 1.35$ fm, and the dashed line is the fit for $^{14}\text{N} + ^{12}\text{C}$ ($V_c = -1.9$ MeV, $r_c = 1.11$ fm).

The comparison of the fusion of $^{16}\text{O} + ^{10}\text{B}$ with $^{14}\text{N} + ^{12}\text{C}$ indicates that, for $E_{c.m.}$ up to 65 MeV, the limitation arises from the entrance channel; however, the difference in the critical distance for fusion (r_c) of about 21% is indicative of microscopic effects in the fusion process. The fusion cross section for $^{16}\text{O} + ^{10}\text{B}$ at the highest energy ($E_{c.m.} = 78$ MeV) drops by 20% from the value expected by the entrance channel (thick solid line in Fig. 2.5), and the extracted critical angular momentum is $26.5\hbar \pm 1$. The drop in the cross section

can be interpreted as the reaching of an absolute maximum angular momentum that the ^{26}Al nucleus can sustain (liquid-drop limit). The value of $26.5\hbar$ extracted for $^{16}\text{O} + ^{10}\text{B}$ compares very favorably with one extracted for $^{14}\text{N} + ^{12}\text{C}$ (ref. 3) of $27\hbar$ and thus reinforces the liquid-drop limit for ^{26}Al .

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COINCIDENCE MEASUREMENTS OF THE $^{14}\text{N} + ^{12}\text{C}$ SYSTEM AT $E_{^{14}\text{N}} = 183$ MeV

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Particle-particle coincidences have been measured for the $^{14}\text{N} + ^{12}\text{C}$ system at $E_{^{14}\text{N}} \approx 183$ MeV using a set of four ΔE (gas ionization chamber) and E counter telescopes. Reaction products were detected from $Z = 2$ to $Z = 10$. One counter was placed at a laboratory angle of $+7.8^\circ$, and angular correlation measurements were made with the remaining counters covering the range for -7° to -62° . All measurements were done in the reaction plane.

Previous singles measurements of the $^{14}\text{N} + ^{12}\text{C}$ system^{1,2} have indicated the presence of two distinctive energy distributions for the yields of isotopes from boron to oxygen, which can be identified as arising from evaporation residues and peripheral reactions. Figure 2.6a shows a typical energy spectrum for carbon ions at $\theta_{\text{lab}} = 7.8^\circ$, where the lower-energy group has the characteristics of evaporation residues and the higher-energy group those of a peripheral reaction. The present coincidence measurements confirm this interpretation, as can be seen from Fig. 2.6b, which shows the energy spectrum of carbon ions at 7.8° resulting from the integration of the angular correlation (from -7° to -62°) of boron, carbon, and nitrogen fragments in coincidence with the carbon ions at $+7.8^\circ$. The fact that only the higher-energy component remains indicates the correct identification of this component as arising from a two-body peripheral reaction. The lower-energy component is, however, in coincidence only with alpha particles, in accordance with an evaporation residue description.

An analysis of the coincidence data in terms of a possible low- l fusion window is in progress, with emphasis on the coincidences between fragments of $Z \leq 5$.

Fig. 2.5. σ_{fus} vs $1/E_{c.m.}$. The solid circles correspond to the fusion of $^{16}\text{O} + ^{10}\text{B}$ and the open triangles to $^{14}\text{N} + ^{12}\text{C}$. The thick solid line is a fit to the $^{16}\text{O} + ^{10}\text{B}$ data with $V_c = 2.5$ MeV and Glas-Mosel $r_c = 1.11$ fm. The thin solid line indicates the behavior of σ_{fus} once the liquid-drop limit has been reached. The $^{14}\text{N} + ^{12}\text{C}$ data are from R. G. Stokstad et al., *Phys. Rev. Lett.* **36**, 1529 (1976), and *Phys. Lett.* **70B**, 289 (1977).

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Fig. 2.6. Energy spectra of carbon ions at $\theta_{\text{lab}} = 7.8^\circ$ and $E_{^{14}\text{N}} = 183 \text{ MeV}$. (a) Singles spectrum. The lower-energy group (centroid about 60 MeV) corresponds to evaporation residues, and the group at higher energies corresponds to a direct peripheral process. (b) Spectrum for carbon ions in coincidence with boron, carbon, and nitrogen fragments measured between -7° and -62° .

LIGHT-PARTICLE EMISSION FROM HEAVY-ION REACTIONS

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Studies of energy spectra and yields of protons and alpha particles from medium-energy heavy-ion-induced reactions have shown large forward-peaked components with particle energies well above those of compound-

nucleus statistical emission spectra.^{1,2} Recently reported measurements³ of spectra of $Z = 1$ particles from the reaction of 192-MeV ^{12}C with ^{56}Fe showed the proton spectra to extend to about 70 MeV and the deuteron and triton spectra, at forward angles, to extend to energies far above the energy per nucleon of the incident projectile.

There has been considerable recent discussion of possible mechanisms for production of these high-energy nuclear particles.³⁻⁸ We have begun a program to obtain a variety of data to assist in the understanding of this phenomenon. These include (a) measurements of energy spectra and yields of $Z = 1$ and 2 particles from reactions with a range of incident particle energy and target mass, (b) measurement of (heavy ion, light ion) coincidences, and (c) measurement of gamma rays in coincidence with the energetic light ions. We have already obtained considerable information from category a, and some of it is presented here.

The data reported here are from 208-MeV ^{16}O (13 MeV/amu) on targets of carbon, iron, and zirconium. Measurements were made at laboratory angles of 8° and 20° . The experimental arrangement is the same as that described in ref. 3.

Figure 2.7 compares the proton energy spectra observed at 20° from the three targets. The principal fea-

Fig. 2.7. Energy spectra of protons at 20° from reactions of 208.2-MeV ^{16}O on targets of carbon, iron, and zirconium.

Fig. 2.8. Energy spectra of $Z = 1$ and 2 particles at 8° from reactions of 208.2 MeV ^{16}O on targets of carbon, iron, and zirconium.

tures of the data are that they extend to more than four times the energy per nucleon of the incident projectile, the cross sections are large, and the energy spectra and cross sections do not vary much with target mass. For the three targets the measured cross sections (at 20° lab) for protons above 13 MeV are 330 , 280 , and 300 mb/sr, respectively, for targets of carbon, iron, and zirconium. At 8° the cross sections vary between targets (for $Z = 1$ particles) by less than a factor of 2 .

In Fig. 2.8 we compare energy spectra (at 8° lab) for protons, deuterons, tritons, and alpha particles for the three targets. The energy spectra and yields for all four particle types do not show large variations with target mass.

Data were obtained for a number of additional incident particle energies and targets of wider range of mass, and analysis of these data is under way.

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BACK SCATTERING AND FUSION IN THE $^{20}\text{Ne} + ^{12}\text{C}$ SYSTEM

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An excitation function has been measured for several reaction products of $^{20}\text{Ne} + ^{12}\text{C}$ collisions. The aim was to make a simultaneous study of resonant behavior of elastic and inelastic backward scattering as well as other channels such as alpha transfer [$^{12}\text{C}(^{20}\text{Ne}, ^{16}\text{O})^{16}\text{O}$] and fusion. Marked resonant behavior of both fusion and scattering channels has been observed for the lighter systems $^{12}\text{C} + ^{12}\text{C}$ and $^{12}\text{C} + ^{16}\text{O}$,⁴ while for heavier systems such as $^{12}\text{C} + ^{24}\text{Mg}$ and $^{12}\text{C} + ^{28}\text{Si}$ only the back-angle elastic and inelastic cross sections exhibit resonant behavior.⁵ The $^{20}\text{Ne} + ^{12}\text{C}$ measurements are intended to bridge the gap between these two sets of data.

The ^{20}Ne (4^+) beam from the ORIC was used to bombard a natural ^{12}C target. In order to measure the back-scattered ^{12}C ions between 2° and 10° a gas absorber plus position-sensitive detector system was used to stop ^{20}Ne but allow the recoiling ^{12}C ions to reach the counter. At larger angles, $\theta_{\text{lab}} > 10^\circ$, a position-

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sensitive ΔE - E telescope system was used.⁶ Measurements were performed at 20 energies in the range of 54 to 84 MeV. Figure 2.9 shows the measured excitation function (a) for the elastic and inelastic backward scattering and (b) for the fusion of $^{20}\text{Ne} + ^{12}\text{C}$. Resonant behavior is clearly evident in the scattering and fusion data.

Analyzing the elastic data by a P_J^2 procedure, we concluded that $J = 14$ provides a preferred description of the data compared with other possible single-resonance terms. It is interesting to note that the grazing angular momentum at this energy is $J_g \approx 20 \pm 1$, and the critical angular momentum for fusion obtained

from our data (at the same energy) is $J_{CR} \approx 19 \pm 2$. These results make it difficult to interpret these resonances as surface-wave phenomena.⁷ Figure 2.10 shows σ/σ_R as a function of energy for back-angle elastic scattering on ^{12}C targets by several alpha-conjugate nuclei. The only system whose average cross section deviates from the systematics appears to be the $^{24}\text{Mg} + ^{12}\text{C}$ system, which was measured with the same collaborators at the MP Tandem at the University of Rochester.⁵

Fig. 2.9. Excitation functions in the $^{20}\text{Ne} + ^{12}\text{C}$ system. (a) Summed excitation functions for inelastic scattering between 162° and 176° (c.m. angles). (b) Excitation functions for fusion.

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Fig. 2.10. Systematics of $A(^{12}\text{C}, ^{12}\text{C})A$ elastic scattering.

STRONGLY DAMPED COLLISIONS OF

$^{20}\text{Ne} + ^{63}\text{Cu}$

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We have made an extensive study of the products produced in the reaction of 165-MeV ^{20}Ne with ^{63}Cu . The measurements of gamma-ray multiplicity reported in the previous annual report⁴ were repeated with special attention to measuring the out-of-plane gamma-ray angular distribution and to reducing the amount of light contaminants in the target. The procedures followed in this latter respect were essential for the subsequent measurement of light-particle emission (protons and alpha particles) in coincidence with the projectile-like fragments ($Z = 3$ to 16).

The simultaneous measurement of the width of the multiplicity distribution σ_γ and the out-of-plane gamma anisotropy A has enabled us to deduce information on the alignment of the strongly damped fragments. The values of $\sigma_\gamma/\langle M_\gamma \rangle$ and $A = [W(90^\circ) - W(0^\circ)]/[W(90^\circ) + W(0^\circ)]$, as well as the skewness, S_γ , are shown in Fig. 2.11. The dashed lines are the values expected on the basis on tangential frictional forces only (i.e., full alignment of the fragments). Corrections for dipole transitions (20%-30%) and emission of light particles have been applied. These expectations are in sharp disagreement with the experimental data. The full curve is the result of a calculation in which a randomly oriented angular momentum I_f has been introduced, in addition to the aligned component I_0 from tangential friction. The agreement with the experimental data for both $\sigma_\gamma/\langle M_\gamma \rangle$ and A is much improved in this case for a value of $I_f/I_0 \approx 0.9$. This value depends, of course, on the amount of dipole admixture assumed. However, significantly larger dipole contributions ($\geq 50\%$) are not consistent with our measurements of the three-point ($\theta = 0^\circ, 45^\circ$, and 90°) out-of-plane gamma-ray angular correlation. Thus we conclude that the strongly damped fragments have a large component of randomly oriented angular momentum.

The light-particle measurements were made with two heavy-ion telescopes placed at 25° on each side of the beam. Six light-particle ΔE - E telescopes were positioned

Fig. 2.11. Reaction of 165-MeV $^{20}\text{Ne} + ^{63}\text{Cu}$. (a) Relative width, σ_γ/M_γ , and (b) skewness, S_γ , of the gamma-ray multiplicity distribution and (c) out-of-plane gamma-ray anisotropy A . The abscissa is the Z of the projectile-like fragment, detected at 45° . The expected values of the ordinates, assuming complete alignment at scission and corrected for the effects of subsequent light-particle emission, are indicated by the dashed curves. The expected gamma-ray anisotropy (dashed curve) has been calculated assuming two dipole transitions and has been divided by 2.0 before plotting. The predicted effect on A of adding a fluctuating component I_f to the aligned component I_0 is illustrated for $I_f/I_0 = 0.9$ by the solid curve and for $I_f/I_0 = 1.2$ by the dashed-dot curve. Very similar values of $\sigma_\gamma/\langle M_\gamma \rangle$ and S_γ are predicted for $I_f/I_0 = 0.9$ and 1.2 and are therefore shown in each case by a single full curve.

(a) on one side of the beam in the reaction plane and (b) in an out-of-plane configuration.

As shown in Fig. 2.12, the in-plane correlations indicate a forward peaking for the alpha particles in coincidence with the fragments detected in the heavy-ion telescopes. The anisotropy of the out-of-plane correlations (shown in Fig. 2.13) decreases as the Z of the heavy-ion fragment increases. This trend, indicative of an increasing loss of alignment as the fragments approach symmetry, is consistent with the interpretation of the gamma-ray results.

The results shown in Figs. 2.12 and 2.13 are currently being analyzed (with J. Gomez del Campo) using the Monte Carlo code LILITA. This should enable us to determine which features of the experimental results can be accounted for by the evaporation of light particles from fully aligned equilibrated fragments. Any discrepancies with this prediction may then be ascribed to a random component of angular momentum and/or pre-equilibrium phenomena.

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Fig. 2.12. The in-plane angular correlations of alpha particles in coincidence with nitrogen and magnesium fragments. The heavy-ion detector is located at $+25^\circ$. The lines are to guide the eye.

Fig. 2.13. The out-of-plane angular correlations. The value of $\theta = 0^\circ$ denotes a detector in the reaction plane at a forward angle, while $\theta = 90^\circ$ is a direction perpendicular to the reaction plane.

NEUTRON EMISSION IN REACTIONS OF 204-MeV ^{16}O and ^{93}Nb

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An experiment has been carried out to test an apparatus for the measurement of heavy-ion-neutron coincidences, and preliminary neutron energy spectra and multiplicities have been obtained for the reaction $204\text{-MeV } ^{16}\text{O} + ^{93}\text{Nb}$. A thin-walled spherical aluminum target chamber was used to minimize external neutron scattering. Six neutron detectors consisting of NE213 liquid scintillator coupled to 5-in. phototubes were placed outside the chamber at 70 cm from the target.

Two ΔE - E telescopes were used to detect scattered heavy ions. One consisted of 30- μm ΔE and 3-mm E silicon surface-barrier detectors, and the other was a miniature telescope that combined a gas ionization chamber with a silicon E detector.

Single heavy-ion events and heavy-ion-neutron coincidence events were recorded using both the new CAMAC and the PACE data acquisition systems. Flight times of neutrons and of heavy ions and neutron-gamma pulse-shape discrimination signals were recorded using 14 CAMAC time-to-digital converters. Pulse-height signals from the neutron detectors were recorded using six CAMAC analog-to-digital converters. For coincident events, heavy-ion E and ΔE signals were recorded on magnetic tape together with the neutron signals and with an indication as to which of the neutron detectors were involved. Absolute neutron detector efficiency calibrations were made using a ^{252}Cf source placed at the target position.

Neutron energy spectra for events coincident with various Z groups, including deeply inelastic projectile-like fragments and evaporation residue products, were generated from the data tapes. Laboratory-to-center-of-mass corrections (assuming neutron emission from the target-like fragments of deeply inelastic collisions) were made together with efficiency corrections. In Fig. 2.14 these spectra are shown for two neutron detectors and for projectile-like fragments with $4 \leq Z \leq 8$. In addition to "evaporation components," which were fitted by Boltzmann distributions with temperature $T = 1.6$ to 2 MeV, an excess of higher-energy neutrons is seen. The entire distributions can be qualitatively described by a two-component Boltzmann distribution including a $T \approx 8$ MeV "high-temperature" component. Similar distributions were obtained for neutrons in coincidence with evaporation residue products.

Coincident heavy-ion distributions, corrected for detection efficiency of the coincident neutrons, were compared with single heavy-ion distributions, and neutron multiplicities (M) were obtained as a function of Z and of reaction inelasticity. The results for projectile-like fragments with $4 \leq Z \leq 8$ are shown in Fig. 2.15 as a function of heavy-ion energy. A roughly linear increase in $\langle M \rangle$ with increasing inelasticity is observed down to $E_{\text{HI}} \approx 70$ MeV, with a slope of approximately 1 neutron per 12 MeV excitation energy. Below this point a value of $\langle M \rangle$ of about 8 is found.

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Fig. 2.14. Neutron distributions have been transformed into c.m. assuming two-body kinematics. The solid curve is a sum of the $T = 1.6$ and the $T = 8$ MeV evaporation distributions.

Fig. 2.15. The neutron multiplicities were obtained from neutron-heavy-ion coincidence data for $4 \leq Z \leq 8$.

NUCLEAR CHARGE DISTRIBUTIONS FROM REACTIONS BETWEEN ^{20}Ne AND ^{27}Al

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The macroscopic aspects of heavy-ion reactions, fusion, and deep inelastic collisions have been described by some models in terms of critical angular momenta or critical distance of approach beyond which no compound nucleus is produced. There has been increasing interest in studying a wide range of systems and determining the extent to which these processes lead to the same final state as a function of energy and mass and charge symmetry. Here, we do not address the problem of compound-nucleus formation, but rather, given these conditions, an angular momentum and excitation energy, what will be the resulting charge distribution of particle evaporation?

We have measured products from the reaction between ^{20}Ne and ^{27}Al at two different energies, 167.5 MeV and 115 MeV. Our charge distributions were determined from measurements with a ΔE ionization chamber and E surface-barrier detector. For this projectile and target combination, we can resolve the atomic numbers of all reaction products with $Z \geq 5$. The highest nuclear charge observed was $Z = 20$. The charge distribution shown in Fig. 2.16 is a composite of all our data at $E_i = 167.5$ MeV. It is a sum of data taken at $\psi = 5^\circ, 10^\circ, 15^\circ, 20^\circ$, and 30° in the laboratory system. The $Z = 10$ point was obtained by excluding the elastically scattered events and making an estimate of the quasi-elastic and deep inelastic events for $\psi = 5^\circ$. The uncertainty in the neon yield is due to this procedure. The points shown for the other elements are simply the total yield for the particular Z . The data for the run at the lower bombarding energy² is shown in Fig. 2.17, and one sees that the two distributions are similar.

As may be seen from the figures, the charges fall into two groups: those with $Z \geq 13$, which may be to a large extent evaporation residue products, and those with $Z < 12$. While the sum of all observed products in the group $Z > 13$ follows an angular distribution which decreases exponentially with increasing angle, which is characteristic of the behavior expected for evaporation residues, the individual products near the target Z do not. Specifically, the products $Z = 13, 14$, and 15 show clear evidence of a two-component angular distribution. This may be interpreted as the range over which the deep inelastic component is becoming negligible compared with the evaporation residue production.

Fig. 2.16. Elemental yields at $E = 167.5$ MeV. Yields from experiment are shown by open circles, calculations from JULIAN by closed circles, and calculations from ALICE by closed triangles.

There are several statistical-model computer programs available which calculate the probability of particle emission and give the resulting distributions of evaporation residue products. The distributions predicted by three such programs have been compared with each other and with experimental data in the case of 366-MeV ^{86}Kr bombardments. Two of the calculations, JULIAN and CASCADE, include couplings to specific final angular momentum of ^{65}Cu states. JULIAN employs a Monte Carlo technique, and a version of the program modified by A. Gavron was used. The CASCADE calculations were performed by F. Pühlhofer. The third calculation, ALICE, does not consider explicitly individual angular momentum states, but several approximations concerning angular momentum dissipation are available. The centroids and widths of the charge and mass distributions predicted by the three

Fig. 2.17. Elemental yields at $E = 120$ MeV. Yields from experiment are shown by open circles, calculations from JULIAN by closed circles, and calculations from ALICE by closed triangles.

calculations are in good agreement with each other and in general describe the experimental data reasonably well. They differ from each other primarily in the details of relative isotopic yields.

In the figures the results of the calculations have been plotted for $^{20}\text{Ne} + ^{27}\text{Al}$ along with the experimental data. It may be seen that, contrary to the $\text{Kr} + \text{Cu}$ case, the approximate program ALICE does not give an adequate description of our data. This disagreement persists regardless of which angular momentum approximation is selected. In contrast, the more exact JULIAN calculation is in reasonably good agreement with the experimental data. The excitation energies involved in the two reactions, $^{86}\text{Kr} + ^{65}\text{Cu}$ and $^{20}\text{Ne} + ^{27}\text{Al}$, are comparable, and the main differences between the two systems are (1) that the $\text{Ne} + \text{Al}$ system is considerably lighter than the $\text{Kr} + \text{Cu}$ system and (2) that it involves lower angular momenta. Our preliminary conclusion is that the approximate ALICE calculations fail to reproduce the experimental results primarily due to an underestimate of alpha emission. It is likely that both angular-momentum enhancement of alpha emission and a more

realistic treatment of binding energies contribute to the good agreement between theory and experiment observed in the case of JULIAN calculations. We conclude that approximate calculations such as those using the ALICE program may not be adequate for very light systems such as $\text{Al} + \text{Ne}$ and that the more exact calculations should be used in this region whenever practical, particularly when reasonably accurate predictions of charge and mass distributions of evaporation residue products are required.

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REACTIONS BETWEEN ^{40}Ar AND ^{27}Al AT 160 MeV

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It has been observed in a number of studies at ORIC that, in ΔE - E measurements of reaction products, it is usually not possible to resolve individual nuclear charges beyond $Z \approx 24$. The reason for this limitation is that heavy reaction products, such as evaporation residues produced with typical projectiles, such as neon and oxygen, at ORIC energies, seldom have sufficient energy to be above the Bragg peak in the range-energy relationship. In order to avoid this limitation on charge resolution, we have initiated a study of the reaction $^{40}\text{Ar} + ^{27}\text{Al}$, in which the projectile is considerably more massive than the target nucleus. The virtue of such an "inverted" target-projectile combination is that the resulting fusion products have considerably higher recoil energies, and thus the resolution range of the ΔE - E technique can be extended.

In this work, we have performed simultaneous mass and charge determinations of all reaction products using a combination of the ΔE - E technique and time-of-flight measurements. We had no trouble in resolving all observed nuclear charges up to $Z = 27$. A mass-charge distribution was obtained only at 5° , and we plan to make a similar measurement also at a greater angle in the future.

In addition to the mass-charge distribution, we have measured angular distributions of all reaction products, as well as Coulomb scattering. From the 1/4-point method we conclude that the total reaction cross section is 1760 ± 140 mb. The cross sections for evapora-

tion residue products, for deeply inelastic products, and for quasi-elastic products were found to be 1580 mb, 25 mb, and 40 mb respectively. Thus the reaction between ^{40}Ar and ^{27}Al at 160 MeV is, surprisingly, completely dominated by fusion reactions, to the point of making the study of competing processes impractical, given the limited geometry of our time-of-flight apparatus. Bass model predictions using a standard set of parameters are 1122 mb for fusion and 1512 mb for the total reaction cross section. Even if we normalize the calculated total reaction cross section to the experimental one and thus increase correspondingly our estimate of the fusion cross section, we find that a significant gap exists between our observation and the Bass model prediction. The reasons for this discrepancy and for the very large fusion cross section are not understood.

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NONSTATISTICAL EFFECTS IN THE REACTIONS OF ^{16}O WITH ^{154}Sm

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Previous studies³⁻⁵ of the deexcitation of ^{170}Yb compound nuclei showed that nonstatistical effects are present when ^{170}Yb is formed by ^{12}C with ≥ 9 MeV per nucleon but not when it is formed by ^{20}Ne with up to 8.7 MeV per nucleon. We are now studying the same compound nucleus formed with ^{16}O and ^{154}Sm .

In one experiment we used a Ge(Li) detector inside an anti-Compton annulus together with an array of nine NaI counters to measure the excitation functions and average gamma-ray multiplicities $\langle M_\gamma \rangle$. The projectile energies were 112, 127, 142, 156, and 169 MeV. The excitation functions (Fig. 2.18) for the xn products show high-energy tails characteristic of nonstatistical emission. One does not have such clear evidence for this effect from the αxn yields because the high-energy region is obscured by the $2p(x+2)n$ cross section, as exemplified here by the $2p8n$ peak on the $6n\alpha$ curve. In Fig. 2.19 the effect of nonstatistical emission of particles is visible for both xn and αxn channels, showing up as the saturation in $\langle M_\gamma \rangle$ for a given x with increasing energy. In contrast, the results³ for $^{20}\text{Ne} + ^{150}\text{Nd}$, indicated by the dashed line, show the normal expectation for equilibrated systems, namely that as more energy is added, more gamma rays are emitted. The saturation in $\langle M_\gamma \rangle$ for xn channels in the O + Sm system is evident for ≥ 8.0 MeV per nucleon.

Fig. 2.18. Excitation functions of the products formed in the bombardments of ^{154}Sm with ^{16}O .

Fig. 2.19. Average multiplicities of the products formed in the bombardments of ^{154}Sm with ^{16}O .

In a second experiment, spectra and angular distributions were measured by time of flight for neutrons and by particle telescopes for charged light particles for individual exit channels in the reactions of 153-MeV ^{16}O with ^{154}Sm . Thus far, $\langle M_\gamma \rangle$ and widths have been determined as a function of the energies and angles of the emitted alpha particles. The analysis of the data is continuing.

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${}^6\text{Li}$ SCATTERING

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Lithium ions are in the mass region between light nuclear particles and heavy ions, and the systematics of their elastic scattering has not been well explored. Data from a number of targets ($A = 40$ to 90) at 26 and 34 MeV² showed very damped structure in the angular distribution reminiscent of heavy-ion elastic scattering. However, a study of 135-MeV ${}^6\text{Li}$ scattering³ from ${}^{28}\text{Si}$ showed results more like that of light ions than heavy ions. Optical-model analyses of 99-MeV ${}^6\text{Li}$ scattering⁴ produced good fits to the data with a Woods-Saxon potential but had less success with a real folded potential, in contrast to a number of heavy-ion optical-model analyses.

The higher-energy ${}^6\text{Li}$ scattering data have shown very pronounced structure in the elastic angular distributions; so data at small angular intervals are needed to measure the details of the angular distributions. With a slice detector that measured an approximately 20° sector at 0.4° intervals in each data run, we measured angular distributions for 88-MeV ${}^6\text{Li}$ scattering from targets of ${}^{24,25,26}\text{Mg}$, ${}^{27}\text{Al}$, ${}^{40,44}\text{Ca}$, ${}^{59}\text{Co}$, and ${}^{60}\text{Ni}$. With this detector arrangement, we obtained data of the quality shown below at the rate of one angular distribution in about one 8-hr shift of cyclotron time.

Figure 2.20 compares elastic angular distributions for ${}^{24,25,26}\text{Mg}$ and ${}^{27}\text{Al}$. These include two targets of $I = 0$ and two neighboring targets of $I \neq 0$. In each case, the minima are deeper for the $I = 0$ targets than the corresponding minima for the neighboring $I \neq 0$ targets. Similar differences are also observed in the ${}^{59}\text{Co}$ and ${}^{60}\text{Ni}$ data. These differences in the elastic scattering of ${}^6\text{Li}$ from neighboring targets are like those previously observed⁵ in elastic scattering of ${}^3\text{He}$ and ${}^4\text{He}$, which were not observed in heavy-ion scattering.⁶ The data show that there is a target spin effect in ${}^6\text{Li}$ elastic scattering which is qualitatively consistent with a quadrupole contribution^{5,7} to elastic scattering from $I \neq 0$ targets. Such a contribution is out of phase with the elastic scattering and hence is strongest in the regions of the elastic scattering minima. Folding-model and coupled-channels analyses of these data are being performed.

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Fig. 2.20. Elastic scattering of 88-MeV ${}^6\text{Li}$ ions from ${}^{24,25,26}\text{Mg}$ and ${}^{27}\text{Al}$. The curves are drawn to guide the eye.

COMPARISON OF THE SINGLE-PROTON PICKUP
REACTIONS $^{40}\text{Ca}(^{11}\text{B}, ^{12}\text{C})^{39}\text{K}$
AND $^{40}\text{Ca}(^{13}\text{C}, ^{14}\text{N})^{39}\text{K}$ AT LOW
AND HIGH BOMBARDING ENERGIES

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The forward-angle enhancement observed in the 40-MeV $^{40}\text{Ca}(^{13}\text{C}, ^{14}\text{N})^{39}\text{K}$ ground-state differential cross section was successfully fitted by introducing a surface transparent potential.^{2,3} However, later measurements at higher energies³ (60, 68 MeV) demonstrated that the surface transparent description was no longer applicable, and, in fact, the oscillatory behavior of the experimental angular distributions was almost exactly out of phase with the predicted shapes calculated from conventional optical potentials.

In order to determine the generality of the surface transparent concept and also to determine if the anomalous phasing persists in a more kinematically favored reaction, we have studied the $^{40}\text{Ca}(^{11}\text{B}, ^{12}\text{C})^{39}\text{K}$ (ground state, $3/2^+$; 2.53 MeV, $1/2^+$; $Q_0 = +7.628$ MeV) reactions at 32 MeV and at 68 MeV incident energies, using the spectrographs at the EN tandem and cyclotron, respectively. At the lower energy, this system is at nearly the same fractional height above the barrier as the 40-MeV $^{40}\text{Ca}(^{13}\text{C}, ^{14}\text{N})^{39}\text{K}$ experiment, while at the higher energy the present reaction is much closer to the optimum Q value.

The single-proton pickup reactions $^{40}\text{Ca}(^{11}\text{B}, ^{12}\text{C})^{39}\text{K}$ and $^{40}\text{Ca}(^{13}\text{C}, ^{14}\text{N})^{39}\text{K}$ are found to produce qualitatively different angular distributions when compared at similar bombarding energies. The surface transparent potential invoked to explain the forward rise in the $^{40}\text{Ca}(^{13}\text{C}, ^{14}\text{N})^{39}\text{K}$ differential cross section at 40 MeV is shown to be inappropriate for the $^{40}\text{Ca}(^{11}\text{B}, ^{12}\text{C})^{39}\text{K}$ data analysis at 32 MeV incident energy. Figure 2.21 compares the $^{40}\text{Ca}(^{11}\text{B}, ^{12}\text{C})$ ground-state data at 32 MeV with distorted-wave Born approximation calculations (using the Vanderbilt exact-finite-range code NICOLE⁴) with the surface transparent potential of Baltz et al.² in both the exit and entrance channels. Since at this energy the exit channel for this system $^{12}\text{C} + ^{39}\text{K}$ is at nearly the same center-of-mass energy as the entrance channel, $^{13}\text{C} + ^{40}\text{Ca}$, of the $^{40}\text{Ca}(^{13}\text{C}, ^{14}\text{N})$ reaction at 40 MeV, a calculation in which a volume absorptive potential was used in the entrance channel

Fig. 2.21. The $^{40}\text{Ca}(^{11}\text{B}, ^{12}\text{C})$ ground-state reaction data. The solid curve is calculated with a surface transparent optical potential in the exit and entrance channels, the dashed curve with conventional volume absorption in the entrance and a surface transparent potential in the exit channel.

and a surface transparent potential in the exit channel is also shown (the dashed curve in Fig. 2.21). Clearly, the surface transparent concept, which is of use in the $(^{13}\text{C}, ^{14}\text{N})$ system, is unsatisfactory in the $(^{11}\text{B}, ^{12}\text{C})$ system at a comparable incident energy.

Figure 2.22 compares the 68-MeV $(^{11}\text{B}, ^{12}\text{C})$ data with DWBA calculations using optical-model potentials which give equally acceptable fits to the elastic data. The solid line results from the use of a conventional volume absorptive potential, whereas the dashed curve is due to the use of a potential similar to that developed by Cramer et al.⁵ in order to fit forward-angle $^{16}\text{O} + ^{28}\text{Si}$ elastic scattering over a wide energy range. At a bombarding energy of 68 MeV, both the $^{40}\text{Ca}(^{13}\text{C}, ^{14}\text{N})$ and $^{40}\text{Ca}(^{11}\text{B}, ^{12}\text{C})$ reactions produce oscillatory angular distributions. But the problem of the $^{40}\text{Ca}(^{13}\text{C}, ^{14}\text{N})$

Fig. 2.22. Transfer reaction data for the $^{40}\text{Ca}(^{11}\text{B},^{12}\text{C})^{39}\text{K}$ reaction at an incident energy of 68 MeV. The solid and broken lines are fits made, respectively, with a conventional absorptive potential and a potential of the type developed by Cramer et al., *Phys. Rev. C14*, 2158 (1976).

68-MeV data being out of phase with the DWBA calculations does not occur for the case of the ($^{11}\text{B},^{12}\text{C}$) data.

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LIGHT-ION FUSION STUDIES WITH A GAS-CELL TARGET

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It has been amply demonstrated¹ that the magnitude and energy dependence of the cross section for complete fusion of two light heavy ions may change drastically with the addition of only one or two nucleons. This evidence points to the importance of the microscopic structure of the colliding nuclei in the fusion process. The way such effects come into play, however, is not understood at the moment. Our purpose is to establish the systematics of fusion cross sections at high energies; the limitation on fusion at these energies could be due to competing processes, and the study of such processes (e.g., direct, deep, and inelastic) is part of this program.

Experimental Apparatus and Procedure

A specially constructed gas cell² provides us with a large variety of high-purity targets. A schematic description and a photograph of the cell are displayed in Fig. 2.23. The compact dimensions of this cell enable us to detect residues from the fusion of two light heavy ions with a relatively low energy threshold (typically a few

Fig. 2.23. Gas cell. (a) Schematic drawing; (b) photograph.

MeV for $A_{\text{residue}} \geq 28$). The charged particles are detected, using a position-sensitive ΔE - E telescope,³ and the evaporation residue yields are integrated to obtain the fusion cross sections.

Measurements and Results

So far three systems have been studied: $^{20}\text{Ne} + ^{20}\text{Ne}$, $^{20}\text{Ne} + ^{16}\text{O}$ and $^{20}\text{Ne} + ^{12}\text{C}$. The 5+ and 6+ ^{20}Ne beams from the ORIC were used to bombard ^{20}Ne and ^{16}O gas targets and a solid ^{12}C target. Results of a preliminary analysis of the fusion cross sections for the three systems are summarized in Table 2.1. V_{CR} and r_{CR} are used to parametrize the energy dependence of the fusion cross sections at high energies:⁴

$$\begin{aligned}\sigma_{\text{fus}}(E) &= \pi R_{\text{CR}}^2 (1 - V_{\text{CR}}/E), \\ R_{\text{CR}} &= r_{\text{CR}} (A_t^{1/3} + A_p^{1/3}), \\ V_{\text{CR}} &= V(R_{\text{CR}}).\end{aligned}$$

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Table 2.1. Preliminary results of the fusion of Ne + Ne, Ne + O, Ne + C

System	V_{CR}	r_{CR}	$\sigma_{\text{fus}}(\text{max})$
Ne + Ne	0	1.12 fm	1150
Ne + O	0	1.02 fm	950
Ne + C			1360

SURFACE STRUCTURE OF DEFORMED NUCLEI

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Heavy-ion projectiles at energies near the Coulomb barrier can excite deformed rare earth and actinide nuclei sufficiently to exhibit Coulomb-nuclear interference (CNI) effects. For such heavy systems the short de Broglie wavelength allows radial localization, and the transfer of multiple rotational quanta permits angular localization around the nuclear surface.³ Recently, refinements to the classical limit S -matrix (CLSM) scattering theory have made tractable the analysis of inelastic excitation of rotational nuclei to high-spin states.^{4,5}

In some early experiments performed at the Berkeley Super HILAC and the Oak Ridge Isochronous Cyclotron, we studied the systems $^{86}\text{Kr} + ^{232}\text{Th}$, $^{40}\text{Ar} + ^{238}\text{U}$, and $^{16}\text{O} + ^{162}\text{Dy}$. We analyzed the data according to the CLSM theory and find support for the basic features of the theory and the first experimental evidence for CNI in the excitation of high-spin states by very heavy projectiles.⁶ In an attempt to make some quantitative measures of the surface structure of these nuclei, we tried to fit the data for each system with a standard complex deformed Woods-Saxon potential with six adjustable parameters. We were successful for some states, but we were unable to meet the criterion that all spin states be fitted simultaneously by the same potential (see Fig. 2.24). These results suggest possible inadequacies in standard parameterizations of the deformed nuclear potential.

In the last few months we have devised a method whereby equipotential contours of the interaction

Fig. 2.24. Excitation functions in the CNI region. The solid line is a calculation for pure Coulomb excitation. ^4He data are from I. Y. Lee et al., *Phys. Rev. C* 12, 1483 (1975), and references therein. The approximate energy uncertainty is indicated by the horizontal bars at the bottom corners. Dashed and dashed-dotted lines are calculations using a nuclear potential as described by M. W. Guidry et al., *Nucl. Phys. A* 274, 183 (1976). The potential parameters are taken from J. R. Birkelund et al., *Phys. Rev. C* 13, 133 (1976) (dashed) and R. Vandenbosch, T. D. Thomas, and M. Webb, contributed paper, Symposium on Classical and Quantum Mechanical Aspects of Heavy Ion Collisions, Heidelberg, 1974 (dash-dotted) and correspond to potentials III and II, respectively, of Guidry et al.

potential are determined without introducing particular models for the potential.³ In addition, it should be possible to probe both charge and mass parameters in the same experiment. We have completed two experiments at ORIC in which the systems studied were $^{40}\text{Ar} + (^{156}\text{Gd}, ^{160}\text{Gd}, ^{162}\text{Dy}, ^{164}\text{Dy})$. Analysis of the data for the system $^{40}\text{Ar} + ^{160}\text{Gd}$ serves as the example for the method described in ref. 3. However, at this time the analysis of the data for the other systems is not yet complete.

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COULOMB EXCITATION OF VIBRATIONAL NUCLEI WITH HEAVY IONS

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Recently the rotational motion of many well-deformed rare-earth^{3,4} and actinide⁵ nuclei has been studied with Coulomb excitation using heavy ions such as ^{136}Xe . Transitional nuclei such as osmium and platinum have also been studied⁶ with the same method. However, our knowledge of vibrational nuclei is limited to low-lying states. In an effort to understand the high-spin behavior of these nuclei and to document their collective nature, we began Coulomb excitation studies

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on the most collective vibrational nuclei around the mass 100 region.

The experiments were carried out with 121- and 130-MeV ^{40}Ar beams from ORIC. Metallic foils of ^{108}Pd , ^{110}Pd , and ^{116}Cd with thicknesses of about 1.5 mg/cm² were used as targets. The backscattered ^{40}Ar projectiles were detected in a solid-state annular detector which extended from 155° to 175°. Gamma rays were detected in two Ge(Li) detectors in coincidence with the backscattered ^{40}Ar . These two detectors, located at 0° and 55° with respect to the beam, were also placed in coincidence with each other to aid in establishing the order of transitions in the level scheme.

Since the energy of a backscattered particle is mainly dependent on the target depth at which the interaction occurs, it is possible to select gamma rays in coincidence with argon ions of different energy ranges. Hence we can obtain an excitation function which provides information on the spin of the levels. Figure 2.25 shows a spectrum from 121-MeV ^{40}Ar on ^{110}Pd . Gamma rays from levels in the ground-state band with spins up to 6⁺ are observed. A 2⁺ and a 4⁺ state in a second band are also observed. An interesting feature of this spectrum is that it does not resemble the spectrum of an ideal vibrator. For an ideal vibrator, the gamma rays between the various phonon states have the same energy. Actually, the spectrum is very similar to a rotational sequence, where the transition energies increase with spin in a rather regular fashion.

Fig. 2.25. Gamma-ray spectrum in coincidence with the back-scattered beam from the Coulomb excitation of ^{110}Pd by 121-MeV ^{40}Ar .

Fig. 2.26. Relative gamma-ray yield from Coulomb excitation of ^{110}Pd by 121-MeV ^{40}Ar . The points are the experimental data, the solid lines are the values calculated with the vibrational model, and the dashed lines are the results from a boson-expansion calculation.

In addition to the level energies, the Coulomb excitation cross section can provide a better insight to the collective properties. We have compared the experimental gamma-ray yields with the predictions of several models. The Coulomb excitation yields are calculated using the program of Winther and de Boer. For the input of the program, we use the experimental level energies and several sets of theoretical matrix elements. The values of the matrix elements are normalized to the known values⁷ of $\langle 0^+ || M(E2) || 2^+ \rangle$.

Figure 2.26 shows the comparisons between the experimental and calculated results. Both the vibrational-model and the boson-expansion-model calculations give good agreement for the ground-state band. However, there are large differences for the second 4⁺ and the second 0⁺ states. The experimental yields are much lower than the calculations. This may indicate the loss of collectivity in the side band and the concentration of collectivity into the ground-state band. Combined with the observed quasi-rotational energy level spacings, these results may be the first indication that these "vibrational" nuclei change to rotational behavior at rather low spin.

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IDENTIFICATION OF ^{148}Ho AND ^{149}Ho

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The properties of low-lying states in dysprosium nuclei near the $N = 82$ closed shell have been investigated⁵ via the decay of holmium isotopes. Previously, evidence was presented⁵ for the discovery of ^{149}Ho . This nuclide was produced by bombarding ^{144}Sm with $^{10}\text{B}^{3+}$ ions accelerated in the ORIC, where the maximum incident energy on target is about 80 MeV. These studies were continued at the Texas A&M University isochronous cyclotron, where more energetic ^{10}B ions are available. As before, a gas-jet system was used to transport products to a shielded area for gamma-ray singles and coincidence measurements.

Data obtained at 85 MeV confirmed the earlier preliminary results.⁵ The half-life of ^{149}Ho was found to be 21 ± 2 sec. Three transitions were identified in the nuclide's electron capture plus position decay: 1091.1 ± 0.1 ($I_\gamma = 100$), 1073.3 ± 0.1 ($I_\gamma = 13$), and 1583.6 ± 0.2 keV ($I_\gamma = 9$). On the basis of systematics (see, e.g., ref. 5) of single-particle states in this mass region, we propose that (1) the 21-sec radioactivity represents the $h_{11/2}$ proton state in ^{149}Ho and (2) the 1091.1- and 1073.3-keV transitions locate the $h_{9/2}$ and $i_{13/2}$ neutron states in ^{149}Dy at 1091 and 1073 keV respectively.

At 96 MeV the intensity of a 1688.3 ± 0.2 keV gamma ray was observed to increase dramatically vis-à-vis its intensity at 85 MeV (see Fig. 2.27). This energy parallels those of transitions deexciting first excited states in even-even $N = 82$ nuclei, which increase gradually from ^{136}Xe to ^{144}Sm (1660 keV). Although in ^{146}Gd the first excited level drops to 1580 keV, the 1688-keV gamma ray is still a good candidate for the transition from the first excited to the ground state in ^{148}Dy .

Fig. 2.27. Gamma-ray spectra obtained in ^{10}B bombardment of ^{144}Sm . (a) Portion of a spectrum obtained at 85 MeV; (b) spectrum covering the same energy range but obtained at 96 MeV. The spectra (a) and (b) represent the first 15 and 7 sec of counting, respectively, accumulated following numerous irradiation and counting cycles. The 1688.3-keV gamma ray, whose intensity increases dramatically at 96 MeV, is assigned to the new isotope ^{148}Ho .

The identification of this new 9 ± 1 sec gamma ray with ^{148}Ho is based on the following evidence: (1) its intensity relative to that of the 620-keV ^{148}Dy gamma ray⁶ remained constant from 85 to 96 MeV, (2) it was in coincidence with dysprosium K x rays, and (3) it had not been observed in the earlier studies^{6,7} of the decay of dysprosium nuclides.

The 1688-keV transition was in coincidence with 661.5 ± 0.2 keV and 504.3 ± 0.3 keV gamma rays. These transitions were also observed in coincidence with one another. (Table 2.2 summarizes transition energies and photon intensities for ^{148}Ho .) The experimental data establish in ^{148}Dy the following cascade and sequence of levels in keV: 504 (2854) $\rightarrow$ 662 (2350) $\rightarrow$ 1688 (1688) $\rightarrow$ ^{148}Dy ground state. This situation resembles the one found⁸ in the decay of the isotone, ^{146}Tb , namely, 441 (3099) $\rightarrow$ 1078 (2658) $\rightarrow$ 1580 (1580) $\rightarrow$ ^{146}Gd ground state. In ^{146}Gd the spins of the first two excited levels were assumed to be $4^+ \rightarrow 2^+ \rightarrow 0^+$, as systematics⁹ for even-even nuclei with $N = 82$ indicated. Recent data,¹⁰ however, show that the first excited state in ^{146}Gd is 3^- , so that the sequence is, instead, $5^- \rightarrow 3^- \rightarrow 0^+$. The fact that in ^{146}Dy as in ^{144}Sm the energy of the first excited state has once again increased relative to its value in ^{146}Gd raises the question whether it is 2^+ or 3^- in character. From the intensities of the 662- and 1688-keV gamma rays, it is

Table 2.2. Transition energies and photon intensities for 9-sec ^{148}Ho

E_γ (keV)	I_γ^a
504.3 ± 0.3	17 ± 3
661.5 ± 0.2	69 ± 7
1688.3 ± 0.2	100

^aRelative intensity based on a value of 100 for the 1688-keV transition.

apparent that both the 2350- and 1688-keV levels are fed directly by the decay of ^{148}Ho . The spin of the parent is, therefore, 3 or 4 depending on the spin of the two levels in ^{148}Dy .

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HIGH-SPIN STATES IN ^{164}Yb

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The "backbending" phenomenon, in which a low-lying rotational band encounters a higher-lying band with an appreciably larger moment of inertia, is a rather common occurrence. Beyond the backbend, one expects the yrast sequence to cross additional bands built on other excited nucleon structures and hence to produce additional backbends. To this point, only one such second band crossing in the yrast sequence has been observed.⁶

In an effort to determine the properties of very high-spin states in ^{164}Yb and especially to search for a

Fig. 2.28. Backbending plot of ^{164}Yb . Here $\mathcal{J}$ is the moment of inertia and ω is the rotational frequency of the nucleus.

second band crossing and study this phenomenon, we have studied the reaction $^{150}\text{Nd}(^{20}\text{Ne}, 6n)^{164}\text{Yb}$ at ORIC. To enhance the desired reaction channel, a multiplicity filter consisting of an array of 14 NaI detectors was used in coincidence with three Ge(Li) detectors. The Ge(Li) detectors were located near 180° and 0° with respect to the beam direction so as to reduce the Doppler broadening effects on the gamma rays. Thin targets ($<1 \text{ mg/cm}^2$) of ^{150}Nd were used to allow the excited nuclei to recoil into a vacuum where they could decay in flight.

A large amount of coincidence data (76 magnetic tapes) was collected. Analysis of these data has led to the assignment of states up to 28^+ in the yrast sequence, as seen in the standard backbending plot shown in Fig. 2.28. Although this is the second-highest population of discrete states in a compound-nucleus reaction leading to a prolate even-even nucleus, there is no evidence for an additional backbend. However, at spin 28^+ , we see that the moment of inertia ($\mathcal{J}$) is once again increasing, and thus there may be a reasonable probability for seeing a second backbend within two or three more states.

We are now planning additional measurements with ^{40}Ar projectiles, which will carry more angular momentum into the compound system and thus enhance the possibility for seeing these higher discrete states.

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MULTIPLE BAND CROSSINGS IN ^{164}Er

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From the amassing experimental evidence it is now generally concluded that the "backbending" phenomenon is caused by the intersection of the ground-state rotational band with a second rotational band possessing an appreciably larger moment of inertia (e.g., see Stephens⁷ and Lee et al.⁸). In the rotation-alignment model⁹ the structure of this band corresponds to two quasi particles whose angular momenta are aligned with the rotating core. Further, this model^{7,9} predicts a series of rather similar rotation-aligned bands commonly called superbands.

The structure of the superbands can be probed by studying their interactions with the ground and the β - and γ -vibrational bands. Thus far, only the interaction of the lowest (yrast) superband with the ground and β bands has been observed. However, the γ band would appear to be a better probe of the superbands, since here one can study the interactions with both even- and odd-spin states. The present measurements on ^{164}Er give the first evidence for higher superbands and also the first example of intersections between the γ band and these superbands.

A beam of 69.6-MeV ^{18}O ions from the Oak Ridge Isochronous Cyclotron (ORIC) was used to bombard a 2.4-mg/cm² metallic neodymium foil enriched to 96% in mass 150. Both gamma-ray singles and gamma-gamma time coincidence data (total of 3.5×10^7 coincidence events) were stored simultaneously in the experiment at a gamma-ray resolution of 2.3 keV for 1.33 MeV. The resulting level scheme for the positive-parity states is shown in Fig. 2.29. This figure shows the ground-state rotational band up to spin 22⁺, the yrast sequence up to 24⁺, and both the odd- and even-spin members of the γ -vibrational band up to 21⁺. Negative-parity bands were found but are not shown in Fig. 2.29.

The plot of the experimental excitation energies vs I (Fig. 2.30a) clearly shows several intersecting rotational bands. To understand these results, a calculation was made using typical parameters to illustrate the general features predicted for ^{164}Er by the rotation-alignment

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Fig. 2.29. Level scheme of ^{164}Er , showing the ground band, the yrast superband, and the γ -vibrational band populated in the reaction $^{150}\text{Nd}(^{18}\text{O}, n)^{164}\text{Er}$. Shown on each transition is the energy and, in parentheses, the relative intensity. Uncertainties range from less than 10% for the intensities of the stronger transitions up to 30%–40% for some of the very weak ones.

model.^{7,9} Both zero- and two-quasi-neutron configurations within the complete $i_{13/2}$ orbit were included. The excitation energies from these calculations are shown in Fig. 2.30b. The γ band is shown for illustration but was not explicitly included in the calculations. The correspondence between experiment and theory is indeed striking.

The interaction between the intersecting bands is most clearly illustrated using the "backbending" plot of the data shown in Fig. 2.31. From the present data and previous work,^{8,10} it is found that near the intersection

Fig. 2.30. Plot of the level excitation energies for various bands in ^{164}Er . (a) Experiment, (b) from the rotation-alignment model. The solid circles correspond to even-spin states and the open circles to odd-spin states.

of the ground-state band and lowest yrast superband, both the level energies and gamma-ray branching ratios indicate the interaction matrix elements of about 45 to 50 keV between these bands.

If a 45-keV interaction is used, then the unperturbed ground-band energies lie on a smooth extension of the lines up through the 18^+ state, and the yrast even-superband energies likewise vary smoothly, as shown by the open circles in the left half of Fig. 2.31. However, the 20^+ and 22^+ members of the ground band are affected very little by this interaction. Interestingly, if we extrapolate the yrare even superband, as shown by the dashed line in Fig. 2.30a, and assume an interaction matrix element of 45 keV, then the upward kink in the ground band for the 20^+ and 22^+ states is largely removed.

Fig. 2.31. Plot of $2J/h^2$ vs $(\hbar\omega)^2$ for members of the ground band, γ -vibrational band, and superbands in ^{164}Er . The open circles on the ground and yrast even superbands are corrections for a 45-keV interaction matrix element. Open circles on the γ band result from a 25-keV shift in the 10^+ energy. The circles represent even-spin and the squares odd-spin states.

On the right-hand side of Fig. 2.31 we show a plot for the transitions in the γ -vibrational band. We have made a 25-keV shift in the 10^+ level energy, which produced equal but opposite shifts in the $10^+ \rightarrow 8^+$ and $12^+ \rightarrow 10^+$ transition energies. Such an energy shift is expected, due to a crossing of the γ band and the lowest (yrast) superband, provided there is an interaction matrix element around 45 keV. The odd-spin-state energies in the γ band are smooth in this spin region without such a shift, providing the first direct evidence that the odd-spin states in the yrast superband lie considerably higher than the even-spin states. Backbends of both the even- and odd-spin members of the γ band are apparent around spins 13 and 14.

A marked reversal in the odd-even staggering occurs through the backbend region in the γ band. The direction of this staggering is that the odd-spin states lie high relative to the even-spin ones below the backbend and low after the backbend. This reversal in the staggering is the strongest evidence that these higher superbands indeed correspond to the higher $i_{13/2}$ bands coupled to the ground band.

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CONTRASTING BEHAVIOR OF $h_{9/2}$ AND $i_{13/2}$ BANDS IN ^{185}Au

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There are legitimate questions about the exact role which the $h_{9/2}$ proton plays in backbending of rotational bands in even-even deformed and transitional nuclei in the $150 < A < 190$ region. The consensus of opinion now seems to be that in most cases the Coriolis rotation alignment⁵ of a high- j , low- Ω pair of particles causes the abrupt increase in $\mathcal{J}$, the moment of inertia, and a corresponding decrease in ω , the rotational frequency. The usual test to determine which Nilsson orbitals contribute most to even-even backbending is to search for the absence of backbending in the rotational bands in adjacent odd- A nuclei where the odd nucleon occupies one of these critical orbitals. Such blocking experiments have been performed on several rare-earth nuclei (e.g., ref. 6) and led to the conclusion that $i_{13/2}$ neutrons are primarily responsible for backbending in that region.

In contrast to the solidarity of experimental evidence indicating $i_{13/2}$ neutron alignment in the rare earth region, is the conflicting information on the cause of backbending in the prolate tungsten-osmium-platinum region. (Note that the heavier platinum isotopes are oblate; the change from oblate to prolate shapes occurs between ^{185}Pt and ^{186}Pt .⁷) A variety of rotational bands in odd- A nuclei in this region have been observed⁸⁻¹⁰ ($^{181,183}\text{Os}$, ^{183}Re , $^{183,185}\text{Ir}$, ^{187}Au). The excitation of the extra nucleon into these various orbitals has been found to sometimes block core backbending, leading to no clear consensus about which particles align most easily in this region. The difficulty in drawing definite conclusions from these experiments is due to the difficulty in comparing the even-even nucleus with the effective even-even core in odd- A nuclei where the Fermi surface is slightly different and where the extra nucleon may have a sizable effect on the core

deformation and thus on the whole alignment mechanism. For example, our earlier blocking experiments⁵ on ^{185}Yb proved rather conclusively that the $i_{13/2}$ neutron dominates even- A backbending in ytterbium. In contrast, Foin and Barneoud¹¹ observed a nonbackbending $1/2[541]$ band in ^{167}Lu , leading one to the conclusion that $h_{9/2}$ protons also contribute to backbending in ytterbium. However, theoretical calculations of Faessler et al.¹² predict the dominance of the $i_{13/2}$ neutrons and attribute the absence of backbending in the $h_{9/2}$ proton band to deformation effects resulting from the steeply sloping $1/2[541]$ orbital.

We present here the results of a rigorous blocking experiment in ^{185}Au where the subtle, but significant, deformation effects of the extra proton should be nearly identical in each band, enabling us to reach definite conclusions about the cause of the gentle backbending in ^{184}Pt .¹³ Levels in ^{185}Au have been populated by the $^{175}\text{Lu}(^{16}\text{O}, 6n\gamma)$ reaction at 113 MeV and the $^{169}\text{Tm}(^{20}\text{Ne}, 4n\gamma)$ reaction at 98 and 103 MeV. At the Oak Ridge Isochronous Cyclotron we performed excitation function and gamma-gamma time coincidence measurements on thin targets and gamma-ray angular distribution measurements on thick targets. In addition, an in-beam conversion-electron experiment was performed at the Texas A&M University cyclotron. Without going into all of the experimental evidence and supporting arguments, we will simply state that, from these measurements and with the aid of preliminary data on the decay of ^{185}Hg studied¹⁴ at the UNISOR facility at Oak Ridge, we have constructed two decoupled bands (Fig. 2.32) and have assigned these to $h_{9/2}$ and $i_{13/2}$ proton orbitals.

The normal backbending plots for these two bands and for the ^{184}Pt core are shown in Fig. 2.33. While the ^{184}Pt nucleus does not severely backbend as do $^{182,184}\text{Os}$,⁸ there is an obvious increase in $\mathcal{J}$ at $I = 12$. The $h_{9/2}$ band deviates from this pattern, but the $i_{13/2}$ band follows the core backbending very closely. This different behavior provides important evidence concerning the dominating high- j orbitals in the backbending process in ^{184}Pt .

Since the $i_{13/2}$ band backbends and the $h_{9/2}$ band does not (Fig. 2.33), even though they both arise from downsloping Nilsson orbitals, we conclude that it is the alignment of a pair of $h_{9/2}$ protons which gives rise to the increase in the moment of inertia in ^{184}Pt . The 79th proton in ^{185}Au excited to the $1/2[541]$ orbital blocks the alignment of a pair of $h_{9/2}$ protons from the core and thus prevents backbending. The presence of this odd proton in the $1/2[660]$ orbital does not block alignment, and so backbending occurs. Thus we have

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Fig. 2.32. ^{185}Au level scheme. Gamma-ray intensities (in parentheses) are corrected for angular anisotropies. The $9/2^- \rightarrow 5/2^-$ transition is unobserved; hence all level energies are given with respect to the $9/2^-$ level. The intensity for the 212.3-keV transition is uncertain due to the doublet nature of this peak. Angular distribution measurements indicate that all transitions are stretched E2 in character, except for those of 292 and 395 keV (mixed), 424 keV (dipole), and 181, 558, 587, and 638 keV (unmeasurable).

provided the first strong evidence for the dominant role of $h_{9/2}$ protons to the backbending process in this region.

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Fig. 2.33. Backbending curves for the ^{184}Pt core (energies obtained from ref. 10) and the $1/2[541]$ and $1/2[660]$ bands in ^{185}Au . The variables plotted are extracted from the level energies and spins (after subtracting $j = 9/2$ or $13/2$ for ^{185}Au) using equations listed in ref. 9.

LIFETIMES OF GROUND-BAND STATES IN ^{192}Pt AND ^{194}Pt AND APPLICATION OF THE ROTATION-ALIGNMENT MODEL

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Recently we carried out lifetime measurements on members of the ground bands in ^{192}Pt and ^{194}Pt . There were two primary reasons for these measurements. In the first place we were interested in understanding some of the strong irregularities observed⁶⁻⁸ in the rotational-like band structure of the even $^{188-194}\text{Pt}$ isotopes. A pronounced compression of the energy spacing between the 10^+ and 12^+ states is observed, and the level spacing pattern above spin 12^+ in ^{190}Pt and ^{192}Pt resembles that of the low-spin states. Furthermore a $B(E2; 12^+ \rightarrow 10^+)$ value of $(0.33 \pm 0.06) e^2 b^2$ has been deduced from the measured⁸ half-life of the 12^+ level in ^{192}Pt , and this value is only about 50% of the rotational limit based on an average of the ^{192}Pt $B(E2; 2^+ \rightarrow 0^+)$ measurements. The above observations have been interpreted^{6,8} within the rotation-alignment (RA) model,^{9,10} and the anomalies are reproduced if an oblate deformation is assumed for the nucleus together with alignment of two $i_{13/2}$ neutrons. A measurement of the lifetimes of the states up to 12^+ should add some clarity to the picture. A second reason for this study involved more than a factor of 2 discrepancy between the previously measured¹¹ half-life value of the 4^+ state in ^{192}Pt and that predicted by either the RA or the pure rotational models.

Lifetime measurements were carried out by the Doppler-shift recoil-distance method. The states were Coulomb-excited by a beam of 149-MeV ^{40}Ar ions from ORIC. The target was a 3.1-mg/cm² metallic platinum foil enriched to 57.3% in ^{192}Pt and 26.1% in ^{194}Pt . The average recoil velocity imparted to the platinum ions when the ^{40}Ar backscattered ions were detected in coincidence with an annular silicon detector was $v/c = 0.0249 \pm 0.0004$. Details of the experimental method and data analysis techniques can be found in refs. 12 and 13.

Due to the low Coulomb excitation cross section with ^{40}Ar ions, we were able to get good data only for three states in ^{192}Pt and two states in ^{194}Pt . A summary of the results and comparisons with previous measurements are given in Table 2.3.

As pointed out in our recent paper (ref. 14), both the RA and pure rotational models give essentially the same predictions, which are in excellent agreement with our experimental values for the states obtained here. There is an obvious need for further measurements following Coulomb excitation with still heavier projectiles in the hope to excite the 10^+ state and provide a more rigorous test of the RA model. This is based on the suggestion by Piiparinen et al.⁷ that the $(\pi h_{11/2})_{10}^2$ configuration is the main component in the wave function of the 10^+ state, while the $I \geq 12^+$ states are primarily described by the $\pi i_{13/2}$ configuration. Calculations⁸ in the RA model indicate that if this is the case, the $B(E2; 10^+ \rightarrow 8^+)$ as well as the $B(E2; 12^+ \rightarrow 10^+)$ will be reduced considerably, so that the lifetime of the 10^+ state would be about 1 psec.

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Table 2.3. Half-life and $B(E2)$ values for ^{192}Pt and ^{194}Pt

Nuclide	Transition	E_γ (keV)	$T_{1/2}$ (psec)		α_γ^a	$B(E2)$ (e^2b^2)
			Previous work	Present work		
^{192}Pt	2 $\rightarrow$ 0	316.49	35.3 $\pm$ 2.8 ^b 33.6 $\pm$ 4.5 ^c 45.1 $\pm$ 0.5 ^d 42.8 $\pm$ 1.5 ^e 39.3 $\pm$ 2.2 ^f	48.5 $\pm$ 2.5	0.0831	0.34 $\pm$ 0.02
	4 $\rightarrow$ 2	468.06	11.8 $\pm$ 2.1 ^b	4.2 $\pm$ 0.2	0.0287	0.58 $\pm$ 0.03
	6 $\rightarrow$ 4	580.80		1.8 $\pm$ 0.7	0.0172	0.47 $\pm$ 0.18
^{194}Pt	2 $\rightarrow$ 0	328.50	37.7 $\pm$ 1.8 ^f 50.5 $\pm$ 2.2 ^g 41.8 $\pm$ 1.0 ^h 41.8 $\pm$ 0.5 ^d 34.7 $\pm$ 3.5 ⁱ 41.8 $\pm$ 2.9 ^j	45.0 $\pm$ 2.4	0.0746	0.31 $\pm$ 0.02
	4 $\rightarrow$ 2	482.65	4.4 $\pm$ 0.7 ^f	3.7 $\pm$ 0.2	0.0267	0.57 $\pm$ 0.03

^aTotal internal conversion coefficients taken from R. S. Hager and E. C. Seltzer, *Nucl. Data A4*, 397 (1968) and O. Dragoun, Z. Plajner, and F. Schmutzler, *Nucl. Data A9*, 119 (1971) have been reduced by 2% to account for possible deviations from theory found in this region by P. H. Stelson and S. Raman (private communication, to be published).

^bValue from A. Schwarzschild [*Phys. Rev.* 141, 1206 (1966)] determined by delayed coincidence method.

^cValue from R. Beraud et al. [*Phys. Rev. C1*, 303 (1970)] determined by centroid-shift method.

^dCalculated from (α, α') Coulomb excitation $B(E2)$ values of R. Ronningen et al., *Bull. Am. Phys. Soc.*, in press.

^eValue from G. J. Smith and P. C. Simms [*Nucl. Phys. A202*, 409 (1973)] determined by centroid-shift method.

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^gRecoil-distance measurement by R. H. Nord, thesis, University of Wisconsin, 1971 (unpublished).

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^jCalculated from inelastic alpha-particle scattering work of F. T. Baker et al., *Phys. Rev. Lett.* 37, 193 (1976).

ANOMALOUS ALPHA DECAY RATE OF ^{192}Pb

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In alpha decay, transitions between ground states of doubly even nuclei are taken to represent unhindered decays. The reduced widths of these s -wave transitions are considered to be standard. A rather regular behavior as a function of both neutron and atomic number is observed for s -wave alpha decays. Their reduced widths are largest for nuclei two or four particles beyond a closed shell (with sharp minima occurring at the closed shell) followed by a decrease as one approaches the next closure. These trends can be understood in terms of single-particle models. Mang, as an example, has shown⁵

that the extremely sharp break at $N = 126$ is essentially a shell-structure effect.

Hansen et al.⁶ measured the alpha decay rates for neutron-deficient lead isotopes from ^{186}Pb to ^{192}Pb . They found that these nuclei did not follow the pattern described above. The reduced width of ^{192}Pb was unexpectedly large. In addition, the widths increased as one went from $N = 104$ (^{186}Pb) to $N = 110$ (^{192}Pb) by a factor of about 30. The expectation was that the values would decrease as one approached $N = 126$. In ref. 6, the electron capture plus positron strengths were determined from K x-ray intensities. Such determinations are subject to a number of corrections. A more precise method involves a known electron capture plus positron decay scheme. To this end, ^{192}Pb was produced in a $^{180}\text{W}(^{16}\text{O}, 4n)$ reaction, and the UNISOR facility was used to study its decay properties. Coincidence data, as well as singles gamma-ray, x-ray, conversion-electron,

and alpha-particle spectra, were taken. From this information the ^{192}Pb alpha/total branching ratio was deduced. The pertinent data, together with the resultant alpha reduced width, are compared in Table 2.4 with the ^{192}Pb results of ref. 6. It is seen that only the total half-lives are in serious disagreement.

Figure 2.34 shows reduced widths for s -wave transitions for neutron-deficient nuclei with Z from 88 to 78 plotted as a function of N . One sees that, with the exception of the lead isotopes, the trends mentioned above do manifest themselves. The open and closed points for ^{192}Pb , $N = 110$, represent the widths deduced from the data of ref. 6 and the present study, respectively. Our value is less by a factor of 2, due primarily

to the fact that the half-life of ^{192}Pb is 3.5 and not 2.2 min. Nevertheless, its reduced width is still much too large. One would expect it to be down by another factor of 3 to place it below the value of ^{188}Pt , deduced from recent measurements⁷ made at the UNISOR facility.

Available information, then, including the new data for ^{192}Pb and ^{188}Pt , indicates that the pattern of the lead alpha reduced widths goes contrary to the one expected from shell-model considerations. Thus far, no theoretical calculations (see, e.g., refs. 8 and 9) have been able to explain this anomaly.

Table 2.4. Alpha decay properties of ^{192}Pb

Property	Present study	Hansen et al. ^a
E_α , keV	5112 ± 5	5110
$T_{1/2}$, min	3.5 ± 0.1	2.2
α/total	$(5.7 \pm 1.0) \times 10^{-5}$	6.9×10^{-5}
δ^2 , MeV	0.050 ± 0.012	0.094

^aP. G. Hansen, B. Jonson, H. L. Ravn, L. Westgard, and O. B. Nielsen, *Nucl. Phys. A230*, 365 (1974).

Fig. 2.34. Reduced widths for s -wave alpha transitions plotted as a function of N for neutron-deficient isotopes with Z from 78 to 88. The open and closed points for ^{192}Pb are deduced from data of P. G. Hansen, B. Jonson, H. L. Ravn, L. Westgard, and O. B. Nielsen, *Nucl. Phys. A230*, 365 (1974) and the present study, respectively. The point shown for ^{188}Pt is taken from Y. A. Ellis, K. S. Toth, and H. K. Carter, *Phys. Rev. C18*, 2713 (1978).

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LASER-INDUCED NUCLEAR POLARIZATION: APPLICATION TO THE STUDY OF SPONTANEOUS FISSION ISOMERS¹

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Optical hyperfine experiments can give information about nuclear spins and nuclear magnetic and quadrupole moments and can lead to a measurement of the nuclear deformation by a determination of the optical isotope or isomer shift.⁵⁻⁹ However, approximately 10^4 atoms per experiment are needed to perform these optical pumping experiments using conventional spectral lamp sources. We are developing and implementing a laser-based optical pumping technique which we call LINUP (laser-induced nuclear polarization) to overcome the light-intensity limitations of conventional sources and thus apply the method to very short-lived nuclei produced in heavy-ion reactions. Similar suggestions for optical-pumping orientation experiments with lasers have also been made.¹⁰ Our first application of the technique is a study of the approximately 1-msec ^{240}Am spontaneous-fission isomer, which is produced in the $^{238}\text{U}(^7\text{Li}, 5n)$ reaction at ORIC. The ^{240m}Am recoils from the $^{238}\text{U}(^7\text{Li}, 5n)$ reaction are stopped in an inert

buffer gas (helium, neon, or argon) within the volume of an intersecting circularly polarized laser beam tuned to one of the $5f^7 7s^2 \rightarrow 5f^7 7s 7p$ transitions in americium. The technique of depopulation optical pumping in the absence of an external magnetic field is used, and if the optical resonance conditions are satisfied, order is transferred from the laser beam to the atomic system. In the case of the absorption of right circularly polarized light ($\Delta m_F = +1$) the nuclear system will eventually be oriented so that $m_I = I = K$ (i.e., along the laser beam propagation axis) in the absence of mitigating relaxation effects and for nonzero nuclear spin. For the ^{240m}Am fission isomer, the optical resonance condition is monitored by the observation of the anisotropic fission fragments detected in position-sensitive gas-filled proportional detectors placed above and below the laser beam.

A determination of the ^{240m}Am optical isomer shift and thus a determination of the nuclear deformation, which is expected to be very large for fission isomers, is the objective of our first experiments. We use an argon-ion laser-pumped, tunable continuous-wave dye laser system with a bandwidth of about 0.5 Å to induce the $f^7 s^2(^8S_{7/2})$ to $f^7 sp(^{10}P_{7/2})$ transition at about 6405 Å in americium. This bandwidth is sufficiently broad to cover the manifold of hyperfine states associated with these levels. Preliminary developmental experiments are currently being performed.

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A SUMMING SODIUM IODIDE CRYSTAL FOR IN-BEAM GAMMA-RAY SPECTROSCOPY

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The strength of in-beam gamma-ray spectroscopy as a tool for determining properties of high-spin states is often limited by the presence of many unwanted

gamma rays. These result because in most heavy-ion reactions, many exit channels are open at the same time. Gamma-ray multiplicity filters, making use of the fractionation of angular momentum among different (H.L.xn) channels, have been used to selectively emphasize one channel, but they have rather low efficiency, and their filtering power is proportional to the average angular momentum of the reaction channel. A better method is to detect the total energy of the cascade gamma ray by using a large NaI crystal covering nearly a 4π solid angle. This method has high efficiency, and its filtering power is proportional to the square of the angular momentum.

We have obtained a 25 × 25 cm NaI crystal for this purpose. The crystal has an axial hole with 5 cm diameter and a transverse hole with 7 cm diameter near one surface. It is divided into four optically isolated quadrants. The photopeak efficiency for the 1.3-MeV gamma ray emitted at the center of the crystal is 0.55.

To investigate the effectiveness of the crystal in selecting different reaction channels in heavy-ion-induced reactions, we have studied the gamma rays from 105-MeV ^{20}Ne incident on a ^{120}Sn target. Sixfold gamma-ray coincidence data were taken with two Ge(Li) detectors and the four quadrants of the crystals. The setup is shown in Fig. 2.35. Gamma-ray spectra

Fig. 2.35. The setup of a 25 × 25 cm NaI crystal and two Ge(Li) detectors for the total-energy experiment.

associated with different total gamma-ray energies (E_T) were obtained by sorting the data with appropriate windows on the total energy. Figure 2.36 shows several of the spectra and the total-energy windows. The total intensities of several strong gamma-ray lines from the $4n$ and $5n$ channels were plotted as a function of E_T in Fig. 2.37. These data indicate that above 15 MeV the integrated yield of the $4n$ channel is about 12 times the yield of the $5n$ channel. Therefore we can achieve almost 100% filtering efficiency with a 50% loss of the data. This can be seen in Fig. 2.36c, where the $4n$ lines are the only gamma-ray lines in the spectrum.

Quantitative analysis of the total energy distribution can also provide information on the high-spin nuclear properties. For example, from the observed peak energy of the $4n$ channel and the efficiency of the crystal, the average total gamma-ray energy can be estimated to be 27 MeV. The yrast energy (E_Y) can be obtained by subtracting 5 MeV statistical gamma-ray energy. From E_Y and the calculated average angular momentum ($47\hbar$)

Fig. 2.36. Gamma-ray spectra observed in the $^{20}\text{Ne} + ^{120}\text{Sn}$ reaction. They are gated on various parts of the total energy spectrum as indicated.

Fig. 2.37. Distribution of the $4n$ and $5n$ reaction channels as a function of the detected total energy.

of the $4n$ channel, the value of the moment of inertia $2\mathcal{J}/\hbar^2 = I(I+1)/E_Y = 47 \times 48/22 = 103 \text{ MeV}^{-1}$ is determined. This value is quite close to the rigid-body value of 97 MeV^{-1} .

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CONSTRUCTION OF A WINDOWLESS SUPERSONIC GAS-JET TARGET FOR HEAVY IONS

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One of the unique features of the new 25-MV heavy-ion tandem as compared with other heavy-ion accelerators will be its high energy resolution. However, perhaps the most difficult problem in performing high-resolution experiments with heavy ions is due to the limitations imposed by the target itself. An almost ideal solution to the above problems is to use a supersonic gas

jet flowing perpendicular to the incident beam direction, since (1) use of a gas target removes a serious limitation on the choice of target material; (2) the target thickness can be varied at will and can be made much thinner than with any self-supporting solid target; (3) gas targets are clean, and contamination can be kept to a minimum; (4) the jet stream can exist in a high-vacuum environment; entrance and exit windows are not needed, thus minimizing the energy degradation of the incident beam and the reaction products; (5) the jet is highly localized, and it is possible to measure reactions with detection systems having large solid angles and yet be able to correct for kinematic energy spread-

ing; (6) the target is indestructible, thus permitting the use of high beam currents.

Figure 2.38 shows an assembly drawing of the gas-jet mechanism. The gas enters through the Laval nozzle at the bottom of the apparatus. Due to its high velocity, approximately 90% of the gas is recaptured in volume 1. Volumes 1 and 2 will be connected to mechanical pumps with pumping speeds of about 15 and 120 liters/sec respectively. The entrance and exit aperture systems for the incident beam and the reaction products present a low impedance to the flow of gas into volume 3, which will be pumped by a cryogenic pump. The pressure in volume 4, the scattering chamber volume

Fig. 2.38. Assembly drawing of the gas-jet mechanism. Volumes 1, 2, 3, and 4, denoted by A, B, C, and D, respectively, on the drawing, are pumped separately. The entrance and exit slit systems to the left and right of the figure, respectively, are indicated by number 53, and the Laval nozzle is indicated by 80.

pumped by a 1000-liter/sec cryogenic pump, should be about 10^{-6} torr. The pumping system should allow the use of targets whose thicknesses vary from less than $1 \mu\text{g}/\text{cm}^2$ to $100 \mu\text{g}/\text{cm}^2$. Our calculations of target thicknesses, different pressures, and required pumping speeds are supported by experience with existing gas-jet targets at other laboratories.³⁻⁵

The exit aperture system can be rotated to any angle between 0 and 60° , so that angular distributions of the reaction products can be measured. It will be possible to integrate the current beam after it has passed through the gas-jet region, as well as monitor the beam with a fixed solid-state detector. Figure 2.39 is a photograph of the assembled gas-jet mechanism.

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Fig. 2.39. Photograph of gas-jet mechanism. The sliding metal seal on the variable-angle exit aperture system for the reaction products is not in place.

A MULTIPARAMETER FOCAL-PLANE DETECTOR FOR HEAVY IONS

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A "hybrid" counter has been constructed for use at the focal planes of the split-pole and Elbek spectrographs similar to those designed elsewhere,^{3,4} although significant improvements were made to the cathode structure. This counter, shown schematically in Fig. 2.40, consists of a large ionization chamber. A signal proportional to the energy of particles which are stopped in the detector volume is obtained from the capacitively coupled cathode and first grid. The complex anode structure includes two position-sensitive proportional counters with a ΔE electrode between them, a residual-energy electrode, and, finally, a proportional counter to provide a reject signal for particles which traverse the entire counter volume. Therefore the position of each particle ray is measured twice, yielding the angle at which the particle enters the counter in addition to its total energy and energy loss.

The active length of the detector is 40 cm, and it was designed to accommodate heavy-ion beams of high energy, such as ^{12}C and ^{16}O , from the new 25-MV tandem. In order to stop these energetic particles without resorting to high pressures (and thick windows), the counter depth is 27.5 cm. The large vertical height of the image at the focal plane of the Elbek spectrograph, plus angular straggling over the depth of the counter, required that the vertical dimension of the detector be 6.5 mm. It was found that an enlarged copy of the Rochester detector³ had an unacceptably large portion of the counter rendered useless by the nonuniformity of the electric field around the edges of the ionization chamber. In order to straighten the electric field, we segmented the sides of the cathode box into three insulated metallic strips — one strip above the window, one strip below the window, and a center strip connected to the aluminized Mylar window (see Fig. 2.40). The grid, the three strips, and the bottom cathode plate were then biased by a voltage divider with potentials chosen to maximize the uniformity of the electric field.

Initial tests were made with the detector mounted at 45° to the focal plane of the Enge split-pole magnetic spectrograph (the particles are then normally incident to the counter). A 39-MeV ^{16}O beam elastically scat-

Fig. 2.40. Schematic of detector.

tered from a gold target gave an energy resolution of 1.4%. The 400-keV noise, which limits the resolution, primarily results from the capacitance of the large electrodes. In these preliminary results, a position resolution of about 0.9 mm was measured. A ΔE resolution of 3.2% was obtained, with the largest contribution due to straggling.

alpha-decay feedings were then calculated from intensity balances, and a total alpha branching of $(4.2 \pm 0.4) \times 10^{-3}\%$ was deduced. Alpha-decay hindrance factors identify the band heads of the $5/2[752]$ and $7/2[743]$ orbitals in ^{233}U at 298.9 and 503.5 keV respectively. Contrastingly, the ^{233}Pa and ^{233}Np decay studies had assigned the $7/2[743]$ state to the level at 298.9 keV.

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^{233}U LEVELS POPULATED IN THE ALPHA DECAY OF ^{237}Pu

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The 45.3-day nuclide ^{237}Pu decays primarily via electron capture. The only information available up to now concerning the nuclide's alpha decay properties has been the observation² of two alpha groups with energies of 5.65 and 5.36 MeV. In the present study, the photon spectrum of ^{237}Pu was investigated with x- and gamma-ray Ge(Li) detectors. A total of 21 transitions were found to belong to ^{237}Pu decay; of these, 16 were assigned to its alpha decay branch. The alpha decay scheme shown in Fig. 2.41 was constructed on the basis of transition energy fits and known ^{233}U levels (including some observed only in reaction studies). The electron-capture decay scheme was used to obtain the absolute photon intensities. The amounts of direct

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DECAY OF 10.2-DAY ^{188}Pt

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The decay properties of ^{188}Pt were investigated with the use of the UNISOR isotope separator facility. Singles and coincidence measurements were made by using x- and gamma-ray Ge(Li) detectors as well as an Si(Li) electron detector. These results were combined with previously available conversion-electron data² which had been obtained with a magnetic spectrometer. From this information, a level scheme (shown in Fig. 2.42) was constructed for ^{188}Ir . A tentatively proposed³ level at 317 keV was eliminated on the basis of our results. In addition, several transitions attributed³ to ^{188}Pt decay were not observed in the present study. The electron-capture decay energy of 525 ± 10 keV was deduced for ^{188}Pt decay from the experimentally determined K -to-total (e_K/e) and L -to-total (e_L/e) ratios for various levels. Alpha-particle and gamma-ray spectra were also measured with the detec-

E_{α} I_{α} (%) HF
 (5098 ~0.5 ~17)

(5155 6.4 3.0)

(5259 0.7 130)
 (5302 12.2 13)
 (5335 43.5 5.8)
 (5353 17.2 20)

73.5 %

(5560)
 (5610)
 (5650)

20

820

Fig. 2.41. Alpha decay scheme of ^{237}Pu . Numbers following energy values represent total transition intensities calculated from photon intensities and internal conversion coefficients. They are expressed in terms of absolute values per 100 ^{237}Pu alpha decays. Dashed lines represent uncertain transitions; dotted lines indicate transitions that are expected but not observed in the present work.

Fig. 2.42. Decay scheme of ^{188}Pt . Dots indicate observed coincidences. Dashed lines indicate uncertain transitions. Numbers following gamma-ray energies represent total transition intensities per 100 ^{188}Pt electron-capture decays. They are calculated from photon intensities and theoretical conversion coefficients.

tors positioned in calibrated geometries. The alpha decay energy and branching ratio of ^{188}Pt were determined to be 3915 ± 10 keV and $(2.8 \pm 0.5) \times 10^{-7}$, respectively, in agreement with ref. 4 and in disagreement with ref. 5.

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2. J. M. Prospero, thesis, Princeton University, report PUC-1963-95 (1963), unpublished.
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POSSIBLE EVIDENCE FOR ASYMMETRIC- DEFORMED AND NEAR-SPHERICAL SHAPE COEXISTENCE IN ^{70}Se

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Even- and odd-parity bands with rotational energy-level spacings are observed^{6,7} in $^{72,74}\text{Se}$. In ^{72}Se the

data are easily interpreted in the framework of a coexistence model with bands built on both near-spherical and symmetric-deformed shapes.⁶ The anomalous behavior of the first excited 0^+ states, which fall at 937 and 854 keV (75 and 219 keV above the first excited 2^+ states) in ^{72}Se and ^{74}Se , respectively,^{7,8} provided important clues in establishing a coexistence picture. These 0^+ states may be interpreted as heads of bands built on more strongly deformed shapes which have dropped down in energy sufficiently low to be observed as N decreases in the selenium isotopes. To help unravel our understanding of the structure of nuclei in this region, levels in ^{70}Se have been investigated by in-beam gamma-ray spectroscopy via the $^{58}\text{Ni}(^{14}\text{N},pn)^{70}\text{Se}$ reaction at 38 MeV. The results of our gamma-gamma coincidence studies are shown in Fig. 2.43. Previously only the 946-, 1701-, and 2040-keV levels were identified.⁹ Several spins are based on DCO ratios. The most surprising result is the indication of an excited state at 710 keV with $I^\pi = 0^+$ based on 780-890 keV gamma-gamma coincidence. This 0^+ energy is lower than that found in ^{72}Se or ^{74}Se . The other marked difference from ^{72}Se is $E_{1,4} < E_{4,2} > E_{2,0}$ and the presence of two and tentatively three 2^+ states. The low 0^+ and high 4^+ energies make it difficult to interpret these data in terms of a band built on an axially symmetric deformed shape as in ^{72}Se . However, the data may be very nicely

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Fig. 2.43. Levels of ^{76}Se .

explained in terms of an excited band of states built on an asymmetric deformed shape with $\gamma \approx 30^\circ$. The energy levels for an asymmetric rotor with $\gamma \approx 30^\circ$ and a small centrifugal stretching term are also in the figure. The predicted 2^+ rotor level at about 1200 keV has the right energy to mix with a vibrational 2^+ level of this energy and split into the 946-1441 keV levels ($\Sigma E = 2387$ keV). The agreement between the experimental and theoretical levels predicted by an asymmetric rotor model (with only a first estimate for μ) is very good. Thus we are led to suggest the possible coexistence of states built on a near-spherical ground state with those of an asymmetric deformed shape. The key to this interpretation is to confirm the 0^+ level. It is possible that the 780-keV gamma ray is a doublet and that a 780-890 keV gamma-gamma cascade actually occurs in another presently unknown nucleus. In-beam electron studies are necessary to test our interpretation. Even without the very low-energy 0^+ level, the several close 2^+ levels, the $4^+ - 2^{++}$ decay, and the 2-4 MeV yrast energy spacings indicate some type of band crossing.

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5. Tennessee Technological University, Cookeville, Tenn.
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LINEAR POLARIZATION OF GAMMA RAYS IN ^{70}Ge

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Earlier we reported⁵ level properties of ^{70}Ge as obtained from gamma rays from the $^{60}\text{Ni}(^{12}\text{C}, 2p)$ and $^{65}\text{Cu}(^7\text{Li}, 2n)$ reactions. We have since then used gamma-ray linear polarization as an additional technique for establishing level properties. No surprises were obtained, but in some cases J^π assignments that were inferred from weak arguments were strengthened. These cases are listed in Table 2.5.

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5. R. L. Robinson, H. J. Kim, R. O. Sayer, J. C. Wells, Jr., R. M. Ronningen, and J. H. Hamilton, *Phys. Rev. C* **16**, 2268 (1977).

Table 2.5. Spin-parities assigned to levels in ^{70}Ge

E level (keV)	J^π
2154	4^+
2807	(4^+)
3298	6^+
3417	5^-
3668	6^-
3956	(7^-)
4205	8^+
4433	(8^-)

BAND STRUCTURES IN $^{74,76}\text{Kr}$

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In the $A = 70$ region we may observe rotational-like bands with several different orbitals. These could give rise to multiple band crossings and backbending. As part

of a systematic program to investigate the band structures of even-even nuclei in the $A = 70$ region to high spins, we have investigated the bands in ^{76}Kr via the reactions $^{64}\text{Zn}(^{12}\text{C}; 39 \text{ MeV}, 2n)^{76}\text{Kr}$ and $^{60}\text{Ni}(^{16}\text{O}; 45 \text{ MeV}, 2n)^{76}\text{Kr}$. The maximum angular momentum brought into the system is about $16\hbar$ in the case of ^{76}Kr and about $12\hbar$ in the case of ^{74}Kr .

In-beam gamma-gamma coincidence studies and gamma-ray angular distribution measurements were carried out in both cases, and polarization measurements also were carried out in ^{76}Kr . The band structures obtained for ^{76}Kr are shown in Fig. 2.44. The yrast band in ^{76}Kr does not show any backbending up to spin 12^+ . Thus there is no evidence for the crossing of this band by a $(g_{9/2})^2$ superband as found in ^{68}Ge and ^{74}Se . The origin of the negative-parity band with band head at 2683 keV (5^-) may be interpreted as coupling of $(g_{9/2}, p_{1/2})$ quasi-particle configuration to the rotor as in the case of ^{74}Se . Two of the other three bands have positive parity and are built on 2^+ and 3^+ levels whose spacings suggest quasi-gamma-like structure.

In case of ^{74}Kr we have observed a positive-parity band as follows (energies in keV): $455(2^+)$, $1012(4^+)$, $1779(6^+)$, $2742(8^+)$, $4327(10^+)$. In addition to the above band, a level at 2810 keV was found to decay to the 4^+ level. From systematics, the spin of this level is most probably 5^- .

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Fig. 2.44. Levels of ^{76}Kr .

HIGH-SPIN STATES IN ^{76}Kr

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Level properties obtained from gamma rays from the $^{68}\text{Zn}(^{12}\text{C}, 2n)$ reaction provide evidence for four bands in ^{76}Kr . $B(E2)$'s for many of the transitions are extracted from lifetimes deduced from Doppler broadening of the gamma rays. By using Doppler-broadened peaks in the coincidence spectra, it was possible to correct for lifetimes associated with gamma rays populating the level of interest.

Figure 2.45 illustrates only the levels which are identified with a band. The $B(E2)$'s for the ground-state band are remarkable in their constancy; this cannot be explained by any existing model. A band built on a 5^- state has been seen in several neighboring nuclei. It is attributed to coupling of two rotational aligned quasi particles with a weakly deformed core: one quasi particle is in a $g_{9/2}$ orbital, the other in a $p_{1/2}$, $p_{3/2}$, or $f_{5/2}$ orbital. Since the relative level spacing is comparable with that of the ground-state band, this suggests that the 5^- state is nearly fully aligned. If so, the primary configuration of this state is $(g_{9/2}, p_{1/2})5^-$.

The $\Delta I = 1$ band has a number of characteristics which are consistent with its being a true γ -vibrational band. Note that the $B(E2)$'s of transitions within the band appear as strong as those of the ground-state band, but the only two observed interband transitions have small $B(E2)$'s. This indicates that the $\Delta I = 1$ band has an independent collective mode of excitation.

Bohr and Mottelson⁴ suggest that information can be obtained about the intrinsic spin $i_\alpha(\omega)$ by plotting half of the gamma-ray energy between states $I+1$ and $I-1$ vs I . This plot, given in Fig. 2.46, shows that the $\Delta I = 1$ band has $i_\alpha(\omega) \approx 0$; this is also consistent with its being a γ -vibrational band. The proposed 5^- band has indeed $i_\alpha(\omega) \approx 5$. There is an interesting break in the yrast state at $I \approx 12$ that might be due to the nearness of a rotational aligned $(g_{9/2})^2_{8^+}$ band.

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4. A. Bohr and B. R. Mottelson, *Supp. J. Phys. Soc. Jpn.* **44**, 157 (1978).

Fig. 2.45. Levels of ^{78}Kr which have been assigned to a band. The number associated with each gamma ray is its $B(E2)$ value in single-particle units.

Fig. 2.46. Bohr-Mottelson plot to show the intrinsic spins $i_0(\omega)$ of the ^{78}Kr bands.

BAND STRUCTURE OF ^{80}Kr

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We have studied levels in ^{80}Kr via the ^{70}Zn - $(^{12}\text{C}, 2n)^{80}\text{Kr}$ reaction at 38 MeV with 50% and 70% ^{70}Zn targets. In-beam gamma-gamma coincidences and gamma-ray angular distribution measurements were carried out. The levels established by our coincidence studies are shown in Fig. 2.47. An independent work of Funke et al.,⁸ who studied levels in ^{80}Kr via the (α, xn) reaction, confirms our work. The spin assignments were based on angular distribution measurements, gamma-gamma angular correlations, and the excitation function studied at projectile energies of 33.5, 35.5, and 38.5 MeV. The spin dependence of gamma-ray yields for some clean transitions were made with the following assumptions: (1) the total cross section $\sigma_r(E)$ is given

Fig. 2.47. Levels of ^{80}Kr . The inset gives the moment of inertia plot for the yrast band.

Table 2.6. Theoretical and experimental ratios of gamma-ray yields

E_γ (keV)	J	R_J (theo)	R_J (expt)	E_γ (keV)	J	R_J (theo)	R_J (expt)
617.0	2	0.77	0.76	1171.8	3	0.79	0.70 ± 0.06
639.9	2	0.77	0.62	1424.2	5	0.98	0.92
721.9	7	1.69	1.60 ± 0.05	248.7	6	1.20	0.96 ± 0.02
819.8	4	0.86	0.83 ± 0.04	871.9	5	0.98	0.77 ± 0.01
956.4	6	1.20	0.91 ± 0.03	531.9	3	0.79	0.83 ± 0.02
				1005.4	4	0.86	1.03 ± 0.08

by $\sigma(617.0)$ from the decay scheme, (2) spin distribution is proportional to $2J_c + 1$ (J_c is the spin of the compound nucleus), (3) population intensity of spin J state $[= \sigma(E)]$ is determined by the area of $J_c \geq J$ in the plot $\sigma(J_c)$ vs J , and (4) maximum angular momentum transfer l_m is given by

$$l_m = 0.219R \left[\mu(E_{c.m.} - V_c) \right]^{1/2} \approx J_m.$$

With these assumptions, one arrives at the ratio of gamma-ray yields from a decaying state J at any two projectile energies given by

$$R_J(\text{th}) =$$

$$\frac{A(E_1)}{A(E_2)} = \frac{J_m(E_1) [2J_m(E_1) + 1]}{J_m(E_2) [2J_m(E_2) + 1]} \frac{J(2J+1)}{J(2J+1)},$$

where $A(E) = 2\sigma_r(E)/J_m(E) [2J_m(E) + 1]$.

The $R_J(\text{th})$ at each assumed J is compared with the $R_J(\text{expt})$, which is just the ratio of gamma-ray intensities at the projectile energies E_1 and E_2 . The results in ^{80}Kr are summarized in Table 2.6.

A moment of inertia plot is shown for the yrast band in Fig. 2.47. One observes that the behavior of $\mathcal{J}$ with spin is similar to that found in the germanium isotopes. There the break at 8^+ is interpreted as evidence for a $(g_{9/2})^2$ structure for the 8^+ state. Also in these nuclei odd-parity bands are observed. Such bands can be expected from the coupling of $g_{9/2}$, $f_{5/2}$, $p_{3/2}$, or $p_{1/2}$ orbitals.

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BAND STRUCTURE OF EVEN-MASS NUCLEI AROUND $A \approx 70$

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During the past five years an ORNL-Vanderbilt collaboration has collected a large amount of new information on the high-spin states of even-mass $A \approx 70$. Besides allowing observation of higher members of the ground-state band, these studies revealed a surprising variety of other bands. The best example is ^{68}Ge , in which eight bands have been identified.

The richness of structure is suggested by a comparison of the moment of inertia ($\mathcal{J}$) plot for the yrast states (Fig. 2.48). The shapes of the lines show considerable variation. Some plots show forward bending (e.g. ^{72}Se); others have backbending, some at the 8^+ level, others at the 6^+ level. The following five types of bands have been suggested:

1. A ground-state band (GSB) attributed to a soft spherical nucleus. The softness is indicated by the change in the moment of inertia with spin. $B(E2)$'s for

ground-state transitions in the GSB have been measured for six nuclei. Although they are consistently large compared with the single-particle estimate, they do not show any systematic pattern. This may indicate mixing of the GSB states with states of the same spin from other bands.

2. A deformed band built on the low-lying excited 0^+ level. In five nuclei in the $A \approx 70$ mass region, there is an excited 0^+ level near the first 2^+ level. Level energies and $B(E2)$'s obtained for two of these nuclei, $^{72,74}\text{Se}$, can be explained by the coexistence of a ground-state spherical shape with a deformed shape for a band built on the 0^+ state. These two bands together give the forward bending observed in Fig. 2.48 for $^{72,74}\text{Se}$. There have been several theoretical calculations with slightly different approaches that support the coexistence of two shapes.

3. A band built on an 8^+ state which results from rotational alignment (RAL) of two $g_{9/2}$ particles. This gives rise to backbending (see Fig. 2.48) at 8^+ . The band implies that the nucleus is somewhat prolate, since then the $g_{9/2}$, $\Omega = 1/2$ Nilsson orbital lies lowest. This is the best condition for Coriolis coupling to align the $g_{9/2}$ particle with the rotational axis of the nucleus. In ^{68}Ge , two backbending bands are observed; one is ascribed to alignment of two $g_{9/2}$ neutrons, the other to two $g_{9/2}$ protons. A two quasi particle plus rotor calculation of the type described by Flaum and Cline² supports this interpretation.

Fig. 2.48. Moment of inertia plot of the yrast states in the even-mass nuclei around A of 70. States of other bands are included for ^{68}Ge , ^{70}Ge , and ^{80}Kr .

4. Odd-parity bands built on two RAL quasi particles, one of which is in the $g_{9/2}$ orbital and the other in the $p_{1/2}$, $p_{3/2}$, or $f_{5/2}$ orbital. The most commonly observed odd-parity band begins with a 5^- level. For some the relative level spacing is similar to that of the ground-state band, indicating that the primary band head configuration is $(g_{9/2}, p_{1/2})_5^-$. In others the energy of the $7^- \rightarrow 5^-$ transition is compressed. This may suggest that the 5^- state is due to not fully aligned particles and the 7^- is the actual band head with its configuration being $(g_{9/2}, f_{5/2})_7^-$. No evidence is seen for odd-parity bands built on the 3^- octupole states.

5. A $\Delta I = 1$ even-parity band which is best characterized as a γ -vibrational band in a permanently deformed nucleus. Bands of this type have been seen to 9^+ . They have several common features: the band head is the second 2^+ level, the states decay predominantly by stretched $E2$ transitions to lower members of the band, energy spacing for the levels with odd-integer and with even-integer spins follows approximately the $I(I+1)$ rule, the transitions between this band and the ground-state band are weak or unobserved, and the intrinsic spin³ is about 0.

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2. C. Flaum and D. Cline, *Phys. Rev.* 14, 1224 (1976).
3. A. Bohr and B. R. Mottelson, *Supp. J. Phys. Soc. Jpn.* 44, 157 (1978).

GAMMA-RAY LINEAR POLARIZATION AS A METHOD FOR ASSIGNING SPINS

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Gamma-ray linear polarization measurements have long been used as a method for establishing the relative parity of two states linked by the gamma ray of interest. But not stated in the literature is how they are also useful in resolving spin ambiguities that occur in the angular distribution studies of in-beam gamma rays. There are two problem areas in angular distributions, as exemplified by Fig. 2.49. They are the similarity of A_2 and A_4 values for the $8 \rightarrow 6$ transition and the $6 \rightarrow 6$ transition with $\delta \approx 1$ and the near identity of values for the $7 \rightarrow 6$ and $5 \rightarrow 6$ transitions with $\delta \approx 0$. The situation is even worse than the figure indicates, since it is for fully aligned nuclei. In a real situation, A_2 is typically reduced by a factor of 0.4 to 0.8 and A_4 by 0.1 to 0.5 because of attenuation in the alignment. The values of the attenuation coefficients α_2 and α_4 are usually not well known. Thus measurements cannot differentiate between an $8 \rightarrow 6$ transition and a $6 \rightarrow 6$ transition with $\delta \approx 1$ or between $5 \rightarrow 6$ and $7 \rightarrow 6$ transitions with $\delta \approx 0$. Curves similar to those in Fig. 2.50 are obtained for spin changes $\Delta J = J_i - J_f = 0, \pm 1, \pm 2$ for any J_f except for special situations at low spin. Thus the ambiguity between $\Delta J = 0$ and 2 and between $\Delta J = \pm 1$ occurs for nearly all spins.

Fig. 2.49. Theoretical A_2 and A_4 gamma-ray angular distribution coefficients for a $J \rightarrow 6$ quadrupole-dipole transition where $J = 4, 5, 6, 7$, or 8 . The numbers on the curves are values of $\delta = (Q/D)^{1/2}$. The alignment attenuation coefficients are taken as 1.

Fig. 2.50. Comparison by means of a χ^2 plot of experimental and theoretical angular distribution coefficients for the 664-keV transition in ^{78}Kr .

Fig. 2.51. χ^2 plot for the angular distribution of the 664-keV transition in ^{78}Kr for the two spins which give acceptable fits. The χ^2 value for the $J=2$ curve is the minimum value obtained by varying δ .

A gamma-ray linear polarization, when taken with the angular distribution results, can resolve the ambiguity between $\Delta J = 0$ and 2 and, at least in some cases, resolve between the $\Delta J = \pm 1$ ambiguity. An example of the former is given by Figs. 2.50–2.52. The χ^2 plot in Fig. 2.50 for the angular distribution results of the 664-keV gamma ray in ^{78}Kr shows that either $J=2$ or 4 is an acceptable assignment. (The experimental values are $A_2 = 0.293 \pm 0.010$ and $A_4 = -0.076 \pm 0.011$.) Figure 2.51 takes the minima for the spin 2 and the χ^2 value for spin 4 as a function of α_2 . Which spin gives the better χ^2 fit depends on the value of α_2 , a coefficient whose value, as stated earlier, is normally not well known. Figure 2.52 includes the polarization results. Again the minima of the χ^2 plots are shown vs α_2 . With polarization ($P_{\text{ex}} = 0.48 \pm 0.04$) included, the spin-parity assignment is established uniquely as 4^+ . Also obtained is the α_2 attenuation coefficient value of 0.58.

Fig. 2.52. χ^2 plot including the polarization results.

HIGH-SPIN STATES IN ^{76}Se

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As part of a program to systematically study higher-spin states and band structure of even-even nuclei in the range $A \approx 70$, we have investigated the gamma rays of ^{76}Se resulting from the $^{71}\text{Ga}(^7\text{Li}, 2n)$ reaction by bombarding an enriched ^{71}Ga target with 15- to 22-MeV ^7Li ions from the ORNL EN tandem accelerator.

Measurements were made of gamma-ray singles and gamma-gamma coincidence spectra, excitation func-

tions, gamma-ray angular distributions, and Doppler broadening of photopeaks. We have constructed an energy-level scheme and have deduced spins and parities, gamma-ray branching ratios, radiative admixtures, and lifetimes for some of the levels. The energy-level scheme is shown in Fig. 2.53.

The yrast band is seen up to the 12^+ member. There is evidence for a second even-parity band built on the 1216-keV 2^+ state and for an odd-parity band built on the 2824-keV 5^- state.

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Fig. 2.53. Levels and transitions of ^{76}Se .

COULOMB EXCITATION OF
^{156,158,160}Gd AND ^{160,162,164}Dy
WITH ⁴He IONS

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The Coulomb excitation reaction induced by ⁴He ions selectively excites 2⁺ and 3⁻ states by direct E2 and E3 Coulomb excitation. We present results from gamma-ray spectroscopy with 13.5-MeV ⁴He ions on isotopically enriched targets of ¹⁵⁶Gd, ¹⁵⁸Gd, ¹⁶⁰Gd, ¹⁶⁰Dy, ¹⁶²Dy, and ¹⁶⁴Dy. Gamma-ray spectra were observed at $\theta_\gamma = 0^\circ$, 55° , and 90° with respect to the beam direction with a 91-cm³ Ge(Li) detector at 10 cm from the target. For the conditions of the experiment, the use of first-order treatment of the excitation process is adequate for the analysis of thick-target gamma-ray yields. The experimental results for the reduced transition probabilities, $B(E\lambda, 0 \rightarrow J = \lambda)$, are summarized in Table 2.7. The K, J^π assignments were deduced primarily from our $\gamma(\theta)$ measurements, ratios of reduced transition probabilities, and other nuclear spectroscopy studies which have been summarized.¹⁻⁵

The experimental $B(E2, 0 \rightarrow 2)$ for ¹⁵⁶⁻¹⁶⁰Gd are compared with recent theoretical calculations by Kumar

and Gupta⁶ based on a dynamic deformation theory combined with the pairing-plus-quadrupole model. In the case of the $K = 2$ γ -vibrational state the $B(E2)$ values are reproduced reasonably well by the predictions. However, the $B(E2)$ values for β -vibrational states are not reproduced satisfactorily by the calculations of Kumar and Gupta.

Collective 3⁻ states have been identified in each of the ¹⁵⁶⁻¹⁶⁰Gd and ¹⁶⁰⁻¹⁶⁴Dy nuclei, and the results are compared with the theoretical calculations of Neergård and Vogel⁷ in Table 2.7. Although the general features of the experimental information are reproduced by the calculations of Neergård and Vogel, the experimental values of $B(E3, 0 \rightarrow 3)$ in most cases tend to be somewhat larger than the predictions.

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Table 2.7. Experimental results for $B(E\lambda, 0 \rightarrow J = \lambda)$

Nucleus	Level (keV)	K, J^π	$E\lambda$	$B(E\lambda, 0 \rightarrow J)$ (e ² · b ^λ)	$\left(\frac{B(E\lambda)}{B(E\lambda)_{s.p.}} \right)^a$	Theory $B(E\lambda, 0 \rightarrow J)$ (e ² · b ^λ)
¹⁵⁶ Gd	1129.4	0.2 ⁺	E2	$(1.58 \pm 0.09) \times 10^{-2}$	0.63	2.0×10^{-2}
	1154.1	2.2 ⁺	E2	$(1.11 \pm 0.06) \times 10^{-1}$	4.46	1.43×10^{-1}
	1258.0	0.2 ⁺	E2	$(7.7 \pm 0.7) \times 10^{-3}$	0.31	2×10^{-3}
	1276.1	1.3 ⁻	E3	$(17.1 \pm 0.9) \times 10^{-3}$	16.9	15.2×10^{-2}
¹⁵⁸ Gd	1041.6	1.3 ⁻	E3	$(12.4 \pm 0.7) \times 10^{-2}$	11.9	7.8×10^{-2}
	1187.1	2.2 ⁺	E2	$(8.48 \pm 0.49) \times 10^{-2}$	3.34	8.3×10^{-2}
	1259.8	0.2 ⁺	E2	$(8.01 \pm 0.56) \times 10^{-3}$	0.32	6.7×10^{-2}
	1402.9	0.3 ⁻	E3	$(2.28 \pm 0.26) \times 10^{-2}$	2.2	3.3×10^{-2}
	1517.4	0.2 ⁺	E2	$(9.33 \pm 0.93) \times 10^{-3}$	0.36	1×10^{-2}
¹⁶⁰ Gd	988.2	2.2 ⁺	E2	$(8.82 \pm 0.44) \times 10^{-2}$	3.42	10.3×10^{-2}
	1289.3	2.3 ⁻	E3	$(11.8 \pm 0.7) \times 10^{-2}$	11.0	11.3×10^{-2}
¹⁶⁰ Dy	966.2	2.2 ⁺	E2	$(1.22 \pm 0.06) \times 10^{-1}$	4.73	
	1286.7	1.3 ⁻	E3	$(17.1 \pm 1.0) \times 10^{-2}$	16	12.9×10^{-2}
	1349.5	0.2 ⁺	E2	$(1.84 \pm 0.15) \times 10^{-2}$	0.71	
	1642	2.3 ⁻	E3	$(6.5 \pm 1.0) \times 10^{-2}$	6.1	1.6×10^{-2}
¹⁶² Dy	888.2	2.2 ⁺	E2	$(1.18 \pm 0.06) \times 10^{-1}$	4.50	
	1210.2	2.3 ⁻	E3	$(10.4 \pm 0.7) \times 10^{-2}$	9.6	8.6×10^{-2}
¹⁶⁴ Dy	761.8	2.2 ⁺	E2	$(1.14 \pm 0.06) \times 10^{-1}$	4.26	
	1039.3	2.3 ⁻	E3	$(8.8 \pm 0.6) \times 10^{-2}$	7.9	6.4×10^{-2}

$$^a B(E\lambda)_{s.p.} = \frac{2\lambda+1}{4\pi} \left(\frac{3}{\lambda+3} \right)^2 (0.124)^{1/2} e^2 \cdot b^\lambda \text{ for } J_i = 0, J_f = \lambda.$$

**REDUCED ELECTRIC DIPOLE
TRANSITION PROBABILITIES
FOR TRANSITIONS IN
¹⁵⁶⁻¹⁶⁰Gd AND ¹⁶⁰Dy**

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Direct $E2$ and $E3$ Coulomb excitation of 2^+ and 3^- states with 13.5-MeV ^4He ions on isotopically enriched thick targets of $^{156-160}\text{Gd}$ and ^{160}Dy has been measured by means of gamma-ray spectroscopy. Gamma-ray spectra were observed at $\theta_\gamma = 0^\circ, 55^\circ$ and 90° with respect to the beam direction with a $91\text{-cm}^3 \text{Ge(Li)}$ detector at 10 cm from the target. Several of the gamma rays emitted during the slowing down of the recoiling nucleus in the target are Doppler-broadened. The maximum kinetic energy imparted to a ^{160}Gd nucleus is 1.28 MeV, which corresponds to $v/c = 4.14 \times 10^{-3}$. The stopping power for these recoil velocities is essentially nuclear stopping power. We used nuclear stopping power taken from the theory of Lindhard et al.¹ in the Doppler-broadened gamma-ray line shape analysis. This choice of stopping powers reproduced the known mean lifetimes of the $K, J^\pi = 2, 2^+$ states in ^{156}Gd and ^{158}Gd , namely, $\tau = (0.85 \pm 0.03)$ and (0.87 ± 0.04) psec respectively. The mean lifetimes, obtained from a least-squares fit of the calculated line shapes to the experimental data for the $3^- \rightarrow 2^+$ and $3^- \rightarrow 4^+$ transitions, of the 3^- states in $^{156, 158, 160}\text{Gd}$, and ^{160}Dy are (0.11 ± 0.03) , $(0.78 \pm$

$0.21)$, (0.074 ± 0.020) , and (0.32 ± 0.09) psec respectively. The uncertainties include the statistical error of the data and the uncertainties of the stopping power.

The experimental results for the reduced transition probabilities, $B(E1, J_i \rightarrow J_f)$, deduced from the mean lifetimes of the 3^- states are summarized in Table 2.8. In addition, we have extracted $B(E1)$ values for $E1$ transitions from the decay of two $K, J^\pi = 0, 2^+$ states feeding the $K = 0$ and 1 octupole bands in ^{158}Gd . For this purpose we used our measured $B(E2, 0 \rightarrow 2)$ values and gamma-ray branching ratio data² from the (n, γ) reaction.

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COULOMB EXCITATION OF ¹⁵³W

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In many odd- A nuclei with deformed equilibrium shapes, the energy levels do not always follow closely the $J(J+1)$ law for rotational bands. The energy levels

Table 2.8. Experimental results for $B(E1, J_i \rightarrow J_f)$

Nucleus	Initial state		Final state		E_γ (keV)	$B(E1, J_i \rightarrow J_f)$ ($e^2 \times 10^{-30} \text{ cm}^2$)	$\left(\frac{B(E1)}{B(E1)_{s.p.}} \right)$
	K_i, J_i^π	E (keV)	K_f, J_f^π	E (keV)			
¹⁵⁶ Gd	1, 3 ⁻	1276.1	0, 2 ⁺	89.0	1187.1	22.7 ± 6.1	1.2×10^{-3}
			0, 4 ⁺	288.2	987.9	19.8 ± 5.3	1.1×10^{-3}
¹⁵⁸ Gd	1, 3 ⁻	1041.6	0, 2 ⁺	79.5	962.1	6.3 ± 1.7	3.3×10^{-4}
			0, 4 ⁺	261.5	780.1	5.1 ± 1.4	2.7×10^{-4}
	0, 2 ⁻	1259.8	1, 1 ⁻	977.0	282.8	1.23 ± 0.14	6.5×10^{-5}
			1, 2 ⁻	1023.6	236.2	0.24 ± 0.3	1.2×10^{-5}
			1, 3 ⁻	1041.6	218.2	3.6 ± 0.4	1.9×10^{-4}
	0, 2 ⁻	1517.4	1, 1 ⁻	977.0	540.2	0.051 ± 0.025	2.7×10^{-6}
			1, 2 ⁻	1023.6	493.8	0.115 ± 0.016	6.1×10^{-6}
			1, 3 ⁻	1041.6	475.8	0.70 ± 0.10	3.7×10^{-5}
			0, 1 ⁻	1263.5	253.9	2.8 ± 0.4	1.5×10^{-4}
¹⁶⁰ Gd	2, 3 ⁻	1289.3	0, 2 ⁺	75.3	1214.0	26.1 ± 7.0	1.4×10^{-3}
			0, 4 ⁺	248.2	1041.1	33.8 ± 9.1	1.8×10^{-3}
¹⁶⁰ Dy	1, 3 ⁻	1286.7	0, 2 ⁺	86.8	1199.9	7.9 ± 2.9	4.1×10^{-4}
			0, 4 ⁺	283.8	1002.9	6.1 ± 1.6	3.2×10^{-4}

Table 2.9. Experimental and calculated $B(E2)$ values for ^{183}W

Transition, $J_i \rightarrow J_f$	E_γ (keV)	I_γ	δ	$B(E2, J_i \rightarrow J_f) (e^2 \cdot b^2)$			
				Experiment	Brockmeier et al., fit B(I)	Brockmeier et al., fit B(II)	Rowe, $Z = 0$
$3/2^L \rightarrow 1/2^L$	46.48	100	-0.061 6	$(8.15 \pm 0.20) \times 10^{-1}$	7.5×10^{-1}	7.7×10^{-1}	7.6×10^{-1}
$5/2^L \rightarrow 1/2^L$	99.07	100	E2	$(7.37 \pm 0.10) \times 10^{-1}$	7.0×10^{-1}	7.1×10^{-1}	7.5×10^{-1}
$5/2^L \rightarrow 3/2^L$	52.59	80	-0.13 2	$(2.3_{-1.5}^{+0.8}) \times 10^{-1}$	2.2×10^{-1}	2.1×10^{-1}	3.0×10^{-1}
$3/2^H \rightarrow 1/2^L$	208.8	13	-0.34 4	$(5 \pm 2) \times 10^{-3}$	0.17×10^{-3}	0.16×10^{-3}	48×10^{-3}
$3/2^H \rightarrow 3/2^L$	162.3	100	0.37 2	$(1.6 \pm 0.6) \times 10^{-1}$	4.3×10^{-1}	3.9×10^{-1}	2.3×10^{-1}
$3/2^H \rightarrow 5/2^L$	109.7	12	0.14 2	$(2.1 \pm 0.8) \times 10^{-2}$	10.8×10^{-2}	8.5×10^{-2}	20×10^{-2}
$5/2^H \rightarrow 1/2^L$	291.7	100	E2	$(8.0 \pm 0.3) \times 10^{-2}$	15.8×10^{-2}	14.2×10^{-2}	9.7×10^{-2}
$5/2^H \rightarrow 3/2^L$	245.2	10	0.16 4	$(4.8 \pm 1.4) \times 10^{-4}$	0.000	1.5×10^{-4}	289×10^{-4}
$5/2^H \rightarrow 5/2^L$	192.6	8.7	0.56 5	$(13.0 \pm 2.2) \times 10^{-3}$	3.9×10^{-3}	3.5×10^{-3}	47×10^{-3}
$5/2^H \rightarrow 7/2^L$	84.5	33	0.15 1	$(2.81 \pm 0.39) \times 10^{-1}$	2.94×10^{-1}	2.36×10^{-1}	2.47×10^{-1}
$5/2^H \rightarrow 3/2^L$	82.9	11	0.63 3	1.34 ± 0.13	1.99	1.88	1.95

and the transition probabilities of many of these nuclei are often better fitted by the rotational model if the decoupling effect of the Coriolis interaction¹ is taken into consideration. Close-lying bands whose K quantum numbers differ by unity may be strongly mixed by the Coriolis interaction (sometimes referred to as rotation-particle coupling). The nucleus ^{183}W is the classic example for such a band-mixing effect. From the precise gamma-ray energy measurements by Murray et al.,² Kerman³ extracted the mixing amplitudes for the states in the $K = 1/2$ and $K = 3/2$ bands of ^{183}W . The fits to the energy levels were excellent, and his predictions for the relative gamma-ray intensities were in fair agreement with the experimental intensities.²

Subsequently, the relative gamma-ray intensities of the transitions in ^{183}W were measured with an accuracy of $\pm 5\%$.^{4,5} Rowe⁶ analyzed these data with the Coriolis coupling between rotational bands and included some $\Delta K = 2$ band-mixing effects of the type found in even-even nuclei. The data were fitted equally well, but there seemed to be no real necessity to require the presence of any $\Delta K = 2$ band mixing to fit the relative gamma-ray intensities. Brockmeier et al.⁷ obtained an improvement in the fit to the energy levels when seven other Nilsson states were also included in the analysis.

These two analyses by Rowe and by Brockmeier et al. do differ, however, for several of the absolute transition probabilities. For example, Rowe neglected the off-diagonal matrix elements in the calculation of the $E2$ transition probabilities because these are of single-particle magnitude. Brockmeier et al., however, calcu-

lated the $E2$ transition probabilities without simplifying assumptions. For instance, the calculations by Brockmeier et al. predict a strong cancellation in the $E2$ transition probabilities for the $3/2^H \rightarrow 1/2^L$, $5/2^H \rightarrow 3/2^L$, and $5/2^H \rightarrow 5/2^L$ transitions (H and L refer to the high- and low-energy states of the same total angular momentum J). Therefore measurements of the absolute transition probabilities would provide a good test of the wave functions used in the calculations. We present results from the Coulomb excitation reactions ($\alpha, \alpha'\gamma$) and (α, α') with 15- and 13-MeV ^4He ions from the EN tandem. In Table 2.9 we give the $B(E2)$ values for transitions between excited states based on our $B(E2)$ values for excitation of states in ^{183}W , adopted⁸ proton intensities I_γ , and recommended⁹ $E2/M1$ mixing ratios δ . The $B(E2)$ obtained from the calculated absolute transition probabilities by Brockmeier et al. and by Rowe are also given in Table 2.9. The strong cancellations in the $E2$ transition probabilities predicted by Brockmeier et al. are indeed verified by the experimental results.

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NONSTATISTICAL STRUCTURE IN THE

$^{12}\text{C}(^9\text{Be}, \alpha)^{17}\text{O}$ AND $^{12}\text{C}(^{13}\text{C}, \alpha)^{25}\text{Mg}$ REACTIONS¹

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Measurements of excitation functions for many states in ^{17}O and ^{21}Ne populated by the $^{12}\text{C}(^9\text{Be}, \alpha)$ and $^{12}\text{C}(^{13}\text{C}, \alpha)$ reactions indicated the presence of non-statistical structure. Excitation functions at a laboratory angle of 7° were obtained in 200-keV steps with the ^9Be beam ($E_{\text{lab}} = 9.0$ to 20.0 MeV) and at 7° and 25° ($E_{\text{lab}} = 18.2$ to 32.4 MeV and 18.4 to 27.0 MeV, respectively) with the ^{13}C beam. The alpha particles were detected at the focal plane of the Enge split-pole magnetic spectrograph at the EN tandem.

A statistical analysis of the $(^9\text{Be}, \alpha)$ excitation functions showed that an anomalously large number of the excitation functions have maxima near $E_{\text{lab}} = 17$ MeV. Thirteen of the fifteen states exhibit peaks near 17 MeV. The statistical-model probability for observing this large number of peaks is 2×10^{-6} . Figure 2.54 shows the energy-dependent correlation coefficient³ for the 15 states. Subsequently, the angular distributions for the first three levels in ^{17}O were measured between 2.5° and 30° in approximately 450-keV steps for ^9Be energies from 16.1 to 17.9 MeV with a position-sensitive surface-barrier detector. These three angular

Fig. 2.54. The energy-dependent correlation coefficient for the first 15 levels populated by the $^{12}\text{C}(^9\text{Be}, \alpha)^{17}\text{O}$ reaction.

distributions were fitted with a Hauser-Feshbach background and a single isolated $15/2^+$ compound-nuclear resonance term using the method developed by Shapira et al.⁴ In addition to the angular distributions measured at the forward angles, angular distributions for the reaction $^9\text{Be}(^{12}\text{C}, \alpha)^{17}\text{O}$ have been measured over the energy range $E_{^{12}\text{C}} = 21.46$ to 24.0 MeV in approximately 667-keV steps. A comparison of angular distributions at forward and backward angles may provide more information about the reaction mechanism.

Energy-averaged $(^{13}\text{C}, \alpha)$ angular distributions were measured near $E_{\text{lab}} = 30$ MeV for 40 states with ^{21}Ne excitation energies less than 10 MeV. Hauser-Feshbach calculations give good agreement with the energy-averaged cross sections at both laboratory angles, except in energy regions near $E_{\text{lab}} = 19.6$ and 21.4 MeV in the forward-angle data. Comparisons of the Hauser-Feshbach predictions with the energy-averaged angular distributions enabled us to make spin suggestions for several excited states in ^{21}Ne as well as determine coherence widths in the compound nucleus ^{25}Mg .

Figure 2.55 shows the Hauser-Feshbach fits for excitation functions summed over the first 22 alpha-particle groups in ^{21}Ne . The energy regions near $E_{\text{lab}} = 19.6$ and 21.4 MeV, where the cross sections appear to be enhanced, are the same two regions where Crozier and Legg⁵ observed anomalies in the $^{12}\text{C} + ^{13}\text{C}$ elastic scattering data and in the alpha-particle channel. A statisti-

Fig. 2.55. The solid lines are the summed excitation functions for all states below 7.0 MeV excitation energy in ^{21}Ne . The dashed line shows the Hauser-Feshbach prediction: using the method described by K. R. Cordell, S. T. Thornton, L. C. Dennis, J. L. C. Ford, Jr., and J. Gomez del Campo, *Nucl. Phys.* A296, 278 (1978). The dot-dashed line shows the Hauser-Feshbach fits when all level-density parameters are increased by 8%.

cal analysis of our data (based on the number of correlated peaks in the various excitation functions) reveals that the statistical-model probabilities for the structures at $E_{lab} = 19.6$ and 21.4 MeV are 10^{-3} and 4×10^{-4} respectively.

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ANGULAR DISTRIBUTION STUDIES OF POSSIBLE YRAST LEVELS IN ^{27}Al POPULATED BY THE $^{12}\text{C}(^{15}\text{N}, \alpha)$ REACTION

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Previous measurements and analyses^{2,3} of the excitation functions of the $^{12}\text{C}(^{15}\text{N}, \alpha)$ reaction at a laboratory angle of 7° have indicated a large number of anomalies that fell outside the statistical-model predictions. These anomalies manifest themselves as large fluctuations (resonances), with widths of two to three times the coherence width and with an unusually large number of correlations in several of the alpha groups studied.^{2,3} A possible explanation for the observed resonances has been given in terms of population of high-spin states close to or at the yrast line of the compound nucleus ^{27}Al .

Such interpretation of the observed resonances should be subject to testing by measuring angular distributions on and off the resonances. Consequently, we used a solid-state position-sensitive detector to measure 14 angles at a time, with a center-of-mass separation of $1\frac{1}{2}^\circ$ to measure detailed angular distributions between 10° and 140° , and sometimes 2° and 140° , at selected energies. Figure 2.56 shows, as an example, distributions measured on and off one of the most prominent peaks observed in the 2.07-MeV excitation function. This figure illustrates what turned out to be the most characteristic features of these angular distributions. First of all, they are much more strongly forward-

Fig. 2.56. Angular distributions measured at the energies indicated on the excitation function at 7° for the 2.07-MeV $7/2^+$ state in ^{27}Na .

peaked on resonance than off. Second, the integrated cross section on resonance is not only, as expected, larger than off resonance, but the differential cross section is also larger on resonance at most of the angles measured. This implies that excitation functions measured at various angles will generally also display the bump seen at 28.6 MeV in the excitation function at 7° (see inset in Fig. 2.56).

The forward-peaking feature of the angular distribution appears to be a signature of the excitation of a high-spin state in the compound nucleus. In Fig. 2.57 are shown calculated angular distributions corresponding to the excitation of a single level in the compound nucleus of the spin and parity shown. The calculated angular distributions are symmetric around 90° . Clearly, the higher the spin, the more forward-peaked is the angular distribution, and it is therefore at forward angles that effects due to relatively isolated high-spin states are likely to be identified. At more backward angles, it becomes more and more likely that the single-level contribution is lost in the sea of Hauser-Feshbach contributions due to low-spin states in the compound nucleus.

Fig. 2.57. Angular distributions for isolated compound-nucleus levels of various spins calculated with a single-level approximation. The state in the residual nucleus was assumed to be the 2.07-MeV $7/2^+$ level in ^{23}Na .

Preliminary efforts to adequately fit the angular distributions are illustrated in Fig. 2.58 by single-level fits. For the case of the $5/2^+$ first excited state, a J_{CN}^{π} value of $25/2^+$ was found to give the best fit to the data. The off-resonance angular distribution is dominated at forward angles by a $21/2^+$ contribution, although more than one spin will be required to fit the data. For the 4.78-MeV $7/2^+$ state, a compound-nuclear spin of $25/2^+$ was favored on resonance, while a value of $17/2^+$ dominates off resonance. These fits are actually insensitive to the parity of the state, as they have been arbitrarily

Fig. 2.58. Comparison of measured angular distributions with single-level calculations on and off the resonant-like structures observed in the excitation functions at 7° for the 0.44-MeV ($5/2^+$) and 4.78-MeV ($7/2^+$) states in ^{23}Na .

normalized to the data in order to give the minimum χ^2 value. In addition, spins within at least $\pm 1h$ of the best-fit value would give almost equally acceptable fits to the data. What appears significant, however, is that when the incident energy is increased from below a resonant energy to on resonance, the value of the angular momentum required in order to obtain an acceptable fit to the data must increase by at least several units of angular momentum. We are attempting to improve the agreement of the fits with the data by including in the calculations one or two isolated levels in the compound nucleus, together with a more general background, such as with a Hauser-Feshbach term, with possible interference between these various contributions.

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SUB-COULOMB FUSION

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Studies of sub-Coulomb fusion were initiated using beams of ^{16}O at the Weizmann Institute and ^{40}Ar at G.S.I. The purpose was to isolate the role of nuclear deformation in the fusion process. This was accomplished by measuring the cross section for production of evaporation residues, using as targets the isotopes of samarium. These isotopes span the transition region at $N = 90$ from a spherical to a deformed equilibrium shape ($\beta \approx 0.3$ for ^{154}Sm , whereas ^{148}Sm is vibrational in character). The experimental techniques involved the off-line detection of delayed x radiation from the radioactive daughter of the evaporation residues trapped in a catcher foil. The experimental results are shown in Figs. 2.59 and 2.60. In the case of oxygen bombardment, the fusion cross sections are all comparable at energies above the barrier. At lower energies, however, the deformed targets show an increased probability to fuse

Fig. 2.59. Cross sections for evaporation-residue production in the reactions of $^{16}\text{O} + ^{148-154}\text{Sm}$ as a function of laboratory energy. Since the probability of fission is negligible, the ordinate is labeled as the fusion cross section. The lines are to guide the eye.

Fig. 2.60. Cross sections for evaporation-residue production in the reactions of $^{40}\text{Ar} + ^{144,148,154}\text{Sm}$ as a function of center-of-mass bombarding energy. The lines are to guide the eye.

with the projectile (i.e., a lower barrier). This phenomenon is also observed with ^{40}Ar projectiles (see Fig. 2.60) and indicates the importance of nuclear deformation.³ For the higher ^{40}Ar energies, the evaporation-residue cross sections differ, in contrast to the results shown in Fig. 2.59. Separate measurements of the fission cross section have shown that σ_{fis} varies from 260 ± 20 mb to 240 ± 20 mb for ^{144}Sm to ^{154}Sm , respectively, at $E_{\text{c.m.}} \approx 142$ MeV. Thus the differences in σ_{er} and in $\sigma_{\text{fus}} = \sigma_{\text{er}} + \sigma_{\text{fis}}$ at high ^{40}Ar energies are not explained by variations in the strength of the fission competition.

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TEST OF THE INDEPENDENCE HYPOTHESIS FOR COMPOUND SYSTEMS FORMED WITH ^{40}Ar AND ^{84}Kr IONS

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Shortly after beams of ^{84}Kr became available at the ALICE accelerator in Orsay, France, experiments were made to compare the decay of erbium compound nuclei, ^{156}Er and ^{158}Er , formed in two different ways, ^{40}Ar with ^{116}Sn and ^{118}Sn and ^{84}Kr with ^{72}Ge and ^{74}Ge . The results of these experiments were unusual:⁴ the thresholds and peaks of the $(^{84}\text{Kr}, xn)$ reactions were systematically shifted by about 15 MeV to higher excitation energies, compared with the corresponding $(^{40}\text{Ar}, xn)$ reactions, for $x = 3$ to 6. To interpret these differences it was necessary to invoke⁴ some special mechanism for the krypton-induced reactions, such as the preequilibrium emission of neutrons or the existence of angular-momentum effects that would reduce the probability of compound-nucleus formation at low l values (the l -window effect).

These studies have continued both at Orsay and at the SuperHILAC at Lawrence Berkeley Laboratory. The ^{158}Er system was reinvestigated to check the initial results; in addition, ^{200}Po , a heavier system in which fission is significant, was studied.

In ref. 4 and in some of our earlier experiments,⁵ the energy values corresponding to the measured cross sections were not measured directly. Instead, absorber foils served to degrade the beam energy, and the Northcliffe-Schilling range-energy tabulation⁶ was used to calculate the energy of the beam on target. However, it has been found recently (as described in an accompanying section of this report) in time-of-flight measurements with ^{84}Kr at Berkeley and in proton-recoil experiments⁷ at Orsay with ^{40}Ar and ^{84}Kr that the Northcliffe-Schilling values differ from measured energy losses. Accordingly, all of our data for the $^{158}\text{Er}^*$ and $^{200}\text{Po}^*$ systems were reanalyzed and tied directly to experiments in which we measured the beam after it had passed through the absorber foils.

Figures 2.61–2.63 show our excitation function data, plotted against the redetermined energy scales. Figure

2.61 shows the $^{74}\text{Ge}(^{84}\text{Kr}, xn)$ reactions leading to ^{153}Er and ^{152}Er , plotted vs laboratory energy. The open points were determined at Orsay and the closed points at Berkeley. There is good agreement between the results obtained at the two laboratories, both in the shapes of the excitation functions and in the independently determined energy scales. Similar conclusions apply to the $^{118}\text{Sn}(^{40}\text{Ar}, xn)$ data. In Fig. 2.62 the $(^{40}\text{Ar}, xn)$ and $(^{84}\text{Kr}, xn)$ data for $^{152,154}\text{Er}$ taken at both laboratories are plotted vs excitation energy. Contrary to the earlier results,⁴ there are no significant differences in reaction thresholds and peak cross sections between the data obtained with the argon and krypton beams. The results, in fact, are consistent with recent measurements⁸ in the erbium region of evaporation-residue cross sections and gamma-ray multiplicities, in which no evidence was found for the existence of an l window. The excitation functions for neutron emission from ^{200}Po compound nuclei formed with projectiles of ^{40}Ar (previously published⁵) and ^{84}Kr are shown in Fig. 2.63. Again the energy scales are the results of direct measurements, and again no significant differences occur in the thresholds and peak positions of the corresponding (Ar, xn) and (Kr, xn) reactions.

We conclude from these studies that the independence hypothesis of compound-nucleus formation and decay is valid for ions as heavy as ^{40}Ar and ^{84}Kr . Special mechanisms, such as angular-momentum windows and preequilibrium neutron emission, are not needed for the interpretation of our new data.

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Fig. 2.61. Relative excitation functions for $^{74}\text{Ge}(^{84}\text{Kr}, 5-6n)^{153, 152}\text{Er}$, plotted vs laboratory energy. The open points were measured at Orsay and the closed points at Berkeley.

Fig. 2.62. Relative excitation functions plotted vs excitation energy for the production of ^{153}Er and ^{152}Er , compared for ^{40}Ar - and ^{84}Kr -induced reactions.

Fig. 2.63. Excitation functions for $^{160}\text{Dy}(^{40}\text{Ar}, xn)^{200}\text{Po}$ and $^{116}\text{Cd}(^{84}\text{Kr}, xn)^{200}\text{Po}$ reactions.

ENERGY LOSSES OF ^{84}Kr IONS

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Energy-loss measurements for energetic heavy ions, with $A \geq 40$, are of practical use in current nuclear physics investigations. In addition, they serve to choose between different theoretical approaches to the problem of the slowing down of ions in matter. Recently published results² have indicated disagreements be-

tween experimental and calculated stopping powers for ions such as argon and krypton. As part of a program to test the independence hypothesis, we have been investigating the behavior of compound nuclei formed in reactions with ^{40}Ar and ^{84}Kr . Because the discrepancies in stopping powers appear to be particularly serious for krypton, we measured energy losses of ^{84}Kr in nickel, aluminum, and titanium foils used as degraders in the determination of excitation functions.

The measurements were made with a beam of 615-MeV ^{84}Kr accelerated at the Lawrence Berkeley Laboratory SuperHILAC. A time-of-flight (TOF) system³ was used to measure the traversal time of the beam over an accurately known distance; thus the beam velocity and energy were determined. Once the energy of the beam was known, individual absorber foils were placed in the beam in front of the TOF system, and the resultant energy losses were measured. A set of energy measurements was concurrently made with a surface-barrier Si(Au) solid-state detector (SSD) placed directly in the attenuated beam, behind the TOF system. The energy scale for the SSD was calibrated against the TOF value for the initial beam energy of 615 MeV. Then, as each foil was placed in the beam, energy-loss values were independently measured with the TOF and SSD systems.

In Fig. 2.64 are plotted the absorber foil thicknesses, ΔR , vs E values obtained from different energy-loss calculations: Northcliffe and Schilling,⁴ Steward,⁵ and Brown and Moak.⁶ The Brown and Moak curves were obtained by extrapolation,⁷ to 7.3 MeV/amu, of an analytic function derived by fitting stopping power data for uranium, iodine, and bromine ions with energies ≤ 1 MeV/amu. Two conclusions are apparent from the figure: (1) there is a significant difference between the Northcliffe-Schilling values and those obtained from Steward and from Brown and Moak; (2) the values of Steward and of Brown and Moak are in close agreement with our measurements. Averages of the replicate values obtained by both the TOF and SSD systems were compared with calculated values to determine fractional deviations. The Northcliffe and Schilling values for ^{84}Kr were found to be 15 to 25% smaller than the measurements, while the Steward and Brown and Moak values varied from 3% above to 7% below the measured values.

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Fig. 2.64. Thickness of absorbers, ΔR , plotted vs the energy of the degraded ^{84}Kr beam, E . Absorbers were foils of nickel, titanium, and aluminum. Measurements were done with time-of-flight (TOF) and solid-state-detector (SSD) systems. Calculated values are taken from Steward (S.) [UCRL-18127 (1968)], Northcliffe and Schilling (N.S.) [*Nucl. Data A7*, 233 (1970)], and Brown and Moak (B.M.) [*Phys. Rev. B6*, 90 (1972)], extrapolated with a program developed by C. D. Moak and W. T. Milner.

TEST OF THE TDHF-PREDICTED ANGULAR-MOMENTUM WINDOW AND OF THE LIQUID-DROP LIMIT IN THE SYSTEM $^{16}\text{O} + ^{48}\text{Ca}$

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There is considerable current interest in predictions of TDHF calculations that, above certain energies, near-head-on collisions between heavy ions and target nuclei do not lead to fusion. This so-called angular-momentum-window prediction implies that at any given energy above a certain threshold, the lowest partial waves do not result in the production of evaporation

residues. The energy range where this phenomenon is expected to occur is such that for the highest partial waves involved, fusion is expected to be limited due to the vanishing fission barrier, as predicted by the liquid-drop model. Thus the fusion cross section is expected to be limited at both ends of the angular-momentum distribution, resulting in a rather drastic reduction in the predicted fusion cross section with increasing bombarding energy.

The system $^{16}\text{O} + ^{48}\text{Ca}$ is favored by most theorists active in TDHF calculations for a test of the theory. Previous results of Kovar et al. were obtained for this system up to a bombarding energy of 216 MeV. This energy is only slightly above the predicted onset of the angular-momentum window, and the cross section was found to be about 1200 mb, which corresponds to the liquid-drop limit. In this work, we have extended the measurements to 316 MeV at the Lawrence Berkeley Laboratory 88-in. cyclotron. Current theoretical results predict the fusion cross section to decrease from about 1000 mb to about 600 mb when the bombarding energy is increased from 216 to 316 MeV. From a very preliminary analysis of our results, it appears that the cross section for evaporation-residue products is, in fact, considerably lower at 316 MeV than at 216 MeV but not as low as the theoretical prediction. Thus it is likely that either the liquid-drop limit or the angular-momentum window determines the fusion cross section, but not both.

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STUDIES OF QUASI-ELASTIC REACTIONS WITH VERY HEAVY IONS

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Studies of quasi-elastic reactions with ^{56}Fe ions have been initiated at the Lawrence Berkeley Laboratory SuperHILAC. Individual nuclear charges and masses of quasi-elastic, projectile-like products have been resolved by means of a time-of-flight apparatus, combined with a telescope consisting of an ionization-chamber ΔE detector and a surface-barrier E detector. Data have been obtained for $^{56}\text{Fe} + ^{66}\text{Cu}$ at 330 MeV. The energy spec-

trum integrated over all product masses and charges can be decomposed in a natural way into a quasi-elastic and a deeply inelastic component. A nuclear charge distribution of products obtained near the grazing angle at 18° and corresponding to the quasi-elastic component is shown in Fig. 2.65a, and mass distributions corresponding to each charge number Z are shown in Fig. 2.65b.

From the figure it can be seen that the tendency toward charge equilibration of the composite system is present even for the low energy losses associated with quasi-elastic reactions. This can be illustrated with reference to mass distributions associated with $Z = 25$ products on the one hand and $Z = 26$ and 27 on the other. For $Z = 25$ the most dominant mass is 55, indicating that proton stripping is the most important mechanism contributing to the yield of products with this charge.

Fig. 2.65. Quasi-elastic reaction products from 330-MeV $^{56}\text{Fe} + ^{65}\text{Cu}$ obtained at 18° . (a) Nuclear charge distribution; (b) mass distributions of quasi-elastic products corresponding to the charges shown in a.

For $Z = 26$ and 27 , however, except for the inelastic $A = 56$ products, the mass distributions are dominated by masses with $A > 56$, indicating that, somewhat unexpectedly, neutron pickup is more probable than stripping. This is probably due to the relatively high N/Z ratio of the target nucleus, and hence of the composite system. A detailed analysis of the data is in progress.

Data have also been obtained at several angles for $^{56}\text{Fe} + ^{58}\text{Ni}$ and $^{56}\text{Fe} + ^{122}\text{Sn}$ at 465 MeV, and we intend to study these systems also at a lower bombarding energy.

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LIFETIME MEASUREMENTS IN ^{164}Er

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The nucleus ^{164}Er is one of the few stable nuclei which shows the backbending effect. Therefore in this case it is possible to study this phenomenon by means of Coulomb excitation. With heavy ions such as ^{136}Xe , one is able to excite the levels in the backbending region with appreciable cross section. The large recoil velocity ($v/c \approx 0.08$) imparted by the xenon projectiles makes the Doppler-broadened line shape a sensitive method for studying the short lifetimes characteristic of the high-spin states excited here.

A beam of 620-MeV ^{136}Xe from the Lawrence Berkeley Laboratory superHILAC was used to bombard a thick (approximately 30 mg/cm^2) ^{164}Er target. The de-excitation gamma rays following the Coulomb excitation were detected in a 50-cm^3 Ge(Li) detector placed at 0° with respect to the beam. The gamma rays emitted during the slowing down of the recoiling nucleus in the target are Doppler-shifted. So, from the shape of the gamma-ray line and the slowing-down time, the lifetime of the state can be determined.

The line shapes were analyzed by the computer program DOPCO.⁸ This program takes the recoil velocity and the angular distribution of the target nucleus, together with the stopping power, and calculates the expected line shape for a given lifetime. The angular distri-

bution and the excitation function of the Coulomb excitation process were calculated using the program of Winther and de Boer. All the $E2$ and $E4$ matrix elements were included. The values of these matrix elements were derived from $B(E2, 0^+ \rightarrow 2^+)$ and $B(E4, 0^+ \rightarrow 4^+)$ using the rotational model. Note that the derived lifetimes are not sensitive to the values of the matrix elements (a 10% change in the matrix element produces negligible change in the angular distribution).

The electronic stopping powers, taken from the table of Northcliffe and Schilling,⁹ were corrected at low energies for the medium dependences using the table of Ziegler and Chu.¹⁰ We used nuclear stopping powers taken from the theory of Lindhard et al.¹¹

Lifetimes are obtained from a least-squares fit of the calculated line shapes to the experimental data. The uncertainties include the statistical error of the data and the uncertainties of the stopping power. The state with highest spin is analyzed first. Hence the gamma ray feeding the next lower state is properly accounted for by using the experimentally determined lifetime.

Figure 2.66 shows the fit to the 8^+ , 10^+ , and 12^+ states. The comparisons with the rigid-rotor values based on the measured $B(E2, 0^+ \rightarrow 2^+)$ value¹² are shown in Table 2.10. These measured lifetimes agree with the rotational-model predictions within about 15%. Further, they agree with the early measurement of the gamma-ray yields,¹³ as well as with the predictions of the rotational-alignment model of backbending.

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Table 2.10. Lifetimes of states in ^{164}Er

I	τ_{exp} (psec)	τ_{rot} (psec)	$\tau_{\text{exp}}/\tau_{\text{rot}}$
8	3.69 (0.18)	3.88	0.95 (0.05)
10	1.46 (0.09)	1.51	0.97 (0.06)
12	0.8 (0.06)	0.76	1.05 (0.08)

m -SUBSTATE DISTRIBUTIONS IN THE $^{16}\text{O} + ^{12}\text{C}$ REACTION

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It has been demonstrated^{2,3} that in favorable cases, information on spin alignment produced in nuclear reactions can be extracted from line shapes of excited reaction products. We have applied this technique to the study of resonances in the $^{16}\text{O} + ^{12}\text{C}$ reaction.

Fig. 2.66. Doppler-broadened line shapes for high-spin states in ^{164}Er . The points are the experimental data, and the solid lines are the calculated fits from the program DOPCO (W. T. Milner).

The experiment was performed at the University of Rochester MP tandem, using the Enge split-pole spectrometer and the Rochester heavy-ion counter.⁴ The same experiment produced data on angular distributions and on spin alignment (m -substate populations) as a function of angle in the $^{12}\text{C}(^{16}\text{O}, ^{12}\text{C}^*(4.43))^{16}\text{O}(\text{g.s.})$ reaction. The spin-alignment analysis focused on a broad region between $E_{\text{c.m.}} = 22.0$ and 22.6 MeV. The angular distribution data, analyzed in terms of a single spin resonance in the compound nucleus, was shown⁵ to imply, within the context of the model, a single $J^\pi = 15^-$ assignment to this entire region. The spin-alignment

data taken at 22.3 MeV are shown in Fig. 2.67. The curve in Fig. 2.67a is that predicted for a pure $J = 15$ resonance using a model analogous to that employed in the angular distribution analysis. The agreement is poor. Figure 2.68 shows the results of fitting the data with various J values both with and without a background component. The results sharply contradict the $J = 15$ assignment. The best-fit ($J = 12$) curve is shown in Fig. 2.67b.

The fact that the angular distribution data and spin-alignment data cannot be simultaneously accounted for in the context of the single J resonance model clearly

Fig. 2.67. m -substate data for $^{12}\text{C}(^{16}\text{O}, ^{12}\text{C}^*(4.43))^{16}\text{O}$ taken at $E(^{16}\text{O}) = 52$ MeV. The curve in a is for a pure $J = 15$ resonance in the compound nucleus. The curve in b is the overall best fit ($J = 12$ plus a background term). The background was calculated allowing J values in the range 0-18 to contribute, including all allowed interference terms between partial waves in both the entrance and exit channels. The optical-model transmission coefficients, phases, and Hauser-Feshbach denominators used in the calculation were obtained with the potential of Shapira.⁶ The solid and dashed curves are for different optical potentials.

Fig. 2.68. Results of pure J resonance fits. Plots of chi-squared vs spin both with (b) and without (a) background are shown.

shows a need for further experiments and more elaborate analyses to establish unequivocally even the basic quantum numbers of these resonances.

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GIANT QUADRUPOLE RESONANCE IN $^{24,26}\text{Mg}$

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The existence or nonexistence of localized isoscalar quadrupole strength in the giant-resonance region of light nuclei has for several years been a topic of considerable controversy. The historical background of this controversy has been described elsewhere.² It is important to note, however, that part of the controversy has arisen from apparent differences between quadrupole strength observed in the continuum of sd -shell nuclei through inelastic scattering and through radiative alpha capture. We have measured the giant-resonance structure in ^{24}Mg and ^{26}Mg using inelastic scattering of 120-MeV alphas and compared the results with those obtained from alpha-capture measurements.

The inelastic alpha-scattering data were obtained with an overall energy resolution of about 100 keV (full width at half maximum) using 120-MeV alpha particles from the Kernfysisch Versneller Instituut, Groningen, cyclotron. Data were taken from 6° to 22° in 1° steps. Typical (α, α') spectra for ^{24}Mg and ^{26}Mg are shown in Figs. 2.69 and 2.70 respectively. The proton data shown in Fig. 2.69 were obtained earlier using 60-MeV protons and have been reported elsewhere.³

In Fig. 2.69 we also show the results of alpha-capture experiments to the giant quadrupole resonance in $^{24,26}\text{Mg}$ which have recently been published.⁴ In these measurements only 2^+ states that have an alpha-decay branch to the $^{20,22}\text{Ne}$ ground states can be observed; hence more $E2$ strength may be present but unobserved in the capture experiments. Therefore the $E2$ strengths obtained from the capture measurements should be considered as well-established lower limits.

The (α, α') spectrum and the (α, γ_0) excitation function for ^{24}Mg in Fig. 2.69 show a striking agreement. All the strong resonances seen in the (α, γ_0) reaction can be correlated with $L = 2$ excitations in the (α, α') spectrum, indicating that even at high excitation energy, multipolarity assignments based on distorted-wave Born approximation fits are reliable. However, some peaks in the (α, α') spectrum of ^{24}Mg , like the ones at $E = 17.0$ and 19.4 MeV, which have distinctly $L = 2$ angular distributions, are not observed in the capture excitation function. This can be explained if it is assumed that 2^+

Fig. 2.69. Spectra of (α, α') at 14° and (p, p') at 15° for ^{24}Mg are compared with the $E2(\gamma, \alpha_0)$ excitation functions. In the inelastic scattering spectra the assumed shape of the continuum is indicated together with the energy bins for which angular distributions are obtained.

Fig. 2.70. Spectra of (α, α') at 14° and (p, p') at 15° for ^{26}Mg are compared with the $E2(\gamma, \alpha_0)$ excitation functions. In the inelastic scattering spectra the assumed shape of the continuum is indicated together with the energy bins for which angular distributions are obtained.

states seen in (α, α') but not in alpha capture have a very weak (or zero) alpha-decay branch to the ground state. The ^{26}Mg data show a similar pattern, as is clear from Fig. 2.70.

In the range of excitation energy between 15 and 24 MeV in ^{24}Mg , we find $(60 \pm 15)\%$ of the $T = 0$, $E2$ energy-weighted sum rule (EWSR). Proton-capture experiments indicate that 10 to 15% of the FWSR is accounted for by direct proton capture to the ground state.⁵ This additional strength cannot be distinguished, in our experiments, from the underlying continuum because of its flat energy distribution. In addition we find in the range of excitation energy below 15 MeV about 45% of the EWSR, in good agreement with an earlier (α, α') experiment.⁶ Thus, using the normalization procedure as described above, we can account for the full $T = 0$, $E2$ EWSR strength in ^{24}Mg . For ^{26}Mg , we measure $(50 \pm 10)\%$ of the $T = 0$, $E2$ EWSR in the excitation energy range between 15 and 22 MeV.

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EXCITATION OF GIANT MONOPOLE RESONANCE IN $^{144,154}\text{Sm}$ VIA INELASTIC PROTON SCATTERING

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In a study² of the inelastic scattering of 67-MeV protons by $^{144,154}\text{Sm}$, it was found that the structure in the giant resonance region of both nuclei was remarkably similar at forward angles. For ^{144}Sm , two peaks were observed at energies expected for the excitation of the giant quadrupole (GQR) and dipole (GDR) resonances. It was pointed out² that a description of the ^{144}Sm resonance structure as arising from only excitation of the GDR and GQR would lead to difficulties in explaining the ^{154}Sm spectra because photonuclear results³ show considerable splitting of the GDR peak. On the other hand, it was found that the differential cross

section for the sum of the two peaks in ^{144}Sm could be reasonably well described by distorted-wave Born approximation (DWBA) calculations for GDR and GQR excitations using the collective model described⁴ by Satchler. Recent direct observations of an $E0$ resonance by the (α, α') reaction^{5,6} and comparisons⁷ between (α, α') and (p, p') excitation of giant resonances in sd -shell nuclei suggest that the early DWBA calculations⁴ may significantly overestimate the GDR strength expected in the (p, p') reaction. For these reasons we have reevaluated the calculations for $T = 1, L = 1$ excitations.

We have reanalyzed the samarium spectra and shown by comparison with new DWBA calculations that the results can be explained in terms of the excitation of isoscalar 0^+ and 2^+ giant resonances, consistent with recent $^{144}\text{Sm}(\alpha, \alpha')$ measurements,⁶ and isovector 1^- giant resonances. This new analysis of the $\text{Sm}(p, p')$ results resolves long-standing questions on the interpretation of these data.

The theoretical calculations used the collective model described in ref. 4. However, for the GDR we used 40% Steinwedel-Jensen (SJ) and 60% Goldhaber-Teller (GT) as suggested by Myers et al.⁸ The $T = 1$ interaction $U_1(r)$ has been a major source of uncertainty in previous calculations. Here we used the energy-dependent global optical potentials derived from a recent unified analysis⁹ of (p, p) , (n, n) , and (p, n) data. The results of these analyses are shown in Fig. 2.71. For further details of this work see *Physical Review C* 8, 2788 (1978).

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Fig. 2.71. Giant multipole resonance structure observed in the $^{144}\text{Sm}(p, p')$ and $^{154}\text{Sm}(p, p')$ reactions at 20° ; $E_p = 67$ MeV. (a) The resonance structure is assumed to be composed of two separate peaks, as shown by the solid curves. The assumed shape and magnitude of the nuclear continuum underlying the resonances are shown by the dashed line. (b) The solid curve is the sum of all the calculated components of the $L = 0, 1$, and 2 giant resonances (shown dashed). For the $L = 0$ and $L = 2$ resonances, a spreading width was assumed to be the same as measured for ^{144}Sm , while the width of the $L = 1$ components was taken from photonuclear measurements.

EXCITATION OF GIANT MULTIPOLE RESONANCES VIA INELASTIC SCATTERING OF 120-MeV ALPHA PARTICLES

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The existence of a giant quadrupole resonance (GQR) has now been well established³ in nuclei spanning the

periodic table. The recent observation⁴ of another new resonance, located at about $80 \times A^{-1/3}$ MeV and interpreted^{4,5} as the giant monopole resonance (GMR), has been of particular interest, since the compressibility of nuclear matter is obtained from the energy of the GMR.

We have recently studied the giant resonance structure in ²⁰⁸Pb, ¹²⁰Sn, ⁹⁰Zr, ⁵⁸Ni, and ⁴⁶Ti using inelastic scattering of 152-MeV alpha particles. For alphas of this energy the resonance spectra are expected to be free from overlap with alphas from competing processes (e.g., α , $^5\text{He} \rightarrow \alpha + n$) than when using lower-energy incident alphas such as were used in previous observations^{4,5} of the monopole resonance. The objective of these measurements is to determine if the monopole resonance observed in nuclei in the lead region is also found in lighter nuclei. Figure 2.72 shows a spectrum from ¹²⁰Sn at 13°. The giant resonance structure is dominated by the GQR located at about 12.8 MeV. However, the shape of the resonance is clearly asymmetric to the high-excitation-energy side, presenting the possibility that a weaker resonance is located at $80 \times A^{-1/3}$ MeV. Detailed quantitative analysis of the data is now in progress.

SYSTEMATICS OF THE ISOSCALAR GIANT MONOPOLE RESONANCE FROM 60-MeV INELASTIC PROTON SCATTERING

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Recently, the giant monopole resonance (GMR) has been directly observed^{2,3} in $A \geq 144$ nuclei by inelastic alpha-particle scattering. Still earlier reports^{4,5} based on more indirect methods indicated that the GMR was to be found at about $80 \times A^{-1/3}$ MeV. Although protons can excite the giant dipole resonance (GDR), which is located at nearly the same energy as the GMR, at forward angles ($\leq 20^\circ$), the GMR (p, p') cross section is several times the GDR cross section. We have analyzed (p, p') data for a number of nuclei in order to investigate the GMR excitation as a function of mass number. Results which cover a wide nuclear mass range are necessary for an understanding of the systematics of the GMR and for extraction of information on the compressibility of nuclear matter.

Most of the data have been previously published.⁶ Measurements were made on ⁴⁰Ca, ⁵⁸Ni, ⁹⁰Zr, ¹²⁰Sn, ¹⁴⁴Sm, ¹⁵⁴Sm, ¹⁹⁷Au, and ²⁰⁸Pb using 60-MeV protons from the Oak Ridge Isochronous Cyclotron. Except for the ¹²⁰Sn target, inelastic protons were detected in the focal plane of a broad-range magnetic spectrograph. The ¹²⁰Sn measurements were made using a solid-state detector telescope.

Typical spectra of the giant resonance region for ²⁰⁸Pb, ⁹⁰Zr, and ⁵⁸Ni are shown in Fig. 2.73 at forward

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Fig. 2.72. Spectrum of inelastically scattered alpha particles from ¹²⁰Sn at 13°. Incident alpha energy is 152 MeV. The broad peak observed near channel 3485 arises from excitation of giant resonances, mostly the GQR located at 12.8 MeV of excitation. The experimental gain is about 40 keV per channel.

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Fig. 2.73. Giant resonance spectra from the 60-MeV (p,p') reaction on ^{208}Pb , ^{90}Zr , and ^{58}Ni . The measured spectra are shown as a histogram. Error bars on the data represent statistical uncertainty only. The resonance structure is assumed to be composed of two separate peaks, as shown by the solid curves and described in the text. The assumed shape and magnitude of the nuclear continuum underlying the resonances are shown by the dashed line.

angles, where the GMR should dominate the GDR. In all cases, the resonance peak is asymmetrical, being wider on the high-excitation side. For ^{90}Zr and heavier nuclei, we assumed that the resonance structure was composed of two peaks, as indicated in Fig. 2.73. The peak located at about $63 \times A^{-1/3}$ MeV is due to excitation of the GQR,⁷ which was assumed to be symmetrically shaped in all the nuclei studied. The higher-lying peak located at about $80 \times A^{-1/3}$ MeV is assumed to be due to excitation of the GMR and GDR. The spectra for ^{58}Ni and ^{40}Ca are somewhat more complex due to an additional peak located 2 to 3 MeV below the GQR (as indicated for ^{58}Ni in Fig. 2.73). The shape of the peak at about $80 \times A^{-1/3}$ MeV was found to be symmetric for nuclei with $A \geq 90$ but asymmetric (wider on the high-excitation side) for the lighter nuclei.

The extracted peak parameters are listed in Table 2.11. They were determined from the small-angle data, where (except for ^{40}Ca) the GDR contribution to the peak is negligible.

Cross sections for the GMR-GDR peak are plotted in Fig. 2.74 for some of the nuclei studied. The uncertainties shown are dominated by the uncertainty in extraction of the peak shape and in the magnitude and shape of the nuclear continuum assumed to underly the giant resonance structure. The curves are from distorted-wave

Fig. 2.74. Cross sections for the GMR-GDR peak in several nuclei compared with DWBA calculations. The fraction of the EWSR strength used for normalization of the calculated cross sections is shown on the curves (%).

Table 2.11. Parameters for the GQR and GMR deduced from 60-MeV inelastic proton scattering

(For each nucleus, the lower-excitation-energy peak is the GQR)

Nucleus	Excitation energy (MeV)	Width (MeV)	Percent of EWSR ($T = 0$)
²⁰⁸ Pb	10.9 ± 0.3	2.6 ± 0.5	80 ± 20
	13.4 ± 0.5	3.0 ± 0.5	90 ± 25
¹⁹⁷ Au	11.2 ± 0.3	3.0 ± 0.5	80 ± 20
	13.6 ± 0.5	3.0 ± 0.5	100 ± 25
¹⁴⁴ Sm	12.8 ± 0.3	2.8 ± 0.5	80 ± 20
	15.5 ± 0.5	2.5 ± 0.5	100 ± 25
¹⁵⁴ Sm	12.0 ± 0.3	3.7 ± 0.5	80 ± 20
	15.5 ± 0.5	2.5 ± 0.5	100 ± 25
¹²⁸ Sn	13.5 ± 0.3	3.4 ± 0.5	80 ± 20
	16.8 ± 0.5	3.5 ± 0.5	100 ± 25
⁹⁰ Zr	14.2 ± 0.3	4.0 ± 0.5	60 ± 15
	17.5 ± 0.5	3.0 ± 0.5	60 ± 25
⁵⁸ Ni	16.5 ± 0.3	3.8 ± 0.5	50 ± 10
	19.8 ± 0.5	3.5 ± 0.5	30 ± 10
⁴⁰ Ca (GQR only)	17.8 ± 0.3	2.5 ± 0.5	40 ± 10

Born approximation calculations. The $T = 0$ excitations were calculated with the usual deformed optical-potential model,^{8,9} version 1 of the monopole model⁹ was used. The sum-rule limits were evaluated with radii suggested by electron scattering data. Two new features were introduced into the isovector giant dipole excitation. We took the mixture of Steinwedel-Jensen (SJ) and Goldhaber-Teller (GT) models suggested by curve *c* of Fig. 3 in Myers et al.¹⁰ More important, the isovector interaction $U_1(r)$ was taken from a recent unified analysis¹¹ of (p,p) , (n,n) , and (p,n) analog transition data. This analysis gave energy-dependent global potentials from which we chose set B; this was also used to generate the distorted waves. The $U_1(r)$ term, especially the imaginary part, is weaker than that used previously⁹ and results in considerably smaller GDR cross sections. The percentage of the classical dipole sum rule used was taken from photonuclear measurements.¹² This was accomplished by determining the fraction of the total photonuclear cross section that lies within the limits of our experimentally extracted GMR-GDR peak.

Except for ⁴⁰Ca, the trend of the angular distributions shown in Fig. 2.74 is the same for all the nuclei studied. The measured cross sections cannot be accounted for by the GDR alone at any angle, and the GMR alone cannot account for them at all angles. How-

ever, the sum of the calculated GMR and GDR cross sections provides excellent agreement with the data.

Comparisons between the measured and calculated cross sections yield a depletion of approximately 100% of the energy-weighted sum rule (EWSR) for the GMR for nuclei with $A > 90$. (⁹⁰Zr results were available at only two angles and are therefore less certain.) For ⁵⁸Ni, 100% would considerably overestimate the measured cross sections. These data are best described by a depletion of $30 \pm 15\%$.

The ⁴⁰Ca cross sections in Fig. 2.74 are clearly different from those for the other nuclei shown. They do not show the strong rise at forward angles, characteristic of the $L = 0$ calculation, and they are consistent with the cross sections calculated for $L = 1$ alone. Thus, assuming that the model used for $L = 0$ and $L = 1$ is valid for light nuclei, we find the ⁴⁰Ca results to be consistent with only excitation of a GDR (plus the GQR). [A small mixture of $L = 0$ ($\leq 15\%$) could be consistent within the uncertainty of the data.]

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THE (p,n) REACTION AT INTERMEDIATE ENERGIES

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Early results from the ORNL-IUCF collaboration to study (p,n) reactions at the Indiana Cyclotron have been interpreted in terms of the nucleon-nucleon force. The dominant peaks in the 0° neutron spectra for $E_p = 120$ belong to states that are known to have or are conjectured to have large Gamow-Teller matrix elements with the target ground state. The GT operator is a spin-isospin operator.

The free nucleon-nucleon force is expected to have a one-pion exchange potential (OPEP) component, but direct evidence for OPEP in nucleon-nucleon scattering is hard to find. However, in scattering from bound nucleons, the nuclear states can act as filters for picking out certain components of the force. In particular, if a nucleon in a nucleus is acted upon by a spin-isospin

operator of the form of the central term in OPEP, the result projects onto final states connected to the initial state by the GT operator. Thus strong selective excitation of states connected by GT matrix elements can be taken as evidence for a spin-isospin component in the interaction.

Calculations of the (p,n) differential cross sections using the impulse approximation and nucleon-nucleon interaction t matrix that yields the known nucleon-nucleon phase shifts are in good agreement in magnitude and shape with the measured (p,n) cross sections for those states with large GT matrix elements.

Figures 2.75 and 2.76 show DWIA calculations compared with data on $^{12}\text{C}(p,n)^{12}\text{N}$ at 120 MeV and 62 MeV.

Figure 2.77 shows fits to $^{28}\text{Si}(p,n)^{28}\text{P}$ and $^{24}\text{Mg}(p,n)^{24}\text{Al}$ at 62 MeV. These calculations are DWBA calculations using the MSU G-matrix interaction⁷ and Wildenthal-Chung wave functions.⁸ In these cases the structure differences are well reproduced and the normalizations are wrong by fairly small amounts, indicat-

Fig. 2.75. $^{12}\text{C}(p,n)^{12}\text{N}$ and $^{12}\text{C}(p,p')^{12}\text{C}(15.1)$ at 120 MeV. The (p,p') data have been multiplied by the isospin coupling factor ($=2$) for comparison with the (p,n) data. The (p,p') data are by J. Comfort, *Indiana University Cyclotron Facility Progress Report Feb. 1977-Jan. 1978*, pp. 91-93. The solid curve is a DWIA calculation by Walker and Picklesimer (unpublished).

Fig. 2.76. $^{12}\text{C}(p,n)^{12}\text{N}$ and $^{12}\text{C}(p,p')^{12}\text{C}(15.1)$ at 62 MeV. The (p,p') data are by C. C. Foster (unpublished). The calculation is by Walker and Picklesimer (unpublished).

Fig. 2.77. $^{28}\text{Si}(p,n)^{28}\text{P}$ and $^{24}\text{Mg}(p,n)^{24}\text{Al}$ compared with DWBA calculations by F. Petrovich (unpublished), as described in the text.

ing considerable validity to the approach and presenting a challenge to improve the normalizations.

The beam swinger has now been installed in the northwest corner of the IUCF building, and flight paths are now outside the building, permitting detector locations unobstructed by the building structures. The use of 50-m and 100-m flight paths is planned for the immediate future. Polarized protons will also be used to mea-

sure asymmetries as an additional test of the interactions.

We thank F. Petrovich and G. Walker for making their calculations available to use prior to publication.

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MASS AND ENERGY DEPENDENCE OF LOW-ENERGY PION-NUCLEUS ELASTIC SCATTERING

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For energies below about 80 MeV, the pion mean free path in nuclear matter is longer than for other commonly used hadronic probes. This fact offers the exciting possibility that low-energy pion elastic scattering may elucidate nuclear structure properties that were heretofore unobserved or untested. Many theoretical calculations have appeared recently which attempt to account for the effects of various nuclear properties on low-energy pion elastic scattering.⁴ In order to test these calculations, it is essential to have high-precision experimental elastic scattering results on a wide range of nuclear masses and using several incident pion energies. We have measured π^+ -nucleus elastic scattering on ^{12}C , ^{16}O , ^{40}Ca , ^{90}Zr , and ^{208}Pb using 30-, 40-, and 50-MeV incident pions.

Scattered pions were detected using an array of ten plastic-scintillator telescopes. The procedure was to measure 18 angles (between 25° and 160°) in two runs, keeping two detectors stationary to provide additional checks on the relative normalization between the two angle sets. The relative pion beam intensity was monitored by using two detectors in coincidence which

detected muons resulting from in-flight decay of the pions. For the 50-MeV data, relative beam intensity was also monitored by detecting protons at 90° to the beam from the $(\pi^+, 2p)$ reaction in the target. Absolute calibration of both monitors was achieved at low beam intensity by directly counting the number of pions in the beam. The uncertainty in the absolute normalization of the data was 7% or less for all the data. Relative uncertainty between data points in the angular distribution for a given target and incident energy is 4% or less.

The measured differential cross sections are presented in Fig. 2.78. As expected, the angular distributions become more structured as the pion energy and target mass are increased. The minimum clearly visible at 65° for ^{12}C , ^{16}O , and ^{40}Ca is explained by interference between the s - and p -wave pion-nucleon amplitudes. For ^{208}Pb and ^{90}Zr (and ^{40}Ca at 50 MeV) the minimum observed in the angular distribution is a diffraction minimum which moves to smaller angles as the target mass and incident energy increase.

The curves shown in Fig. 2.78 are the result of fitting the data with a first-order nonlocal optical model. The form of the pion-nucleon t matrix used to calculate the first-order optical potential was:

$$t_k(k'', k') \propto (\alpha(b_0 + b_1 k'' \cdot k')) \times \{k^2 + \alpha^2\} / \{(\alpha^2 + k''^2)(\alpha^2 + k'^2)\},$$

where k is the incoming pion momentum, k' and k'' are the off-shell momenta in a single π -nucleon scattering, and α is a parameter indicating the pion-nucleon interaction range. In the limit $\alpha \rightarrow \infty$, the expression reduces to the usual zero-range local limit. Values for α range from about 300 MeV/ c to about 700 MeV/ c .⁵ We have varied α and find the fit to our data to be relatively insensitive to values in the above range; therefore α was fixed at 500 MeV/ c for these calculations. The fitting program varies the strength parameters b_0 and b_1 to minimize χ^2 between the calculated and measured cross sections.

The values of b_0 and b_1 which give the best unitary fit (lowest χ^2) to the data are shown in Fig. 2.79. The dotted lines show the values of the strength parameters obtained from free π -nucleon phase shifts. The values of the real part of the parameters needed to fit the data are considerably different from the free values; however, the mass dependence of the fitted parameters is the same as that for the free π -nucleon phase shifts. This similarity in mass dependence between the fitted and free parameters suggests that the concept of parameter variation using an optical potential is a valid means of describing the low-energy pion elastic scattering data. No evidence is found for an energy dependence to the real parts of the potential. Although the imaginary parts of the fitted parameters agree more closely with the free π -nucleus values and they show some indication of an

Fig. 2.78. Angular distribution of elastic scattering of π^+ on ^{12}C , ^{16}O , ^{40}Ca , ^{90}Zr , and ^{208}Pb from $E_{\pi^+} = 30, 40$, and 50 MeV. The solid curve is the result of a first-order optical-model calculation in which the strength parameters (see text) were varied to provide a best fit to the data.

Fig. 2.79. Values of the real and imaginary parts of the strength parameters determined from best fits to the data of Fig. 2.78. The dashed curves are the values of the parameters obtained from free π -nucleon phase shifts.

energy dependence, the fitted values are very poorly determined, and no significance is put on these agreements or apparent energy dependences. We are extending our measurements to 20-, 65-, and 80-MeV incident π^+ in order to study further the mass and possible energy dependence of the optical potential used to describe π^+ -nucleus elastic scattering.

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3. Nuclear Physics with Neutrons

INTRODUCTION

Neutron total, capture, scattering, and fission cross-section measurements and (n,γ) spectral measurements have continued on many isotopes and elements of interest to basic nuclear physics, to nucleosynthesis, and to the fusion and fission energy programs.

In basic nuclear physics, the analyses of total, scattering, capture, and (n,γ) spectral measurements on ^{207}Pb at ORELA have shown that the magnetic dipole strength in ^{208}Pb is highly fragmented and that the 7.4–8.0 MeV region contains only about 20% of the $M1$ strength, contrary to earlier claims. Also, high-resolution total and scattering data on ^{206}Pb have correctly identified the $M1$ strength in ^{207}Pb . Doorway states observed in the s -, p -, and d -wave neutron channels for $^{206}\text{Pb} + n$ can be interpreted in terms of a particle-core coupling model. Spin-orbit splitting for the $p_{1/2}$ and $p_{3/2}$ phase shifts is obvious from a detailed analysis of the total cross section of ^{32}S . The results of neutron resonance-capture gamma-ray measurements on ^{100}Mo are not in agreement with predictions from a simple valency model which was successful for ^{92}Mo and ^{98}Mo .

The neutron capture cross sections of the osmium isotopes 186, 187, and 188 were measured because of their interest to nucleosynthesis. From these data a value of about 12×10^9 years was obtained for the duration of nucleosynthesis prior to the formation of the solar system, on the basis of an exponential model for nucleosynthesis. This value is significantly larger than estimates derived from uranium-thorium dating. However, the neutron inelastic scattering cross section of approximately 30-keV neutrons to the 10-keV level in ^{187}Os is an important input to the calculation, and an experimental measurement of it using 24-keV iron-window neutrons combined with the time-of-flight technique is planned.

The temperature of a $d-d$ experimental fusion plasma can be determined from the transmission of neutrons in the region of the 2.35-MeV window in oxygen. Accurate measurements of the neutron total cross section of oxygen in this energy region ($\sigma_T = 114.0 \pm 1.7$ mb at the minimum) were made for this application.

Fission, capture, and total cross-section measurements were made upon several nuclides needed for the actinide program relating to fission energy. The fission cross section of ^{241}Am (important for the actinide waste problem) was measured to be much lower in the keV energy region than had been obtained from earlier underground explosion measurements. A new program to compare the chemical and isotopic abundances of the actinides in samples of ^{232}Th , ..., ^{241}Pu irradiated in the fast flux of EBR-II with those calculated from neutron cross sections has been initiated.

DOORWAY STATES OBSERVED IN THE $^{206}\text{Pb} + n$ REACTION AND THE QUESTION OF $M1$ GROUND-STATE RADIATION IN ^{207}Pb

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High-resolution neutron transmission and differential-scattering measurements have been made with a ^{206}Pb sample. Typical spectra and theoretical calculations are shown in Fig. 3.1. Doorway states are observed in the s -, p -, and d -wave neutron channels. Resonances in both

the $p_{1/2}$ and $p_{3/2}$ channels (see Fig. 3.2) are evident and are consistent with observations in the $^{207}\text{Pb} + n$ system.³ These doorways are suggested to arise from a $d_{5/2}$ -particle, 3^- -core excitation. The d -wave doorways probably arise from a recoupling of the $g_{9/2}$ -particle, 4^+ -core excitation which is believed to be responsible for the s -wave doorway in the lead isotopes.

A major fraction of the resonances previously assigned⁴ as p -wave are found to be s - or d -wave. In the interval $E = 3$ to 600 keV we can set as an upper limit for $M1$ ground-state radiation $\Sigma g_{\gamma} \Gamma_{\gamma 0} \Gamma_n / \Gamma < 24$ eV. This represents less than 40% of the strength given in ref. 4.

Fig. 3.1. Total (top) and differential elastic scattering cross sections at 39° , 55° , 90° , 126° , and 150° for $^{206}\text{Pb} + n$ reaction for $E = 165$ to 240 keV. The data are represented by the points and the calculated curves by the solid lines. The total cross section is for an effectively pure ^{206}Pb sample, while the differential data are for radiogenic lead. See text for discussion of R -matrix fit to σ_T and calculations of $\sigma(E, \theta)$, as well as normalization of the latter with the data.

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NUCLEAR LEVEL DENSITIES NEAR THE NEUTRON SEPARATION ENERGY IN ^{207}Pb

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There exists little definitive information with which to test the J and parity dependence of nuclear level-density formulas. From our data for $^{206}\text{Pb} + n$ study we have deduced J^π values for a large fraction of the observed resonances up to $E = 605$ keV. In Fig. 3.3 are plotted the number of s -, p -, and d -wave levels vs neutron energy. Of particular importance is the curvature in the plot for s waves, which clearly shows a change in the s -wave level density of about 12% per 100 keV. This is about the amount of change in the level density that would be expected from most level-density formulas.

We have fitted the s -wave data (up to 800 keV) with a constant-temperature model which gives $T = 0.9$ MeV. The dashed lines in each figure represent the calculated cumulative number of levels assuming $\rho(E, J^\pi) = (J + 1/2)ke^{E/T}$, where k is a constant. The calculated curve reproduces the d -wave data reasonably well up to about

Fig. 3.2. Plots of the sum of reduced neutron widths ($\Sigma \Gamma_n^1$) for p waves vs neutron energy. The top figure is for $J = 3/2$ and the middle for $J = 1/2$. The bottom figure is the weighted sum $[\Sigma \Gamma_n^1 / (2I + 1)]$. The strength function is given by the slope of the curve. See text for discussion.

500 keV but underestimates the number of p waves. The number of firmly established $1/2^-$ resonances is equal to the number of $1/2^+$ resonances up to 605 keV. However, since it is unlikely that none of the 38 unassigned p waves will have $J = 1/2^-$, the data are suggestive that the level-density formula is not parity-independent.

COMPLETION OF CRUCIAL TESTS REGARDING LEVELS IN ^{208}Pb PURPORTED TO HAVE LARGE $M1$ GROUND-STATE RADIATION WIDTHS

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In the 1977 Physics Division annual report, positive identification of $M1$ radiating states in the unbound

region of ^{208}Pb was reported. Based upon high-resolution neutron transmission and scattering measurements on ^{207}Pb , a cluster of states within a p -wave doorway state near $E = 120$ keV were found² to have $J^\pi = 1^+$. Since these states had previously been shown³ from a $^{207}\text{Pb}(n,\gamma)$ study to have ground-state radiation widths, these observations represented positive identification of $M1$ strength in the unbound region of ^{208}Pb . In subsequent (n,γ) measurements at ORELA, Raman et al.⁴ observed radiation ($\Gamma_{\gamma 0} \lesssim 2$ eV) from a number of additional resonances for which they deduced $J = 1$ and which were known⁵ to have $\pi = +$. Together, these results indicated that the $M1$ ground-state radiation in the unbound region of ^{208}Pb was fragmented, except for a resonance^{6,7} at 616 keV (energy in n,γ system), observed in (γn) studies, reported to have $J^\pi = 1^+$ and

Fig. 3.3. Plots of the cumulative number of s -, p -, and d -wave resonances (top to bottom, respectively) vs neutron energy. The dashed lines represent calculated curves using the constant-temperature model with $T = 0.9$ MeV. See text for discussion.

$\Gamma_{\gamma 0} \approx 19.7$ eV. In the bound-state region of ^{208}Pb , Horen et al.⁸ have shown that the level at 7.064 MeV previously reported to have $J^\pi = 1^+$ and $\Gamma_{\gamma 0} = 23$ eV has in fact negative parity and hence gives rise to $E1$ rather than $M1$ radiation.

The high-resolution neutron transmission and scattering data (see Fig. 3.4) for ^{207}Pb taken at ORELA were analyzed using R -matrix total cross section and differential scattering codes. Eleven resonances were observed in the region $E = 602$ to 623 keV. Of special significance is

a resonance at 616.0 keV which was found to have $J^\pi = 1^-$. A preliminary (n, γ) measurement performed at 150 m at ORELA established an energy correspondence between our neutron measurements and the (γ, n) work. Because of the poorer resolution in the latter, only two peaks were observed in this energy interval, namely, $E = 602$ keV ($\Gamma_{\gamma 0} = 8$ eV) and $E = 613$ keV ($\Gamma_{\gamma 0} = 19.7$ eV). Based upon measurements of the polarization of emitted photons, these were reported⁷ to have $J^\pi = 1^-$ and 1^+ respectively.

Fig. 3.4. Experimental and calculated total (top figure) and differential elastic scattering (bottom figure) cross sections for $^{207}\text{Pb} + n$ for the energy interval $E_n = 600$ to 627 keV. The differential cross sections are relative. The calculated cross sections have been normalized to the experimental data at 39° and displaced upward for clarity.

Because the neutron data were insufficient to allow unambiguous J assignments to the resonances at 616.8 and 717.7 keV, as well as the complications created by the fact that ^{207}Pb has a ground-state spin of $1/2^-$, which allows two channel spins to participate in the excitation of a $J = 1^+$ resonance, it was necessary to make a general R -matrix analysis of all the data (neutron transmission and scattering and photoneutron angular distribution and polarization measurements). A generalized R -matrix code due to Dodder et al.⁹ was used for this purpose.

If the 616.8 -keV resonance has $J^\pi = 1^+$, we find that it would have to have $\Gamma_{\gamma 0} \leq 4.5$ eV. Under these conditions we were able to fit all the experimental data reasonably well (including the photoneutron polarization, Fig. 3.5). This upper limit for $M1$ radiation near $E = 616$ keV is rather conservative and would be lower if a 1^+ resonance was located nearer the 616.0 -keV resonance. If the 616.8 -keV resonance were in fact 2^+ , we

Fig. 3.5. Comparison of calculated (solid curve for 90° and dashed curve for 135°) and experimental photoneutron polarizations at 90° and 135° for $E_n = 600$ to 625 keV in the (n, γ) system. See D. J. Horen, G. F. Auchampaugh, and J. A. Harvey, *Phys. Lett.* 79B, 39 (1978) for details.

find that the data can also be reasonably well reproduced with $\Gamma_{\gamma 0} < 0.7$ eV for this resonance.

These results¹⁰ have appeared in *Physics Letters* and, taken together with previous studies indicated above, clearly show that there are no levels observed thus far in ^{208}Pb up to an excitation energy of 8 MeV which involve more than $B(M1) \approx 2\mu_0^2$, with the possible exception¹¹ of a questionable (1^+) level at 4.843 MeV.

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NEUTRON TOTAL CROSS SECTION OF SULFUR

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Using the 5-nsec pulsed neutron source and 200-m flight path at ORELA we have measured the neutron total cross section of sulfur for energies above 15 keV. We have analyzed the resonances up to 1100 keV and obtained J^π assignments for 28 of the 53 observed resonances in this region.

For the analysis we neglect the small radiative widths, so that the R matrix reduces to a simple R function for each neutron partial wave. For further simplicity in the region near each resonance we express the phase shift as the sum of a single level plus the effect of all other levels and hard-sphere scattering. This expression involves no approximation to the R function. Each resonance was analyzed by least squares by adjustment of a potential phase ϕ' , the level parameters Γ , E_0 , and J (where J is a half integer), and a linear background for other levels and minor isotopes. Doppler and resolution broadening were included.

Figure 3.6 shows the potential phases for the definite $s_{1/2}$, $p_{1/2}$, and $p_{3/2}$ levels. The p -wave spin-orbit split-

ting is clearly observed. From each phase we calculate an R function $R_{IJ}^0(E_0)$ and then deduce an $R_{IJ}^e(E_0)$ for the external levels by subtracting the contribution of other levels within our energy region. A least-squares fit to $R_{IJ}^e(E)$ is made using the functional form

$$R_{IJ}^e(E) = R_{IJ}^e - s_{IJ} \int dE' (E' - E)^{-1},$$

where the integration limits are the limits of our analysis and s_{IJ} is the observed strength function. The parameter R_{IJ}^e is an average R function that is assumed to be constant. The curves in the figure were calculated using the least-squares R_{IJ}^e .

Figures 3.7 and 3.8 show observed cross sections and the multilevel curve calculated using the fitted $R_{IJ}^e(E)$

Fig. 3.6. Potential phases deduced by single-level analysis of $s_{1/2}$, $p_{1/2}$, and $p_{3/2}$ resonances in $^{32}\text{S} + n$.

Fig. 3.7. Neutron total cross sections for sulfur up to 660 keV. The multilevel curve was deduced from the single-level analyses.

Fig. 3.8. Neutron total cross sections for sulfur. This is a continuation of Fig. 3.7. to 1.1 MeV.

with level parameters deduced from the "single-level" analysis. Narrow levels with unknown J^π are not included in the curves. Doppler and resolution broadening are omitted for these figures. The conversion to the multilevel form requires that each observed width be increased by $1 + (R_{lJ}^0 P_l)^2$, where P_l is the penetrability. The data are well described by the curve, and the description of the broad s -wave levels is particularly striking.

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MEASUREMENT OF THE 2.35-MeV WINDOW IN $^{16}\text{O} + n$

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Stelson and Barnett suggested³ that the neutron transmission of a thick oxygen scatterer be used to measure the temperature of a d - d plasma. For a thick oxygen scatterer, neutrons are transmitted only near the 2.35-MeV minimum in the total cross section. The relative number of plasma neutrons near this minimum depends on the ion temperature.

Using the ORELA pulsed neutron source with a 200-m flight path we have measured the transmission of a 1.5-m liquid oxygen sample. The liquid and vapor were maintained in equilibrium, and the vapor pressure was measured by a precision gauge. We deduced the liquid density from the known relationship to the vapor pressure. We measured the sample length at room temperature and corrected for contraction to the liquid temperature. Two independent analyses of the oxygen purity were obtained; these agreed to 0.2% and averaged 99.83%. Correcting for the 0.17% impurities of nitrogen and argon, we find a cross section at the minimum of 114.0 ± 1.7 mb. The uncertainty is a combination in quadrature of ± 0.7 mb statistical and ± 1.5 mb for the impurities.

The cross sections on the sides of the minimum are also needed. We have made measurements and partial analyses of the relative transmission of thinner matched samples of Be and BeO.

Calculations show that the transmission of d - d neutrons will increase up to an ion temperature of about 6 keV. From 6 to 10 keV the transmission is nearly constant. These calculations depend on the shape of the $D(d,n)^3\text{He}$ excitation function but are relatively insensitive to the absolute cross sections.

1. Instrumentation and Controls Division.
2. ORAU student trainee, 1978.
3. P. H. Stelson and C. F. Barnett, *Bull. Am. Phys. Soc.* 23, 882 (1978).

NEUTRON TOTAL CROSS SECTIONS FOR FILTER, FISSION, AND FUSION APPLICATIONS

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Transmission measurements have been made upon thick samples of ^{58}Ni (99.93%) and ^{60}Ni (99.68%) to assess their usefulness as neutron filters to produce neutron beams of about 14 and about 4 keV energy respectively. This "window" technique is presently used at several reactors to produce beams of 2, 24, and 120 keV using thick filters of scandium, iron, and silicon. Figure 3.9 shows the transmission (equivalent to flux distribution for a dE/E moderated neutron source) of a 60-g ^{58}Ni ($N = 0.596$ atoms/b) filter. The contribution of neutrons above 14 keV can be reduced by using thicker ^{58}Ni samples or other appropriate filters. Windows at 160 eV in ^{184}W and at 2.1 keV in ^{64}Zn are being

Fig. 3.9. Transmission of ^{58}Ni ($N = 0.596$ atoms/b) vs neutron energy.

investigated. These "monoenergetic" neutron beams can be used for basic nuclear physics, instrument calibrations, fundamental radiobiology, and radiotherapy of brain tumors.⁴

Transmission measurements have also been made at ORELA on several materials of interest to the fast breeder and fusion energy programs. Data have been obtained for H, C, Al, Si, Ni, Nb, and Mo up to about 20 MeV using the tantalum target.

Finally, we have demonstrated that ORELA has a useful neutron flux up to about 60 MeV using the beryllium block target. Using this capability, we have measured neutron total cross sections up to about 50 MeV for hydrogen, carbon, oxygen, and iron. These data are required for design of the Fusion Materials Irradiation Test (FMIT) Facility, since it will produce neutrons up to about 50 MeV.

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2. Berkeley Nuclear Laboratories, Gloucestershire, England.
3. Engineering Physics Division.
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NEUTRON CAPTURE CROSS SECTION MEASUREMENTS AT ORELA AND NUCLEOSYNTHESIS

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Continuing a well-established tradition of ORELA contribution to astrophysics, the capture cross sections of the osmium isotopes 186, 187, and 188 have been

measured in the kilo-electron-volt incident neutron energy range. As first pointed out by Clayton (1964), the beta decay of ^{187}Re to ^{187}Os is apparently one of the few suitable chronometers for nucleosynthesis. The half-life of the decay is long compared with the estimated age of the universe, and additional ^{187}Os is produced only by the well-understood s-process theory of nucleosynthesis. Hence, the duration T of nucleosynthesis prior to the formation of the solar system can be expressed in terms of ratios of observed terrestrial abundances and the ratio of the measured Maxwellian-averaged capture cross sections, $\bar{\sigma}_\gamma(186)/\bar{\sigma}_\gamma(187)$. Figure 3.10 presents the measured capture cross sections (not Maxwellian-averaged) for the two osmium isotopes, and Fig. 3.11 presents a preliminary estimate of T derived from this ratio, assuming an exponential model for nucleosynthesis. As indicated in Fig. 3.11, this estimate of $T \approx 12 \times 10^9$ years agrees well with that of Browne and Berman³ but is significantly larger than the estimates derived from uranium-thorium dating. This implies an age for a Big Bang universe of about 19×10^9 years.

Also of importance to our understanding of stellar nucleosynthesis are the capture cross sections of $^{20,22}\text{Ne}$. A thin-walled (0.15-mm) sample cell has been constructed for use with rare gas samples at pressures up

Fig. 3.10. Averaged capture cross sections for ^{186}Os and ^{187}Os from 2.5 to 120 keV.

Fig. 3.11. The rhenium-osmium clock. The exponential model for nucleosynthesis used for the estimate of T .

to 40 atm. Preliminary results have been obtained for $^{40}\text{Ar}(n,\gamma)$, but resonance parameter analysis has not yet been completed.

New capture cross-section measurements on solid samples during the reporting period include ^{64}Zn , ^{66}Zn , ^{67}Zn , ^{68}Zn , ^{75}As , ^{58}Fe , ^{133}Cs , ^{35}Cl , and ^{37}Cl . Measurements of the detector sensitivity to scattered neutrons were continued, and a lengthy intercomparison of our 0.5-mm $^6\text{Li}(n,\alpha)\text{T}$ glass scintillation flux monitor with a ^{235}U fission chamber was undertaken to extend our working neutron energy range upward to a few MeV.

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2. On leave from Denison University, Granville, Ohio.

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RESONANCE NEUTRON CAPTURE GAMMA-RAY MEASUREMENTS

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The large number of stable isotopes of tin facilitates any study aimed at the elucidation of systematic trends

in experimental or shell-model features of these nuclei. This situation, for some investigations, results at the same time in interference from unwanted isotopes. The power of resonance neutron capture, when used in combination with enriched targets, comes from the suppression of resonances known to be due to nuclei other than those under investigation. In a series of papers,⁷ we have reported results of such level-structure investigations for ^{115}Sn , ^{117}Sn , ^{119}Sn , ^{121}Sn , ^{123}Sn , and ^{125}Sn . The experimental regularities that have been observed are summarized in Fig. 3.12. We have also calculated various spectroscopic properties (level energies, electromagnetic moments, and transition rates) of ^{119}Sn , ^{117}Sn , and ^{115}Sn on the basis of a model which pictures these nuclei as being formed by coupling the motion of the odd neutron quasi particle to the states of the neighboring even-mass core. The experimentally determined level properties of these tin isotopes have been qualitatively reproduced by these calculations.

We have also carried out a series of (n,γ) spectral measurements following resonance neutron capture on all stable iron isotopes. The results obtained with the even iron targets have been recently published.⁸ In the (n,γ) reaction with low-energy neutrons, the partial radiation widths from adjacent resonances are almost always uncorrelated with each other. However, in our study of the $^{58}\text{Fe}(n,\gamma)^{59}\text{Fe}$ reaction, we found that the gamma-ray spectrum from the p -wave, 230-eV resonance capture is similar to the spectrum from the s -wave thermal neutron capture. The correlation coefficients have been discussed in ref. 8.

We have concluded a detailed study of neutron resonance reactions on an 88%-enriched ^{206}Pb target.⁹ We were particularly interested in studying the neutron energy region up to 50 keV. The (n,γ) measurements with a Ge(Li) detector were supplemented by capture cross-section and transmission measurements. The magnetic dipole ($M1$) transitions from several p -wave resonances to the first three excited states in ^{207}Pb showed some enhancement. A possible doorway state in the $p_{1/2}$ neutron channel was observed at about 6.774 MeV excitation energy.

In the (n,γ) reaction, the observed transitions originating from the capturing state are known as primary transitions. These transitions are predominantly electric dipole ($E1$) or magnetic dipole ($M1$); primary electric quadrupole ($E2$) transitions are extremely rare. We have made a survey of the literature and identified 16 such $E2$ transitions in 15 different nuclei.¹⁰ We have also exploited the $^{207}\text{Pb}(n,\gamma)$ reaction, over a wide neutron energy range, in order to systematically identify primary $E2$ transitions, measure their radiation widths,

For nearly a decade, experimentalists have been struggling with the problem of locating the magnetic dipole ($M1$) strength in ^{208}Pb (ref. 10). Simple and basic theoretical notions would predict that this strength should be found mainly at an excitation energy of 7–8 MeV. Initially, measurements indicated a surfeit of strength (see Fig. 3.13). It is now known that many of the states shown in the top part of Fig. 3.13 are 1^- states and not 1^+ states. The present status is shown in the bottom part of Fig. 3.13. Recent contributions from ORELA concerning this problem were reported in refs. 12 and 13. The 7–8 MeV region contains only about 20% of the total predicted $M1$ strength. Confronted by these results, theorists have started reexamining the assumptions made in their calculations. In particular, Brown, Dehesa, and Speth¹⁴ have argued that for particle-hole excitations above the Fermi surface, it is not correct to use empirical single-particle energies. Instead, it would be better to begin with single-particle energies corresponding to an effective mass of $m^*/m \approx 0.6$ to 0.7.

Among the most convincing examples of valence capture are the strong p -wave resonances in ^{92}Mo and ^{98}Mo , where, for the strongest transitions, quantitative agreement is observed between partial radiation widths and the corresponding valence-model predictions. A neighboring isotope, ^{100}Mo , also shows strong p -wave resonances at low neutron energies and therefore provides another interesting test case for the validity of this

Fig. 3.13. Claims prior to 1977 and present status in 1978 of $M1$ strengths to the ground state of ^{208}Pb . From S. Raman, invited paper, Third International Symposium on Neutron Capture Gamma-Ray Spectroscopy and Related Topics, Brookhaven National Laboratory, September 1978. A dashed line indicates uncertain 1^+ assignment.

model. We have completed a series of measurements on ^{100}Mo (ref. 15). The situation for the ground-state transition is illustrated in Fig. 3.14, where experimental ground-state partial radiation widths are shown together with the valence-model predictions for the three and four strongest resonances in ^{98}Mo and ^{100}Mo , respectively. The different behavior of ^{100}Mo , except for the $1/2^-$, 1068.2-eV resonance, as compared with ^{98}Mo is obvious from this figure.

In view of the great success that the simple valence model has had in quantitatively explaining the observed partial radiation widths in ^{92}Mo and ^{98}Mo , the failure of this model in ^{100}Mo warrants an explanation. A simple one would be to assume accidental cancellation (destructive interference) of the valence and compound-nuclear amplitudes for the ground-state transitions from the ^{100}Mo resonances at 1259, 1695, and 2418 eV. The probability P for this to happen can be shown to be small ($P < 0.002$) with the aid of a Monte Carlo simulation. Two other interpretations are plausible: (1) A necessary condition for the simple valence

Fig. 3.14. Comparison of experimental partial radiation widths with valence-model (v.m.) predictions for ground-state transitions from strong p -wave resonances in ^{98}Mo and ^{100}Mo . From H. Weigmann et al., *Phys. Rev. C*, submitted for publication.

model to work is that the $E1$ strength of the single-particle state acting as a common doorway is essentially decoupled from the giant dipole resonance. The absence of ground-state transitions from the strong $3/2^-$ resonances in ^{100}Mo may indicate that for the $p_{3/2}$ single-particle state, which probably is further below threshold than the $p_{1/2}$ state, this decoupling is less effective. (2) The idea of destructive interferences may explain the present results at least for the ground-state transition if, instead of assuming destructive interference between the valence and compound amplitudes, one assumes such interference between the valence amplitude and another amplitude due to a narrow doorway (or a "hallway"). Such an amplitude may be sufficiently large, and the fact that the interference is destructive in all three $3/2^-$ resonances would be readily explained.

Finally, improvements to our detection system are planned. Discrete gamma-ray measurements following resonance neutron capture have been studied at ORELA since 1969 with a simple 40-cm³ Ge(Li) detector. We intend to replace this detector with a new three-crystal

[one Ge(Li) and two NaI(Tl)] pair spectrometer, which will improve and simplify the spectra to a great extent. Moreover, the existing fixed shadow bar, employed to reduce the gamma flash, will be replaced by a remotely controlled shadow bar. This change will permit the optimization of the shadow bar position each time the ORELA tantalum target is replaced.

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ACTINIDE NEUTRON CROSS SECTIONS PROGRAM

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Fission

Development of a new type (honeycomb) fission chamber for $>10^8$ α /sec samples was completed and reported.⁴ Together with specially developed ultrafast

amplifiers⁵ and a new Xe gas scintillator ⁶Li(n, α) neutron beam monitor of large area,⁶ this chamber permitted the measurement of the fission cross section of ²⁴¹Am over an energy range thermal–20 MeV at ORELA. Preliminary results show a much lower cross section over part of this range when compared with earlier underground explosion measurements.⁷ Other laboratories have also confirmed the strikingly lower fission cross section in this energy range. Papers on fission of ²³⁴U and ²³⁵U were completed and published.⁸ In the latter paper, the spins of some 375 resonances and structures below 300 eV were definitively established.

Capture

Results of capture cross-section measurements on ²⁴⁰Pu were published.⁹ Measurements of the capture cross section of ²⁴¹Pu with a simultaneous fission cross-section determination were completed and published.¹⁰ Multilevel resonance parameters for this nuclide (Adler formalism) were derived and published.¹¹ The ²³²Th(n, γ) cross section from 2.6 to 800 keV was measured and published.¹² A measurement extending into the keV region has been made on ²³⁷Np capture. Figure 3.15 illustrates the results obtained. The new values in the 0.5-eV region may be of importance in thermal reactors.

Fig. 3.15. Capture cross section of ²³⁷Np at low energies. Note additional width found at 0.5-eV resonance.

Total

Analysis of transmission data on 98% ²⁴⁰Bk was completed and reported.¹³ The sample was permitted to decay to ²⁴⁰Cf (330-day half-life) and remeasured twice.

A preliminary analysis of data from the 70% ^{249}Cf was made¹⁴ and data have been taken on 86% ^{249}Cf and converted to cross section. A resonance analysis is in progress.¹⁵ High-resolution transmission data have been taken on ^{237}Np at liquid nitrogen temperature.

Integral Cross-Section Determinations

Several separated actinide samples ranging from ^{232}Th to ^{241}Pu were irradiated for four years in EBR-II at Idaho Falls. A new program of measuring the present composition of these samples has been initiated in conjunction with the Analytical Chemistry¹⁶ and Engineering Physics¹⁷ Divisions. First results, for a ^{239}Pu sample, have been published recently.¹⁸

Actinide Newsletter

A newsletter, detailing worldwide developments in actinide research (edited by S. Raman), was published by ORNL in November 1977. A second issue is in preparation and will be published in February 1979.

Visitors and Collaborators

The following have made substantial contributions to this program: R. W. Benjamin (Savannah River Laboratory); R. F. Carlton (Middle Tennessee State University); G. D. James (AERE Harwell); G. F. Auchampaugh, G. A. Keyworth, M. S. Moore, J. D. Moses, and R. Nelson (Los Alamos Scientific Laboratory), M. S. Pandey (College of William and Mary); and H. W. Sang, Jr. (Massachusetts Institute of Technology).

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2. Instrumentation and Controls Division.
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14. By M. S. Pandey (College of William and Mary).
15. By R. F. Carlton (Middle Tennessee State University).
16. J. E. Bigelow, J. A. Carter, J. H. Cooper, J. C. Price, J. R. Sites, and R. L. Walker are collaborating in the chemical and isotopic analyses.
17. M. L. Williams will make comparisons with calculations using ORIGEN and related codes.

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DEVELOPMENT OF A $^6\text{Li-Xe}$ GAS SCINTILLATOR NEUTRON BEAM MONITOR AT ORELA

J. W. T. Dabbs

Preliminary direct calculations by R. L. Macklin,¹ confirmed by Monte Carlo (KENO code) calculations by L. M. Petrie,¹ showed that the response of the earlier ^6Li -plastic scintillator was affected severely (~25%) at energies below 100 keV by multiple scattering in the front 6-mil layer of NE110 plastic, which contains 52% hydrogen. However, the Monte Carlo calculations could not be made to be sufficiently accurate, nor carried to energies below 10 eV, within reasonable time, effort, and cost limits.

A modified neutron beam monitor has accordingly been developed, in which the two NE110 plastic scintillator sheets have been replaced with Xe gas. Two versions have been constructed and used. The first has a sensitive area 2 cm in diameter and was intended as an exact replacement for the NE110- ^6Li -NE110 sandwich unit previously used. It was used to obtain a measured correction curve for the earlier unit. This correction must be applied to a large amount of data on the fission cross sections of ^{243}Cm and ^{245}Cm ; background analysis and correction of these data are in progress and in the case of ^{243}Cm are nearly complete at this writing. The second gas scintillator unit was designed for a 7.62-cm-diam beam. A pressure of 3 atm absolute of Xe gas is needed to stop tritons within the volume viewed by the two 5-in. photomultiplier tubes. The 2-cm unit used only 1 atm of Xe.

A major problem in gas scintillators is gas purity. The cost of pure Xe gas precluded continuous supply of fresh gas; sources of contamination in the system required continuous purification. Thermally driven circulation in a two-stage purification loop was used. The first stage was about 20 cc of molecular sieve; the second stage was a Ba-Al alloy layer, evaporated from a commercial ring source² onto the interior of a glass finger by rf induction heating. This purification loop getter must be replaced every three to six months but provides a visible indication of its remaining life.

The performance of the two gas scintillator units has been gratifying. The upper energy limit is now 800 keV instead of 300 keV; this limitation is electronic rather than fundamental. Figure 3.16 shows the plastic scintillator and the large-beam gas scintillator. The moderated-neutron errors of the plastic scintillator sandwich have been eliminated. Figure 3.17 shows the correction factor as measured by comparison of the

Fig. 3.16. Cross-sectional views of two neutron beam monitors. RCA 4522 photomultiplier tubes are used in both systems to detect scintillations from $^6\text{Li}(n,t)$ events. The plastic scintillator unit has a response enhanced by 25% at certain energies because of neutron moderation in the scintillator. The xenon gas unit does not suffer from this fault.

Fig. 3.17. Fractional error in NE110 plastic-scintillator- ^6Li neutron beam monitor as a function of neutron energy. Filled circles are R. L. Macklin's direct estimate (unit tilted 1°); points with error bars are from L. M. Petrie's Monte Carlo calculation. Histogram is measured error.

small-beam gas scintillator with the plastic scintillator, together with calculations¹ which had earlier indicated the need for the new beam monitor. The Xe gas exhibits large absorption of neutrons at 9 eV and 14.4 eV. This requires corrections which are awkward but limited to these two energies.

Vacuum evaporations and foil preparations were ably performed by D. M. Galbraith. Two special evaporations were done at the K-25 plant by Helen M. Henson. We acknowledge the contributions of V. C. Miller, R. E. Zedler, R. H. Ward, R. Barnes, N. W. Hill, and E. I. Arakawa.

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2. Kindly furnished by M. Dorota, Pres., Apex Electronics, Inc., 100 8th Street, Passaic, N.J. 07055.

OAK RIDGE ELECTRON LINEAR ACCELERATOR

J. A. Harvey H. A. Todd¹ T. A. Lewis¹

During the first 13 months of this report period, the Oak Ridge Electron Linear Accelerator (ORELA) was

operated an average of 400 hr per month for neutron measurements. The maximum pulse repetition rate was increased to 1250 per second, and further modifications will make 1500 per second operation possible in 1979. A preliminary study and calculations were made of special targets for ORELA which would optimize the neutron flux in specific energy regions for particular experiments. Electron guns are now being fabricated at the ORELA site, and optimum procedures are still being developed. Additional improvements in electrode geometry and gun processing to increase the beam (goal of about 60 A from the electron gun) and to improve reliability are currently being tried with promising results.

Starting in August 1978, priority was given to the accelerator improvement project to increase the beam intensity in short pulses (about 4 nsec). The installation and acceptance-testing phases of the components of this system were completed in December with the exception of the installation of additional vacuum pumps that have not yet arrived. System integration and tuning of the nonlinear pulse-forming equipment will continue as development engineering tasks during 1979.

1. Instrumentation and Controls Division.

4. Theoretical Physics

INTRODUCTION

J. B. McGrory

In the period covered by this report, the main thrust in the theoretical nuclear physics program has been in the area of heavy-ion physics. This has encompassed studies of the ion-ion potential and a number of investigations of the gross properties of ion-ion scattering in both microscopic and macroscopic models. A new area of study has been that of Coulomb fission. In nuclear spectroscopy, the shell-model structure of high-spin yrast levels has been studied. These areas of interest are also those of the experimental program at ORIC and the expected program on Phase I of the Holifield Heavy-Ion Research Facility.

In the period since the last Physics Division report, a significant new program of theoretical atomic physics has evolved. Many of the questions being studied in this area are of great interest to the magnetic fusion energy program, where an understanding of ion-atom charge-exchange processes is essential.

We have emphasized brevity in this report. What follows are brief highlight statements of the ongoing research programs. More details are available in the given references and in the last annual report.

TDHF CALCULATIONS

K. T. R. Davies	S. J. Krieger ⁵
K. R. Sandhya Devi ¹	V. Maruhn-Rezwani ⁶
H. T. Feldmeier ²	J. W. Negele ⁷
H. Flocard ³	M. R. Strayer ⁸
S. E. Koonin ⁴	M. S. Weiss ⁹

Time-dependent Hartree-Fock (TDHF) calculations have been performed using several models and for a variety of systems. Two-dimensional (2D) and three-dimensional (3D) results have been compared for $^{16}\text{O} + ^{16}\text{O}$ and $^{40}\text{Ca} + ^{40}\text{Ca}$. In the 2D calculations it is assumed that the nuclear system is axially symmetric about the line joining the mass centers of the colliding ions. It is concluded that the 2D calculations reproduce well the 3D results for angular momenta both below and above the 3D fusion window. Also, as the bombarding energy is decreased, there is improved agreement between the two methods, including cases in which the angular momentum is within the fusion region.

We have made axially symmetric 2D calculations of $^{84}\text{Kr} + ^{208}\text{Pb}$ at $E_{\text{lab}} = 494$ MeV and $^{84}\text{Kr} + ^{209}\text{Bi}$ at

$E_{\text{lab}} = 600$ MeV. The main results are displayed in Fig. 4.1, and in Fig. 4.2 we show the final center-of-mass energy TKE_{cm} and angle θ_{cm} for each impact parameter on the experimental $^{84}\text{Kr} + ^{208}\text{Pb}$ Wilczyński plot. Both figures show that there is a strong focusing of L values, with respect to both energy and angle, near the experimental deep inelastic peaks. There is strong damping in these calculations, and the experimentally observed energy dissipation is well reproduced. In the strongly damped region for $^{84}\text{Kr} + ^{209}\text{Bi}$ centered at $\theta_{\text{cm}} \approx 50^\circ$, ΔA fluctuates about the observed value of zero. The most serious disagreement with experiment is for the width Γ_A , which is an order of magnitude too small.

Fusion cross sections have been calculated for $^{16}\text{O} + ^{16}\text{O}$ and $^{40}\text{Ca} + ^{40}\text{Ca}$. We have studied the sensitivity to the nuclear interaction used and the effects of Coulomb exchange and of removing isospin degeneracy.

Deep inelastic effects are being studied for the reaction $^{86}\text{Kr} + ^{139}\text{La}$ at $E_{\text{lab}} = 505, 610$, and 710 MeV. For $L = 0$ no fusion is seen at the lower two energies, but fusion is seen at 710 MeV. Alpha-particle emission

Fig. 4.1. Quantitative summary of TDHF results for krypton-induced collisions. Plotted as functions of the initial orbital angular momentum are: θ_{cm} , the final center-of-mass scattering angle; TKE_{cm} , the final c.m. total kinetic energy of the fragments; τ , the contact time; ΔA , the net mass change of the light fragment; Γ_A , the full width at half maximum of the mass distribution; and P_{Kr} , the percentage of krypton orbitals remaining in the light fragment after the collision. Also shown on the θ_{cm} graph are: θ_{COUL} , the Rutherford deflection function, and θ_P , the peak angle in the experimental strongly damped angular distribution.

Fig. 4.2. Comparison of calculated points, labeled by the orbital angular momentum, with the experimental Wilczynski plot for $^{84}\text{Kr} + ^{208}\text{Pb}$ at $E_{\text{lab}} = 494 \text{ MeV}$.

from the neck is also observed in a narrow L window at 710 MeV. Additional TDHF calculations are being performed for $^{16}\text{O} + ^{40}\text{Ca}$, $^{28}\text{Si} + ^{28}\text{Si}$, $^{16}\text{O} + ^{12}\text{C}$, and $^{18}\text{O} + ^{12}\text{C}$.

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ANALYSIS OF THE $^{14}\text{N} + ^{12}\text{C}$ REACTION

R. Y. Cusson¹ J. Gomez del Campo

The ^{14}N ($E_{\text{lab}} = 106$ and 167 MeV) + ^{12}C heavy-ion reaction was analyzed in terms of a modified version of the semiclassical scattering model of Broglia followed by an evaporation calculation. The deflection and energy-loss functions were taken from recent time-dependent Hartree-Fock calculations. The complete

fusion amplitude vs the angular momentum l was obtained phenomenologically. A comparison between the model predictions and experiment was made for the following quantities: the total integrated cross sections for production of a fragment with given Z , $\sigma(Z)$; energy distributions $(d^2\sigma/d\Omega dE)_Z$ at fixed laboratory angle and fragment charge; angular distribution $(d\sigma/d\Omega)_Z$ at fixed fragment charge Z and integrated over energy. The agreement was satisfactory. It was concluded that the Z spread observed in this reaction would be due only to evaporation effects in the highly excited reaction fragments produced in the original inelastic collision.

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THREE-DIMENSIONAL TDHFB CALCULATIONS

R. Y. Cusson¹ H. W. Meldner²

The three-dimensional momentum-space time-dependent Hartree-Fock (TDHF) code has been generalized to include a time-dependent constant-strength B.C.S. calculation of the occupation number. This allows a more reliable estimate of the two-body density matrix over the cases where the filling approximations would otherwise be used. The code was used to calculate deflection functions for $^{20}\text{Ne}(132 \text{ MeV}) + ^{20}\text{Ne}$, $^{20}\text{Ne}(164 \text{ MeV}) + ^{58}\text{Ni}$, $^{118}\text{Pd}(637 \text{ MeV}) + ^{118}\text{Pd}$, and $^{238}\text{U}(1770 \text{ MeV}) + ^{238}\text{U}$. The fusion cross section for $^{118}\text{Pd} + ^{118}\text{Pd}$ was $\geq 280 \text{ mb}$, which is a factor of 2 greater than the one found using classical hydrodynamics without friction. A strong time dependence of the pairing gap was also seen at constant pairing strength. Surface standing and traveling waves were also seen in this reaction, as predicted by the Copenhagen group (see Fig. 4.3). No fusion and no surface waves were found for $\text{U} + \text{U}$ because the Coulomb barrier is too high and the energy is too close to the barrier. The sequence of shapes is similar to those found in classical hydrodynamics plus friction, including a very long neck which breaks suddenly at its center. The residual uranium has an internal excitation energy of 130 MeV at scission, but only about 10 MeV of it is collective energy. This collective energy is almost all dissipated 200 fm/c after scission. Thus no dynamical fission of the residual uranium was observed. This suggests that the observed fission is statistical in nature, a process which the TDHFB method cannot describe, since TDHF describes the time-dependent density shapes in a semi-classical fashion. The energy loss and deflection angles were consistent with the available data.

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Fig. 4.3. $^{118}\text{Pd}(E_{\text{lab}} = 637 \text{ MeV}) + ^{118}\text{Pd}$ at impact parameter $B = 3.0 \text{ fm}$. These snapshots illustrate the nonaxial surface collective modes. The first picture at $t = 130 \text{ fm/c}$ shows a smooth surface with a characteristic overall nonaxiality. At $t = 150 \text{ fm/c}$ several bumps have appeared, some of which are indicated by arrows. These effects appear independent of the grid size used. The distance from bump to bump is about 5 fm. The deviation from a smooth surface is of order 0.5 to 0.7 fm.

NUCLEAR DYNAMICS FROM A MICROSCOPIC AND MACROSCOPIC VIEWPOINT

C. Y. Wong H. H. K. Tang¹

A comprehensive program of studying nuclear dynamics from a microscopic and a macroscopic viewpoint has been pursued in the past year. We list here the most notable advances:

1. We have extended the time-dependent Hartree-Fock approximation to include particle collisions due to residual interactions, with the usual time-dependent Hartree-Fock approximation as the collisionless limit.² Our new formulation extends the region of validity of the TDHF approximation to higher energies.
2. Working with the extended TDHF approximation, we have introduced concepts such as entropy, temperature, and thermal equilibrium.² We have shown how a nuclear system approaches thermal equilibrium and proven the well-known theorem that entropy never decreases. New types of level-crossing formulas were obtained to exhibit the salient features as to how a nonequilibrium fermion system approaches thermal equilibrium.

3. In order to facilitate comparison with other classical theories and to help guide our intuition, we have shown that the TDHF approximation is approximately equivalent to a purely classical pseudoparticle simulation.³ In this simulation, a collection of pseudoparticles is introduced to discretize the Wigner space, and the dynamics is completely determined by following the classical trajectories of the pseudoparticles in their mean field.

4. As an application of the pseudoparticle simulation, we studied the origin of the nonfusion events in nearly head-on heavy-ion collisions as obtained in the TDHF approximation. We argue that the emergence of the most energetic pseudonucleons of one nucleus outside the far surface of the other nucleus initiates a coherent flow-through motion leading to the breakup of the composite system. Based on this picture, we obtain estimates of the threshold energies and the low- l fusion window which agree well with the TDHF results.

5. We have studied the collective vibrational energies of various types and multiplicities in the hydrodynamical model in order to confront the hydrodynamical model with experiment.⁴ We have investigated the dispersion of sound waves due to the range of the interaction. In particular, the plasma oscillation arising from the long-range Coulomb interaction is found to lead to a simple modification of the energies of the isoscalar and isovector collective vibrational states. When applied to the nuclear giant dipole and monopole resonances, the inclusion of plasma oscillation gives an improved agreement between the hydrodynamical and experimental giant dipole energies and modifies the extracted nuclear incompressibility by as much as 15%.

6. We have continued the development of a two-dimensional and a three-dimensional computer code to study the dynamics of nuclear collisions within the framework of the hydrodynamical model.⁵ So far, we have found that the transfer of longitudinal momentum into the transverse direction is a prominent feature of nuclear hydrodynamics, as distinctly different from the results of the TDHF approximation. This leads to a suggestion of using the formation and the subsequent breakup of the toroidal shape in a heavy-ion reaction as a crucial test of the TDHF dynamics vs nuclear hydrodynamics.⁶ We have done calculations for low energies, as well as for high energies. We follow the formation of shock waves and the subsequent phase of expansion. We observe that central collisions at energies greater than 100 MeV per projectile nucleon in the laboratory system will lead to a nearly complete disintegration of the system, but at an energy only many tens of MeV per

projectile nucleon, these collisions can result in the projectile punching a hole through a bigger nucleus. This mode of reaction mechanism may have interesting experimental consequences.

7. In order to understand the behavior of collisions of intermediate-energy heavy ions on various targets, we analyze the longitudinal and transverse momentum distributions of fragments from the collisions of 90-MeV/ ^{16}O ions on various target nuclei.⁷ Excellent qualitative agreement with data is reached by considering the Fermi motion of the nucleons and the orbital dispersion of the projectile prior to breakup.

1. Student Guest from Yale University.
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3. C. Y. Wong, "Dynamics of Nuclear Fluid VI: The TDHF Approximation from Classical Viewpoint" (to be published).
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MORE SIMPLE-SIMON RESULTS FOR FAST $^{20}\text{Ne} + ^{238}\text{U}$ COLLISIONS

E. C. Halbert

SIMON, a simple three-dimensional classical cascade approach appropriate for considering heavy-ion collisions at a few hundred MeV per nucleon, is being applied to $^{20}\text{Ne} + ^{238}\text{U}$ for impact parameters 0 and 5 fm. The calculated results include densities $\rho(r, t)$ of nucleon matter during the collision and energy-angle distributions $d^2n_p/dE d \cos \theta$ of proton matter emerging from the collision. Both kinds of results are displayed as ensemble averages, where an ensemble consists of many $^{20}\text{Ne} + ^{238}\text{U}$ collisions all identical in their nucleus-nucleus impact parameter but randomly different in some details of the internal degrees of freedom. All of the present calculations use idealized nucleon-nucleon interactions, implying cross sections σ_{NN} that are purely elastic, isotropic, and independent of the initial NN state. Some of these calculations also introduce excluded-volume effects such as those associated with a classical hard core in the NN interaction. The results indicate that $\rho(r, t)$ is noticeably sensitive to changes in the size of the excluded volume (we tried minimum separation of nucleons = 0, 0.5, 0.9 fm), while $d^2n_p/dE d \cos \theta$ is noticeably sensitive to changes

in the NN cross section ($\sigma_{NN} = 15.4, 25.4,$ and 53.1 mb). Figures 4.4 and 4.5 show some of these sensitivities. For the combination $\{0.9 \text{ fm}, 25.4 \text{ mb}\}$ our cascade calculation reduces to a case in which each nucleon is modeled precisely as a classical billiard ball. For this case our cascade results are especially suitable for future comparisons with fluid-dynamic results — these latter to

Fig. 4.4. Examples of SIMON results for nuclear-matter density during a collision with incident impact parameter $b_{NeU} = 5 \text{ fm}$. In the compression ratio ρ/ρ_0 , the denominator ρ_0 is the uniform density assumed in the precollision nuclei. All results in this figure come from calculations assuming $\sigma_{NN} = 25.4 \text{ mb}$, and all show ρ/ρ_0 at a time such that, if there were no interaction, the neon projectile would be $z = 3 \text{ fm}$ past the center of the uranium target. Part a shows ρ/ρ_0 in a central slice around the collision plane, as obtained from a nucleon-nucleon interaction RC involving a hard-core radius of 0.5 fm . Part b shows ρ/ρ_0 only near the collision axis but compares results obtained from two different nucleon-nucleon interactions, 4π and BB, involving hard-core radii 0 and 0.9 fm respectively.

Fig. 4.5. Sensitivity of σ_{NN} of some SIMON-calculated proton-matter yields after a head-on Ne + U collision. The results shown come from calculations with a nucleon-nucleon interaction RC involving a hard-core radius of 0.5 fm . The vertical bars are estimated standard deviations, associated with statistical errors in the finite-ensemble averages.

be computed using the known equation of state of a hard-sphere gas. Such a comparison could teach us something about the effects introduced by presupposing *instantaneous local equilibrium*, a condition assumed in fluid-dynamic approaches but not assumed in SIMON and other cascade approaches.

NUCLEAR DIRECT REACTIONS

G. R. Satchler W. G. Love¹ B. Castel²

The emphasis of the work on direct reactions has been to understand nuclear scattering from a "microscopic" point of view instead of using purely phenomenological models to analyze data. Underlying much of this has been the use of realistic nucleon-nucleon effective interactions based upon G matrices.

Nucleon Scattering

The calculation of the contributions from pickup and stripping to the imaginary (absorptive) part of the proton optical potential was completed.³ Although almost 90% of the observed reaction cross section can be reproduced, a more detailed study indicates that only about one-half of the empirical imaginary potential strength is accounted for. The remainder is probably

due to continuum excitations [such as (p,pn)], which are much harder to calculate.

The Oak Ridge data for giant resonance excitation by protons of about 65 MeV were reanalyzed, making use of a more modern isovector interaction obtained from (p,n) studies. This resulted⁴ in the estimates of the cross section for the giant dipole resonance being reduced considerably: the remaining cross section in this region of excitation energy is very well explained³ as due to the giant monopole resonance. The same model was used for the coupling of valence nucleons to the core in a study⁵ of the effective charges for $E0$ transitions between bound states due to virtual excitation of the giant monopole resonance.

This work made use of the collective, deformed optical-potential model. Currently, studies are being made with folded transition potentials using realistic nucleon-nucleon interactions. In this way it is hoped we can correlate the results from using different projectiles (electrons, protons, alphas,...) in a more consistent manner.

Heavy-Ion Scattering

A survey of heavy-ion elastic scattering for over 30 systems at a variety of energies has been completed⁶ (see Fig. 4.6, for example). This made use of the double-folding model for the real part of the potential with realistic interactions.⁷ The model predicts the correct potential to within about 20%, except for the anomalous case of ${}^6\text{Li}$ scattering, which requires⁸ the potential to be reduced in strength by a factor of about 0.6. Even the backward scattering of systems like ${}^{16}\text{O} + {}^{28}\text{Si}$ and ${}^{16}\text{O} + {}^{40}\text{Ca}$ can be reproduced qualitatively, as well as the large-angle scattering⁹ for ${}^{12}\text{C} + {}^{12}\text{C}$. (These cases are sensitive to the potential inside the strong absorption radii and are being studied in more detail to see what can be learned about any modifications to the folded potential that may be required.) For example (Fig. 4.7), the backscattering of ${}^6\text{Li}$ from ${}^{40}\text{Ca}$ is explained by the use of a simple renormalization factor $N = 0.6$ even though this scattering is sensitive to the potential at distances of less than 3 fm. A few representative inelastic transitions were also studied and are fitted⁶ without parameter adjustment.

The success of this folding model suggests that the couplings to all the other channels have little effect on the real potential, predominantly being responsible for the imaginary potential.¹⁰ This is being investigated further using the same formalism that was developed to include the effects of Coulomb excitation.¹¹ Current work also includes the development¹² of more sophisticated effective interactions such as have been used recently for nucleon scattering.¹³

1. University of Georgia, Athens.
2. Guest Assignee from Queen's University, Kingston, Ontario, Canada, summer 1978.
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Fig. 4.6. Example of the fits to elastic data using the double-folding model for the real potential [G. Bertsch et al., *Nucl. Phys. A*284, 399 (1977); Y. Eisen and B. Day, *Phys. Lett.* 63B, 253 (1976)]. The imaginary potential was adjusted to fit the data for 74 MeV and the same potential used at the other energies.

Fig. 4.7. Fits to the scattering of $^6\text{Li} + ^{40}\text{Ca}$ at 30 MeV with the real folded potential kept fixed ($N = 1.0$: dashed curve) and with it renormalized to optimize the fit to the data ($N = 0.6$: full curve).

RESONANCE AND INTERFERENCE PHENOMENA IN HEAVY-ION REACTIONS.

Christian Toepffer¹

Quadrupole Giant Resonances in the $^{12}\text{C}^{12}\text{C}$ System

C. Toepffer¹ R. H. Lemmer²

For some heavy-ion systems, notably for $^{12}\text{C}^{12}\text{C}$, one observes highly excited rotational bands of narrow resonances in reactions which proceed through the compound nucleus. The band head in ^{24}Mg lies around 20 ± 2 MeV excitation energy, that is, in the vicinity of and below the $^{12}\text{C}^{12}\text{C}$ Coulomb barrier, which region is important for astrophysical reasons. There are several indications that the isoscalar giant quadrupole resonance (GQR) serves as a doorway state for such resonances. It is known³ that the GQR exhausts about 65% of the energy-weighted sum rule between 15 and 24 MeV excitation energy in ^{24}Mg , and, as shown in Fig. 4.8, this has been very well reproduced in an RPA calculation of the GQR using the two-center shell model as a basis.⁴ (^{24}Mg corresponds to a distance of 3 fm between the centers.) The GQR wave functions in the $^{12}\text{C}^{12}\text{C}$

Fig. 4.8. The strengths S_α of isoscalar GQR states in ^{24}Mg obtained in an RPA calculation with a two-center basis as a function of excitation energy. The states are labeled by the projection quantum number K on the symmetry axis, and the continuous curves are the strength functions dS/dE obtained by smearing over the zero-point relative motion (R. H. Lemmer and C. Toepffer, *Nucl. Phys. A*, in print).

two-center system are currently used to calculate the width for the fission of ^{24}Mg and of the GQR. Preliminary results show a good agreement with the data obtained in the photofission and radiative capture experiments.⁵

Inversion of Nuclear Molecules⁶

C. Toepffer¹ B. J. Cole²

The symmetry of the nuclear Hamiltonian with respect to a permutation of the particles is spontaneously broken in the scattering of two unlike nuclei. There must therefore exist an inversion degree of freedom describing the mutual transformation of the unlike nuclei into each other. We study the collective $\lambda^\pi = 0^-$ inversion of the system as continuation of the relative motion toward negative distances, as in the NH_3 molecule. This is only possible if the moment of inertia is nonzero at the origin. The interference between the reflected waves and the transmitted waves describing the inverted system leads to an even-odd staggering for the low partial-wave S -matrix elements. If the absorption is not too strong, the inversion yields a backward rise in the angular distribution and interference oscillations.

tions in the backward excitation functions. A comparison with experiment is shown in Fig. 4.9.

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2. Witwatersrand University, Johannesburg, South Africa.
3. F. E. Bertrand et al., *Phys. Rev. Lett.* **40**, 635 (1978).
4. R. H. Lemmer and C. Toepfer, *Nucl. Phys. A*, in print.
5. R. H. Lemmer and C. Toepfer, to be published.
6. J. Barrette et al., *Phys. Rev. Lett.* **40**, 445 (1978).

Fig. 4.9. Elastic $^{16}\text{O}-^{28}\text{Si}$ excitation function. Data from J. Barrette et al., *Phys. Rev. Lett.* **40**, 445 (1978). Continuous curve: optical model with inversion. Dashed curve: conventional optical model with infinite centrifugal barrier. Dashed-dotted curve: conventional optical model with finite centrifugal barrier.

THEORETICAL INVESTIGATIONS OF COULOMB FISSION

V. Oberacker

Coulomb fission of actinide nuclei is formulated within a new semiquantal theory¹ which treats the continuum problem exactly. By means of a projection operator technique, we generate a new basis consisting of the resonance part of the collective wave functions

and an orthogonal resonance-free continuum. A formal treatment of damping and gamma-decay competition is also included in the theory but neglected later on. Within this formalism, we show that Coulomb fission is determined mainly by the excitation amplitudes of the resonance states; in the actual numerical calculations these are approximated by rotation-vibration-model wave functions. About 260 levels are taken into account simultaneously. For a variety of projectiles, the differential cross sections are studied as functions of bombarding energy (E) and impact parameter. We find a strong dependence on projectile charge number, $PCF(180^\circ) \approx (Z_p)^6$, in the region $50 \leq Z_p \leq 92$ for fixed ratio E/E_{Coul} . This strong Z dependence might be used to separate Coulomb fission from competing fission processes experimentally. Figure 4.10 shows the theoretical results for ^{54}Xe incident on ^{238}U . The solid lines have been calculated including destructive Coulomb-nuclear interference; the dotted lines correspond to a pure Coulomb coupling potential. In each

Fig. 4.10. Theoretical calculations for xenon-induced Coulomb fission of ^{238}U . The experimental data give an upper limit for Coulomb fission.

case, the results are given for two models of the moment of inertia as a function of deformation. The Coulomb barrier is defined by

$$E_{\text{Coul}} = Z_1 Z_2 e^2 / R_{\text{int}},$$

where $R_{\text{int}} = 1.16(A_1^{1/3} + A_2^{1/3} + 2)$ fm. Experimental fission data,^{2,3} which are included in Fig. 4.10, give an upper limit for Coulomb fission. Obviously, the cross sections measured at backward scattering angles are in reasonable agreement with the calculations at energies $E < 0.90E_{\text{Coul}}$. Above that energy we expect particle-transfer-induced fission to be more important than Coulomb fission.

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SHELL-MODEL STRUCTURE OF HIGH-SPIN STATES

J. B. McGrory

Shell-model calculations of the properties of high-spin states have been carried out in the $A = 56$ and $A = 208$ mass regions, and calculations on a pseudonucleus were performed to investigate a primary assumption of the now-familiar interacting boson model.¹

$A = 56$ Region

Heavy-ion-induced reactions have populated states with $J \leq 10$ in the even iron isotopes ^{56}Fe , ^{58}Fe , and ^{60}Fe .² There is evidence from these experiments of the existence of rotational bands in these nuclei, and there are suggestions of an abrupt shape change in the ground-state band between ^{56}Fe and ^{58}Fe . Shell-model calculations of these iron isotopes have been made. The model space restricts the protons to the $f_{7/2}$ shell and neutrons to the $p_{3/2}$, $p_{1/2}$, and $f_{5/2}$ shells. The calculated energy levels are in good agreement with experiment. Calculated $B(E2)$ values are in qualitative agreement with measurements. If one then assumes that an adiabatic rigid rotor model underlies the shell model for these nuclei, it is observed that there is no shape change between ^{56}Fe and ^{58}Fe and that all nuclei start out prolate and "anti-stretch" as J increases; that is, the intrinsic quadrupole moment decreases in the prolate band as J increases. In ^{60}Fe , there is a definite shape change in the yrast levels. As J increases up to $J = 6$, the

states are prolate; for $J = 8, 10$, and 12 , the states are oblate, with increasingly large intrinsic quadrupole moments.

$A = 208$ Region

As a first step in a study of the spectroscopy of high-spin states around the ^{208}Pb core, preliminary shell-model calculations have been made of the yrast levels in ^{212}Rn and ^{204}Pb . The shell model treats ^{208}Pb as an inert core and includes the lowest six proton particle states for ^{212}Rn and the lowest six neutron holes for ^{204}Pb . For the yrast levels for $J = 8$ to 20 , there are strong deviations from the $J(J+1)$ spacing of the rigid rotor. The sharp discontinuities can be accounted for by shell-structure effects. Yrast traps are predicted at $J = 18$ and $J = 20$ in ^{212}Rn .

A Test of the Interacting Boson Model

A shell-model calculation³ has been made of a pseudonucleus in which six protons in the pseudo s - d shell are coupled to four neutrons in the pseudo f - p shell through a surface delta residual effective interaction. The calculations show three distinct rotational bands. No restriction is imposed on the coupling of any two identical particles, but the calculated wave functions are dominated by states generated from states of two identical particles coupled to $J = 0$ and $J = 2$. This is consistent with the assumption of the interacting boson model of Iachello and Arima³ that only $J = 0$ and $J = 2$ bosons are needed to describe collective phenomena.

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CLASSICAL AND QUANTUM MECHANICAL CALCULATIONS OF ELECTRON TRANSFER AND IONIZATION

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A. L. Ford¹

J. F. Reading¹

Statistical calculations of ion-atom collisions involving three-body classical trajectories have had considerable success in accounting for high-energy data for singly and multiply stripped ions colliding with atomic hydrogen. We have developed a four-body code to calculate collisions of two hydrogen-like ions. Results³ for $\text{H} + \text{H}$, for which experimental data for stripping are available,⁴ are shown in Fig. 4.11. Calculations are in progress for He^+ and Li^{2+} on H .

Fig. 4.11. Projectile electron loss σ_e and double ionization σ_{D1} cross sections in $H(1s) + H(1s)$ collisions. The open circles (σ_e) and open triangles (σ_{D1}) represent our classical trajectory Monte Carlo calculations, with statistical standard deviations as indicated. Solid lines are drawn through the points to guide the eye. For electron loss, experimental data are represented by solid circles [G. W. McClure, *Phys. Rev.* 166, 22 (1968)] and solid triangles [A. B. Wittkower, G. Levy, and H. B. Gilbody, *Proc. Phys. Soc., London* 91, 306 (1967)]. The dotted curve is a Born approximation calculation for double ionization [D. R. Bates and G. W. Griffing, *Proc. Phys. Soc., London* A68, 90 (1955)].

An extensive set of codes for single-center coupled-channels calculations of inner-shell vacancy production, developed and used at Texas A&M University over the past several years,⁵ is being extended and refined there and at ORNL. The program was originally designed for direct ionization of a heavy target by a light projectile, but charge transfer to a hydrogenic ground state has been included recently. The full Hartree-Fock potential and the Hartree-Fock orbitals of the target are employed. Resonant virtual excitation of the continuum of the target (the dominant second-order process) is included. A recent calculation⁶ agrees well with K -shell electron capture and vacancy-production data for protons of 2.5 to 9 MeV on argon (see Fig. 4.12). Preliminary calculations⁷ for $O^{q+} + H$ with $q = 3$ and 6 give good agreement with ORNL electron-capture data⁸ on absolute cross sections and variation with ionic charge.

1. Dept. of Physics, Texas A&M University, College Station, Tex.

2. Dept. of Physics, University of Kentucky, Lexington, Ky.

3. A. D. MacKellar and R. L. Becker, paper at the 2nd Topical Conference on Atomic Processes in High Temperature Plasmas, Boulder, Colo., January 1979.

4. See *Atomic Data for Controlled Fusion Research*, ed. by C. F. Barnett et al. (ORNL-5206), vol. I, p. A.5.28.

5. J. F. Reading, A. L. Ford, G. L. Swafford, and A. Fitchard, *Phys. Rev. A*, in press.

6. A. L. Ford, J. F. Reading, and R. L. Becker, submitted to *J. Phys. B*.

7. R. L. Becker, J. F. Reading, and A. L. Ford (unpublished).

8. R. A. Phaneuf, F. W. Meyer, and R. H. McKnight, *Phys. Rev. A* 17, 534 (1978).

Fig. 4.12. Our calculated cross sections for $p + Ar$ are compared with the experimental ones of J. R. Macdonald, C. L. Cocke, and W. W. Eidson, *Phys. Rev. Lett.* 32, 648 (1974) and to the calculation of C. D. Lin, S. C. Soong, and L. N. Tunnell, *Phys. Rev. A* 17, 1646 (1978). The cross section σ_{vK} is for K -shell vacancy production, σ_{CT} is the total charge transfer cross section, and σ_{CK} is the cross section for charge transfer from the K shell.

ATOMIC AND MOLECULAR THEORY

C. Bottcher¹ K. Kulander²
C. Feuilleade¹ S. Berry³

1. A transition-state approach (see Fig. 4.13) has been developed for charge capture from hydrogen atoms by heavy ions which relates the capture cross section to the amplitude for free-electron-ion scattering. Besides explaining the general variation of cross

Fig. 4.13. Potential surface for electron in the field of two charges (+e, +9e) showing the saddle point (transition-state region) between the charges but nearer the lesser charge.

sections with charge state and energy, this theory predicts two types of oscillatory structure. (i) For ions of atomic number 70–80 and charge states 4–8, a structure has been observed and explained as an f -wave resonance in the electron-ion amplitude.⁴ (ii) As a function of atomic number, the cross sections are predicted to oscillate, with extrema in agreement with experiment for ions up to molybdenum. In heavier systems, charge transfer is reduced by the excitation in the projectile of autoionizing states; preliminary calculations are in accord with experiment.⁵

Charge capture from H_2 molecules has been considered in a semiempirical framework, and departures from the simple rule that H_2 is two independent atoms are explained. By fitting data, the final state in capture can be assigned.

2. A theory has been developed of the forward-ejected electrons from partially stripped projectiles incident on gas targets; the excitation of continuum and autoionizing states is described by unitarized first and second Born approximations, and Hartree-Fock orbitals are used for bound and continuum states. It is predicted that the prominent Rydberg series seen in the ejected-electron spectrum of O^{6+} must be $1s^2 2pnp \ ^1S$ ($n \geq 6$), and this assignment has been positively confirmed by spectroscopic data. Such states are important in many processes, for example, dielectronic recombination, which is not readily accessible to experiment. We are now investigating forward-ejected-electron spectroscopy (FEES) as a detailed probe of collision mechanisms such as charge capture and electron-ion scattering.

3. Work has been initiated on the dissociative recombination of H_3^+ and other large molecular ions.⁶ For appreciable rates, H_3^+ must be vibrationally excited, and the only significant products are $H(n=2) + H_2(X)$, the latter being highly vibrationally excited. Calculations have been completed on dissociative attachment to metastable $H_2(c \ ^3\Pi_u)$; the cross sections explain the production of H^- in low-density discharges, while a negligible isotope effect is predicted, in harmony with recent experiments.

4. Methods have been developed for economically solving very large systems of coupled equations and applied to ion-polar-molecule collisions below a few electron volts. The rates of ion-polar-molecule reactions have long been in disagreement with the accepted Langevin theory. Our calculations suggest an alternative mechanism in which a complex is formed by converting translational to rotational energy; the observed temperature dependence of the rates is predicted, while the Langevin theory is recovered at very high temperatures.

5. A very general system of Bloch equations has been developed to describe the radiative pumping, with collisional relaxation, of a transition between two highly excited states, for example, the $J=40, 41$ levels of H_2O or the $40d, 41f$ levels of Na. This development opens up the application of maser theory to realistic systems, as opposed to few-level atoms. The first applications we have made are to predict line profiles and transient signals. Studies are progressing on modeling of far-infrared and x-ray lasers, diagnostics of highly excited atoms in plasmas, and multiphoton dissociation.

1. Guest Assignee from Manchester University, Manchester, England, summer 1978.

2. Guest Assignee from Daresbury Laboratory, Daresbury, Warrington, England, summer 1978.

3. Great Lakes Colleges Association/Associated Colleges of the Midwest participant from Albion College, Albion, Mich.
4. H. J. Kim, P. Hveplund, F. W. Meyer, R. A. Phaneuf, P. H. Stelson, and C. Bottcher, *Phys. Rev. Lett.* **40**, 1635 (1978).
5. C. Bottcher, submitted to *Phys. Rev. A*.
6. C. Bottcher, *J. Phys. B* **11**, 3887 (1978).

TWO-CENTER BATES-BORN THEORY OF ION-ATOM COLLISIONS

B. R. Junker¹

A modification of the Born approximation which properly takes into account the nonorthogonality of atomic orbitals centered, respectively, on projectile and target nuclei was given by Bates in 1958. However, the few calculations performed so far have been rather approximate and have been restricted by the availability of only a few two-center matrix elements containing plane-wave translational factors. Similar matrix elements arise in the Bethe theory of the scattering of a structureless charged particle (e.g., an electron) by a diatomic molecule and in the theory of x-ray scattering by molecules. A general expression has been derived² for the evaluation of these integrals for Slater-type orbitals. The expression contains only small sums and a single numerical integral over an integrand which contains a spherical Bessel function. Symmetries of these matrix elements are used to reduce the general Bates-Born charge-transfer cross section to a time integral from zero to infinity. *K*-shell charge-transfer cross sections have been computed³ in the Bates-Born formalism and in various approximations to it for H^+ , Li^{3+} , and B^{5+} projectiles and He, C, and Ne targets. The cross section is sensitive to the various approximations, particularly at the lower collision energies and for the cases nearer to resonance.

1. Oak Ridge Associated Universities Research Participant from the University of Georgia during the summer of 1976, and visitor from the Office of Naval Research during the summer of 1978.

2. B. R. Junker, "Fourier Transform of Two Center Charge Distribution," submitted to *J. Phys. B*.

3. B. R. Junker, "Charge Transfer Cross Sections in the Bates-Born Formalism," *IEEE Trans. Nucl. Sci.* (to be published).

GENERAL EXPRESSIONS FOR DIVERGENCE RELATIONS AND MULTIPOLE EXPANSIONS FOR ARBITRARY SCALAR FUNCTIONS

R. L. Davies R. L. Becker

In theories of the cohesion of a system whose matter density is constant (e.g., classical liquid drops) or nearly

constant except in a thin surface region (e.g., nuclei or neutron stars), there occur computationally difficult single and double volume integrals of energy densities. Such integrals have been important in recent dynamical calculations of fission and heavy-ion reactions. Even if the matter density is diffuse, the integrals can be written as integrals over finite volumes by modeling the density as the convolution of a step function and a diffuseness function. If the integrands can be written as divergences of tensor fields, the integrals over finite volumes can be reduced to surface integrals by Gauss's theorem. We have found general expressions, which we call divergence relations, for a vector field whose divergence is a given scalar function and for a second-rank tensor field whose double divergence is the scalar. The equations derived are much easier to use and apply to a wider class of functions than formulas previously obtained in the literature. The generalization to *n*th order for application to many-body forces is included, and for all orders the dimensionality is arbitrary.

QUENCHING OF GAMOW-TELLER BETA TRANSITIONS IN MIRROR NUCLEI

S. Raman T. A. Walkiewicz²
C. A. Houser¹ I. S. Towner³

In 1975, we published a "horizontal compilation"⁴ of superallowed and isospin-forbidden Fermi transitions.⁵ This work has now been extended to include mixed Fermi and Gamow-Teller beta transitions.⁶ The product of the axial vector coupling constant and the Gamow-Teller matrix element, $G_A \langle \sigma_3 \tau_3 \rangle$, can be extracted from experimental data on superallowed $J^\pi \rightarrow J^\pi$ (but $J \neq 0$) beta transitions. Likewise, the matrix element $\langle \sigma_3 \rangle$ can be extracted from the knowledge of the magnetic moment for the same beta-decaying nuclei and their isobaric mirrors. By further assuming that the shell-model prediction for the small matrix element difference $\langle \sigma_3 (1 \pm \tau_3) \rangle$ may be relied upon, the coupling constant effective in the nuclear medium was deduced and found to be typically of order 20% smaller than the free-nucleon value derived from neutron decay. This result is in rough accord with estimates of the quenching of G_A arising from the inadequacies of shell-model wave functions (the core-polarization correction) and from the presence of meson-exchange currents in complex nuclei.⁷

1. Senior student from the Pennsylvania State University, University Park, Pa.

2. Edinboro State College, Edinboro, Pa.

3. AECL, Chalk River Nuclear Laboratories, Chalk River, Ontario.

4. This term was coined by P. H. Stelson to denote a compilation of a specific property for all pertinent nuclei, in contradistinction to "vertical compilation," which denotes a compilation of all pertinent properties for a specific nucleus.

5. S. Raman, T. A. Walkiewicz, and H. Behrens, *At. Data Nucl. Data Tables* 16, 451 (1975).

6. S. Raman, C. A. Houser, T. A. Walkiewicz, and I. S. Towner, *At. Data Nucl. Data Tables* 21, 567 (1978).

7. E. Oset and M. Rho, *Phys. Rev. Lett.* 42, 47 (1979); I. S. Towner and F. C. Khanna, *Phys. Rev. Lett.* 42, 51 (1979); A. Barroso and R. J. Blin-Stoyle, *Nucl. Phys. A* 251, 446 (1975); F. C. Khanna, I. S. Towner, and H. C. Lee, *Nucl. Phys. A* 305, 349 (1978).

5. Nuclear Data Project

R. L. Auble ¹	W. B. Ewbank	M. R. McGinnis ²
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INTRODUCTION

The Nuclear Data Project (NDP) is a comprehensive information analysis center which provides the basic research community with indexed references and collections of critically evaluated nuclear structure data. The systematic publication in *Nuclear Data Sheets* of new evaluations provides nuclear structure physics with an information service far in advance of what is available to most areas of science. The computer files of evaluated data developed by the NDP also present the basic research scientist with a valuable tool for looking at extensive nuclear-level information in order to make comparison with new measurements or new theoretical calculations.

These computer files of nuclear data also are being used as a means of making the results of basic research quickly and easily available to a broader audience. Radioactivity information, in particular, has wide application in fields such as nuclear medicine, reactor engineering, environmental impact assessment, and nuclear waste management. Often the specialists in these areas have neither the time nor the training to make effective use of the data generated by basic nuclear research. The NDP has made important progress during the last few years toward providing a channel through which the results of new nuclear measurements can be transferred to any engineer or scientist who needs evaluated data to factor into his or her own work.

The Evaluated Nuclear Structure Data File (ENSDF) developed and implemented by the NDP contains a documented summary of the current status of nuclear measurements. The supporting systems for the ENSDF make it possible to assemble various collections of data and to present them in a form convenient for further study or application. Nuclear Data Project's MEDLIST program, which provides tables of both atomic and nuclear radiations, has been applied to over 1000 decay schemes in the ENSDF. Earlier collections of MEDLIST-type output^{3,4} have been widely used in both basic and applied research. *Citation Index* notes that nearly a third of the citations to the "Radioactive Atoms" publications³ are from periodicals such as *Journal of Radiation Chemistry*, *Health Physics*, *Journal of Geophysical Research*, and *Journal of Nuclear Medicine*.

Special collections of computer-readable radioactivity data have been assembled from the ENSDF by MEDLIST for use by ORNL programs concerned with nuclear waste management⁵ and Monte Carlo studies of accelerator-target cooling problems.⁶

The NAS-NRC study⁷ by the Committee on Data Needs for Science and Technology places the principal responsibility for utilization of scientific data on the specialists who create and understand those data. By making the results of nuclear structure measurements easily available to specialist and nonspecialist alike, the NDP is helping nuclear science to maintain its high quality and quantity of accessible information.

ACTIVITIES

OFNL-DWG 79-8771

Data Evaluation

As part of the international network for nuclear structure data evaluation, the NDP has continuing responsibility for approximately 100 mass chains in three regions: $A = 45$ to 69, 101 to 118, and 195 up. Since each evaluator can prepare about four new evaluations per year, a commitment of approximately six person-years per year is needed to maintain the ENSDF and *Nuclear Data Sheets* up-to-date with the planned four-year cycle.

Since the new evaluation groups would necessarily begin slowly, an additional commitment was made by the ORNL Physics Division to provide a staff level of eight person-years during 1977-1978. A total of 50 new mass-chain evaluations was prepared and published during these two years, and six more from temporary or former NDP evaluators are nearly complete as of the beginning of 1979. Figure 5.1 gives the publication status of the mass chains for which the NDP is responsible. (Ten older mass chains from other regions were also revised recently by NDP staff.) For comparison, the status of all published mass chains is shown in Fig. 5.2.

In addition to its evaluation responsibility, the NDP is committed to maintaining uniform, high standards for the ENSDF (and consequently for *Nuclear Data Sheets*) by providing training for new evaluators, followed by a thorough review of the first few mass chains prepared by each new evaluator. NDP staff members have organized training seminars for 28 new data evaluators in order to introduce them to NDP evaluation techniques, analysis programs, and conventions used in the ENSDF and *Nuclear Data Sheets*.

During 1977-1978, NDP staff have reviewed 14 mass chains prepared by new evaluators from six other data evaluation centers. About half of these have already been published in *Nuclear Data Sheets* or accepted for publication. Others are undergoing final revisions before acceptance.

Summary by Year of Publication

Date: 12-31-78

Fig. 5.1. Status of mass-chain evaluations in NDP's regions of responsibility.

Nuclear Structure References

Nuclear Data Project's Nuclear Structure References (NSR) file continues to grow, with the addition of approximately 5000 indexed new research works each year. About half of the additions are journal publications; the other half consists of reports, conference abstracts, preprints, etc. The keyword indexing system used in the NSR file since 1964 has been shown⁸ to allow more complete retrievals from the nuclear structure literature than the much larger INIS system (extended from the former *Nuclear Science Abstracts*).

Summary by Year of Publication

Date: 12-31-78

Fig. 5.2. Status of all mass-chain evaluations, $A > 5$.

The NSR file is used routinely to direct interested users to the nuclear structure literature. Special reference collections are assembled in partial response to most of the 100 information requests processed each year. A shorter version of the NSR file (1969 to present) is available for interactive search through the remote terminals of the DOE/RECON network. This file is queried an average of two times every working day.

Each month an SDI (selective dissemination of information) service is provided from new entries to the NSR file. The service is used by data evaluators from the international network and by other extensive users of new nuclear structure data.

An index to the new literature is published three times per year as "Recent References" issues of

Nuclear Data Sheets. "Recent References" includes both isotope and reaction indexes for both journal and nonjournal literature. A second indexed cumulation of journal literature was published in 1978.⁹

The NSR file is used as an international standard for the systematic computer storage and exchange of indexed reference information. Two copies of the complete indexed file have been distributed to international data evaluation centers. The regular distribution of computer-readable copies of the new literature summarized in "Recent References" will begin in 1979.

Evaluated Nuclear Structure Data File

Nuclear Data Project's ENSDF has grown considerably since our last report. The file now contains 6600

distinct sets of evaluated nuclear information. This includes:

- 1950 sets of adopted level properties
- 1850 decay schemes
- 3020 nuclear reaction data collections, including
 - 230 (n,γ) reactions
 - 225 (d,p) reactions
 - 500 (charged-particle, $xn\gamma$) reactions

A set of adopted levels and their properties is now included for every nucleus. Several complete collections of level properties have been assembled from the ENSDF, for example, all levels with lifetimes between 1 psec and 1 fsec and odd-parity states in even nuclei. A collection of levels with spontaneous-fission branching has recently been published.¹⁰

All decay scheme information in the ENSDF is now as complete as the measurements warrant. Normalization information is included wherever available, and details of electron capture and internal conversion have been added systematically, so that complete tables of atomic and nuclear radiations can be assembled for more than 1000 decay schemes. This information is being prepared for distribution in microfiche form.

The ENSDF computer format has been adopted as an international standard for the systematic storage and exchange of nuclear structure data. At six-month intervals, beginning in 1977, the NDP has prepared complete copies of the ENSDF on magnetic tape for distribution through international data centers.

Publications

The NDP is the editorial and publications office for the journal *Nuclear Data Sheets*. The NDP prepares camera-ready copy which is sent to Academic Press for publication and distribution. Implementation of the ENSDF system, with computer programs to select information from the data file, organize it into tables or drawings, and assemble the tables or drawings onto pages, has revolutionized the preparation of copy for *Nuclear Data Sheets*. The principal advantage of the computer system is the elimination of much redundant data copying and most proofreading. Although the same data item may appear in several places in the data sheets and drawings, it is contained only once in the ENSDF and must therefore be correctly entered only one time. Tables or drawings are also prepared in a precisely reproducible way. The computer programs have helped to establish and maintain greater uniformity among manuscripts from different evaluators,

so that the user needs to adjust to fewer style variations.

Each year the NDP prepares approximately 2100 pages of camera-ready copy for publication in three volumes of *Nuclear Data Sheets*. Since each page goes through several scientific and editorial reviews, the preparation of this much material (including revisions and corrections) would be enormously time-consuming without the ENSDF system. Each manuscript goes through at least three draft stages. In each draft, corrected numbers or revised text appears as requested in all appropriate places; drawings or tables may be added, reordered, or deleted; data columns in each table may be interchanged; and selected data items may be omitted. The special NDP font train, which includes 164 different characters (Greek letters and special symbols, as well as standard characters), allows publication-quality copy to be prepared by a standard line printer at over 500 lines/min. Final editing and arrangement of material on the publication copy are completed by hand.

Manuscripts are now being received from several data evaluation centers other than the NDP. Twenty percent of the new evaluations published during 1978 were prepared by non-NDP evaluators. The distribution of mass-chain responsibility requires that this fraction increase to more than 50%. Maintaining tolerant limits on the style variations used by many different evaluators has added to the editorial work for *Nuclear Data Sheets*. The ENSDF system has avoided a much more substantial problem in the production of manuscripts.

Information Requests

The NDP receives about two requests for information each week. Most are easily answered by a combination of ENSDF listings and references to new literature on some special topic. Occasionally, more challenging requests are received which require some new effort. The ENSDF system includes several program steps, which can be modified to define very sophisticated conditions that must be met before any data are retrieved from the data file or displayed in a table. It is a simple task to revise one of these programs to prepare requested tables such as:

- $E0$ γ transitions in heavy nuclei,
- γ rays with high multipolarity ($E4$, $M4$, and higher),
- β^+ radiations tagged with parent, half-life, and intensity,
- β^- transitions with $\log ft \leq 5$.

New Directions

When the ENSDF was extended in early 1978 to include adopted level properties for every nucleus, it became possible to prepare many new and enlightening displays of nuclear-level systematics. Several such displays have been shown at meetings of the American Physical Society. Three examples are shown here (Figs. 5.3–5.6) to demonstrate the power of the ENSDF system as a teaching tool and as a technique for exploring systematic properties of nuclear levels.

Figure 5.3 shows the N and Z dependence of the energies of the first 2^+ states in even nuclei. The surface clearly shows the low energy associated with the two deformed regions, and the projections illustrate the effects of shell closures. In Fig. 5.4 the surface has been rotated to show the onset of deformation in the region of $Z > 50$, $50 < N < 82$. A similar effect can also be observed for $Z < 50$.

Figure 5.5 shows the energy ratio of the first 4^+ and first 2^+ states, compared with the value 2.24 predicted for "soft" nuclei by Mariscotti et al.¹¹ The plateaus of strong deformation [$E(4^+)/E(2^+) \approx 3.33$] are evident.

Figure 5.6 illustrates the behavior of the energy ratio for the second and first 2^+ states in even nuclei. The reasonably constant value of this ratio is interrupted only in the two regions of strong nuclear deformation. The "saddle" in the lanthanide peak indicates a minor shell closure near $Z = 66$. A closed shell in this region has been suggested previously from systematics of reduced widths for α decay,¹² although the evidence is less compelling because of the difficulty in obtaining sufficiently precise data.

NATIONAL-INTERNATIONAL EVALUATION NETWORKS

Beginning in 1975 a program was initiated by ERDA (now DOE) to increase non-U.S. participation in nuclear structure data evaluation. The National Nuclear Data Center (NNDC) at Brookhaven was designated to coordinate the U.S. program and to interface this program with non-U.S. efforts. The NDP continues to provide indexed references, computer data files, and mass-chain publication, as well as the

principal scientific direction and most of the new evaluations.

In November 1977 the NDP hosted a meeting of the IAEA/NSDD working group.¹⁴ At the Oak Ridge meeting the distribution of mass-chain responsibility was ratified, with the NDP receiving continued responsibility for approximately 100 mass chains. Continuing programs (University of Pennsylvania, University of Utrecht) for evaluation of data on light nuclei were recognized, responsibility for 59 mass chains was assigned to three other U.S. centers, and 60 mass chains were assigned to non-U.S. centers. Procedures were also established for monitoring progress toward a four-year cycle for revision of all mass chains.

The formats developed by the NDP for its reference file (NSR) and evaluated data file (ENSDF) have been adopted by the international network as standards for exchange of bibliographic and numeric information in computer-readable form. The NDP continues its responsibility to maintain and regularly distribute copies of both computer files.

The NDP is also expected to carry out a detailed review of the first few mass chains prepared by each new center and to provide for a review of every revised mass chain. Acceptable new evaluations are prepared by the NDP for publication in *Nuclear Data Sheets*.

In 1977, all 33 mass chains published in *Nuclear Data Sheets* were prepared with active involvement of NDP staff. Of the 24 mass chains published in 1978, three were prepared at another U.S. center.

Besides the NDP, the U.S. Nuclear Data Network includes data evaluation groups at Brookhaven (NNDC), Idaho (INEL), Berkeley (Table of Isotopes), Pennsylvania (Light Nuclei), and NBS (Photonuclear Data Center). The Nuclear Data Network, which meets once or twice each year, provides a forum for reviewing progress, discussing problems, and establishing future priorities. The network also contributes to development of standards and procedures that will be recommended for the international network.

The international network for nuclear structure data evaluation has been established through the International Atomic Energy Agency's Working Group on Nuclear Structure and Decay Data (IAEA/NSDD). The

Fig. 5.3. Energies of first 2^+ states in even nuclei (from ENSDF).

Fig. 5.4. Same as Fig. 5.3 but from a different perspective.

ORNL-DWG 78-14650

Fig. 5.5. Energy ratio $R = E(4^+)/E(2^+)$ for even nuclei, compared with $R = 2.24$ for "soft" nuclei and showing the rotational plateaus with $R = 3.33$.

ORNL-DWG 78-11852

Fig. 5.6. Energy ratio $E(2^+_{1/2})/E(2^+_{1/2})$ for even nuclei shows effects of a minor shell closure near $Z = 66$.

preliminary form of the international network was established at Vienna in 1976.¹³ (BNL/NNDC), and two were prepared at non-U.S. centers.

1. Part-time assignment to Nuclear Data Project.
2. Technical support staff.
3. M. J. Martin, *Nucl. Data Tables A8*, 1 (1970); M. J. Martin, *Radioactive Atoms - Supplement I*, ORNL-4923 (November 1973); M. J. Martin, *Nuclear Decay Data for Selected Radionuclides*, ORNL-5114 (March 1976).
4. D. C. Kocher, *Nuclear Decay Data for Radionuclides Occurring in Routine Releases from Nuclear Fuel Cycle Facilities*, ORNL/NUREG/TM-102 (August 1977).
5. A. G. Croff, R. L. Haese, and N. B. Gove, *Updated Decay and Photon Libraries for the ORIGEN Code*, ORNL/TM-6055 (February 1979).
6. R. G. Alsmüller, Jr., T. A. Gabriel, and J. Barish, *Photon Dose Rate from Induced Activity in the Beam Stop of a 400-GeV Proton Accelerator*, ORNL/TM-6238 (February 1978).
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8. H. Behrens and J. W. Tepel, *Comparison of the International Nuclear Information System (INIS) and Recent References (RR) (Mass Chains A = 27 and A = 86)*, ZAED-M-13, Zentralstelle für Atomkernenergie-Dokumentation, Karlsruhe, West Germany (October 1977).
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13. IAEA Advisory Group Meeting on Nuclear Structure and Decay Data for Applications, Summary Report, INDC(NDS)-79/LN, IAEA, Vienna, Austria (December 1976).
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6. Accelerator-Based Atomic Physics

INTRODUCTION

P. D. Miller C. D. Moak

The present fiscal year (FY 79) is a transition year in the operation of the ORNL EN tandem. Prior to this year the experimental mix has been about 50% nuclear and 50% nonnuclear physics. During the present fiscal year the mix will be 80% nonnuclear, 20% nuclear, and in the future it will be almost entirely high-energy atomic physics. Tables 6.1 and 6.2 have been prepared to illustrate the scope of nonnuclear research, and to delineate how much of the program is under the leadership of researchers within the ORNL Physics Division and how much is led by researchers outside the Physics Division.

The last year has been perhaps the most productive ever for atomic physics on the EN tandem. Space limitations preclude highlighting every activity, but a sampler of recent accomplishments will be given in the sections which follow.

New areas of research are planned for the future. An electron beam device is being assembled, which will enable us to merge a multiply charged heavy-ion beam with a concentric electron beam over a path length of 1 m followed by a charge-state detector. The maximum electron energy will be 10 keV with a maximum current of 1 A. The beam will be magnetically compressed with a solenoid, and the central 1/2 mm of diameter will be merged with the heavy-ion beam. Initial measurements of ionization cross sections will be followed by measurements of energy-differential dielectronic recombination cross sections.

The laser group, led by G. S. Hurst from the Health and Safety Research Division of ORNL, is planning to consolidate its high-power lasers in one of our target rooms. They plan on pulsing the tandem and using a small fraction of the tandem beam time for studying lifetimes of excited states in gases by resonance ionization. This project will equip us with the means for studying heavy-ion-beam laser interactions.

An obvious third new area of research involves the Holifield Heavy-Ion Research Facility. All of the instruments in use at the EN tandem will be available to users of the Holifield Heavy-Ion Facility. We anticipate working in the following areas initially:

1. Search for photons from resonant coherent excitation (RCE).
2. With a broader range of projectile Z and velocity, a systematic study of static and dynamic potentials within crystals will be undertaken using RCE.
3. Extension of electron cusp studies to higher, and perhaps asymptotic, energies and to higher projectile Z .
4. Both inner-shell ionization and spectroscopy of few electron ions will be pursued for heavier projectiles and targets, where relativistic effects are appreciable.

Table 6.1. EN tandem nonnuclear physics led by Physics Division personnel

Activity	1977-78 % of use	Personnel					
		Physics Division		Other ORNL divisions		Outside ORNL	
I. Atomic collisions in solids Resonant coherent excitation	8	Moak ^a Biggerstaff Miller ^a Gomez del Campo	Nuc. sci. Nuc. sci.	Datz ^a Dittner ^a Krause ^a Crawford ^a	Chem. Chem. Chem. Chem.	Knudsen ^b (1 yr) Hvelplund ^b (1 yr)	Univ. of Aarhus Univ. of Aarhus
II. Charge exchange cross sections with atomic and molecular hydrogen	6	Kim Phaneuf Meyer Stelson	DMFE DMFE DMFE Nuc. sci.			Hvelplund ^b (1 yr)	Univ. of Aarhus
III. Stripping and multiple electron loss cross sections	6	Alton ^b (0.25) Jones Moak ^a Miller ^a Sayer	 Nuc. sci. Nuc. sci.			Bridwell Kessel Antar Scott ^b (6 mo) Knudsen ^b (1 yr)	Murray State Univ. Univ. of Conn. Univ. of Conn. Cornell Univ. of Aarhus
IV. He ⁺ lifetime and resonance ionization	2	Alton ^b (0.25)		Compton	Health and Safety Research		
V. Radiative electron capture in channels, and stopping power in channels	2	Moak ^a Biggerstaff	Nuc. sci.	Appleton Noggle White	Solid St. Solid St. Solid St.	Clark	C.S.I.R.O. Sydney, Australia

^aIndicates total support by the Division of Chemical Sciences.^bIndicates partial support by the Division of Chemical Sciences.

Table 6.2. EN tandem nonnuclear physics with leadership outside the Physics Division

Activity	1977-78 % of use	Personnel			
		Physics Division	Other ORNL divisions		Outside ORNL
I. High velocity ion-atom and ion-solid collisions, and associated atomic structure studies Continuum electron capture and electron loss to the continuum	6	Griffin ^a Alton ^b (0.25) Sellin ^b (0.2) Thoe ^b (0.2)		Sellin Thoe Elston Vane Suter Schuman Laubert 3 graduate students Hayden	Univ. of Tennessee Univ. of Tennessee Univ. of Tennessee Univ. of Tennessee Univ. of Tennessee Frankfurt/Maine NYU Univ. of Tenn. Univ. of Conn.
II. Heavy-ion x-ray studies	6	Miller ^a Alton ^b (0.25) Thoe ^b (0.2)		Barbas Duggan McDaniel ^b (2 weeks) 11 graduate students Chaturvedi, Wheeler Kuenhold Zander Rayburn Cipolla Lapicki Thoe Peterson	NTSU NTSU NTSU NTSU SUNY-Cortland Univ. of Tula E. Texas State Univ. Univ. of Texas, Arlington Creighton Univ. NYU Univ. of Tennessee Univ. of Conn.
III. Depth distribution of ionic radiation damage	2		Noggle Appleton Williams Poker	Solid St. Solid St. Solid St. Solid St.	Iwata Japan Atomic Energy Research Institute, Tokai, Japan
IV. Beam foil spectroscopy in the vacuum ultraviolet lifetimes and wavelengths	4	Griffin ^a Pegg ^b (0.2) Thoe ^b (0.2)		Pegg, Thoe, Elston, Suter, Sellin, + 2 graduate students Hayden	Univ. of Tenn. Univ. of Conn.

^aIndicates total support by the Division of Chemical Sciences.^bIndicates partial support by the Division of Chemical Sciences.

RESONANT COHERENT EXCITATION OF CHANNELED IONS

C. D. Moak	J. Gomez del Campo
S. Datz ¹	J. A. Biggerstaff
O. H. Crawford ¹	P. D. Miller
H. F. Krause ¹	P. Hvelplund ²
P. F. Dittner ¹	H. Knudsen ²

The hydrogen-like ions B^{4+} , C^{5+} , N^{6+} , O^{7+} , and F^{8+} and the helium-like ions N^{5+} and F^{7+} have been shown to exhibit resonant coherent excitation from the atomic level $n = 1$ to $n = 2$, caused by the periodic potential oscillations which occur as the ion moves in axial and nearly axial planar channels in thin crystals of Au and Ag.^{3,4} Various harmonics of the lattice string periodicity are effective, at certain critical ion velocities, in reducing the number of one-electron ions which survive passage through the crystal without electron loss. Resonances, appearing as minima in the incident ion charge-state fraction vs velocity, have been found for several axial channels and for two planar channel directions at a number of different harmonics of the string frequencies. In some cases the resonances can be split by small crystal tilts which produce sidebands upon the string frequency. Certain harmonics have been shown to produce tilt-insensitive double minima which measure Stark splittings of the $n = 2$ levels.

Theoretical analyses of the crystal fields have shown that for the $\langle 100 \rangle$ axis in face-centered cubic crystals, odd or even harmonics of the string frequency give predominantly transverse or longitudinal disturbances to the ion. For the odd-harmonic case, Fig. 6.1, slight tilts of the crystal produce two side bands or beat frequencies whose separation depends upon the angle of tilt. For the even-harmonic case, splitting occurs for a different reason; here the $n = 2$ level of the ion is Stark-split by the braking field which is parallel to this longitudinal disturbance, and as shown in Fig. 6.2 the splitting is essentially insensitive to crystal tilt. These splittings correspond to Stark fields, which are in agreement with the fields expected from the stopping power of the ion in the crystal.

The positions of the resonances indicate that the energy level of the $n = 2$ state of the ion is different from the vacuum field-free value. These differences relate to the electron density distribution inside the crystal.

1. Chemistry Division.
2. University of Aarhus, Aarhus C, Denmark.
3. S. Datz et al., *Phys. Rev. Lett.* 40, 843-47 (1978).
4. C. D. Moak et al., *Phys. Rev.* 19, 977-93 (1979).

Fig. 6.1. Ratio of O^{7+} counts to the sum of O^{7+} and O^{8+} counts as a function of initial velocity, for $\langle 100 \rangle$ axial channeling in Au and for three tilt angles. The incident beam is O^{7+} .

Fig. 6.2. Ratio of N^{6+} counts to the sum of N^{6+} and N^{7+} counts as a function of initial velocity, for $\langle 100 \rangle$ axial channeling in Au and for three tilt angles. The incident beam is N^{6+} .

ATOMIC STRUCTURE AND COLLISION EXPERIMENTS

G. D. Alton	R. S. Thoe ¹
C. Bottcher	J. P. Forester ²
P. M. Griffin	R. Laubert ³
S. B. Elston ¹	M. Suter ¹
D. J. Pegg ¹	G. A. Glass ¹
I. A. Sellin ¹	C. R. Vane ¹
L. E. Williams ¹	

The University of Tennessee–Oak Ridge National Laboratory accelerator-based atomic physics research group is active in research on highly ionized particles and collision phenomena concerning these and other heavy projectiles. The research is being carried out at the Oak Ridge National Laboratory, the Brookhaven National Laboratory, the Gesellschaft für Schwerionenforschung in Germany, Atomfysik in Sweden, and occasional other sites. This group consists of three Physics Division staff members, four University of Tennessee faculty members, two postdoctoral research associates, two graduate students, and a number of occasional collaborators from other institutions whose participation is frequent. The primary objective of our research is the study of highly ionized heavy ions and their modes of formation and destruction in collisions with target atoms and molecules. Decay of excited states of these ions by radiative and also by electron emission processes is the phenomenon most often studied in carrying out these experiments. Our principal tools are: (1) suitable heavy-ion accelerators, (2) electron, x-ray, soft x-ray, extreme ultraviolet, and heavy-particle spectrometers, and (3) a variety of peripheral equipment associated with these devices.

The Forward Peak in Electron Production by Highly Ionized Projectiles

New work has been initiated concerning the forward peak of electrons accompanying fast, highly charged ions at nearly the same vector velocity subsequent to electron capture and loss to projectile-centered continuum states, in both ion-atom and ion-solid collisions. Sample cusps are displayed in Fig. 6.3. The pioneering experimental work in this area was undertaken by Crooks and Rudd⁴ for protons on He, and early theoretical work was done by Macek.⁵ The work in our laboratory is distinct from all previous work in this area by virtue of the use of faster, heavier, bare, and highly ionized projectile ions, permitting the study of

Fig. 6.3. Electron spectrum measured in the forward direction for 25-MeV O^{8+} on an argon gas target. Projectile autoionization lines are visible on both sides of the cusp. The shortest lines are of the following kind: $(1s^2 2pnl) \rightarrow (1s^2 2s) + e^- (k)$ (peaks a, b, c, d correspond to $n = 6, 7, 8, 9$).

wide projectile charge-state variations on properties of the forward peak.

All three of our initial exploratory experiments devoted to the forward peak arising from highly charged ion stripping and electron capture have led both to unanticipated discoveries and to significant differences with theoretical descriptions of the forward peak. Unexpected results from all three of these experiments have been published in *Physical Review Letters* during 1978.⁶⁻⁸ The first of the three experiments⁶ is in disagreement with two different classes of theories concerning the projectile Z dependence of electron capture to the continuum. The second concerns our discovery⁷ of interesting structure in the wings of the forward peak in the electron loss to continuum channel. The third concerns the failure of both electron capture to continuum and solid-state "wake-riding" models to describe our solid-target results.⁸

Figure 6.4 presents more recently acquired, higher resolution data concerning structure in the wings of the electron loss to continuum cusp. The lines seem to appear to correspond to very-low-energy Auger transitions (2 to 20 eV in the projectile rest frame) arising from intrinsically double-electron excitation to high Rydberg states. An account of these data will appear shortly in *Zeitschrift für Physik - Short Notes*.⁹

Fig. 6.4. Normalized spectra for electron capture and loss to continuum states in the forward direction for 2.5-MeV/amu O^{q+} and Si^{q+} on Ar. Zero-count baselines are shown for each spectrum. Statistical errors are about 2% at the peaks. The "difference" spectrum in the lower left-hand portion of the figure results from direct subtraction of the O^{5+} from the O^{4+} normalized data.

**Continuation of f -Value Determinations for
Electrostatic Fine-Structure ($\Delta n = 0$)
Transitions in the Li, Be, Na, and
Other Isoelectronic Sequences**

Our major continuing activity has been in the area of oscillator strength determinations for intrashell ($\Delta n = 0$) transitions in a large number of multiply ionized ions. Frequently, such transitions are the resonance transitions, for example, in ions with incomplete $n = 2$ or $n = 3$ shells, and as such are important in both stellar atmosphere and fusion energy reactor contexts. Since the relativistic, QED, and electron correlation energy interactions represent a much larger portion of the available photon energy than is normally the case

in $\Delta n \neq 0$ transitions, the f values and photon energies for these transitions are correspondingly more sensitive to these same interactions and represent a good test of theoretical calculation of the sizes of such interactions.

The voluminous data acquired, represent the culmination of our effort of 1973-74 to build and instrument a 2.2-m grazing incidence spectrometric apparatus for atomic structure and collisions experiments concerning multiply ionized ions (a project ably aided by the contributions of Prof. Roman Laubert, then also a visitor here). To expedite summarizing results in condensed form, we present several accompanying tables (6.3-6.5). These tables contain only a representative fraction of a much larger number of results published in articles cited in refs. 10 through 18. In a number of cases, similar results obtained in collaboration with colleagues at LBL, BNL, the Universities of Lund and Uppsala (Sweden), Princeton, and Rutgers have been combined with our data and are incorporated in the tables.

1. University of Tennessee, Knoxville.
2. University of Tennessee at Chattanooga, Chattanooga, Tenn.
3. East Carolina University, Greenville.
4. J. Crooks and M. E. Rudd, *Phys. Rev. Lett.* **21**, 1559 (1970).
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17. J. P. Forester et al., *J. Phys. (Paris)* (to be published in 1979).
18. D. J. Pegg et al., *J. Phys. (Paris)* (to be published in 1979).

Table 6.3. Oscillator strengths for the $2s$ - $2p$ principal resonance transitions in Li-like ions

Transition	Al XI	Si XII	S XIV	Cl XV	Fe XXIV
$(2s)^2S_{1/2} - 2p^2P_{1/2}$	0.036 ^a		0.032 ^c	0.028 ^d	0.018 ^e
$(2s)^2S_{1/2} - 2p^2P_{3/2}$	0.076 ^a	0.074 ^b	0.068 ^c	0.057 ^d	0.047 ^e

^aMeasurements made in Uppsala, Sweden (a collaboration of the Uppsala-Lund-Tennessee groups).

^bMeasurements made in Uppsala, Sweden, and Oak Ridge (a collaboration of the Uppsala-Lund-Tennessee groups and the Tennessee-Oak Ridge-Brookhaven groups respectively).

^cMeasurements made in Oak Ridge (a collaboration of the Tennessee-Connecticut-Frankfurt-Oak Ridge groups).

^dMeasurements made in Oak Ridge (a collaboration of the Tennessee-Connecticut-New Hampshire-Oak Ridge groups).

^eMeasurements made at Berkeley Superhilac (a collaboration of the Berkeley-Argonne-Tennessee-Brookhaven-Oak Ridge groups).

Table 6.4. Oscillator strengths for $\Delta n = 0$ transitions ($n = 2$) in Be-like ions

Transition	Al X	Si XI	P XII	S XIII	Cl XIV
$(2s)^1S - (2s2p)^1P$		0.23 ^b	0.21 ^c	0.19 ^d	0.17 ^e
$(2s2p)^1P - 2p^2^1D$	0.11 ^a	0.12 ^b	0.10 ^c	0.091 ^d	0.088 ^e
$(2s2p)^1P - 2p^2^1S$				0.057 ^d	0.058 ^e
$(2s2p)^3P - 2p^2^3P$		0.015 ^b	0.094 ^c	0.085 ^d	0.076 ^e

^aMeasurements made in Uppsala, Sweden (a collaboration of the Uppsala-Lund-Tennessee groups).

^bMeasurements made in Uppsala, Sweden, and Oak Ridge (a collaboration of the Uppsala-Lund-Tennessee groups and the Tennessee-Oak Ridge-Brookhaven groups respectively).

^cMeasurements made at Uppsala, Sweden, and Oak Ridge (a collaboration of the Uppsala-Lund-Tennessee and the Tennessee-Brookhaven-Oak Ridge groups respectively).

^dMeasurements made in Oak Ridge (a collaboration of the Tennessee-Connecticut-Frankfurt-Oak Ridge groups).

^eMeasurements made at Oak Ridge (a collaboration of the Tennessee-Brookhaven-Oak Ridge groups).

Table 6.5. Oscillator strengths for $\Delta n = 0$ transitions ($n = 3$) in Na-like ions

Transition	Ni XVIII	Cu XIX	Br XXV
$(3s)^2S_{1/2} - 3p^2P_{1/2}$	0.11	0.16	0.072
$(3s)^2S_{1/2} - 3p^2P_{3/2}$	0.24	0.26	0.17
$(3p)^2P_{3/2} - 3d^2D_{3/2}$	0.19	0.22	0.15

Measurements made at Brookhaven National Laboratory (collaboration of the Tennessee-Rutgers-Princeton-Brookhaven-Oak Ridge groups).

**STRIPPING AND MULTIPLE ELECTRON LOSS
CROSS SECTIONS FOR HEAVY IONS
INCIDENT ON VARIOUS ATOMIC AND
MOLECULAR GASES**

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C. D. Moak	H. Knudsen ³
G. D. Alton	L. B. Bridwell ⁴
C. M. Jones	Q. C. Kessel ⁵
R. O. Sayer ¹	A. Antar ⁵

Differential cross sections for charge change resulting from the scattering of 20-MeV $^{127}\text{I}^{5+}$ and 20-MeV $^{35}\text{Cl}^{4+}$ ions from thin gaseous targets of Xe, Ar, and N_2 have been measured⁶ using an apparatus virtually identical to that described earlier.⁷ Total cross sections for multiple electron loss have been determined by integration of the differential charge-state yields over angle. Care was taken to assure that the pressure in the 2-cm-long differentially pumped cell was sufficiently low that single-collision conditions were satisfied.

At each laboratory scattering angle θ_i , a complete charge-state distribution was recorded so that charge-state fractions $f_q(\theta_i)$ could be derived. If these charge-state fractions are expressed as a function of impact parameter p , instead of scattering angle θ_i , then the total charge-changing cross section, $\sigma(q_i, q)$, can be obtained from the following expression:

$$\sigma(q_i, q) = 2\pi \int_0^\infty f_q(p) p \, dp. \quad (1)$$

The classical correspondence between center-of-mass scattering angle θ and impact parameter p for scattering by a central potential $V(r)$ is given by⁸

$$\theta = \pi - 2 \int_{r_0}^\infty \frac{p/r^2}{[1 - p^2/r^2 - V(r)/E]^{1/2}} dr, \quad (2)$$

where E is the center-of-mass energy, r is the inter-nuclear distance, and r_0 is the distance of closest approach.

Since the total electron loss cross section $\sigma(q_i, q)$ can be obtained, both by direct integration of the absolute differential cross sections and from Eq. (1), using Eq. (2), a comparison of the two results is indicative of the efficacy of the potential $V(r)$ assumed in Eq. (2). Three potentials were investigated for each case: (1) the Bohr exponentially screened Coulomb potential,

(2) the Thomas-Fermi potential, and (3) the Lens-Jensen potential. Figure 6.5 shows the results of such a comparison. For both Cl and I incident on the three targets it is seen that the predictions using the Thomas-Fermi potential lie closest to the direct experimental results, while the predictions using the Bohr potential are considerably too small. The results using a Rutherford (bare ion, bare target) potential were calculated and lie much higher than the results of direction integration; therefore it seems that a potential which takes account of the fact that the interacting particles are not neutral would be more appropriate. For example, in the case of I on Xe, the iodine ions have charge 5 and the xenon atom is neutral during approach, and the emerging iodine ion may have charge 15; therefore it is reasonable to expect that the xenon atom would also be ionized to a comparable degree. Work is in process to construct potentials which will give better agreement with the measured cross sections.

In another experiment, total electron loss cross sections were measured for 20-MeV Fe^{4+} ions transmitted through a variety of atomic and molecular gaseous targets. The apparatus used for these measurements was similar to that described in the previous section, but was modified to include a quadrupole doublet as described in ref. 9. This doublet lens was used to focus ions of a selected charge state at the position-sensitive detector, which follows the charge-state analyzer. Because of power supply limitations, the quadrupole lens could not focus charge states below +7. However, at low gas pressures, the scattering in the cell was so small and the angular distributions are so peaked forward that all low-charge-state peaks were well resolved and totally collected; therefore these yields could be measured accurately with the lens set to focus charge +7. The spectra were very similar to those shown in Fig. 2 of ref. 10. Count rates in the position-sensitive detector were held to ~ 1000 counts/sec so as to minimize spectral distortion and deadtime. For these measurements a 9.4-cm-long differentially pumped gas cell was used, and again great care was taken to assure that the pressure was sufficiently low so that single-collision conditions obtained. The data analysis method which takes into account the small fraction of double-scattering events and which corrects for residual gas in the cell and beam lines is described completely in ref. 9.

The measured total cross sections *per target atom* for loss of one to eleven electrons in a single collision for 20-MeV Fe^{4+} ions transmitted through gases of

Fig. 6.5. Electron loss cross sections $\sigma(5, q)$ for 20-MeV $^{137}\text{I}^{5+}$ on Xe, Ar, and N_2 (a); and $\sigma(4, q)$ for 20-MeV $^{35}\text{Cl}^{4+}$ on the same gases (b). Symbols refer to means of determining cross sections. Open circles were derived from the integration of measured absolute differential cross sections; points were derived from Eq. (2) with Bohr (Δ), Thomas-Fermi ($\times$), and Lenz-Jensen ($+$) potentials. Lines are drawn to facilitate comparison.

N_2 , SF_6 , Ar, Kr, and Xe are shown in Fig. 6.6 as a function of the final charge state q . For each of the target gases, the data show the same trend as a function of q : There is an overall rather steep decrease for increasing q , interrupted by a weaker decrease between $q = 6$ and $q = 8$. For the highest q values, the cross sections follow a nearly exponential decrease with q . Comparing the results for the different gases, it is observed that the cross sections are smaller and the decrease at high q values is more pronounced, the lighter the target atoms. It can also be seen that the cross sections are smaller for molecular targets than

for the noble gases. This effect may be attributable to effects stemming from the spatial correlation between the atoms in the molecule, as has been investigated theoretically by Sigmund.¹¹

In conclusion, two experimental methods, and data illustrating each, have been presented for measuring electron loss cross sections for heavy ions. Angular differential cross sections were measured for high charge states, and an analysis was made in terms of potential models. The second method used a quadrupole doublet to focus the angular distribution and thus measure directly total cross sections. This second

Fig. 6.6. Total single and multiple electron loss cross sections plotted as a function of the final charge state q . The gas cell length was 9.4 cm. The curves are drawn to guide the eye. For the majority of cases, double and higher-order collisions were negligible at the three lowest pressures used (~ 2 , 5, and 10 millitorr). However, for $q < 12$ with SF_6 gas, and for all charge states with Xe gas, the presence of double scattering events was indicated at the three lowest pressures. This introduced uncertainty into the data treatment, which is indicated by parentheses around the corresponding cross-section points.

method has the advantage of being applicable to all charge states instead of just the high ones, and the accuracy is better. It has the disadvantage, however, that angular information is not obtained, and therefore analysis in terms of the impact parameter dependence of multiple electron loss cross sections is not

possible. Thus the methods are complementary and both are useful.

1. Computer Sciences Division.
2. Graduate student from Cornell University, Ithaca, N.Y.
3. University of Aarhus, Aarhus C, Denmark.
4. Murray State University, Murray, Ky.
5. University of Connecticut, Storrs.
6. H. A. Scott et al., *Phys. Rev. A* **18**, 2459 (1978).
7. G. D. Alton et al., *IEEE Trans. Nucl. Sci.* **NS22**, 1685 (1975).
8. N. F. Mott and H. A. W. Massey, *The Theory of Atomic Collisions*, 2d ed., chap. VII, Oxford University Press, London, 1949.
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HEAVY-ION X-RAY PRODUCTION

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 J. L. Duggan¹ R. S. Peterson²
 J. D. Gressett¹ S. R. Wilson¹
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$L\alpha$ x-ray production cross sections have been measured for solid targets of Nd, Ho, and Au for 1.86-MeV/amu ^{19}F and ^{28}Si , and 1.8-MeV/amu ^{35}Cl ions as a function of the incident charge state. From the projectile charge-state dependence of the cross sections, both direct ionization and electron capture contributions were extracted for a comparison to Coulomb ionization theories. The data provide supporting evidence for the theory of electron capture with a reduced binding effect. With standard fluorescence and Coster-Kronig yields uncorrected for multiple ionization effects, the direct ionization theories did not simultaneously reproduce the projectile- Z_1 and target- Z_2 dependences of the data.

In another experiment the production of noncharacteristic x rays (NCR) has been observed in 19-MeV $^{19}\text{F}^{q*} \rightarrow \text{Ne}$ collisions as a function of incident projectile charge state q . The NCR production rate was found to be weakly dependent upon the number of L -shell vacancies brought into the collision and increased by almost an order of magnitude when the incident projectile had a K -shell vacancy. Two incident projectile

K-shell vacancies approximately doubled the single-vacancy yield. These NCR are interpreted as being primarily molecular-orbital (MO) x rays. The MO x-ray production rates indicate the importance in nearly symmetric, low-*Z* ion-atom collisions of the two-collision production of MO x rays in solid targets for high relative velocities, $v/v_e \sim 1$.

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1. North Texas State University, Denton.
 2. University of Connecticut, Storrs.
 3. New York University, New York.
 4. University of Tennessee, Knoxville.

RADIATIVE ELECTRON CAPTURE BY OXYGEN IONS IN SINGLE-CRYSTAL CHANNELS: EXPERIMENT AND THEORY

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R. H. Ritchie ²	C. D. Moak
J. A. Biggerstaff	H. Verbeek ⁴
T. S. Nogge ¹	V. N. Neelavathi ⁵

The phenomenon of radiative electron capture (REC) has been studied for 17- to 40-MeV O ions channeled through thin single crystals of Ag and Si. As a consequence of the unique constraints imposed on the interactions of well-channeled ions, it is possible to study the REC phenomenon for fully stripped oxygen ions interacting primarily with the free or weakly bound electrons in single-crystal channels. Radiation is identified which results from electrons captured directly into the lowest energy state of the moving oxygen ions as well as that arising from a number of bremsstrahlung processes. The measured cross sections and widths of the REC radiation and the bremsstrahlung processes are compared with calculations made specifically for the channeling situation. The calculations incorporate standard radiation theory and a statistical model of the electron states in the single crystal. The space-varying electron density is averaged over impact parameters appropriate for the channeled ions. The measured REC cross sections show a marked deviation from theory which is not understood at this time. The shapes of the REC lines and the x-ray background present in the measured spectra are in reasonable agreement with the calculations, but the widths of the REC lines as a function

of ion energy show only fair agreement. Results of these studies are discussed and possible explanations offered for some of the discrepancies.

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1. Solid State Division.
 2. Health and Safety Research Division.
 3. Chemistry Division.
 4. Max-Planck-Institut für Plasmaphysik, 8046 Garching, West Germany.
 5. Subsequently at Bhabha Atomic Research Centre, Bombay, India (now deceased).
 6. B. R. Appleton et al., accepted for publication, *Phys. Rev.* 13.

TANDEM VAN DE GRAAFF OPERATIONS

J. L. C. Ford, Jr.	E. G. Richardson
N. F. Ziegler	R. P. Cumby ¹
	G. F. Wells

The EN tandem operated very reliably during 1977. Problems with the tandem due to sparking caused by resistors vibrating loose so that they came into close contact with neighboring resistors developed during 1978. Reworking what appeared to be the marginal resistor sockets in the machine reduced this difficulty.

A wide range of research activities were accommodated on the tandem in 1977-78. The research programs, investigators, and approximate beam-time utilization for each activity are listed in Table 6.6. The research time was about equally divided between nuclear physics and atomic or solid-state research. Heavy-ion acceleration accounted for almost the entire program of the machine.

Two cryopumps were purchased as a first step in improving the vacuum in the EN tandem's beam lines as needed for accelerating heavier-ion species. One of these pumps was installed following the 90° analyzing magnet, substantially reducing the pressure within the magnet, and the second will be located just after the 90° deflecting magnet. The control and display systems for the ion sources were improved. In order to monitor voltage breakdown problems more carefully, x-ray counters and photomultipliers were installed, viewing the low- and high-energy sections of the accelerator.

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1. Instrumentation and Controls Division.

Table 6.6. Research activities on the tandem Van de Graaff accelerator

Type	Investigators	Approximate percent of utilized beam time
Atomic physics	Griffin, Sellin, ^a Pegg, ^a Thoe, ^a Elston, ^a Forester, ^b Vane, ^a Suter, ^a Schumann, ^c Laubert, ^a Williams, ^c Hayden, ^d Alton, Berry, ^e Glass ^e	10
Atomic collisions in solids	Datz, ^f Biggerstaff, Miller, Moak, Dittner, ^f Gomez del Campo, Crawford, ^f Krause, ^f Knudsen, ^h Hvelplund ^h	8
Compound-nucleus studies	Thornton, ⁱ Cordell, ⁱ Dennis, ⁱ Doering, ⁱ Parks, ⁱ Ford, Gomez del Campo, Shapira	8
Charge-exchange cross sections	Kim, Phaneuf, Meyer, Stelson, Hvelplund ^h	8
In-beam gamma-ray studies	Robinson, Sayer, ^{aa} Lin, ^k Wells, ^k Hamilton, ^l Ramayya, ^l Piercey, ^l Ahmed, ^l Nettles ^l Korub, ^k Lin, ^k Wells, ^k Stuk, ^k Robinson	8
X-ray studies	Müller, Basbas, ^{mm} Duggan, ^{mm} McDaniel, ^{mm} Gressett, ⁿⁿ Johnson, ⁿⁿ Rice, ⁿⁿ Totten, ⁿⁿ Trkumi, ⁿⁿ Castorvedi, ^{oo} Wheeler, ^{oo} Kuenhold, ^{oo} Zander, ^{oo} Rayburn, ^{oo} Cimola, ^{ss} Lapicki, ^{ss} Wilson, ⁿⁿ Rowe, ⁿⁿ Alton, Thoe, ^a Mehta, ⁿⁿ Monigold, ⁿⁿ Peterson, ^{ss} Button, ⁿⁿ Andrews ⁿⁿ	6
Edge-magnet heavy-ion reaction studies	Ford, Gomez del Campo, Robinson, Shapira, Thornton ⁱ	6
Heavy-ion-produced neutron cross sections	Bar, Miller, Gomez del Campo, Stelson	6
High-charge-state stripping studies	Alton, Jones, Moak, Miller, Bridwell, ^l Kessel, ^{ss} Scott, ⁿⁿ Antar, ^{ss} Sayer, ^{aa} Knudsen ^h	6
Heavy-ion reaction mechanisms	Maguire, ^l Ramayya, ^l Bomar, ^l Ford, Gomez del Campo, Shapira	5
Beam buncher tests	Ziegler, Milner	5
Heavy-ion reaction studies	Dacal, ^{vv} Ortiz, ^{vv} Menchacca-Rocha, ^{vv} Cardenas, ^{vv} Ford, Gomez del Campo, Shapira	4
Coulomb excitation	Bemis, ^l McGowan, Milner, Ford Hamilton, ^l Maguire, ^l Piercey, ^l Ramayya ^l	3
Radiation damage studies	Clark, ^{ww} Biggerstaff, Appleton, ^x Moak, White ^x	2
Charge-exchange cross sections	Bayfield, ^y Gardner, ^y Koch, ^l Sellin, ^a Pegg, ^a Thoe, ^a Hayden, ^d Forester, ^b Kim	2
Radiation damage effects	Noggle, ^x Appleton, ^x Moak	2
Heavy-ion neutron production	Fulmer, Butler ^z	2
In-beam gamma-ray spectroscopy	Wells, ^k Robinson, Kim, Sayer, ^{aa} Coffrey, ^{bb} Piercey ^l	2
Coulomb excitation	McGowan, Stelson	2

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7. Magnetic Fusion Energy—Applied Physics Research

CONTROLLED FUSION ATOMIC DATA CENTER

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B. J. Farmer

The evaluation and editing of our indexed bibliography of atomic and molecular processes for the period 1950–75 have been completed with the addition of new data and the correction of errors in existing data sets. Copies of this bibliography were sent to ten laboratories in the U.S. and abroad, and magnetic tapes of the file were supplied to the IAEA for use in publishing a comprehensive bibliography composed of data from several countries. Final corrections are in progress for our 1976–77 bibliography, which will receive similar distribution. Searches of 1978 reference data are being received and processed on a current basis.

To facilitate creating and manipulating bibliographical data files, a new computer code was brought on-line January 1978. The new code implements an up-to-date, more universal data format which is compatible with ORCHIS (Oak Ridge Computerized Hierarchical Information System, developed by the ORNL Computer Sciences Division), thus permitting convenient and straightforward file management. Data entry is on-line in an interactive environment in which each entry is prompted, checked for certain classes of errors, and expanded in the case of coded responses used for repetitive fields. Hardware for the system includes a Hewlett-Packard 2645A video display terminal and a DECWRITER III high-speed digital printer.

Four indexed bibliographies of primary use to fusion research have been published as ORNL reports. These cover the period 1950–75 and include molecular dissociation, atomic and molecular excitation, electron transfer, and ionization and stripping (ORNL-5500, -5501, -5502, and -5503).

The two-volume *Atomic Data for Controlled Fusion Research* is being updated with the revision of previous data and the addition of new sections on sputtering, particle reflection, and ion trapping. A third volume is in progress which emphasizes those atomic collisions involving impurities found in high-temperature plasmas. A computer code, using the DISSPLA graphics package, has been written to generate production quality plots of the multiply charged ion cross-section data, using plot parameters specified in a data file that can be created under TECO. Data compilation has been completed for charge exchange of plasma impurity ions with H, H₂, and He. Other compilations in this volume include electron excitation and ionization of multicharged ions. For these processes the lack of sufficient experimental data to correlate with theory has created difficulties in presenting the data graphically. In an effort to compensate for this problem, we have prepared a full bibliography of relevant experimental and theoretical work to preface each section of data.

To make our evaluated data more compatible with the needs of plasma modeling, we have devised and implemented a computer program to convert cross sections to reaction rates for Maxwellian-Maxwellian as well as Beam-Maxwellian energy distributions. The new code produces publication-quality output of the calculated rate coefficients in both tabular and graphical forms, as well as in the form of Tschebysheff polynomial fits to the calculated rates.

In cooperation with the Atomic Transition Probabilities Data Center of the National Bureau of Standards, we have continued publication of the bulletin *Atomic Data for Fusion*. As a supplement to our bi-monthly issues, an author and subject index is produced annually. A recent survey of bulletin recipients indicates that the publication continues to serve as a useful information tool for fusion researchers.

ELECTRON IMPACT IONIZATION OF MULTICHARGED IONS

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B. E. Hasselquist¹ D. C. Gregory²

Cross sections have been measured for electron impact ionization of a number of multiply charged ions, employing a crossed-beams apparatus. After the first reported measurements³ for C^{3+} and N^{4+} the apparatus was improved to extend the upper energy limit to 1500 eV and to reduce scattered photons which interfere with measurement of the ionization signal. Cross sections have now been measured for B^{3+} , $C^{3,4+}$, $N^{3,4,5+}$, $O^{3,4,5+}$, and Ar^{4+} .

For He-like ions B^{3+} , C^{4+} , and N^{5+} , the semiempirical formula by Lotz⁴ and scaled Coulomb-Born calculations of Golden and Sampson⁵ agree with the measurements to within experimental uncertainties (roughly $\pm 10\%$) at all energies. However, the present measurements for these ions are lower than those computed using classical binary encounter theory.⁶

The measured cross sections for Li-like ions C^{3+} , N^{4+} , and O^{5+} do not agree so well with theoretical estimates.⁴⁻⁸ For the Li-like ions the most important feature of the ionization cross sections is the finding that inner-shell excitation followed by autoionization contributes significantly to total ionization. Figure 7.1

Fig. 7.1. Cross section for electron impact ionization of N^{4+} showing comparison of present experimental results with various theoretical estimates and illustrating the contribution of excitation-autoionization.

shows the results for N^{4+} , where a second peak beginning abruptly at 420 ± 5 eV is attributed to the excitation $e^- + N^{4+}(1s^2 2s) \rightarrow e^- + N^{4+}(1s2s2l)$, where $l = s$ or p . The excitations of states $(1s2s^2) {}^2S$ at 413 eV, $(1s^2 2s2p) {}^4P$ at 416 eV, and two states $(1s^2 2s2p) {}^2P$ at 423 and 429 eV have recently been calculated by Henry⁹ in a six-state close-coupling quantum formalism. The sum of these excitation cross sections predicts a rise in the ionization, which agrees with our measurements to within 25% at 456 eV. For C^{3+} , excitation cross sections recently tabulated by Magee et al.¹⁰ for the $1s^2 2s \rightarrow 1s2s2l$ transitions predict a rise in ionization in even better agreement with our experiment.

An important observation from the data on Li-like ions is that the relative contribution of excitation-autoionization increases with increasing nuclear charge along the isoelectronic sequence: that is, for O^{5+} the second peak (excitation-autoionization) is larger than the first (direct) peak; for N^{4+} (Fig. 7.1) the two peaks are equal; for C^{3+} the first (direct) peak is larger. Thus, for higher members of the sequence, the excitation contribution to total ionization may dominate. This process is likely in other isoelectronic sequences as well (such as Na-like ions¹¹), and the effects of excitation-autoionization on the ionization balance of high-temperature plasmas need further investigation.

The cross-section measurements for ions of other electronic configurations (neither He-like nor Li-like) also exhibit interesting features. Excitation-autoionization peaks are observed for O^{4+} (see Fig. 7.2

Fig. 7.2. Cross section for electron impact ionization of O^{4+} . For this case the beam contains an unusually high fraction of metastable ions, and the discrepancy with Coulomb-Born predictions is significant.

at 550 eV) and Ar^{4+} . For O^{4+} and N^{3+} — Be-like ions — the beam is apparently about 50% ground-state ions ($1s^2 2s^2$) 1S and about 50% metastable ions ($1s^2 2s 2p$) 3P , as determined by detailed measurement of the threshold behavior of ionization, which can occur at energies a few eV lower for the metastable states than for the ground state. Figure 7.2 shows the cross section for ionization of our mixed-state beam of O^{4+} and compares it with scaled Coulomb-Born and Lotz formula calculations for a 50-50 mixture of ground-state and metastable-state ions. The Be-like ions (O^{4+} and N^{3+}) are interesting because the cross sections are higher than predicted by the best theory (Coulomb-Born) and because of the unusually large fraction of metastables in the beam. It is expected that metastable states of Be-like ions will be highly populated in most plasmas. The role of metastables in plasma processes needs further clarification, and present results can improve the understanding of metastable content and collisional behavior in plasmas.

1. Summer student participant from the University of Wisconsin, River Falls.
2. Participant from Joint Institute for Laboratory Astrophysics, Boulder, Colo.
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ELECTRON IMPACT EXCITATION OF N^{4+}

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G. H. Dunn¹

Measurements of excitation of multicharged ions have continued, employing a crossed-beams apparatus with ions from the ORNL-PIG source crossed by a monoenergetic electron beam. A collaborative effort with the Joint Institute for Laboratory Astrophysics (JILA), these measurements are intended to test the developing

collisional excitation theories and are directly applicable to understanding photon emissions from high-temperature fusion and astrophysical plasmas.

Results for the excitation of C^{3+} ($1s^2 2s \rightarrow 1s^2 2p$) were reported previously⁴ and gave good agreement with recent theory. As a further test of the theory, the measurements have been extended to the next member of the Li isoelectronic sequence, N^{4+} . Figure 7.3 compares the N^{4+} results with the close-coupling calculations of Van Wyngaarden and Henry⁵ in the most critical near-threshold region. For N^{4+} the agreement of

Fig. 7.3. Electron impact excitation of N^{4+} . The dashed line is theory of Van Wyngaarden and Henry (ref. 5), and the solid line is the same theory folded with the experimental energy spread. The solid data point is the present absolute measurement, and open data points are measured relative to that. Error bars are 90% confidence level counting statistics.

experiment and theory is well within experimental uncertainty, confirming the reliability of theory for predicting excitation cross sections. We now expect that quantum theory can predict the cross sections accurately for resonance lines of Li-like ions. For other electronic configurations (e.g., Be-like ions), theoretical computations may not be as reliable; thus our future measurements will be extended to B^+ , C^{2+} , and N^{3+} .

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3. Summer student participant from the University of Wisconsin, River Falls.

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EXCITED-STATE CONTRIBUTION TO THE ELECTRON-LOSS COLLISIONS OF A FAST H^0 BEAM ON N^{3+} IONS

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Our crossed-beams experiment designed to measure total electron-loss cross sections by H^0 in collision with various multiply charged plasma impurity ions utilizes a fast H^0 beam obtained by passing energy-analyzed protons through a neutralizer cell. Since such a neutral beam is known to contain a small but finite amount of excited atoms in various n states with relative population P_n and since the cross sections σ_n increase rapidly with n , the values of P_n are needed to deduce σ_n from the measured apparent cross section σ_A , which is a sum of products $P_n \sigma_n$ of all contributing states. Figure 7.4 shows the measured σ_A for 40-keV H^0 on N^{3+} ions as a

function of a transverse electric field applied to the H^0 beam prior to the interaction regions. Since the high H^0 Rydberg states are ionized and attenuated by the electric field, the apparent cross section σ_A decreases with increasing field, as illustrated in Fig. 7.4. The populations P_n were determined from auxiliary experiments in which the intensity of the H^0 beam transmitted through the ionizing field was measured for a range of field strengths $\mathcal{E}$. Shown in Fig. 7.5 are the measured transmissions vs $\mathcal{E}^{1/2}$ for a 40-keV H^0 beam. The fact that the transmission is linear in $\mathcal{E}^{1/2}$ implies¹ that $P_n = a/n^3$, where a is a normalization constant, which is 0.41 for this particular case. Incorporation of the above relation between P_n and n into the data analysis indicates that the present results are inconsistent with the $\sigma_n \propto n^2$ theoretical prediction,² but that σ_n varies more nearly as the geometric cross section, which varies as n^4 .

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Fig. 7.4. Apparent cross section σ_A vs ionized field strength $\mathcal{E}$.

Fig. 7.5. Transmission of 40-keV H^+ high Rydberg states as a function of $E^{1/2}$.

MEASUREMENTS OF ELECTRON TRANSFER FROM HYDROGEN ATOMS AND MOLECULES TO MULTICHARGED IONS, USING THE TANDEM VAN DE GRAAFF

P. Hvelplund¹ H. J. Kim
F. W. Meyer R. A. Phaneuf
P. H. Stelson

Partially stripped ions from the Tandem Van de Graaff accelerator have been used to measure electron capture cross sections in atomic and molecular hydrogen. The ion species investigated were O, Si, Fe, Mo, Ta, W, and Au in charge states q ranging from 4 to 19, and for collision velocities ranging from 2.2 to 6.2×10^8 cm/sec (energies of 25 to 200 keV/amu). Modifications to the detector instrumentation² permitted measurements of more highly charged ion projectiles. The primary objective of the experiments was to investigate the scaling of electron capture cross sections in atomic hydrogen with ionic charge q and mass. Such information is important in the neutral-beam injection heating and fueling of magnetically confined fusion plasmas.

Experimental cross sections for three representative ion species at a collision velocity of 3.4×10^8 cm/sec are plotted vs initial ionic charge q in Fig. 7.6. The results for ions O through Fe are similar to those previously reported.² Except for sharp dips at initial charges q corresponding to closed-shell configurations of the projectile ion, the electron capture cross sections

$\sigma_{q,q-1}$ for Fe and Mo projectiles increase rapidly with q . This increase can be represented by a simple power law in q , q^p , with p ranging from 1 to 2 for the collision velocities of the present experiments. The value of p increases slowly with velocity. The straight lines which accompany the data in Fig. 7.6 represent power-law least-squares fits to the data.

The q dependences of the cross sections for the heavier projectiles are more complicated. Superimposed upon the strong increase with q , all three of the heavier projectiles investigated (Ta, W, and Au) exhibit a common oscillatory structure whose relative magnitude is independent of ion species and velocity. In Fig. 7.6 this behavior can be seen for Au ions. Data for a molecular hydrogen target also show the oscillations, but with somewhat reduced amplitude. To emphasize this structure, the experimental cross sections, divided by the value obtained in a power-law least-squares fit, are plotted vs q for Ta, W, and Au ions in Fig. 7.7. These oscillations are attributed to interference in the amplitude for scattering of the captured electron by a pure Coulomb potential modified by a short-range term that accounts for screening by the other ionic electrons. A theoretical impulse model for the collision reproduces the period and phase of the observed oscillations.³ More refined calculations by Bottcher⁴ account for the oscillations observed near atomic number 70 in terms of an f -wave resonance in the target electron-projectile scattering.

Except for the anomalies noted above, which are generally at the 25% level or less, the magnitudes of the capture cross sections in atomic hydrogen are characterized by ion charge and velocity, rather than by species. The experiments are also in good agreement with classical-trajectory Monte Carlo calculations of Olson and Salop.⁵

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Fig. 7.6. Experimental electron capture cross sections $\sigma_{q,q-1}$ vs ionic charge q for multicharged Fe, Mo, and Au ions in atomic hydrogen at a velocity of 3.4×10^8 cm/sec. The straight lines represent power-law least-squares fits to the data.

Fig. 7.7. Ratio of experimental electron capture cross sections $\sigma_{q,q-1}$ to power-law least-squares fits to the data ($\sigma_{q,q-1}^P$) for Ta, W, and Au ions in atomic hydrogen vs ionic charge q . Collision velocities are 3.4×10^8 cm/sec for W and Au, and 2.9×10^8 cm/sec for Ta ions.

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LOW-ENERGY MEASUREMENTS OF ELECTRON TRANSFER FROM HYDROGEN ATOMS AND MOLECULES TO MULTICHARGED IONS

D. H. Crandall F. W. Meyer
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Measurements of total electron capture cross sections by various multicharged ions in atomic and molecular hydrogen at low velocities ($v < 10^8$ cm/sec) have continued. Apart from their relevance to plasma diagnostics and particle transport, the measurements provide a basis for testing our understanding of electron transfer collisions. Theoretical calculations at low velocities are based on a quasi-molecular model and are difficult.

The general experimental method, including the implementation and calibration of the atomic hydrogen target, was described previously.¹ Experiments have concentrated on multicharged ions of the He and Li isoelectronic sequences; single-electron capture data have been obtained for the ions B^{q*} ($q = 2, 3, 4, 5$), C^{q*} ($q = 3, 4, 5$), N^{q*} ($q = 3, 4, 5$), O^{q*} ($q = 5, 6$), F^{6*} , and Ar^{8*} in collisions with H and H_2 in the velocity range

0.4 to 1.3×10^8 cm/sec. Electron capture cross sections vs collision velocity for He-like B^{3+} and C^{4+} ions colliding with hydrogen atoms are shown in Fig. 7.8 and compared with the theoretical calculations of Olson, Shipsey, and Browne² and with measurements of Gardner, Bayfield, et al.³ The theory utilizes ab initio potential energy curves in multistate close-coupling calculations and, within the combined uncertainties, satisfactorily reproduces both the magnitudes and velocity dependences of the experimental cross sections for $B^{3+} + H$ and $C^{4+} + H$ collisions.

Fig. 7.8. Electron capture collision cross section vs velocity for B^{3+} (circles) and C^{4+} (triangles) in atomic hydrogen. Solid points are present experimental data, and open points are results of Gardner, Bayfield, et al. (ref. 3). Dashed curves are theoretical results of Olson, Shipsey, and Browne (ref. 2) for these ions. Error bars on present data are total absolute uncertainties at good confidence level.

Unlike measurements made at higher velocities,¹ the cross sections at low velocities exhibit neither uniform scalings with ionic charge nor general behavior with velocity. However, for initial ion charge $q \geq 4$, the cross sections at low velocity appear to be characterized by initial ionic charge rather than by projectile mass or electronic structure.

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H^- EQUILIBRIUM YIELDS IN A THICK Cs VAPOR TARGET

F. W. Meyer

The equilibrium factor F_{-1}^{∞} for H^+ (or D^+) incident on a thick Cs vapor target is an important parameter in the design of charge transfer cells for use in MFE neutral-beam injection schemes. Considerable disagreement exists in previously reported measurements of F_{-1}^{∞} for H^+ incident on Cs, particularly in the vicinity of the maximum in the equilibrium fraction curve at proton energies in the range 200 to 500 eV.¹⁻³

To determine whether excitation of the Cs (6p) state by H^+ significantly affects the thick-target H^- yield, we have measured F_{-1}^{∞} for both H^+ and H^- incident on Cs in the energy range 150 to 1000 eV. The cross section for H^- production from H^0 is about an order of magnitude larger for collisions with Cs (6p) than for collisions with Cs (6s). If Cs (6p) excitation by H^+ is an important mechanism in H^- formation, then differences in the Cs (6p) population due to variations in target cell geometries and incident H^+ intensities might explain the discrepant results in the existing F_{-1}^{∞} measurements.

In the present H^- yield measurements, an analyzed H^- beam of the desired energy was incident on a Cs heat-pipe target. The charge components of the beam emerging from the target were monitored as a function of the Cs target thickness π by a secondary emission detector located a short distance downstream of the target. Appropriate biasing of high-transmission grids in front of the detector allowed separate measurements of the H^+ , H^0 , and H^- beam fractions. Upon reaching the equilibrium target thickness where the beam fractions become independent of π , the incident beam was switched to H^+ , and F_{-1}^{∞} was again determined.

As shown in Fig. 7.9, the yields F_{-1}^{∞} were found to be the same for H^+ and H^- incident on Cs, suggesting that Cs (6p) excitation by H^+ plays a negligible role in H^- formation in a thick target. Measurements of F_{-1}^{∞} with D^+ incident showed no observable isotope effect, consistent with earlier observations³ that the equilibrium yields for D^+ and H^+ incident on a thick Cs vapor target are the same for equal incident velocities. The discrepancy between the present measurements and those

Fig. 7.9. The H^+ (D^+) equilibrium fraction $F_{H^+} (D^+)$ for H^+ (D^+) and H^+ incident on a thick Cs vapor target as a function of the energy per nucleon of the incident ions [ref. 1: textual ref. 1; ref. 2: textual ref. 2; ref. 3: textual ref. 3; ref. 4: F. W. Meyer and L. W. Anderson, *Phys. Rev. A* 11, 583 (1975)].

of Schlachter et al.¹ and Agafanov et al.² at low energies is not understood and will be the basis for further experiments.

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LASER ION SOURCE

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To obtain hydrogen-like and completely stripped ions for collision studies in the low-energy region (less than a few keV), an apparatus has been fabricated to investigate the feasibility of using as an ion source the plasma formed by a pulsed laser beam focused in vacuum onto a solid surface. Laser fusion research has revealed that highly stripped ions emerging from such plasmas account for a significant fraction of the energy deposited and of the target mass ablated by the laser beam.²

In the present experiments, a pulsed laser beam from a modest 10-J commercial TEA CO_2 laser was focused onto a solid target at power densities as high as 8×10^{10} W/cm². An ion beam was collimated from the plasma blow-off normal to the target surface, directed through a cylindrical electrostatic analyzer, and detected using a channel-plate electron multiplier. The combination of time-of-flight and electrostatic analysis permitted isolation and identification of ions with different charge-to-mass ratios. Typical energy distributions for the various charge states of carbon in the pulsed ion beam are plotted in Fig. 7.10 for a graphite target with an incident laser power density of 4×10^9 W/cm²; note that hydrogen-like C^{5+} ions are produced even at relatively modest laser power levels. Focused power densities in current laser fusion experiments are typically 10^{16} W/cm².

Modifications to the CO_2 laser to permit fundamental-mode operation have resulted in an order-of-magnitude increase in focused power and yielded measurable fluxes of fully stripped C^{6+} ions. The technique

Fig. 7.10. Measured charge and energy distributions of carbon ions emerging from a laser-produced plasma. The CO_2 laser pulse was focused onto graphite in vacuum to a power density of 4×10^9 W/cm². The numbers represent the carbon ion charge.

is suitable for producing ions of any element that exists as a solid or in a solid compound. We are implementing a CAMAC-based computer data acquisition system to facilitate the development of the ion source and its application to cross-section measurements for such fundamental atomic processes as electron capture by fully stripped and hydrogen-like ions in the low-energy region.

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2. See, for example, W. A. Ehler, *J. Appl. Phys.* 46, 2464 (1975); E. A. McLean, R. Decoste, B. H. Ripin, J. A. Stamper, H. R. Griem, and S. E. Bodner, *Appl. Phys. Lett.* 31, 9 (1977).

PLASMA ION TEMPERATURE MEASUREMENT BY THOMSON SCATTERING

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Theory predicts that plasma ion temperatures may be determined by measuring the scattered spectrum resulting from Thomson scattering of an intense submillimeter laser beam incident on a plasma. The laser and detector systems required for a plasma of 10^{14} cm^{-3} density are (1) a wavelength between 100 and 600 μm ; (2) 1 MW of laser power; (3) a linewidth less than 30 MHz (full width at half maximum); (4) a pulse length greater than or equal to 200 nsec; (5) a peak power-to-background ratio of 10^4 ; and (6) a heterodyne detector with noise equivalent power of 10^{-18} W/Hz , a bandwidth greater than or equal to 1 GHz, and a cw local oscillator. To obtain the required laser characteristics, D_2O vapor was chosen as the lasing medium. An injection-tuned 150-J CO_2 laser optically pumps an unstable-resonator D_2O oscillator operating on the 385- μm transition. The 150-kW oscillator power output is then transmitted to the amplifier. Two geometries have been used to obtain the required 1-MW power: (1) a 1-m beam-expanding amplifier and (2) a 5-m, 15-cm-diam straight pipe extension to absorb both the oscillator and pump power. The gain of the beam-expanding amplifier was insufficient to provide 1-MW output. Total power output measured from the 5-m extension was 1.2 MW, with approximately 70% of the power in the 385- μm line and 30% in the 359- μm cascade line. Plans are to use a fast digital transient analyzer to record the scattered photon time profile, which will be Fourier analyzed to provide the frequency spectrum.

This system has been used to determine the characteristics of the laser beam from both the oscillator and amplifier sections. Analysis of the amplifier output indicates a single frequency with a frequency profile of less than 10 MHz, which is the resolution of the analyzer.

Frequency analysis by Fourier transformation of time profiles is limited to frequencies between 10 MHz and 1 GHz. To explore a broader spectrum, a Fabry-Perot interferometer with a 50-MHz resolution has been installed on the oscillator output. Both the 385- and 359- μm transitions were present. In addition, the Fabry-Perot interferometer revealed a transition at 198 MHz from the 385- μm line center. The origin of this line may be a longitudinal mode or a Raman transition. The Fourier transform analysis did not detect this line, and this discrepancy is being investigated.

From other studies made during this period we have observed that an increase in the injection cw CO_2 tuning power to the 150-J CO_2 pump laser increases the pulse length of both the CO_2 pump laser and the submillimeter laser pulse. This behavior will be examined as a possible way to extend the present 100-nsec pulse.

A local oscillator will be required in detecting the scattered spectrum from our Thomson scattering experiment. Since D_2O does not function as a cw laser, a DCOOD (deuterated formic acid) laser has been constructed to operate at 381 μm with a power level of 25 mW. A quasi-optical mixer and detector has been purchased to mix the two signals. The output signal at 8.4 GHz will be amplified by a 50-db amplifier with 2-GHz bandwidth and noise temperature approximately less than 100 K. The 8.4-GHz signal will be reduced to the usable megahertz range by beating against an x-band local oscillator.

MEASUREMENTS OF TOKAMAK POLOIDAL FIELDS BY FARADAY ROTATION

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In the experimental study of tokamak plasmas it is important to know the spatial profile of the poloidal magnetic field, since this field provides MHD stability. Theoretical analysis indicates that the poloidal field can be determined by projecting several chords of linearly polarized electromagnetic waves through the plasma and measuring the Faraday rotation of the polarization. Since the rotation angle is proportional to the square of

the wavelength, tokamaks require lasers whose wavelength is in the submillimeter range. In addition, the rotation angle of the polarization vector is proportional to the line integral of the electron density times the magnetic field along the path, provided the incident polarization is either parallel or perpendicular to the toroidal magnetic field. Thus a multichannel electron density interferometer is used to obtain the line electron density along the same chord.

During the past year and a half a Faraday rotation apparatus was constructed and placed in use. Our first investigations consisted in a bench test to simulate a plasma experiment. A 393- μm (cw) HCOOH laser was pumped by a cw CO_2 laser. The 393- μm laser beam passed through two wire grid polarizers, a ferrite plasma simulator, and an rf modulator. A liquid-helium-cooled InSb detector and lock-in amplifier were employed to measure the low-level signal. For small modulation, the amplitude of the output signal at the modulation frequency was directly proportional to $\theta_m \sin(2\theta_p)$, where θ_m is the amplitude of the modulation angle, and θ_p is the angle of the simulated plasma rotation. The results of the simulation tests are shown in Fig. 7.11, where both the predicted and measured results are plotted. A polarization sensitivity of 26 mV/milliradian was obtained at a modulation angle of 149 milliradians with an FIR laser power of 4 mW. The system was

installed on ISX-A for preliminary tests, but because of large losses of submillimeter power in transmission, low sensitivity of the available detector, and high x-ray fluxes, the signal at the modulation frequency was indistinguishable from the noise.

Subsequently, the apparatus was installed on the RENTOR tokamak at Rensselaer Polytechnic Institute, with improvements in the detector, laser power, optics, and electronics. Initial measurements with the electron density interferometer indicated that the electron density was 2 to 3 $\times 10^{12} \text{ cm}^{-3}$, that the plasma diameter was much smaller than that of the vacuum vessel, and that the spatial position of the plasma was unstable. The apparatus is now installed on ISX-B, where multichannel experiments will be performed.

In other advances during this period a lithium tantalate crystal was tested as a high-frequency polarization modulator, which allows one detector to be used for detecting both Faraday rotation and interferometer signals. At submillimeter wavelengths the crystal did not modulate the polarization vector, but at visible wavelengths the crystal modulates as expected. We also developed circuits for pyroelectric detectors, permitting a detector response of 1000 V/W with flat frequency response to 10 to 15 kHz. Finally, output power of our cw HCOOH laser was increased to 50 mW.

Fig. 7.11. Predicted and measured rotation angles at a modulation frequency of 9.1 kHz.

ABSOLUTE CALIBRATION OF A HYDROGEN ATOM SECONDARY EMISSION DETECTOR

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Most neutral-particle analyzers used to measure plasma ion temperatures by detecting low-velocity H^+ , H^0 , and H^- have been calibrated under the assumption that secondary electron emission is the same for both ions and atoms. This assumption has remained untested due to the difficulty of determining the absolute flux of low-energy atoms independent of secondary electron emission. An independent calibration of the H^0 flux was achieved by photodetaching an H^- beam passed through a Nd laser cavity. The attenuation of the H^- beam provided a known absolute flux of H atoms. Over the energy range 30 to 2500 eV the secondary emission by H was 15% greater than that by H^+ , as shown in Fig. 7.12. In this energy range the secondary emission of H^- was consistently greater than that for H^+ or H^0 , being a factor of 6 greater at 50 eV. For clean surfaces the secondary emission yield should be dominated by

Fig. 7.12. Secondary emission coefficient for H, H⁺, and H₂⁺ impact on a gas-covered Cu surface.

potential electron ejection below 200 eV and is characterized by the electron yield being independent of incident particle energy. At energies as low as 30 eV, there was no evidence of the potential electron ejection mechanism. Comparison of the data in Fig. 7.12 with both cross sections for production of free electrons in O₂ and N₂ and electron yields from clean surfaces gave indications that the secondary yield from surfaces normally found in vacuum systems is dominated by the gas contamination on the surface. The absolute measurements of neutral particles permit the use of both

neutral-particle analyzers and time-of-flight analyzers for low-energy neutral particles coming from plasmas or reflected from surfaces.

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PLASMA ION TEMPERATURE MEASURED BY NEUTRON TRANSMISSION THROUGH LIQUID OXYGEN

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At a neutron energy of 2.35 MeV, the total neutron cross section of oxygen has an unusually deep minimum, down to 0.1 barn, compared with values of over 1 barn on the shoulders. The mean energy of the *d-d* neutrons, 2.46 MeV, places these neutrons on the shoulder of the minimum in the σ_T for oxygen. However, the kinetic broadening in neutron energies from the plasma *d-d* reactions puts some of these neutrons into the minimum region. Because the fraction of neutrons in the minimum region is a strong function of ion temperature, one can use a simple transmission measurement to deduce the ion temperature. Calculations indicate that for a thick oxygen sample a 5% accuracy in a transmission measurement results in a 10% accuracy in the temperature determination, which is independent of both the absolute *d-d* cross section and the ion density. Preliminary measurements on the ISX plasma were inconclusive because the ion temperature was approximately 0.3 keV. This method should be successful for determining ion temperatures from 1 to 10 keV, using previously measured values of σ_T . However, recent measurements indicate that the upper limit of applicability of the method is 6 keV.

8. Electron Spectroscopy

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Use of angularly resolved photoelectron spectroscopy (ARPES) has been employed to study the properties of free molecules and molecules adsorbed on metal surfaces. Particular emphasis has been placed on surface studies in which an oriented metal crystal is cleaned under ultrahigh vacuum, and a gas is allowed to adsorb on the metal surface. The photoelectron spectrum of the adsorbed gas is taken with a polarized source of HeI(21.22 eV) radiation. Angular studies are carried out by (1) rotating the target crystal and (2) rotating the polarization vector of our specially designed light source.⁶ Several molecules have been studied on the (111) surfaces of copper and nickel. Of particular note are the results of CO and benzene on nickel. In the case of CO it has been possible to ascertain through comparison of experiment with calculations on free molecules by Davenport⁷ that CO is oriented perpendicular to the surface, as expected from various data in the literature. This observation is further verified from symmetry arguments used to explain the disappearance of the 5σ peak under perpendicular polarization. In the case of benzene, variation of the relative band intensities with crystal angle indicates that the molecule is oriented with respect to the surface. The more precise nature of this orientation is being examined by comparison of polarization data on adsorbed benzene with calculations.

In support of the experimental program, calculations are being performed on the angular distribution of electrons from free molecules. The theoretical portion of our program follows two different but complementary approaches: (1) the employment of Davenport's code, which makes use of the X_α scattering method, and (2)

the development of a new program that uses multi-centered Hartree-Fock molecular wave functions for the bound state and a single center expansion for the continuum. Recently, calculations on the angular distribution of photoelectrons, using the X_α scattering method, have been completed for the valence orbitals of CO, CO₂, COS, and CS₂ for photon energies of 15 to 45 eV. For randomly oriented molecules in the gas phase, a single parameter β is sufficient to describe the angular behavior and is dependent on the photoelectron energy and nature of the molecular orbital. Theory is compared with experiment in Fig. 8.1 and Table 8.1. To help evaluate our calculations, the β values were determined experimentally at 16.9 and 21.2 eV, using our polarized light source. For CO the theory gives reasonable results for the 4σ and 1π orbitals, but rather poor agreement in the case of the 5σ (similar findings occurred for N₂). For the triatomic molecules the agreement at 21.2 eV was quite satisfactory for CO₂ and COS but less so for CS₂. This can be understood in part because the larger the molecule, the larger the number of spherical waves required, and the solutions in this case of the σ orbitals of CS₂ are far from convergence.

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7. J. W. Davenport, *Phys. Rev. Lett.* **36**, 945 (1976); thesis, University of Pennsylvania (1976).

Fig. 8.1. Angular asymmetry parameter (β) as a function of photon energy and molecular orbital for CO. Dashed line, experimental values from synchrotron radiation: G. V. Marr, J. M. Morton, R. M. Holmes, and D. G. McCoy, *J. Phys. B* 12, 43 (1978); $\bar{x}$, experimental values, using HeI, NeI polarized radiation; solid line, theoretical calculations based on X_α scattering method with overlapping spheres - transition-state potential; dash-dot, theoretical calculations based on X_α scattering with "muffin tin" potential (ref. 7).

Table 8.1. Angular asymmetry parameter (β)

Orbital	Experiment ^a	Theory ^b
CO₂		
$1\pi_g$	0.0	-0.2
$1\pi_u$	1.0	0.7
$3\sigma_u$	-0.9	-0.3
$4\sigma_g$	1.2	1.3
COS		
3π	1.3	1.0
2π	0.6	0.2
9σ	0.5	0.4
8σ	0.7	0.8
CS₂		
$2\pi_g$	1.5	0.7
$2\pi_u$	1.3	1.2
$5\sigma_u$	0.5	0.1
$6\sigma_g$	1.4	1.0
$4\sigma_u$	1.4	0.1

^aRecent results from polarization lamp.

^bBased on X_α scattering model.

9. High-Energy Physics

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The research effort of the ORNL High-Energy Physics program encompasses several bubble-chamber experiments with emphasis on hybrid spectrometer experiments and neutral-secondary-particle detection. In an experiment at Fermi National Accelerator Laboratory (FNAL), accurate momentum measurement of fast secondary particles from interactions at 150 GeV/c momentum was achieved in the 30-in. liquid-hydrogen bubble chamber in conjunction with position-sensitive counters. Gammas from the decay of neutral particles were detected with a lead-glass shower detector for part of the data. At Stanford Linear Accelerator Center (SLAC) we are collaborating in an experiment designed to study pion-proton interactions in which neutral secondaries are produced. Tantalum plates inside the bubble chamber and an external very large lead-glass gamma shower detector permit measurements on the neutrals, while selection of desired events is accomplished by counter-controlled triggering of the 40-in. rapid-cycling bubble chamber.

In another experiment at Argonne National Laboratory (ANL) with the 12-ft bubble chamber, gamma detection is accomplished by use of a large bubble-chamber volume filled with a neon-hydrogen mixture, and the event is studied in a track-sensitive target filled with hydrogen placed inside the bubble chamber. We further have analyzed data from conventional bubble-chamber experiments: π^-p at 8 GeV/c and π^+d at 15 GeV/c in the SLAC 82-in. bubble chamber, and $\bar{p}p$ at rest in the ANL 12-ft chamber. ORNL is deeply involved in the design and construction of position-sensitive counters and external-particle identifiers for the above-mentioned experiments.

Hybrid Bubble-Chamber Experiments

Results from analysis of the interaction of π^+ , K^+ , and protons in hydrogen at 150-GeV/c momentum include

the measurement of topological cross sections, neutral strange-particle production, and Δ^{**} production. These results were obtained in collaboration with a consortium that has constructed and uses the hybrid bubble-chamber spectrometer at FNAL. ORNL is actively engaged in the instrumentation for updating this system to permit better particle identification and momentum measurement accuracy. Perhaps the most interesting and controversial new result comes from an analysis of our previous experimental data of π^-p interactions at 150 GeV/c. We observe that after removal of leading particle effects, the low t data from the central production region show striking similarities to the recently published high t data from deep inelastic electron scattering. If these similarities persist in other data, the implications could be most important for models of hadron production. We have started taking pictures in the SLAC 40-in. bubble-chamber hybrid system. The construction of the lead-glass gamma-detector wall and associated scintillator hodoscope was the responsibility of Duke University, Florida State University, University of Tennessee, and ORNL. A successful test has been completed.

Antiproton-Proton Interaction

We are scanning film from the exposure of 4.1-GeV/c antiprotons in a track-sensitive target mounted in the ANL 12-ft bubble chamber. By restricting the scan to frames containing a single event, the speed and efficiency of finding events with associated e pairs have improved greatly. The principal goal of the experiment (a collaboration with Notre Dame and the University of Melbourne) is to study the annihilations in which more than one π^0 is produced. Early results indicate that the average π^0 multiplicity in $\bar{p}p$ interactions is 1.35 ± 0.13 , 1.28 ± 0.12 , and 1.57 ± 0.16 for events with 2, 4, and 6 charged prongs, respectively. The ratio of the average number of charged particles produced in a hydrogen

annihilation to the number produced in a neon annihilation is 1.4 ± 0.2 , and the average number of pions produced in $\bar{p}p$ annihilation is about the same as that observed in e^+e^- annihilation at the same c.m. energy, but differs considerably from the value obtained in pp interaction.

π^- -Proton Interaction

In collaboration with MIT and Tohoku University, we have performed a high-statistics study of the π^-p reaction at 8-GeV/c incident π^- momentum for which two prongs were observed in the final state. Results on π^-p elastic scattering, the dipion system, and baryonic resonances have been obtained. Partial cross sections of various resonance production were determined by use of the prism plot technique. The ρ , f , and g meson production could be accounted for by a Regge model with π and A_2 exchanges. Baryon resonances were studied in terms of a moments analysis.

π^+ -Deuteron Reaction

In the study of the reaction π^+d at 15-GeV/c incident π^+ momentum, a principal feature is the observation of at least two neutral odd G parity bosons more massive than the $\omega(1675)$. Evidence is also found for the production of an $N^*(1700)$ which decays into a $\pi\Delta(1236)$ and which is produced at low momentum transfers ($t_{\pi, N^*}^{'} < 0.1 \text{ GeV}^2/c^2$). Cross sections for the more common baryon and meson resonance production were obtained. In the study of the dipion system we find evidence for a wide ($\Gamma \sim 200 \text{ MeV}$) state at $\approx 1920 \text{ MeV}$. This experiment is carried out in collaboration with Florida State University.

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10. Publications

Prepared by Wilma L. Stair

The following listing of publications includes primarily those articles by Physics Division staff members and associates which have appeared in print from May 1977 through December 1978. Some few articles published in 1976, not previously reported in the Division's Annual Report, are also included. Articles pending publication as of January 1, 1979, are listed immediately following this section.

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11. Papers Presented at Scientific and Technical Meetings May 1977 through December 1978

Prepared by Wilma L. Stair

Symposium on Electron Spectroscopy, Uppsala, Sweden, May 9-11, 1977

Carlson, T. A., W. B. Dress, and G. L. Nyberg (invited talk), "Study of *KLL* Auger Processes for Elements from $Z = 10$ to 20."

Second International Conference on Electrostatic Accelerator Technology, Strasbourg, France, May 24-27, 1977

Ball, J. B., "The Use of Cyclotrons as Energy Boosters for Electrostatic Accelerators."

Jones, C. M. (invited talk), "The Holifield Heavy-Ion Research Facility at Oak Ridge."

Larson, J. D. (invited talk), "Resolving Beam Transport Problems in Electrostatic Accelerators."

Sayer, R. O., "Semi-Empirical Formulas for Heavy-Ion Stripping Data."

Workshop on New Directions in Mössbauer Spectroscopy, Argonne, Illinois, June 9-11, 1977

Obenshain, F. E. (invited talk), "Test of Weyl's Gauge Invariant Geometry by the Mössbauer Effect."

American Nuclear Society, New York, New York, June 12-17, 1977

Barnett, C. F., "Controlled Fusion Atomic Data Center."

Ewbank, W. B. (invited talk), "Evaluated Nuclear Structure Data File (ENSDF) for Basic and Applied Research."

Meeting on Heavy-Ion Collisions, Pikeville, Tennessee, June 13-17, 1977

Cussor, R. Y. (invited talk), "Quantal Theory of Heavy-Ion Collisions Using a Three Dimensional TDHF Scheme."

Love, W. G., T. Terasawa, and G. R. Satchler, "Coulomb Excitation Effects on Heavy-Ion Elastic Scattering."

Maruhn, J. A. (invited talk), "The Fluid-Dynamical Model for Heavy-Ion Collisions in Three Dimensions."

Stokstad, R. G. (invited talk), "Heavy-Ion Reactions - An Experimental Vista."

Third International Symposium on Plasma Chemistry, Limoges, France, July 13-19, 1977

Crandall, D. H., "Atomic Reactions in Very High Temperature Plasmas."

Tenth International Conference on the Physics of Electronic and Atomic Collisions, Paris, France, July 21-27, 1977

Cisneros, C., I. Alvarez, R. Garcia, C. F. Barnett, and A. Russek, "Electron Capture to D_3^- Repulsive States by D_3^+ in Cs."

Crandall, D. H., P. O. Taylor, and R. A. Phaneuf, "Electron Impact Ionization of C IV and N V."

Hayden, H. C., and R. S. Thoe, "Least-Squares Deconvolution Method for Spectroscopic Data."

Olson, R. E., A. Salop, R. A. Phaneuf, and F. W. Meyer, "Electron Capture and Impact Ionization Cross Sections of He^{++} in Atomic Hydrogen."

Peterson, R. S., F. K. Chen, S. B. Elston, J. P. Forester, P. M. Griffin, H. C. Hayden, R. Laubert, C. A. Peterson, R. S. Thoe, C. R. Vane, and I. A. Sellin, "Neon Characteristic X-ray Production in Neon-Neon Collisions as a Function of Incident Projectile Charge State."

Phaneuff, R. A., F. W. Meyer, R. H. McKnight, and D. H. Crandall, "Electron Transfer between Multicharged Ions and Atomic Hydrogen."

Schumann, S., S. B. Elston, C. R. Vane, J. P. Forester, P. M. Griffin, D. J. Pegg, I. A. Sellin, R. S. Thoe, and J. J. Wright, "Spin-Dependent Excitation of Autoionizing States of Li Produced in Collisions with Noble Gas Targets."

Sellin, I. A., S. B. Elston, J. P. Forester, P. M. Griffin, D. J. Pegg, R. S. Peterson, R. S. Thoe, C. R. Vane, J. J. Wright, and K. O. Groeneveld, "Recoil Ion Spectroscopy in the XUV-Soft X-ray Region following Heavy Ion Impact on Thin Gas Targets."

Taylor, P. O., R. A. Phaneuf, D. Gregory, and G. H. Dunn, "Absolute Cross Sections for Electron Impact Excitation of C^{+3} ."

Vane, C. R., I. A. Sellin, F. Chen, S. B. Elston, J. P. Forester, P. M. Griffin, K. O. Groeneveld, R. Laubert, D. J. Pegg, R. S. Peterson, R. S. Thoe, and J. J. Wright, "High Resolution Studies of Extensive Ne *L*-Shell Excitation by Energetic Heavy Ion Impact."

Thirty-Fifth Annual Meeting of the Electron Microscopy Society of America, Boston, Massachusetts, August 22–26, 1977

Welton, T. A., "Optimized Programs for Testing Image Processing Algorithms."

Seventh Conference on High Energy Physics and Nuclear Structure, Basel, Switzerland, August 22–26, 1977

Milder, F., M. Blecher, K. Gotow, D. Jenkins, P. Roberson, F. E. Bertrand, T. P. Cleary, E. E. Gross, C. A. Ludemann, C. W. Darden, R. D. Edge, D. Malbrough, T. Marks, B. M. Freedom, R. L. Burman, M. Moinester, and R. P. Redwine, "Pion-Nuclear Inelastic Scattering at 50 MeV."

Milder, F., M. Blecher, D. A. Jenkins, K. Gotow, R. P. Redwine, M. A. Moinester, R. L. Burman, F. E. Bertrand, T. P. Cleary, E. E. Gross, C. A. Ludemann, D. A. Malbrough, C. W. Darden, R. D. Edge, T. Marks, and B. M. Freedom, "Low-Energy Elastic Scattering of Positive Pions from Nuclei."

American Chemical Society, Chicago, Illinois, August 28–September 2, 1977

Braga, R. A., G. M. Gowdy, J. L. Wood, and R. W. Fink, "Decay of Mass-Separated $^{195-197}\text{Tl}$."

Symposium on Shell-Model Investigations of Medium-Weight Nuclei, Tokyo, Japan, September 4, 1977

McGrory, J. B. (invited talk), "Shell-Model Origins of Collective Effects in Light- and Medium-Weight Nuclei."

International Conference on Nuclear Structure, Tokyo, Japan, September 5–10, 1977

deLima, A. P., J. H. Hamilton, A. V. Ramayya, B. van Nooijen, R. M. Ronningen, H. Kawakami, R. B. Piercey, L. K. Peker, R. L. Robinson, H. J. Kim and W. K. Tuttle, "Multiple Band Structure in ^{68}Ge and the $g_{9/2}$ Orbital."

Horen, D. J., and J. A. Harvey, "A Neutron Doorway State Correlated with *M1* Radiation in ^{208}Pb ."

Kawakami, H., A. P. deLima, J. H. Hamilton, R. M. Ronningen, A. V. Ramayya, R. L. Robinson, H. J. Kim, and L. K. Peker, "Evidence for Band Structure and Possible Triaxial Deformation in ^{65}Ga ."

McGrory, J. B., "Backbending in the $0f_{7/2}$ Shell."

Peker, L. K., J. H. Hamilton, A. V. Ramayya, R. B. Piercey, and R. L. Robinson, "Band Structure in Even-Even Nuclei in the $A \approx 70$ Region and the Role of the $g_{9/2}$ Orbital."

Raman, S., P. V. Gentry, C. J. Sparks, Jr., W. H. Christie, M. O. Krause, E. Ricci, C. A. Gossett, and J. B. Bates, "New Results from Studies on Radioactive Giant Halos."

Raman, S., W. T. Milner, C. W. Nestor, Jr., and P. H. Stelson, "Nuclear Transition Probability, $B(E2)$, for $0^+_{g.s.} \rightarrow 2^+_{\text{first}}$ Transitions."

Raman, S., M. Mizumoto, R. L. Macklin, G. G. Slaughter, G. L. Morgan, J. Halperin, G. T. Chapman, and R. R. Winters, "Fine Structure of a New *M1* Giant Resonance and the Tail of an Isoscalar *E2* Giant Resonance, in ^{208}Pb ."

Ramayya, A. V., J. H. Hamilton, H. Kawakami, R. B. Piercey, C. F. Maguire, W. T. Pinkston, A. P. de Lima, D. L. Sastry, J. C. Wells, A. C. Rester, R. L. Robinson, and H. J. Kim, "Possible Evidence for Asymmetric-Deformed-Near-Spherical Coexistence in ^{70}Se ."

Rester, A. C., J. B. Ball, and R. L. Auble, " $^{74,76}\text{Ge}(p,t)$ Reaction Studies."

Rester, A. C., A. P. de Lima, J. H. Hamilton, A. V. Ramayya, H. Kawakami, D. de Lima, R. M. Ronningen, R. L. Robinson, and H. J. Kim, "In-Beam Spectroscopy of ^{72}Ge ."

Rester, A. C., R. Gosselar, C. Gunther, H. Hubel, J. Lange, L. Posthumus, J. Konijn, and B. van Nooijen, "Energy Levels in ^{86}Zr Populated by $^{84}\text{Sr}(\alpha,2n\gamma)$."

Ronningen, R. M., J. H. Hamilton, L. Varnell, J. Lange, A. V. Ramayya, G. Garcia-Bermudez, W. Lourens, L. L. Riedinger, F. K. McGowan, P. H. Stelson, R. L. Robinson, and J. L. C. Ford, Jr., "Anomalous Hexadecapole Reduced Transition Matrix Elements in $^{176-180}\text{Hf}$."

Sastry, D. L., A. Ahmed, A. V. Ramayya, R. B. Piercey, J. H. Hamilton, C. F. Maguire, H. Kawakami, A. P. de Lima, R. L. Robinson, H. J. Kim, and J. C. Wells, "Band Structure of ^{80}Kr ."

Conference on Electro- and Photoexcitation, Sendai, Japan, September 12-13, 1977

Raman, S., M. Mizumoto, and R. L. Macklin, "The M1 and E2 Giant Resonances in ^{208}Pb Studied via the $^{207}\text{Pb}(n,\gamma)$ Reaction."

Symposium on Highly Excited States and Polarization Phenomena, Osaka, Japan, September 14-16, 1977

Raman, S., M. Mizumoto, and R. L. Macklin, "M1 and E2 Giant Resonances in ^{208}Pb ."

Second Conference on Hot Plasma Diagnostics, Kharkov, U.S.S.R., September 22-27, 1977

Barnett, C. F. (invited talk), "Status of U.S. Program to Measure Plasma Ion Temperature with Submillimeter Lasers."

Symposium of Northeastern Accelerator Personnel (SNEAP), Los Alamos, New Mexico, September 26-28, 1977

Larson, J. D., "Thoughts on Accelerator Tubes."

Moak, C. D., L. B. Bridwell, H. A. Scott, G. D. Alton, C. M. Jones, P. D. Miller, R. O. Sayer, Q. C. Kessel, and A. Antar, "Absolute Charge State Yields of 20 MeV ^{127}I Ions Emerging from a Gas Stripper."

Symposium on the Production and Neutralization of Negative Hydrogen Ions, Upton, New York, September 26-30, 1977

Crandall, D. H., and C. F. Barnett (invited talk), "Fundamental Atomic Collisional Processes in Negative Ion Sources for H^- ."

International Symposium on Nuclear Collisions and Their Microscopic Description, Bled, Yugoslavia, September 26 - October 1, 1977

Maruhn, J. A., R. Y. Cusson, and H. W. Meldner, "Time-Dependent Hartree-Fock Theory: Application to the $^{14}\text{N} + ^{12}\text{C}$ Reaction."

1977 Fall Meeting of the Optical Society of America, Toronto, Canada, October 9-15, 1977

Vander Sluis, K. L., D. P. Hutchinson, and P. A. Staats, "Performance of a High Power Submillimeter Oscillator-Amplifier System."

Workshop on Fundamental Physics Experiments with Reactor Neutrons and Neutrinos, Grenoble, France, October 10-14, 1977

Dress, W. B., and P. D. Miller (invited talk), "The Neutron Electric Dipole Moment."

IEEE 1977 Nuclear Science Symposium, San Francisco, California, October 19-21, 1977

Goodman, C. D., J. Rapaport, D. E. Bainum, M. B. Greenfield, and C. A. Goulding, "High Efficiency Detectors for Time-of-Flight with High Energy Neutrons."

American Physical Society (Division of Nuclear Physics), Rochester, New York, October 27-29, 1977

Bainum, D., J. Rapaport, C. Goulding, M. Greenfield, C. C. Foster, B. Anderson, A. Baldwin, J. Knudson, R. Madey, T. Witten, and C. D. Goodman, "Analogues of Magnetic Dipole States Observed in (p,n) Reactions on Self-Conjugate Targets," *Bull. Am. Phys. Soc.* 22, 998 (1977).

Bart, S., E. V. Hungerford, E. E. Gross, T. P. Cleary, D. C. Hensley, and C. R. Bingham, "Observation of Inflight Alpha Decay of ^{217}Ac by a New Technique," *Bull. Am. Phys. Soc.* 22, 1011 (1977).

Ewbank, W. B., "An Evaluated Nuclear Structure Data File," *Bull. Am. Phys. Soc.* 22, 996 (1977).

Gomez del Campo, J., R. A. Dayras, P. H. Stelson, R. G. Stokstad, J. A. Biggerstaff, and A. H. Snell, "Limitation on the Fusion of $^{16}\text{O} + ^{10}\text{B}$ Entrance Channel or Compound Nucleus," *Bull. Am. Phys. Soc.* 22, 1019 (1977).

Horen, D. J., and J. A. Harvey, "Evidence for $J^\pi = 1^-$ for the 7.99-MeV Level in ^{208}Pb ," *Bull. Am. Phys. Soc.* 22, 997 (1977).

Johnson, C. H., "Statistical Model Radiation Widths for $75 < A < 130$ and the Enhancement of p -Wave Neutron Capture for $A \approx 90$," *Bull. Am. Phys. Soc.* 22, 993 (1977).

Macklin, R. L., and J. Halperin, "Fast Neutron Capture by Thorium," *Bull. Am. Phys. Soc.* 22, 993 (1977).

Maguire, C. F., A. V. Ramayya, R. B. Piercey, G. Bomar, J. L. C. Ford, Jr., J. Gomez del Campo, and D. Shapira, "Investigation of the $^{40}\text{Ca}(^{11}\text{B}, ^{12}\text{C})^{39}\text{K}$ Reaction," *Bull. Am. Phys. Soc.* 22, 1010 (1977).

Mustafa, M. G., and R. L. Ferguson, "Fission of Very Heavy Elements ($100 \leq Z \leq 106$): What Are the Limits on Z and N for Which Fission is Asymmetric and Why?"

Plasil, F., R. L. Ferguson, H. C. Britt, B. H. Erkkila, P. D. Goldstone, R. H. Stokes, and H. H. Gutbrod, "Correlated Mass and Charge Distributions of Evaporation Residue Products from ^{86}Kr -Bombardments of ^{65}Cu ," *Bull. Am. Phys. Soc.* 22, 1020 (1977).

Raman, S., and E. T. Jurney, "The $^{59}\text{Ni}(n,\gamma)^{60}\text{Ni}$ Reaction with Thermal Neutrons," *Bull. Am. Phys. Soc.* 22, 1023 (1977).

Robinson, R. L., H. J. Kim, R. O. Sayer, R. B. Piercey, A. V. Ramayya, J. H. Hamilton, and J. C. Wells, Jr., "High-Spin States in ^{78}Kr ," *Bull. Am. Phys. Soc.* 22, 1027 (1977).

Sastry, D. L., A. Ahmed, C. F. Maguire, A. V. Ramayya, R. B. Piercey, H. Kawakami, J. H. Hamilton, A. P. deLima, R. L. Robinson, and H. J. Kim, "In-Beam Gamma-Ray Studies of ^{80}Kr ," *Bull. Am. Phys. Soc.* 22, 1028 (1977).

Webb, M. P., R. L. Ferguson, F. E. Obenshain, and F. Plasil, "Kinetic Energies of Deep Inelastic Products," *Bull. Am. Phys. Soc.* 22, 1021 (1977).

Weil, J. L., and B. D. Kern, "Positron Decay of ^{195}Pb and ^{195}Tl ," *Bull. Am. Phys. Soc.* 22, 996 (1977).

Western, W. R., J. L. Wood, R. A. Braga, and R. W. Fink, "The Decay of Mass-Separated $^{201}\text{m.g.p.}$," *Bull. Am. Phys. Soc.* 22, 996 (1977).

Wong, C. Y., "Plasma Oscillations in Finite Nuclei," *Bull. Am. Phys. Soc.* 22, 999 (1977).

Workshop on Isotope Separators On-Line, Upton, New York, October 31–November 1, 1977

Spejewski, E. H. (invited talk), "The UNISOR Project: Techniques and Results."

American Physical Society (Division of Plasma Physics), Atlanta, Georgia, November 7–11, 1977

Brisson, D. A., C. F. Barnett, J. A. Ray, and F. W. Baily, "Ceisum Heat-Pipe Neutral Particle Energy Analyzer," *Bull. Am. Phys. Soc.* 22, 1203 (1977).

Hutchinson, D. P., K. L. Vander Sluis, and P. A. Staats, "Characteristics of a High-Power Submillimeter Oscillator-Amplifier System," *Bull. Am. Phys. Soc.* 22, 1202 (1977).

Ma, C. H., D. P. Hutchinson, and K. L. Vander Sluis, "Measurement of Tokamak Current Density by Faraday Rotation of a Submillimeter Laser Beam," *Bull. Am. Phys. Soc.* 22, 1203 (1977).

Ray, J. A., C. F. Barnett, F. W. Baity, and B. H. Quon, "Velocity-Energy Neutral-Particle Analyzer," *Bull. Am. Phys. Soc.* 22, 1203 (1977).

American Physical Society, Miami Beach, Florida, November 21–23, 1977

Fowler, J. L., and C. H. Johnson, "Strength Functions for *s*-, *p*-, and *d*-Wave Neutron Resonances in ^{40}Ca ," *Bull. Am. Phys. Soc.* 22, 1246 (1977).

Johnson, C. H. (invited talk), "Giant Resonances below the Proton Coulomb Barrier," *Bull. Am. Phys. Soc.* 22, 1259 (1977).

Plasil, F., R. L. Ferguson, H. C. Britt, B. H. Erkkila, P. D. Goldstone, R. H. Stokes, M. Blann, and H. H. Gutbrod, "Measurement of Evaporation Residue Products from Reactions of ^{86}Kr with ^{70}Ge and ^{74}Ge ," *Bull. Am. Phys. Soc.* 22, 1247 (1977).

Ramayya, A. V., J. H. Hamilton, R. B. Piercey, H. Kawakami, C. F. Maguire, A. P. de Lima, H. J. Kim, and R. L. Robinson, "In-Beam Gamma-Ray Spectroscopy Studies in ^{70}Se ," *Bull. Am. Phys. Soc.* 22, 1247 (1977).

Stone, R. E., C. R. Bingham, L. L. Riedinger, R. W. Lide, H. K. Carter, E. H. Spejewski, and R. L. Mlekodaj, "Decay of Mass-Separated ^{199}Po ," *Bull. Am. Phys. Soc.* 22, 1243 (1977).

American Nuclear Society, San Francisco, California, November 27–December 2, 1977

Benjamin, R. W., J. A. Harvey, and N. W. Hill, "Neutron Total Cross-Section Measurements for ^{249}Bk and ^{249}Cf ,"

American Physical Society (Division of Electron and Atomic Physics), Knoxville, Tennessee, December 5–7, 1977

Bottcher, C. (invited talk), "Stripping of Light Systems by Highly Charged Species," *Bull. Am. Phys. Soc.* 22, 1324 (1977).

Crandall, D. H. (invited talk), "Experiments on Electron Impact Excitation and Ionization of Multicharged Ions," *Bull. Am. Phys. Soc.* 22, 1324 (1977).

Elston, S. B., C. R. Vane, J. P. Forester, P. M. Griffin, D. J. Pegg, S. Schumann, I. A. Sellin, M. Suter, and R. S. Thoe, "Target Specificity Effects on the Production of Core-Excited States of Li and Li^+ for 10 to 50 keV Collisions of Li^+ with Gas Targets," *Bull. Am. Phys. Soc.* 22, 1334 (1977).

Forester, J. P., D. J. Pegg, P. M. Griffin, G. D. Alton, S. B. Elston, H. C. Hayden, R. S. Thoe, C. R. Vane, and J. J. Wright, "Decay Measurements on the $n = 2$ States of Li-, Be-, and B-Like Chlorine," *Bull. Am. Phys. Soc.* 22, 1321 (1977).

Gregory, D., G. H. Dunn, D. H. Crandall, R. A. Phaneuf, and B. Hasselquist, "Absolute Cross Sections for $2s-2p$ Excitation of N^{4+} by Electron Impact," *Bull. Am. Phys. Soc.* 22, 1329 (1977).

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Johnson, B. M., K. W. Jones, D. J. Pegg, P. M. Griffin, T. H. Kruse, and J. L. Cecchi, "Decay Studies of $n = 3$ Transitions in Sodium-Like Bromine," *Bull. Am. Phys. Soc.* 22, 1321 (1977).

McDaniel, F. D., D. E. Johnson, G. Basbas, J. L. Duggan, R. Rice, R. Mehta, P. D. Miller, and K. A. Kuenhold, "*L*- and *M*-Shell X-Ray Production Cross Sections for the Ionization of Au , Pb , and Bi by 0.4 to 3.4 MeV/amu Carbon Ions," *Bull. Am. Phys. Soc.* 22, 1313 (1977).

Pegg, D. J., P. M. Griffin, G. D. Alton, S. B. Elston, J. P. Forester, M. Suter, R. S. Thoe, C. R. Vane, and B. M. Johnson, "Oscillator Strengths for the Principal Resonance Transitions in Si XI and XII," *Bull. Am. Phys. Soc.* 22, 1321 (1977).

Phaneuf, R. A. (invited talk), "Measurements of Electron Transfer from Hydrogen Atoms to Multiply Charged Ions," *Bull. Am. Phys. Soc.* 22, 1323 (1977).

Scott, H. A., L. B. Bridwell, C. D. Moak, G. D. Alton, C. M. Jones, P. D. Miller, R. O. Sayer, Q. C. Kessel, and A. Antar, "Investigations of Interatomic Potential Models through Multiple Electron Loss Processes," *Bull. Am. Phys. Soc.* 22, 1333 (1977).

Thoe, R. S., J. P. Forester, D. J. Pegg, P. M. Griffin, G. D. Alton, S. B. Elston, H. C. Hayden, C. R. Vane, and J. J. Wright, "Lifetimes and Oscillator Strength for $\Delta n + 0$ Dipole Transitions in C-, N-, O-, and F-Like Chlorine," *Bull. Am. Phys. Soc.* 22, 1321 (1977).

Specialists Meeting on Neutron Data of Structural Materials for Fast Reactors, Geel, Belgium, December 5-8, 1977

Weigmann, H., J. A. Harvey, R. L. Macklin, S. Raman, and G. G. Slaughter, "Resonance Parameters, Capture Gamma-Rays and Reaction Mechanism in $^{98,100}\text{Mo} + n$."

IAEA Symposium on National and International Standardization of Radiation Dosimetry, Atlanta, Georgia, December 5-9, 1977

Kocher, D. C., W. B. Ewbank, and M. J. Martin, "Standardized Radioactive Decay Data Sets for Use in Radiation Dosimetry."

Nuclear Data Forum, London, England, December 10, 1977

Fowler, J. L., J. A. Cookson, M. Hussain, R. B. Schwartz, M. T. Swinhoe, C. A. Uttley, and C. Wise, "Measurement of Neutron Detector Efficiencies by an Associated Particle Technique."

Symposium on Nuclear Physics, Oaxtepec, Mexico, January 3-5, 1978

Ford, J. L. C., Jr. (invited talk), "Heavy Ion Research at ORNL."

Informal Workshop on Current Stopping Power Problems, New York, New York, January 5-7, 1978

Hvelplund, P., "Energy Loss Straggling."

Moak, C. D. (invited talk), "Resonance Coherent Excitation of Channeled Ions."

International Workshop VI on Gross Properties of Nuclei and Nuclear Excitations, Hirschegg, Austria, January 15-21, 1978

Plasil, F., R. L. Ferguson, H. C. Britt, B. H. Erkkila, P. D. Goldstone, R. H. Stokes, M. Blann, and H. H. Gutbrod, "Studies of Evaporation Residue Products from Krypton and Argon Reactions."

Conference on Present and Future Aspects of In-Beam Gamma-Ray Spectroscopy, Aussois, France, January 22-28, 1978

Dayras, R. A., R. G. Stokstad, D. C. Hensley, M. L. Halbert, C. B. Fulmer, R. L. Robinson, D. G. Sarantites, and L. Westerberg, "Angular Momentum Transfer in Deep Inelastic Scattering."

American Physical Society, San Francisco, California, January 23-26, 1978

Benary, O., ..., H. O. Cohn, and other collaborators, "Study of the $(3\pi)^{\pm}$ System Produced in Four-Prong $\pi^{\pm}p$ Interactions at 147 GeV/c," *Bull. Am. Phys. Soc.* 23, 100 (1978).

Bertrand, F. E., M. Blecher, R. L. Burman, T. P. Cleary, S. Dam, C. W. Darden, R. D. Edge, K. Gotow, E. E. Gross, D. Jenkins, C. A. Ludemann, T. Marks, D. J. Malbrough, F. Milder, M. Moinester, B. M. Preedom, R. P. Redwine, and M. Yeater-Williams, "Positive Pion-Nucleus Elastic Scattering at 40 MeV," *Bull. Am. Phys. Soc.* 23, 81 (1978).

Bertrand, F. E., M. Blecher, R. L. Burman, T. P. Cleary, C. W. Darden, R. D. Edge, K. Gotow, E. E. Gross, D. Jenkins, C. A. Ludemann, D. J. Malbrough, T. Marks, F. Milder, M. A. Moinester, B. M. Preedom, and R. P. Redwine, "Elastic Scattering of Positive Pions at 30 MeV," *Bull. Am. Phys. Soc.* 23, 80 (1978).

Brau, J., ..., H. O. Cohn, E. L. Hart, and other collaborators, "Local Compensation of Charge in $\pi^{\pm}p$ and $\pi^{\pm}p$ Multiparticle Production at 147 GeV/c," *Bull. Am. Phys. Soc.* 23, 100 (1978).

Hafen, E. S., ..., H. O. Cohn, E. L. Hart, and other collaborators, "Off-Mass Shell Inclusive Reactions in $\pi^{\pm}p$ Collisions at 147 GeV/c," *Bull. Am. Phys. Soc.* 23, 100 (1978).

Horen, D. J., J. A. Harvey, and N. W. Hill, "s-, p-, and d-Wave Neutron Strength Functions for ^{207}Pb ," *Bull. Am. Phys. Soc.* 23, 91 (1978).

McDaniel, F. D., A. Toten, R. S. Peterson, J. L. Duggan, S. R. Wilson, D. Gressett, G. Basbas, G. Lapicki, P. D. Miller, R. M. Wheeler, R. P. Chaturvedi, A. Zander, K. Kuenhold, and L. A. Rayburn, "L- to K-Shell Electron Capture for ^{28}Si Ions Penetrating Thin Solid Targets of Nd, ^{14}Ho , and Au," *Bull. Am. Phys. Soc.* 23, 18 (1978).

Napier, A., ..., H. O. Cohn, W. M. Bugg, and other collaborators, "Forward π^0 Production in π^+p Interactions at 147 GeV/c," *Bull. Am. Phys. Soc.* 23, 100 (1978).

Stamer, P., ..., H. O. Cohn, and other collaborators, "Neutral Particle Production in π^+K^+p Collisions on Hydrogen at 147 GeV/c," *Bull. Am. Phys. Soc.* 23, 99 (1978).

Wheeler, R. M., R. P. Chaturvedi, F. D. McDaniel, J. L. Duggan, R. Rice, D. Johnson, R. Mehta, P. D. Miller, L. A. Rayburn, J. Lin, and K. Kuenhold, "14–38 MeV Boron Induced Ionization Cross Sections of Ho, Au, Pb, and Bi," *Bull. Am. Phys. Soc.* 23, 92 (1978).

Yamamoto, R. K., ..., H. O. Cohn, G. T. Condo, and other collaborators, "Analysis of the Reactions $\pi^-p \rightarrow \pi^-f + X^+$ and $\pi^-p \rightarrow p_f + X^-$ at 147 GeV/c," *Bull. Am. Phys. Soc.* 23, 100 (1978).

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Wong, C. Y., "Superheavy Toroidal Nuclei."

Third International Conference on Submillimeter Waves and Their Applications, Guildford, United Kingdom, March 29–April 1, 1978

Hutchinson, D. P., K. L. Vander Sluis, and C. H. Ma, "Measurement of Tokamak Current Density by Faraday Rotation of a FIR Laser Beam."

Vander Sluis, K. L., D. P. Hutchinson, and P. A. Staats, "Performance of a High-Power Submillimeter Oscillator-Amplifier System."

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Stokstad, R. G., Y. Eisen, S. Kaplanis, D. Pelte, U. Smilansky, and I. Tserruya, "The Effect of Nuclear Deformation on Heavy-Ion Fusion."

Symposium on Atomic Inner Shell Phenomena, Geilo, Norway, April 17–21, 1978

Carlson, T. A. (invited talk), "Summary of Conference."

American Physical Society, Washington, D.C., April 24–27, 1978

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- Wong, C. Y., and H. H. K. Tang, "Nuclear Lens Effect and Density Compression," *Bull. Am. Phys. Soc.* 23, 538 (1978).
- Oak Ridge Microscopy Evaluation Workshop, Washington, D.C., April 27–28, 1978**
- Welton, T. A., "ORNL Work in the Microscope Program."
- Japanese-U.S. Seminar on the Fundamentals and Applications of Particle Channeling, Tokai, Japan, May 8–12, 1978**
- Moskalev, D. (invited talk), "Resonant Coherent Excitation of Channeled Ions."

IEEE International Conference on Plasma Science, Monterey, California, May 14–17, 1978

Barnett, C. F. (invited talk), "Toroidal Plasma Current Density Measurements."

Conference on Applications of Ion Beams to Materials Science, Saitama, Japan, May 15–16, 1978

Moak, C. D. (invited talk), "Resonance Coherent Excitation of Channeled Ions."

Sixth International CODATA Conference, Santa Flavia (Palermo), Sicily, Italy, May 22–25, 1978

Ewbank, W. B., "Versatile Output from a Simple Numeric Data File."

Tenth International Quantum Electronics Conference, Atlanta, Georgia, May 29–June 1, 1978

Bottcher, C., and C. Feuillede, "Microscopic Derivation of Bloch Equations and Relaxation Time."

Hutchinson, D. P., K. L. Vander Sluis, and C. H. Ma, "A Submillimeter-Wave Laser Polarimeter for Tokamak Plasma Diagnostics."

Workshop on High Resolution Heavy Ion Physics at 20–100 MeV/A, Saclay, France, May 31–June 2, 1978

McGrory, J. B., "Time-Dependent Hartree-Fock Calculations of Kr-Induced Strongly Damped Collisions."

Workshop on the 'Interacting Boson Model,' Erice, Italy, June 5–9, 1978

McGrory, J. B. (invited talk), "Shell Model Tests of the Interacting Boson Model Description of Nuclear Collective Motion."

American Chemical Society 52nd Colloid and Surface Science Symposium, Knoxville, Tennessee, June 6–12, 1978

Agron, P. A., W. B. Dress, and T. A. Carlson, "UV-Angular Resolved Photoemission Studies of Adsorbed Species on Single Crystals."

Twenty-Eighth Annual Conference on Physical Electronics, Gatlinburg, Tennessee, June 19–21, 1978

Dress, W. B., P. A. Agron, and J. O. Thomson, "Angle-Resolved, Polarized UV-Photoemission from Benzene Oriented on Nickel (111)."

Gordon Research Conference on Nuclear Chemistry, New London, New Hampshire, June 19–23, 1978

Davies, K. T. R. (invited talk), "Is There Life after TDHF?"

Third International Conference on Clustering Aspects of Nuclear Structure and Nuclear Reactions, Winnipeg, Canada, June 19–23, 1978

Clover, M. R., R. M. DeVries, B. Fulton, R. Ost, N. J. A. Rust, N. Anantaraman, J. L. C. Ford, Jr., and D. Shapira, "Elastic Back Angle Scattering of ^{12}C ."

Cusson, R. Y., J. Gomez del Campo, and H. W. Meldner, "Heavy Ion Clusters in the TDHF Approximation,"

Fourth International Conference on $\bar{N}N$ Interactions, Strasbourg, France, June 26–30, 1978

Biswas, N. N., ..., W. M. Bugg, G. T. Condo, T. Handler, E. L. Hart, H. O. Cohn, and other collaborators, "Neutral Particle Production in 4.1 GeV/c $\bar{p}p$ Interactions Using the 12-Foot Bubble Chamber with TST."

1978 IEEE-MTT-S International Microwave Symposium, Ottawa, Canada, June 27–29, 1978

Ma, C. H., D. P. Hutchinson, and K. L. Vander Sluis, "A Submillimeter-Wave Polarimeter for Plasma Diagnostics."

European Group on Atomic Spectroscopy Conference, Munich, West Germany, July 11–14, 1978

Pegg, D. J., J. P. Forester, P. M. Griffin, G. D. Alton, S. B. Elston, B. M. Johnson, M. Suter, R. S. Thoe, and C. R. Vane, "Time-Resolved Spectroscopic Measurements on Multiply Charged Si, P, and Cl Ions."

Latin-American School of Physics, Mayaguez, Puerto Rico, July 17–21, 1978

Wong, C. Y. (invited talks – three lectures), "Applications of Green's Functions to Nuclear Dynamics."

Gordon Research Conference on Electron Spectroscopy, Wolfeboro, New Hampshire, July 17–21, 1978

Carlson, T. A. (invited talk), "Photoelectron Angular Distribution of Free Molecules."

Dress, W. B. (poster session), "Oriented Benzene."

International Conference on Dynamical Properties of Heavy-Ion Reactions, Johannesburg, South Africa, August 1–3, 1978

Stokstad, R. G., "Resonances and Backward-Angle Scattering."

Gordon Research Conference on Particle Solid Interactions, Andover, New Hampshire, August 7–11, 1978

Moak, C. D. (invited talk), "Studies of Resonant Coherent Excitation of Atomic States in Crystal Channels."

Gordon Research Conference on Photonuclear Reactions, Meriden, New Hampshire, August 14–18, 1978

Raman, S. (invited talk), "Radiative Neutron Capture."

Sixth International Conference on Atomic Physics, Riga, U.S.S.R., August 17–22, 1978

Bottcher, C., H. J. Kim, F. W. Meyer, R. A. Phaneuf, P. H. Stelson, and P. Hvelplund, "Observation of Coulomb Interference in Total Electron Capture Cross Sections."

1978 NATO Advanced Study Institute in Nuclear Theory, Banff, Alberta, Canada, August 21–26, 1978

Bertrand, F. E. (invited talk), "The New Giant Resonances – An Experimental Overview."

Seventh International Conference on Plasma Physics and Controlled Thermonuclear Research, Innsbruck, Austria, August 23–30, 1978

Phaneuf, R. A., J. T. Hogan, H. J. Kim, F. W. Meyer, P. H. Stelson, P. Hvelplund, D. H. Crandall, C. F. Barnett, R. E. Olson, K. H. Berkner, W. G. Graham, R. V. Pyle, A. S. Schlachter, and J. W. Stearns, "Neutral Beam Penetration into Plasmas with $Z_{\text{eff}} > 1$."

Nineteenth International Conference on High Energy Physics, Tokyo, Japan, August 23–30, 1978

Brick, D., ..., H. O. Cohn, W. M. Bugg, G. T. Condo, T. Handler, E. Hart, and other collaborators, "The Fitted Channels $\pi^- \rightarrow \pi^- p \pi^+ \pi^-$ and $\pi^- p \rightarrow \pi^- p 2\pi^+ 2\pi^-$ at 147 GeV/c Incident Momentum."

Brick, D., ..., H. O. Cohn, G. T. Condo, E. L. Hart, and other collaborators, "A Comparison of Δ^{++} Production in $\pi^+ p$ and pp ."

Brick, D., ..., H. O. Cohn, G. T. Condo, E. L. Hart, and other collaborators, "Topological Cross Section for $K^+ p$ Interactions at 147 GeV/c."

Kitagaki, T., ..., H. O. Cohn, W. M. Bugg, G. T. Condo, T. Handler, and E. L. Hart, "Study of Two-Charged Particle Final States of 8 GeV/c $\pi^- p$ Interactions."

Pless, I. A., ..., H. O. Cohn, W. M. Bugg, T. Handler, and other collaborators, "Inclusive and Semi-Inclusive Charge Structure in $\pi^- p$ Multiparticle Production at 147 GeV/c."

International Conference on Nuclear Interactions, Canberra, Australia, August 28–September 1, 1978

deLima, A. P., J. H. Hamilton, A. V. Ramayya, B. van Nooijen, R. M. Ronningen, H. Kawakami, R. B. Piercey, R. L. Robinson, H. J. Kim, W. K. Tuttle, L. K. Peker, F. A. Rickey, and R. Popli, "Multiple Band Structure in ^{68}Ge and the $g_{9/2}$ Orbital."

Halbert, M. L., R. A. Dayras, J. R. Beene, D. C. Hensley, L. Westerberg, D. G. Sarantites, and K. A. Geoffroy, "Studies of the Gamma Continuum from ^{20}Ne on ^{150}Nd ."

Hamilton, J. H., R. B. Piercey, A. V. Ramayya, R. L. Robinson, D. L. Sastry, A. Ahmed, L. K. Peker, H. Kawakami, A. P. deLima, H. J. Kim, R. O. Sayer, and J. C. Wells, "Possible New Region of Trapping Near $N = 40$."

Hamilton, J. H., R. L. Robinson, and A. V. Ramayya, "Collective Motions and Band Structures in $A = 60$ –80, Even-Even Nuclei."

Piercey, R. B., A. V. Ramayya, J. H. Hamilton, C. F. Maguire, R. L. Robinson, H. J. Kim, and J. C. Wells, "Band Structures in $^{64,76}\text{Kr}$."

Piercey, R. B., A. V. Ramayya, J. H. Hamilton, R. L. Robinson, L. K. Peker, D. L. Sastry, A. Ahmed, H. Kawakami, A. P. deLima, H. L. Crowell, H. J. Kim, R. O. Sayer, and J. C. Wells, "Band Structures in $^{76,78,80}\text{Kr}$."

Robinson, R. L., H. J. Kim, R. O. Sayer, W. T. Milner, R. Piercey, A. V. Ramayya, J. H. Hamilton, and J. C. Wells, Jr., "In-Beam Gamma Rays from ^{78}Kr ."

Fifth International Conference on Beam Foil Spectroscopy, Villeurbanne, France, September 4-8, 1978

Forester, J. P., D. J. Pegg, P. M. Griffin, G. D. Alton, S. B. Elston, H. C. Hayden, R. S. Thoe, C. R. Vane, and J. J. Wright, "A Systematic Study of $2s^2 2p^k - 2s2p^{k+1} - 2p^{k+2}$ Transitions in Multiply Charged Cl Ions."

Pegg, D. J., J. P. Forester, P. M. Griffin, G. D. Alton, S. B. Elston, B. M. Johnson, M. Suter, R. S. Thoe, and C. R. Vane, "Oscillator Strength Determinations for $\Delta n = 0$ Transitions in Be-Like Ions of the Third Period Elements."

Sellin, I. A., "Creation of Mixed-Parity Excited States in $\text{H}(n=2)$ Following Single, Charge Transfer Collisions of Fast H^+ in Gases."

Sellin, I. A. (invited talk), "Electron 'Cusp' Spectroscopy of the Forward Peak in Continuum Electron Capture and Loss in Gases and Solids."

Sellin, I. A., C. R. Vane, M. Suter, S. B. Elston, G. D. Alton, R. S. Thoe, and P. M. Griffin, "Zero-Degree Electron 'Cusps' from Charge Transfer to Continuum States of Bare and Highly Ionized Ions."

Fourth European Sectional Conference on Atomic and Molecular Physics of Ionized Gases, Essen, West Germany, September 18-20, 1978

Barnett, C. F. (invited talk), "Atomic and Molecular Data Needs Relevant to Fusion Research."

International Workshop on Coherence and Correlation in Atomic Collisions, London, England, September 18-20, 1978

Bottcher, C. (invited talk), "Coherence Effects in Heavy Ion-Atom Collisions."

Eighth International Conference on Cyclotrons and Their Applications, Bloomington, Indiana, September 18-21, 1978

Ball, J. B., E. D. Hudson, R. S. Lord, J. A. Martin, G. S. McNeilly, and S. W. Mosko (invited talk), "Status of the Holifield Heavy Ion Research Facility Phase II Booster."

Fulmer, C. B., H. M. Butler, W. F. Ohnesorge, and S. W. Mosko, "Fast Neutron Dose Rates in Heavy Ion Target Areas."

Goodman, C. D., C. C. Foster, M. B. Greenfield, and J. Rapaport, "A Facility for Studying Neutron Energy Spectra from Reactions Such as (p,n) at Intermediate Energies."

Third International Conference on Neutron Capture Gamma Ray Spectroscopy, Upton, L.I., New York, September 18-22, 1978

Carlton, R. F., S. Raman, and E. T. Jurney, "The $^{115}\text{Sn}(n,\gamma)$ Reaction with Thermal Neutrons."

Horen, D. J., J. A. Harvey, and N. W. Hill, "Parity Assignments from High Resolution Neutron Scattering and M1 Radiative Strength in ^{208}Pb ."

Macklin, R. L. (invited talk), "Resonance Capture Reactions with a Total Energy Detector."

Mizumoto, M., J. H. Hamilton, S. Raman, R. L. Macklin, G. G. Slaughter, and J. A. Harvey, "Enhanced Primary M1 Transitions in ^{207}Pb ."

Raman, S. (invited talk), "Localized Dipole and Quadrupole Radiation Strengths in ^{208}Pb ."

Raman, S., and E. T. Jurney, "The $^{59}\text{Ni}(n,\gamma)$ Reaction with Thermal Neutrons."

Weigmann, H., S. Raman, J. A. Harvey, R. L. Macklin, and G. G. Slaughter, "Capture Gamma-rays and Reaction Mechanism in $^{100}\text{Mo} + n$."

Wells, J. C., Jr., S. Raman, and G. G. Slaughter, "Correlation of the Primary Gamma-Ray Intensities Following s- and p-Wave Neutron Capture in ^{58}Fe ."

International Conference on Neutron Physics and Nuclear Data for Reactors and Other Applied Purposes, Harwell, England, September 25–29, 1978

Musgrove, A. R. de L., B. J. Allen, J. W. Boldemann, and R. L. Macklin, "Recent Measurements of Neutron Capture Cross Sections in the Fission Product Mass Region."

Musgrove, A. R. de L., B. J. Allen, and R. L. Macklin, "Resonance E Neutron Capture in ^{23}Na and ^{27}Al from 3 to 600 keV."

1978 Nuclear Science Symposium, Washington, D.C., October 18–20, 1978

Hensley, D. C., "The Event Handler – A Fast Programmable, CAMAC-Coupled Data Acquisition Interface."

RCNP Seminar on Nuclear Reactions, Osaka, Japan, October 23, 1978

Satchler, G. R. (invited talk), "Excitation of Giant Resonances by Proton Scattering."

Symposium of Northeast Accelerator Personnel (SNEAP), Oak Ridge, Tennessee, October 23–25, 1978

Alton, G. D. (invited talk), "Negative Ion Source Developments at ORNL."

Ziegler, N. F. (invited talk), "Operating Features of 25 MV Accelerator Control System."

Institute for Nuclear Studies (INS) International Symposium on Nuclear Direct Reaction Mechanisms, Fukuoka, Japan, October 25–28, 1978

Satchler, G. R. (invited talk), "Microscopic, Semi-Realistic Interactions for Both Light- and Heavy-Ion Scattering."

Southeastern Section of the American Physical Society, Blacksburg, Virginia, October 26–28, 1978

Lide, R. W., C. R. Bingham, L. L. Riedinger, M. W. Guidry, J. A. Vrba, and E. F. Zganjar, "Decay of a Low-Spin Isomer of ^{200}Bi ," *Bull. Am. Phys. Soc.* 24, 108 (1979).

Ritchie, B. G., H. K. Carter, R. L. Mlekodaj, and E. H. Spejewski, "The Decay of Mass-Separated ^{208}Fr ," *Bull. Am. Phys. Soc.* 24, 108 (1979).

Soundranayagam, R., R. B. Piercey, J. H. Hamilton, A. V. Ramayya, C. F. Maguire, R. L. Robinson, and H. J. Kim, "Yrast Band in ^{74}Kr ," *Bull. Am. Phys. Soc.* 24, 108 (1979).

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Sixth Institute for Nuclear Studies (INS) Summer School on Nuclear Physics, Dogashima, Japan, October 30–November 2, 1978

Satchler, G. R. (invited talk), "Some Aspects of Heavy-Ion Scattering."

American Physical Society, (Division of Plasma Physics), Colorado Springs, Colorado, October 30–November 3, 1978

Hutchinson, D. P., C. H. Ma, K. L. Vander Sluis, and P. A. Staats, "Simultaneous Measurement of Electron Density and Plasma Current in a Tokamak," *Bull. Am. Phys. Soc.* 23, 850 (1978).

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American Physical Society (Division of Nuclear Physics), Asilomar, California, November 1–3, 1978

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Garg, J. B., V. K. Tikku, I. A. Harvey, and N. Hill, "High Resolution Neutron Total Cross Sections in the Separated Isotopes of Zn," *Bull. Am. Phys. Soc.* 23, 943 (1978).

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Gomez del Campo, J., R. A. Dayras, J. A. Biggerstaff, A. H. Snell, D. Shapira, P. H. Stelson, and R. G. Stokstad, "Fusion of $^{16}\text{O} + ^{10}\text{B}$ and the Liquid Drop Limit," *Bull. Am. Phys. Soc.* 23, 949 (1978).

Goodman, C. D. (invited talk), "The (p,n) Reaction at Intermediate Energy," *Bull. Am. Phys. Soc.* 23, 939 (1978).

Gross, E. E., T. P. Cleary, J. L. C. Ford, D. C. Hensley, K. S. Toth, F. T. Baker, A. Scott, C. R. Bingham, and J. A. Vrba, " $^{22}\text{Ne}(131\text{ MeV}) + ^{208}\text{Pb}$ Elastic and Inelastic Scattering," *Bull. Am. Phys. Soc.* 23, 942 (1978).

Guidry, M. W., R. E. Neese, C. R. Bingham, J. A. Vrba, I. Y. Lee, and N. R. Johnson, "A Fundamental Determination of the Surface Structure of Deformed Nuclei," *Bull. Am. Phys. Soc.* 23, 946 (1978).

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Raman, S. (invited talk), "Dipole and Quadrupole Radiation Strengths from Discrete States of ^{208}Pb ," *Bull. Am. Phys. Soc.* 23, 957 (1978).

Ramos, M. P. M., L. L. Riedinger, C. R. Bingham, M. W. Guidry, R. W. Lide, J. A. Vrba, J. L. Wood, R. W. Fink, E. H. Spejewski, R. L. Mlekodaj, and H. K. Carter, "Decay of Mass-Separated ^{202}At and ^{202}Po ," *Bull. Am. Phys. Soc.* 23, 946 (1978).

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Sarantites, D. G., L. Westerberg, K. Geoffroy, J. R. Beene, R. A. Dayras, M. L. Halbert, D. C. Hensley, and J. H. Barker, "Properties of the Gamma-Continuum from $^{150}\text{Nd}(^{20}\text{Ne},\alpha\gamma)$ Reactions at 115 and 130 MeV," *Bull. Am. Phys. Soc.* 23, 942 (1978).

Sayer, R. O., "Rocket Plots of Charge State Distributions for Tandem Electrostatic Accelerators," *Bull. Am. Phys. Soc.* 23, 937 (1978).

Shapira, D., R. Dayras, J. L. C. Ford, J. Gomez del Campo, A. H. Snell, P. H. Stelson, and R. G. Stokstad, "Fusion of $^{20}\text{Ne} + ^{20}\text{Ne}$ and $^{20}\text{Ne} + ^{16}\text{O}$," *Bull. Am. Phys. Soc.* 23, 949 (1978).

Tang, H. H. K., and C. Y. Wong, "Extended Time-Dependent Hartree-Fock Approximation Illuminates the Approach to Thermal Equilibrium," *Bull. Am. Phys. Soc.* 23, 955 (1978).

Vrba, J. A., C. R. Bingham, M. W. Guidry, T. P. Cleary, E. E. Gross, D. C. Hensley, S. Bart, and E. V. Hungerford, "Alpha Decay from a High Spin Isomer," *Bull. Am. Phys. Soc.* 23, 963 (1978).

Fifth International Conference on Application of Small Accelerators, Denton, Texas, November 6-8, 1978

Alton, G. D. (invited talk), "Recent Developments in Heavy Ion Sources for Accelerators," *Bull. Am. Phys. Soc.* 23, 1039 (1978).

Button, T. M., R. S. Peterson, F. D. McDaniel, A. Toten, M. C. Andrews III, R. Rice, J. D. Gressett, J. L. Duggan, R. S. Thoe, G. D. Alton, and P. D. Miller, "Radiative Electron Capture X-ray Profiles from Fast Collisions of F^{+q} with He, N_2 , Ne, and Ar," *Bull. Am. Phys. Soc.* 23, 1059 (1978).

Elston, S. B. (invited talk), "Failure of Single Electron Descriptions of Molecular Orbital Collision Processes," *Bull. Am. Phys. Soc.* 23, 1026 (1978).

Martin, J. A. (invited talk), "Status of the Holifield Heavy Ion Research Facility," *Bull. Am. Phys. Soc.* 23, 1039 (1978).

Miller, P. D. (invited talk), "Multiple Electron Loss Cross Sections for Heavy Ions Incident on Various Atomic and Molecular Gases," *Bull. Am. Phys. Soc.* 23, 1048 (1978).

Milner, W. T. (invited talk), "Double-Drift Beam Bunching Systems," *Bull. Am. Phys. Soc.* 23, 1039 (1978).

Peterson, R. S., F. D. McDaniel, M. C. Andrews III, A. Toten, J. L. Duggan, R. S. Thoe, and P. D. Miller, "Projectile Charge State Enhancement of MO X-Ray Production in F^{+q} -Ne Collisions," *Bull. Am. Phys. Soc.* 23, 1059 (1978).

Peterson, R. S., F. D. McDaniel, J. L. Duggan, R. S. Thoe, and P. D. Miller, " MO X-Ray Production in Collisions of F^{+q} with Ne," *Bull. Am. Phys. Soc.* 23, 1059 (1978).

Raman, S., and C. J. Sparks, Jr. (invited talk), "X-Ray Fluorescence with Synchrotron Radiation," *Bull. Am. Phys. Soc.* 23, 1036 (1978).

Toten, A., F. D. McDaniel, R. S. Peterson, J. L. Duggan, S. R. Wilson, J. D. Gressett, P. D. Miller, and G. Lapicki, "Projectile Charge State Dependence of Target L_{α} X-Ray Production," *Bull. Am. Phys. Soc.* 23, 1053 (1978).

American Nuclear Society, Washington, D.C., November 12-16, 1978

Williams, M. L., and S. Raman, "Calculational and Experimental Analysis of a ^{239}Pu Sample Irradiated in EBR-II."

Specialists Meeting on the Nuclear Data of Higher Plutonium and Americium Isotopes for Reactor Applications, Upton, Long Island, New York, November 19-22, 1978

Dabbs, J. W. T. (invited talk), "Instrumentation for Actinide Cross Section Research."

Heavy Ion Resonance Workshop, Tallahassee, Florida, November 20-21, 1978

Ford, J. L. C., Jr., "Anomalies in the $^{12}C(^{15}N, \alpha)$ Excitation Functions and Angular Distributions."

Gomez del Campo, J., "Search for Resonances in the Total Neutron Yield of Light Heavy-Ion Systems."

Shapira, D., "Fusion of $^{20}N + ^{12}C$ and Other Channels."

American Physical Society (Division of Electron and Atomic Physics), Madison, Wisconsin, November 29-December 1, 1978

Crandall, D. H., "Electron Impact Ionization of O^{3+} ," *Bull. Am. Phys. Soc.* 23, 1099 (1978).

Elston, S. B., I. A. Sellin, M. Suter, C. R. Vane, G. D. Alton, P. M. Griffin, and R. S. Thoe, "Systematics of Continuum Capture and Loss by Bare and Highly Ionized H, C, O, and Si Projectile Ions Traversing He, Ne, and Ar Targets," *Bull. Am. Phys. Soc.* 23, 1086 (1978).

Gregory, D. C., B. E. Hasselquist, R. A. Phaneuf, and D. H. Crandall, "Structure in Electron Impact Ionization of N^{4+} ," *Bull. Am. Phys. Soc.* 23, 1100 (1978).

Kim, H. J., and F. W. Meyer, "Total Electron Loss by Atomic Hydrogen in Collisions with N^{+q} ," *Bull. Am. Phys. Soc.* 23, 1095 (1978).

Liljeby, L., B. Jelenkovic, S. Mannervik, S. Hultberg, and I. A. Sellin, "Molecular Modulation of $H(n \approx 4)$ Quantum Beats Following Single Foil Excitation of H^+ , H_2^+ , H_3^+ Beams," *Bull. Am. Phys. Soc.* 23, 1099 (1978).

Meyer, F. W., "The H^- Equilibrium Fraction in Hydrogen Beams Traversing a Thick Cs Target," *Bull. Am. Phys. Soc.* 23, 1108 (1978).

Sellin, I. A., L. Liljeby, S. Mannervik, and S. Hultberg, "Consequences for Parity Violation Experiments of Creation of Mixed-Parity Excited States in $H(n=2)$ following Single Collisions of Fast H^+ Gases," *Bull. Am. Phys. Soc.* 23, 1095 (1978).

Suter, M., C. R. Vane, I. A. Sellin, S. B. Elston, G. D. Alton, R. S. Thoe, and R. Laubert, "Observation of Strong Structure in the Forward Peak from Fast-Projectile Electron Loss," *Bull. Am. Phys. Soc.* 23, 1086 (1978).

Thoe, R. S., C. R. Vane, S. B. Elston, P. M. Griffin, G. D. Alton, G. Glass, L. E. Williams, and M. Suter, "Search for Correlation Effects between Multiple Electron Loss to Continuum Events in High Energy O^{+4} -Ar Collisions," *Bull. Am. Phys. Soc.* 23, 1086 (1978).

Vane, C. R., M. Suter, I. A. Sellin, G. D. Alton, S. B. Elston, P. M. Griffin, and R. S. Thoe, "Electron Capture to Continuum States by Bare Projectile Ions," *Bull. Am. Phys. Soc.* 23, 1086 (1978).

12. General Information

Prepared by F. E. Bertrand, C. R. Wallace, and W. L. Stair

ANNOUNCEMENTS

In October 1978 the Nuclear Physics Research Section of the Physics Division was reorganized as shown below.

Manager, Nuclear Physics Research Section -- E. F. Gross

Group 1	Group 2	Group 3
F. E. Bertrand ¹	F. Plasil ¹	R. G. Stokstad ¹
C. B. Fulmer ³	C. R. Bingham ⁴	J. R. Beene ¹⁰
C. D. Goodman	R. L. Ferguson ⁵	J. A. Biggerstaff ²
M. W. Guidry ⁴	D. C. Hensley	J. L. C. Ford
N. R. Johnson ⁵	F. E. Cbenschain	J. Gomez del Campo
H. J. Kim ⁶	A. H. Snell ⁹	M. L. Halbert
I. Y. Lee ¹⁰	K. S. Toth	D. C. Hensley
F. K. McGowan	G. Young	D. Shapira
W. T. Milner ²		
R. L. Robinson ⁷		
J. C. Wells ⁸		

PERSONNEL CHANGES

C. R. Bingham (ORIC -- Heavy-Ion Research) -- University of Tennessee; began part-time appointment in October 1977

G. L. Bomar (Tandem -- Heavy-Ion Research) -- Vanderbilt University; completed part-time temporary appointment in November 1978

C. Bottcher (Theoretical Physics) -- Began a two-year appointment in September 1977

W. M. Bugg (High-Energy Physics) -- University of Tennessee; began part-time appointment in October 1977

R. F. Carlton (Oak Ridge Electron Linear Accelerator) -- Middle Tennessee State University; began part-time appointment in October 1977

T. P. Cleary (ORIC -- Heavy-Ion Research) -- Transferred to Computer Sciences Division in February 1978

G. T. Condo (High-Energy Physics) -- University of Tennessee; began part-time appointment in October 1977

J. J. Cowan (Infrared Spectroscopy) -- Completed temporary appointment in December 1977

R. A. Dayras (ORIC -- Heavy-Ion Research) -- Completed temporary postdoctoral appointment in October 1978

1. Group leader.
2. 20% nuclear physics research; remainder HHIRF.
3. 20% nuclear physics research; remainder on assignment to ORAU.
4. Consultant from University of Tennessee.
5. Chemistry Division.
6. 20% nuclear physics research; 80% atomic physics research.
7. 50% nuclear physics research; 50% HHIRF.
8. Consultant from Tennessee Technological Institute, Cookeville.
9. Consultant.
10. 50% Chemistry Division support.

- L. C. Dennis (Tandem – Heavy-Ion Research) – University of Virginia; completed temporary appointment in September 1978
- J. L. Fowler (Oak Ridge Electron Linear Accelerator) – Retired in November 1978
- J. Gomez del Campo (Tandem – Heavy-Ion Research) – National University of Mexico, Mexico City; continued temporary appointment begun in May 1976
- F. A. Grimm (Electron Spectroscopy) – University of Tennessee; began part-time appointment in October 1977
- M. W. Guidry (ORIC – Heavy-Ion Research) – University of Tennessee; began part-time appointment in October 1977
- E. L. Hart (High-Energy Physics) – University of Tennessee; began part-time appointment in October 1977
- B. E. Hasselquist (Atomic Physics) – University of Wisconsin; completed temporary appointment in August 1978
- I. A. Howard (Atomic Physics) – Massachusetts Institute of Technology; completed temporary summer appointment in June 1977
- W. A. Huber (Electron Spectroscopy) – Haverford College; completed temporary summer appointment in August 1978
- P. Hvelplund (Tandem – Atomic Physics) – Completed a one-year appointment in July 1978
- H. Knudsen (Tandem – Atomic Physics) – Completed a one-year appointment in August 1978
- J. D. Larson (Holifield Heavy-Ion Research Facility) – Completed temporary part-time appointment in December 1977
- I. Y. Lee (ORIC – Heavy-Ion Research) – Began two-year appointment in September 1977
- M. W. Lucas (Tandem – Atomic Physics) – Began one-year appointment in August 1978
- M. L. Mallory (Holifield Heavy-Ion Research Facility) – Terminated employment in June 1978
- J. A. Maruhn (Theoretical Physics) – Completed three-year appointment in August 1977
- V. Maruhn (Theoretical Physics) – Completed one-year appointment in July 1977
- H. W. Morgan (Atomic Physics) – Retired in December 1978
- V. E. Oberacker (Theoretical Physics) – Began two-year appointment in September 1978
- D. J. Pegg (Accelerator-Based Atomic Physics) – University of Tennessee; terminated part-time appointment in March 1978
- R. A. Phaneuf (CTR-Related Atomic Physics) – Continued temporary appointment begun in October 1976
- R. B. Piercey (Tandem – Heavy-Ion Physics) – Vanderbilt University; completed temporary appointment in December 1977
- S. Ramavataram (Nuclear Data Project) – Began part-time appointment in December 1978
- L. L. Riedinger (ORIC – Heavy-Ion Research) – University of Tennessee; terminated part-time appointment in July 1978
- M. J. Saltmarsh (ORIC – Heavy-Ion Research) – Transferred to Fusion Energy Division in December 1977
- H. W. Sang, Jr. (Oak Ridge Electron Linear Accelerator) – Massachusetts Institute of Technology; completed temporary summer appointment in September 1977
- D. G. Sarantites (ORIC – Heavy-Ion Research) – Washington University; completed temporary summer appointments in August 1977 and August 1978
- H. A. Scott (Tandem – Atomic Physics) – Cornell University; completed temporary summer appointment in August 1977
- I. A. Sellin (Accelerator-Based Atomic Physics) – University of Tennessee; began part-time appointment in October 1977
- D. Shapira (ORIC – Heavy-Ion Research) – Continued temporary appointment begun in September 1976
- J. F. Shriner, Jr. (Oak Ridge Electron Linear Accelerator) – University of the South; completed temporary summer appointment in August 1978
- D. M. Thomas (Experimental Plasma Physics) – University of Texas at Austin; completed temporary summer appointment in July 1977
- J. O. Thomson (Electron Spectroscopy) – University of Tennessee; began part-time appointment in November 1977
- C. Toepffer (Theoretical Physics) – University of Witwatersrand, Johannesburg, South Africa; began six-month temporary appointment (sabbatical leave) in October 1978
- M. P. Webb (Nuclear Data Project and ORIC – Heavy-Ion Research) – Completed two-year appointment in August 1978

J. C. Wells (Tandem – Heavy-Ion Research) – Tennessee Technological University; began part-time appointment in October 1977

R. E. Worsham (Electron Microscope) – Transferred to Fusion Energy Division in August 1977

G. R. Young (ORIC – Heavy-Ion Research) – Began temporary two-year appointment as Eugene P. Wigner Fellow in September 1978

C. B. Fulmer (ORIC – Heavy-Ion Research) – Assigned to Oak Ridge Associated Universities as manager of the ORAU/ORNL training program in nuclear science for scientists and engineers from the Esfahan Nuclear Technology Center in Iran, December 1977–January 1979

M. L. Mallory (Oak Ridge Isochronous Cyclotron) – Assigned to Michigan State University, July 1976–June 1978

J. B. McGroarty (Theoretical Physics) – Completed assignment begun in October 1975 with the ORNL Program Planning and Analysis Office

R. G. Stokstad (ORIC – Heavy-Ion Research) – Assigned to Weizmann Institute of Science, Rehovot, Israel, July 1977–January 1978, and to GSI, Darmstadt, West Germany, January 1978–August 1978

STAFF ASSIGNMENTS

T. A. Carlson (Electron Spectroscopy) – Assigned to Forskningsinstitutet for Atomphysik (Research Institute for Physics), Stockholm, Sweden, September 1977–September 1978

PERSONNEL ASSIGNMENTS

During 1977–78 the Physics Division was host to guests from abroad as well as from the United States. Some of these were short-term assignments, variously sponsored by different organizations and institutions. Physics Division staff members have also been the guests of laboratories located outside the United States.

Research Participants from Abroad

E. I. Andrade – Universidad Nacional Autonoma, Mexico City, Mexico (Tandem – Heavy-Ion Research)

J. Blachot – Commissariat a l'Energie Atomique, Grenoble, France (Nuclear Data Project)

P. F. Bortignon – University of Padova, Italy (Theoretical Physics)

J. S. Briggs – Atomic Energy Research Establishment, Harwell, England (Atomic Physics Theory)

R. A. Broglia – Niels Bohr Institute, Copenhagen, Denmark (Theoretical Physics)

M. Cardenas – Universidad Nacional Autonoma, Mexico City, Mexico (Tandem – Heavy-Ion Research)

B. Castel – Queen's University, Kingston, Ontario, Canada (Theoretical Physics)

N. M. Clarke – King's College, London, England (ORIC – Heavy-Ion Research)

A. J. Cole – University of Grenoble, France (Tandem – Heavy-Ion Research)

A. A. Dacal – Ciudad Universitaria, Mexico (Tandem – Heavy-Ion Research)

S. R. Devi – Schuster Laboratory, Manchester University, Manchester, England (Theoretical Physics)

N. A. Fazzini – Argentine Atomic Energy Commission, Buenos Aires, Argentina (Holifield Heavy-Ion Research Facility)

H. T. Feldmeier – Technische Hochschule, Darmstadt, West Germany (Theoretical Physics)

C. Feuillade – Schuster Laboratory, Manchester University, Manchester, England (Theoretical Physics)

F. G. Garcia Santibanez – Ciudad Universitaria, Mexico (Electron Spectroscopy)

A. I. Gavron – Weizmann Institute of Science, Rehovot, Israel (ORIC – Heavy-Ion Research)

M. Ghanbari – Atomic Energy Organization of Iran (ORELA research)

B. Gilbody – Queen's University, Belfast, Ireland (Atomic Physics)

W. Greiner – University of Frankfurt, West Germany (Theoretical Physics)

F. Kearns – University of Liverpool, England (Nuclear Data Project)

K. C. Kulander – Daresbury Laboratory, England (Theoretical Physics)

B. Mahdavian – Atomic Energy Organization of Iran (ORELA research)

- A. Menchaca-Rocha – Universidad Nacional Autonoma, Mexico City, Mexico (Tandem – Heavy-Ion Research)
- M. Mizumoto – Japan Atomic Energy Research Institute, Ibaraki-ken, Japan (ORELA research)
- J. N. Mo – University of Manchester, England (Nuclear Data Project)
- U. B. Mosel – Institut für theoretische Physik, Justus Liebig University, Giessen, West Germany (Theoretical Physics)
- J. A. Nicolai – Argentine Atomic Energy Commission, Buenos Aires (Holifield Heavy-Ion Research Facility)
- V. E. Oberacker – University of Frankfurt, West Germany (Theoretical Physics)
- S. M. E. Ortiz – Universidad Nacional Autonoma, Mexico City, Mexico (Tandem – Heavy-Ion Research)
- C. Renner – Institute de Engrgia Atomic, Sao Paulo, Brazil (ORELA research)
- G. E. Soff – University of Frankfurt, West Germany (Theoretical Physics)
- M. F. Steeden – University of London, King's College, London, England (ORIC – Heavy-Ion Research)
- H. Stocker – University of Frankfurt, West Germany (Theoretical Physics)
- M. Suter – ETH, Zurich Switzerland (Tandem – Atomic Physics Research)
- A. van der Woude – Kernfysisch Versneller Instituut, Groningen, The Netherlands (ORIC – Light-Ion Research)
- D. A. Viggars – Kuwait University, Kuwait, Arabian Gulf (Nuclear Data Project)
- G. F. Bertsch – Michigan State University (Theoretical Physics)
- M. Blecher – Virginia Polytechnic Institute and State University (Pion Physics)
- H. G. Blosser – Michigan State University (Holifield Heavy-Ion Research Facility)
- G. L. Bomar – Vanderbilt University (Tandem – Heavy-Ion Research)
- L. B. Bridwell – Murray State University (Tandem – Atomic Physics Research)
- D. A. Bromley – Yale University (Nuclear Physics)
- H. K. Carter – Oak Ridge Associated Universities (UNISOR Project)
- R. Y. Cusson – Duke University (Theoretical Physics)
- A. P. deLima – Vanderbilt University (Tandem – Heavy-Ion Research)
- R. M. DeVries – Los Alamos Scientific Laboratory (ORIC – Heavy-Ion Research)
- D. M. Drake – Los Alamos Scientific Laboratory (ORELA research)
- S. Elston – University of Tennessee (Tandem – Atomic Physics Research)
- J. P. Felvinci – Columbia University (ORELA research)
- E. J. Fisher – University of Pittsburgh (Atomic Physics)
- J. P. Forester – University of Tennessee at Chattanooga (Tandem – Atomic Physics Research)
- J. L. Fowler – self, ORNL retiree (ORELA research)
- J. Gaiser – Auburn University (ORIC – Heavy-Ion Research)
- L. D. Gardner – Yale University (Tandem – Atomic Physics Research)
- J. Garg – State University of New York at Albany (ORELA research)
- K. A. Geoffroy – Washington University (ORIC – Heavy-Ion Research)
- G. A. Glass – University of Tennessee (Tandem – Atomic Physics Research)
- K. Gotow – Virginia Polytechnic Institute and State University (Pion Physics)
- G. M. Gowdy – Georgia Institute of Technology (UNISOR Project)
- D. C. Gregory – University of Colorado-JILA (Atomic Physics)
- M. A. Grimm, Jr. – University of Georgia at Athens (UNISOR Project)

Research Participants from the United States

- A. Y. Ahmed – Vanderbilt University (Tandem – Heavy-Ion Research)
- A. A-G. Antar – University of Connecticut (Tandem – Atomic Physics Research)
- G. Auchampaugh – Los Alamos Scientific Laboratory (ORELA research)
- P. M. Bakshi – Boston College (experimental plasma research)
- J. E. Bayfield – Yale University (Atomic Physics)
- S. D. Berry – Albion College (Tandem – Atomic Physics Research) Formerly with the GLCA-ORNL Science Semester Program (Theoretical Physics)

- J. H. Hamilton – Vanderbilt University (Tandem – Heavy-Ion Research)
- T. Handler – University of Tennessee (High-Energy Physics)
- H. Hayden – University of Connecticut (Tandem – Atomic Physics Research)
- D. L. Hillis – University of Tennessee (ORIC – Heavy-Ion Research)
- B. R. Junker – Office of Naval Research (Theoretical Physics)
- A. C. Kahler III – University of Tennessee (ORIC – Heavy-Ion Research)
- S. E. Koonin – California Institute of Technology (Theoretical Physics)
- R. Laubert – New York University (Tandem – Heavy-Ion Research)
- P. W. Lisowski – Los Alamos Scientific Laboratory (ORELA research)
- W. G. Love – University of Georgia (Theoretical Physics)
- B. Luers – Columbia University (ORELA research)
- C. H. Ma – University of Mississippi (Experimental Plasma Physics)
- J. J. Malanify – Los Alamos Scientific Laboratory (ORELA research)
- F. McDaniel – North Texas State University (Tandem – Atomic Physics Research)
- E. McDaniels – Georgia Institute of Technology (Atomic Physics)
- R. H. McKnight – University of Virginia (Atomic Physics)
- R. Mehta – North Texas State University (Tandem – Atomic Physics Research)
- F. L. Milder – Virginia Polytechnic Institute and State University (Pion Physics)
- R. L. Mlekodaj – Oak Ridge Associated Universities (UNISOR Project)
- T. J. Morgan – Wesleyan University (Atomic Physics)
- J. D. Moses – Los Alamos Scientific Laboratory (ORELA research)
- R. E. Neese – University of Tennessee (ORIC – Heavy-Ion Research)
- B. Newbolt – Washington and Lee University (Tandem – Heavy-Ion Research)
- T. L. Nichols – University of Tennessee (UNISOR Project)
- M. S. Pandey – College of William and Mary (ORELA research)
- R. L. Parks – University of Virginia (Tandem – Heavy-Ion Research)
- P. Z. Peebles – University of Tennessee (Holifield Heavy-Ion Research Facility)
- R. Peterson – North Texas State University (Tandem – Atomic Physics Research)
- G. A. Petitt – Georgia State University (ORIC – Heavy-Ion Research)
- R. B. Piercey – Vanderbilt University (ORIC – Heavy-Ion Research)
- F. Pleasonton – self, ORNL retiree (ORIC – Heavy-Ion Research)
- B. Freedom – University of South Carolina (Pion Physics)
- M. P. M. Ramos – University of Tennessee (UNISOR Project)
- J. F. Reading – Texas A&M University (Theoretical Physics)
- A. C. Rester – Tennessee Technological University (ORIC – Heavy-Ion Research)
- B. G. Ritchie – University of South Carolina (UNISOR Project)
- R. M. Ronningen – Michigan State University (Tandem – Heavy-Ion Research)
- A. Russek – University of Connecticut (Atomic Physics)
- Y. Sangsingkeow – North Texas State University (Tandem – Atomic Physics Research)
- D. G. Sarantites – Washington University (ORIC – Heavy-Ion Research)
- P. Singh – Virginia Polytechnic Institute and State University (UNISOR Project)
- L. A. Slover – self, ORNL retiree (Holifield Heavy-Ion Research Facility)
- A. H. Snell – self, ORNL retiree (ORIC – Heavy-Ion Research)
- D. C. Sousa – University of Tennessee (UNISOR Project)
- E. H. Spejewski – Oak Ridge Associated Universities (UNISOR Project)

R. E. Stone, Jr. – University of Tennessee (UNISOR Project)
 M. R. Strayer – Texas A&M University (Theoretical Physics)
 H. Tang – Yale University (Theoretical Physics)
 E. W. Thomas – Georgia Institute of Technology (Atomic Physics)
 T. M. Thomas – University of Tennessee (Electron Spectroscopy)
 J. R. Thompson – University of Tennessee (Holifield Heavy-Ion Research Facility)
 S. T. Thornton – University of Virginia (Tandem – Heavy-Ion Research)
 R. Vane – University of Tennessee (Tandem – Atomic Physics Research)
 J. A. Vrba – University of Tennessee (ORIC – Heavy-Ion Research)
 L. A. Westerberg – Washington University (ORIC – Heavy-Ion Research)
 K. E. Wikstrom – Washington University (ORIC – Heavy-Ion Research)
 L. F. Williams – University of Tennessee (Tandem – Atomic Physics Research)
 R. R. Winters – Denison University (ORELA research)
 R. Woodward – Washington University (ORIC – Heavy-Ion Research)

Undergraduate Students

M. E. Barclay – Tennessee Technological University (Tandem Accelerator, with R. L. Robinson)
 J. K. Black – North Carolina State University, 1977 summer appointment with ORAU (Tandem Accelerator, with G. D. Alton)
 G. C. Blazey – South Dakota State University, 1978 summer appointment with ORAU (Tandem Accelerator, with G. D. Alton)
 C. A. Dawson – Angelo State University, summer appointment with ORAU (Tandem Accelerator, with R. L. Robinson)
 R. W. Eastes – Tennessee Technological University (Tandem Accelerator, with R. L. Robinson)
 S. E. Greco – LaSalle College, 1977 summer appointment with ORAU (Experimental Plasma Physics, with D. P. Hutchinson)
 K. A. Griffioen – Calvin College, 1978 summer appointment with ORAU (Oak Ridge Electron Linear Accelerator, with S. Raman)
 M. W. Hart – Florida Institute of Technology, 1978 summer appointment with ORAU (Oak Ridge Isochronous Cyclotron, with D. C. Hensley)
 B. E. Hasselquist – University of Wisconsin, 1977 summer appointment with ORAU (Atomic Physics, with D. H. Crandall)
 E. L. Hill – Norris High School graduate, 1978 Youth Opportunity Program (Tandem Accelerator, with P. D. Miller)
 K. A. Holcomb – Oklahoma State University, 1978 summer appointment with ORAU (Theoretical Physics)
 I. Howard – Massachusetts Institute of Technology (Atomic Physics, with R. P. Phaneuf)
 M. W. Howard – University of Tennessee employee (High-Energy Physics, with H. O. Cohn)
 J. M. Kiser – Volunteer State Community College, 1978 summer appointment with ORAU (Tandem Accelerator, with W. T. Milner)
 C. M. Manning – University of Tennessee employee (High-Energy Physics, with H. O. Cohn)
 R. Megson – University of Tennessee employee (High-Energy Physics, with H. O. Cohn)
 R. L. Monday – University of Tennessee, ORNL co-op student (Van de Graaff Laboratory, with J. L. C. Ford)
 J. M. Ortolfo – State University of New York at Buffalo, 1978 summer appointment with ORAU (Oak Ridge Electron Linear Accelerator, with C. H. Johnson)
 S. M. Sergiwa – Tennessee Technological University (UNISOR Project)
 J. Shriner – University of the South (Oak Ridge Linear Electron Accelerator, with D. J. Horen)
 B. J. Smith – Washington University (Oak Ridge Isochronous Cyclotron, with M. L. Halbert)
 L. F. Stuk – Tennessee Technological University (Tandem Accelerator, with R. L. Robinson)
 D. Thomas – University of Texas (Experimental Plasma Physics, with C. F. Barnett)
 A. L. Wintenberg – University of Tennessee, ORNL co-op student (Tandem Accelerator, with J. L. C. Ford)

RESEARCH PARTICIPANTS UNDER CONTRACT ARRANGEMENT WITH OAK RIDGE ASSOCIATED UNIVERSITIES

Under arrangements with Oak Ridge Associated Universities ("S" contracts and "U" contracts), 80 university or college faculty members and students visited the Physics Division for consultation and collaboration during 1977-78. These individuals and their affiliation are listed below:

R. G. Albridge, Vanderbilt University	O. W. Holland, North Texas State University
M. C. Andrews, North Texas State University	E. V. Hungerford, University of Houston
F. T. Avignone III, University of South Carolina	M. A. Ijaz, Virginia Polytechnic Institute and State University
N. Azziz, University of Puerto Rico at Mayaguez	R. W. Jones, University of South Dakota
F. T. Baker, University of Georgia	M. Kaplan, Carnegie-Mellon University
J. H. Barker, Saint Louis University	H. Kawakami, Vanderbilt University
S. Bart, University of Houston	B. D. Kern, University of Kentucky
G. L. Bomar, Vanderbilt University	R. L. Kozub, Tennessee Technological University
R. A. Braga, Georgia Institute of Technology	S. J. Krieger, University of Illinois at Chicago Circle
W. H. Brantley, Furman University	K. A. Kuenhold, University of Tulsa
L. B. Bridwell, Murray State University	R. L. Laubert, New York University
T. Button, North Texas State University	J. Lin, Tennessee Technological University
A. J. Caffrey III, Johns Hopkins University	P. Lookadoo, University of Virginia
A. Caretto, Carnegie-Mellon University	A. Mackellar, University of Kentucky
E. W. Carriere, Louisiana State University at Shreveport	C. F. Maguire, Vanderbilt University
R. P. Chaturvedi, State University of New York at Cortland	D. Malbrough, Los Alamos Scientific Laboratory
S. J. Cipolla, Creighton University	F. D. McDaniel, North Texas State University
M. R. Clover, University of Rochester	W. G. Nettles, Vanderbilt University
K. R. Cordell, University of Virginia	W. B. Newbolt, Washington and Lee University
F. L. Culp, Tennessee Technological University	P. J. Ouseph, University of Louisville
L. C. Dennis, University of Virginia	R. L. Parks, University of Virginia
R. R. Doering, University of Virginia	G. A. Petitt, Georgia State University
J. L. Duggan, North Texas State University	W. T. Pinkston, Vanderbilt University
R. D. Edge, University of South Carolina	A. V. Ramayya, Vanderbilt University
D. H. Feng, Drexel University	P. V. Rao, Emory University
R. W. Fink, Georgia Institute of Technology	L. A. Rayburn, University of Texas at Arlington
A. L. Ford, Jr., Texas A&M University	J. F. Reading, Texas A&M University
J. P. Forester, University of Tennessee at Chattanooga	R. K. Rice, North Texas State University
J. D. Fox, Florida State University	E. L. Robinson, University of Alabama at Birmingham
J. E. Gaiser, Auburn University	D. G. Sarantites, Washington University
T. A. Girard, University of South Carolina	A. Scott, University of Georgia
A. Goodman, Tulane University	D. C. Sousa, Eastern Kentucky University
J. D. Gressett, North Texas State University	M. R. Strayer, Texas A&M University
J. H. Hamilton, Vanderbilt University	S. T. Thornton, University of Virginia

A. Toten, North Texas State University	S. R. Wilson, North Texas State University
A. Visvanathan, Louisiana State University	R. R. Winters, Denison University
T. A. Walkiewicz, Edinboro State College	J. L. Wood, Georgia Institute of Technology
J. Weil, University of Kentucky	R. F. Woodward, Washington University
W. Western, Georgia Institute of Technology	A. R. Zander, East Texas State University
R. M. Wheeler, State University of New York at Cortland	E. F. Zganjar, Louisiana State University

GRADUATE THESIS RESEARCH

During 1977-78, Physics Division staff and associates served as advisors for 12 students engaged in thesis research. All projects listed below were carried out with facilities operated at least in part by the Division.

Ph.D. Thesis Research

Candidate	Advisor(s)	Thesis title or field of research
A. V. Ahmed, Vanderbilt University	R. L. Robinson	In-beam gamma-ray spectroscopy of $A \approx 70$ nuclei
G. L. Bomar, Vanderbilt University	J. L. C. Ford	Heavy-ion reactions
A. P. deLima, Vanderbilt University	R. L. Robinson	High-spin states in $^{68,72}\text{Ge}$
J. P. Forester, University of Tennessee	D. J. Pegg	An investigation of radiative lifetimes and oscillator strengths for allowed intra L -shell transitions in multiply charged chlorine ions
James Gaiser, Auburn University	F. E. Obenshain	Correlated mass and charge distribution by time-of-flight methods
M. A. Grimm, Georgia Institute of Technology	E. H. Spejewski R. L. Mlekodaj	Shape coexistence near the $Z = 82$ closed shell: A study of the excited states of ^{187}Au and ^{187}Pb in the β^+ decay of ^{187}Hg and ^{187}Au
R. S. Peterson, University of Tennessee	I. A. Sellin	Neon characteristic x-ray production in neon-neon collisions
B. G. Ritchie, University of South Carolina	H. K. Carter E. H. Spejewski	Collective structure of levels of ^{208}Rn , ^{206}Rn
T. M. Thomas, University of Tennessee	T. A. Carlson	Photoelectron spectroscopy
J. A. Vrba, University of Tennessee	E. E. Gross	Alpha decay of high-spin isomers

Master's Thesis Research

S. Bart,
University of Houston

E. E. Gross

Measurement of short alpha
half-lives by a decay-in-
flight technique

D. A. Brisson,
North Carolina State
University

C. F. Barnett

A cesium heat-pipe neutral-
particle spectrometer

MISCELLANEOUS PROFESSIONAL ACTIVITIES OF DIVISIONAL PERSONNEL

Staff members are frequently involved in professional work incidental to their primary laboratory responsibilities. For example, a majority of the professional staff act as referees for over two dozen journals, principally the *Physical Review*, *Physical Review Letters*, and *Nuclear Physics*, and many review proposals for funding organizations. Other activities include those listed below.

J. B. Ball – member, Program Committee for Division of Nuclear Physics of APS; member, ORNL Landscape and Architecture Committee

F. E. Bertrand – member, APS Division of Nuclear Physics Committee on Nuclear Science Resources; member of Indiana University Users Group, LAMPF Users Group, and TRIUMF Users Group; member, Scientific Advisory Committee for 1979 Topical Conference on Large Amplitude Collective Nuclear Motion, Lake Balaton, Hungary; member, Organizing Committee for 1979 Topical Conference on Giant Multipole Resonances, Oak Ridge, Tennessee

J. A. Biggerstaff – member, U.S. NIM/CAMAC Committee and Fast System Design Group; member, Program Committee for 1979 Topical Conference on Computerized Data Acquisition Systems in Particle and Nuclear Physics

T. A. Carlson – member, Editorial Board of Journal of Electron Spectroscopy; chairman, ORNL-ORAU Users Group for VUV Beam Line at 0.7 GeV Storage at Brookhaven National Laboratory; member, international committee for evaluating Atomic and Molecular Physics in Sweden

D. H. Crandall – member, General Committee of the International Conference on Physics of Electron and Atomic Collisions (1977–81); symposia organizer for "Capture Processes Involving Multicharged Ions" at International Conference on the Physics of Electronic and Atomic Collisions at Kyoto, Japan (1979); member, Program Committee of Division of Electron and Atomic Physics of the American Physical Society (for 1979 annual meeting); member, Proposal Review Committee of Seed Money Program at ORNL

J. W. T. Dabbs – Registered Professional Engineer (Tenn. No. 11475); University Relations Coordinator for ORAU and ORNL summer student trainee, faculty research participant, and graduate student summer programs 1974–78 and GLCA science program 1976–78; member, Editorial Board, Nuclear Instruments and Methods, 1978–

W. B. Ewbank – delegate, Tennessee Conference on Library and Information Services, held November 19–21, 1978, Nashville, Tennessee

R. L. Ferguson – ORIC scheduling coordinator; guest scientist ("Outside User"), SuperHILAC, Lawrence Berkeley Laboratory, Berkeley, California

J. L. C. Ford – Physics Division EN Tandem mentor; member, Users Groups of LBL SuperHILAC, Brookhaven National Laboratory Cyclotron Facility and Indiana University Cyclotron Facility

C. B. Fulmer – Radiation Control Officer and Division Safety Officer (through February 15, 1978)

C. D. Goodman – chairman, ORNL Science and Technology Colloquium; chairman elect, IUCF Users Group; chairman, IUCF Neutron Working Group; member, board of directors American Committee for the Weizmann Institute of Science; chairman, Organizing Committee for the Conference on the (p, n) Reaction and the Nucleon-Nucleon Force, Telluride, Colorado, March 29–31, 1979

E. E. Gross – member, UNISOR Executive Committee; member, Organizing Committee for 2nd International Conference on Meson Nuclear Physics, Houston, March 5–9, 1979; member, Organizing Committee for Topical Conference on Giant Multipole Resonances, Oak Ridge, October 15–17, 1979

- N. R. Johnson — member, ORIC Program Committee; ORIC Scheduling Coordinator; member, SuperHILAC Users Executive Committee; mentor, HHIRF Gamma-Ray Facilities; vice-chairman, 1978 Gordon Research Conference on Nuclear Chemistry; chairman, 1979 Gordon Research Conference on Nuclear Chemistry; member, Program Committee, Division of Nuclear Chemistry and Technology, American Chemical Society, 1977; guest scientist ("Outside User"), SuperHILAC, Lawrence Berkeley Laboratory; chairman, nominating committee for members of Users Executive Committee, HHIRF, ORNL; symposium chairman, American Chemical Society Meeting, Chicago, Illinois, August 29, 1977; member, Directory Committee, Nuclear Chemistry and Technology Section, American Chemical Society, 1978–79
- C. M. Jones — member, Program Committee, 1979 Particle Accelerator Conference
- J. A. Martin — chairman, Technical Committee on Accelerators and member of Administrative Committee of the IEEE Nuclear and Plasma Sciences Society; member, Board of Directors Mid-Continent Electronics Conference (MIDCON); member, Meetings Committee of IEEE Technical Accelerator Board; member, Editorial Advisory Board of *Particle Accelerators*; consultant, National Science Foundation Physics Section as member of Accelerator Visiting Committee; consultant, Union Carbide Medical Products Division; member, Organizing Committee for the 1979 Particle Accelerator Conference; member, International Organizing Committee for Eighth International Conference on Cyclotrons and Their Applications at Indiana University; member, Lawrence Berkeley Laboratory Accelerator Division Review Committee
- F. K. McGowan — associate editor, Atomic Data and Nuclear Data Tables
- J. B. McGrory — member, ORIC Scheduling Committee; member of ORNL Computer Advisory Committee
- F. Plasil — chairman, ORNL Graduate Participant Selection Panel; member, SuperHILAC Users Executive Committee; chairman, 1978 Gordon Research Conference on Nuclear Chemistry; member, LAMPF Users Association; member of the Holifield Heavy-Ion Facility Users Group Executive Committee
- S. Raman — member, International Advisory Committee, Third International Symposium on Neutron Capture Gamma-Ray Spectroscopy and Related Topics, Brookhaven National Laboratory, September 18, 1978
- R. L. Robinson — Liaison Officer for the Users Group of the Holifield Heavy-Ion Research Facility; member of Organizing Committee for Fall 1979 APS Nuclear Physics Meeting
- G. R. Satchler — member, Contacts with the Press Committee of Division of Nuclear Physics of American Physical Society; member, Editorial Board of Atomic Data and Nuclear Data Tables; member, Organizing Committee for the Symposium on Heavy-Ion Elastic Scattering, University of Rochester, October 25–26, 1977; member, International Advisory Committee for the Topical Research Institute of Theoretical Physics, University of Washington, Seattle, July 23–August 24, 1979; member, International Advisory Committee for the International Symposium on Nuclear Collisions and Their Microscopic Description, Bled, Yugoslavia, September 26–October 1, 1977; member, Organizing Committee for the Conference on the (p,n) Reaction and the Nucleon-Nucleon Force, Telluride, Colorado, March 29–31, 1979; member, Organizing Committee for the Topical Conference on Giant Multipole Resonances, Oak Ridge, October 15–17, 1979; member, International Advisory Committee for the Fifth Polarization Conference, Los Alamos, New Mexico, 1980
- P. H. Stelson — part-time faculty member, Department of Physics, University of Tennessee; associate editor of Nuclear Physics; member, Executive Committee, Division of Nuclear Physics of the American Physical Society; member, Visiting Committee for Nuclear Science Division, Lawrence Berkeley Laboratory
- R. G. Stokstad — member, SuperHILAC Program Advisory Committee; member, Brookhaven Tandem Program Advisory Committee; member, National Science Foundation Subcommittee for the Review of Nuclear Science; member, NUSAC Facilities Subcommittee; member, Editorial Board, *Physical Review C*; member, Scientific Program Committee, International Conference on Nuclear Structure, Berkeley, 1980
- K. S. Toth — chairman (during 1977), Major Nuclear Chemistry Facilities Committee of the American Chemical Society; chairman, UNISOR Scheduling Committee; member, UNISOR Technical Committee

PHYSICS DIVISION SEMINARS – MAY 26, 1977–DECEMBER 31, 1978

The Physics Division seminars were held generally on Thursdays at 3:00 PM in the Building 6010 Conference Room. In addition, there are more specialized meetings – atomic physics seminars, nuclear research coffees, and theoretical circuses – which may not be announced laboratory-wide in the Technical Calendar. During the period covered by this report, F. Plasil served as chairman until August 1977 and F. Obenshain until January 1979.

Date	Speaker	Title
5/26/77	W. B. Dress, Division Staff	Precision Measurement of the Magnetic Moment of the Neutron
6/02/77	G. G. Slaughter, Division Staff	ACES – How to Heat and Cool a House
6/17/77	J. Vervier, Université de Louvain, Belgium	High-Spin States in the Ground-State and Side Bands of ^{156}Dy , ^{162}Er , and ^{168}Hf , Investigated through Proton- and ^{14}N -Induced Reactions
6/21/77	Carl Sofield, AERE, Harwell, England	Charge-Exchange Considerations in the Energy-Loss Straggling of Partially Stripped Fast Ions
6/23/77	B. W. Farmery, University of Sussex, England	Heavy-Ion Ranges in Aluminum and Silicon
6/28/77	Pascal Colombani, Institute of Nuclear Physics, Orsay, France	Recent Experiments at Orsay: Identification of Heavy Fragments and Reaction Mechanism Studies
6/30/77	D. L. Hillis, Niels Bohr Institute, Roskilde, Denmark	Gamma-Ray Multiplicity Measurements for ^{40}Ar - and ^{86}Kr -Induced Reactions
7/01/77	A. H. Wapstra, IKO, Amsterdam, The Netherlands	Status of Nuclear Mass Determinations
7/06/77	W. Trautmann, University of Munich, West Germany	Circular Polarization of Gamma Rays in Deep Inelastic Reactions
7/07/77	R. de Meijer, Nuclear Physics Accelerator Institute, University of Groningen, The Netherlands	What Do We Learn from Reactions with Unbound Particles in the Exit Channel?
7/12/77	V. Druin, Joint Institute for Nuclear Research, Dubna, U.S.S.R.	Experiments on the Synthesis of Element 104
7/13/77	G. M. Ter-Akopyan, Joint Institute for Nuclear Research, Dubna, U.S.S.R.	Search for Super-Heavy Elements in Meteorites
7/14/77	H. J. Krappe, Hahn-Meitner für Kernforschung, Berlin, West Germany	Adiabatic Potential Energies in Heavy-Ion Reactions
7/19/77	J. A. Maruhn, Division Staff	Fluid Dynamic Model for Heavy-Ion Collisions in Three Dimensions
7/21/77	G. J. Wagner, Max-Planck Institute, Heidelberg, West Germany	Giant Quadrupole Resonances

8/12/77	K. H. Purser, General Ionics Corporation, Ipswich, Massachusetts	Possible Revolution in Radioisotope Dating
8/25/77	Shang-Fang Tsai, University of Minnesota, Duluth	Nuclear Response in RPA
9/28/77	Marie-Madeleine Aleonard, Lawrence Berkeley Laboratory, Berkeley, California	Angular Momentum Transfer Induced by ^{86}Kr on Ag, Ho, and Au
10/06/77	Chris Bottcher, Division Staff	Exotic Processes in Heavy-Ion-on-Atom Scattering
10/13/77	Rubby Sherr, Princeton University, Princeton, New Jersey	Charge-Dependent and Size-Dependent Effects on Coulomb Displacement Energies ($A = 17$ to 55)
10/20/77	K. Geoffroy, Washington University, St. Louis, Missouri	Continuing Tale of the Continuum Gamma Rays – Now Appearing in C with Al and Ni and in Ne with Al
10/26/77	Wolfgang Tietsch, Goethe Institute, Frankfurt, West Germany	Windowless Gas-Jet Target for Nuclear Physics Research
10/27/77	John Briggs, AERE, Harwell, England	Excitation of Atoms and Molecules by Near-Resonant Laser Light
11/03/77	L. L. Riedinger, University of Tennessee, Knoxville	Backbending in Heavy Nuclei: Current Status
11/10/77	C. van der Leun, University of Utrecht, The Netherlands	Resonant Absorption of Gamma Rays
11/17/77	J. R. Nix, Los Alamos Scientific Laboratory, Los Alamos, New Mexico	Dynamics of Fission and Heavy-Ion Reactions
11/21/77	Brian Buck, Duke University, Durham, North Carolina	Clustering in Light Nuclei
12/01/77	M. W. Guidry, University of Tennessee, Knoxville	Heavy-Ion Inelastic Scattering from Highly Deformed Nuclei
12/08/77	Aaron Temkin, NASA-Goddard Space Flight Center, Greenbelt, Maryland	Hybrid Theory of Electron-Molecule Scattering
12/09/77	P. Braun-Munzinger, State University of New York, Stony Brook	Surface Resonances in Heavy-Ion Scattering
12/15/77	C. D. Goodman, Division Staff	Strong Spin-Flip Transitions in (p,n) Reactions
1/05/78	G. R. Young, Massachusetts Institute of Technology, Cambridge	Particle Gamma Coincidence Studies of $\text{O}^{16} + \text{Al}^{27}$ Deep-Inelastic Collisions
1/13/78	G. Mantzouranis, Lawrence Berkeley Laboratory, Berkeley, California	Collective and Dissipative Effects in Nuclear Systems
1/19/78	R. Blankenbecler, Stanford Linear Accelerator Center, Stanford, California	High-Energy Heavy Ion Collisions
1/26/78	C. Y. Wong, Division Staff	Nuclear Dynamics: From Giant Resonances to Heavy-Ion Collisions

2/02/78	H. Feshbach, Massachusetts Institute of Technology, Cambridge	Statistical Multi-Step Direct Reactions
2/08/78	Volker Oberacker, University of Frankfurt, West Germany	Present Status of Coulomb Fission (Theory and Experiment)
2/09/78	D. G. Sarantites, Washington University, St. Louis, Missouri	Equilibrium, and Pre-Equilibrium Neutron and Alpha Emission in Heavy-Ion Fusion Reactions
2/15/78	G. R. Rao, University of Montreal, Canada	Resonances in the $^{12}\text{C} + ^{16}\text{O}$ Systems
2/16/78	Gerhard Soff, University of Frankfurt, West Germany	Is a Spectroscopy of Superheavy Quasi-Molecules in Heavy-Ion Collisions Possible?
2/23/78	M. R. Strayer, Texas A&M University, College Station	Microscopic Analysis of (p,t) Reactions
3/01/78	W. G. Meyer, Lawrence Berkeley Laboratory, Berkeley, California	Unique Signatures of Peripheral and Central Relativistic Heavy-Ion Interactions
3/02/78	D. L. Hanson, Los Alamos Scientific Laboratory, Los Alamos, New Mexico	Alpha Transfer Spectroscopy in the f - p Shell
3/09/78	D. J. Pegg, University of Tennessee, Knoxville	Nuclear-Charge Dependence of Atomic Transition Rates and Energies
3/14/78	Reinhard Brandt, Philipps University, Marburg, West Germany	Superheavy Elements: Not to Be or to Be?
3/21/78	Willy Wölfl, ETH, Zurich, Switzerland	Possible X-Ray Spectroscopy of Superheavy Quasi-Molecules
3/30/78	Walter Greiner, University of Frankfurt, West Germany	Quantum Electrodynamics of Strong Fields: Theory and Experiments
4/03/78	Hörst Stocker, University of Frankfurt, West Germany	Relativistic Heavy-Ion Collisions
4/06/78	R. K. Smith, Duke University, Durham, North Carolina	Microscopic Approach to Relativistic Heavy-Ion Collisions
4/13/78	Gabriel Karl, University of Guelph, Canada	Parity Violation in Neutron Scattering
4/21/78	Ulrich Mosel, University of Giessen, West Germany	Yrast Line vs Entrance Channel Limitation in Heavy-Ion-Induced Fusion Reactions
5/02/78	K. C. Kulander, Daresbury Laboratory, Daresbury, Warrington, England	Photodissociation of Polyatomic Molecules - Two Pictures
5/04/78	D. L. Hillis, Niels Bohr Institutet, Roskilde, Denmark	Experimental Study of Nuclei at High Angular Momenta
5/05/78	Kai Neergård, Niels Bohr Institutet, Roskilde, Denmark	Shapes of Nuclei with Very Large Angular Momentum and Yrast Traps
5/10/78	E. M. Henley, University of Washington, Seattle	Neutral Currents in Atoms

5/11/78	G. E. Walker, Indiana University Bloomington	Probing the Nucleus at Intermediate Energies and High Momentum Transfer
5/18/78	P. Shorer, Center for Astro- physics, Harvard University, Cambridge, Massachusetts	Application of the Relativistic Random Phase Approximations to the Calculation of Atomic Transition Probabilities
5/25/78	Philippe Quentin, Los Alamos Scientific Laboratory, Los Alamos, New Mexico	On the Adiabaticity of a TDHF Solution
5/30/78	Thomas Marks, TRIUMF/UBC, Vancouver, Canada	Results of Recent Low-Energy, Pion Elastic Scattering Experiments
6/01/78	T. A. Welton, Division Staff	Object Reconstruction in Bright-Field Electron Microscopy
6/08/78	K. K. Seth, Northwestern University, Evanston, Illinois	Studies of Matter Distribution in Nuclei by Intermediate Energy Probes
6/13/78	Richard Slansky, Los Alamos Scientific Laboratory, Los Alamos, New Mexico	Neutrino-Antineutrino Oscillations
6/14/78	H. Nifenecker, Center for Nuclear Studies, Grenoble, France	Superfluidity Effects in Nuclear Fission
6/15/78	Bernard Tamain, Institute of Nuclear Physics, Orsay, France	Gamma-Ray Multiplicities in Deep Inelastic Reactions with Cu and Ar Beams
6/22/78	W. A. Lanford, Yale University, New Haven, Connecticut	Hydrogen Profiling: Neutron Bottles and Other Applications
6/27/78	Helmut Bockemeyer, G.S.I., Darmstadt, West Germany	Experimental Evidence for Positron Creation in Superheavy Ion-Atom Collision
6/27/78	F. Pougheon, Institute of Nuclear Physics, Orsay, France	Polarization of the Residual Nucleus in the $^{16}\text{O}(^{16}\text{O}, ^{12}\text{C})^{20}\text{Ne}$ Transfer Reactions
6/29/78	R. W. Hasse, University of Munich, West Germany	Frictional Schrödinger Equations – Heuristic and Microscopic Foundations
6/29/78	H. T. Feldmeier, Technical University, Darmstadt, West Germany	Mass Dispersion in Heavy-Ion Collisions
6/29/78	Yang Fu-chia, Fudan University, Peoples Republic of China	Further Studies of the Mass Formula
7/06/78	M. R. Strayer, Texas A&M University, College Station	Folding Model Potential from Nuclear Matter?
7/10/78	J. J. Griffin, University of Maryland, College Park	Theories of Fermidynamics: A Survey and a Proposal
7/11/78	D. H. Epperson, Duke University, Durham, North Carolina	Systematics of Mass Yield Distribution for the Nuclear Fission of Neptunium

7/13/78	R. A. Esterlund, University of Marburg, West Germany	Radiochemical Studies of the Fusion and Deep-Inelastic Processes in Heavy-Ion Reactions
7/17/78	C. M. Castaneda, Indiana University, Bloomington	Production of Fast $Z = 1$ and $Z = 2$ Particles in ${}^6\text{Li}$ -Induced Reactions at 75 and 95 MeV
7/20/78	Yvon LeBeyec, Institute of Nuclear Physics, Orsay, France	Emission of One and Two Nucleons in Reactions with Copper Beams; Statistical Analyses of Heavy-Ion Reactions
7/24/78	D. L. Moores, University College, London, England	Theory of Ionization of Positive Ions by Electron Impact
7/27/78	Avigdor Gavron, Weizmann Institute of Science, Rehovot, Israel	Neutron Emission During Strongly Damped Collisions
7/31/78	C. K. Gelbke, Michigan State University, East Lansing	Intermediate-Energy Heavy Ions – From the Low-Energy Perspective
8/03/78	George Vourvopoulos, Nuclear Physics Lab, Dimokrotus, Greece	Heavy-Ion Resonances in the s, d Shell
8/10/78	H. B. Gilbody, Queen's University of Belfast, Northern Ireland	Charge Transfer and Ionization in Ion-Ion Collisions
8/11/78	R. A. Broglia, Niels Bohr Institutet, Copenhagen, Denmark	Nuclear Field Theory of the Interacting Boson Model
8/15/78	R. A. Broglia, Niels Bohr Institutet, Copenhagen, Denmark	Microscopic Description of Deep Inelastic Reactions
8/16/78	Bert Van Zyl, University of Denver, Denver, Colorado	Atomic Scattering Processes of Importance in the Aurora Borealis
8/17/78	R. E. Olson, SRI International, Menlo Park, California	Theory of Atomic Processes in Ion-Atom Collisions
8/18/78	M. R. Anastasio, KFA, Jülich, West Germany	Non-Nucleonic Degrees of Freedom in the Ground State of ${}^{16}\text{O}$
8/22/78	H. B. Gilbody, Queen's University of Belfast, Northern Ireland	Collisions between Multiply Charged Ions and Hydrogen
8/23/78	R. M. Mackintosh, Daresbury Laboratories, England	New Phenomena in Proton Scattering
8/24/78	B. D. Buckley, Daresbury Laboratories, England	Recent Advances in Electron-Molecule Scattering
8/28/78	P. F. Bortignon, University of Padova, Italy	Damping of Single-Particle States and Giant Resonances in ${}^{208}\text{Pb}$
9/07/78	Hans Krappe, Hahn-Meitner Institut, Berlin, West Germany	Various Approaches to One-Body Dissipation

9/11/78	H. Kamitsubo, Institute for Nuclear Studies and Institute for Physical and Chemical Research, Tokyo, Japan	$^{14}\text{N} + ^{93}\text{Nb}$ Reactions at Energies Between 100 and 210 MeV
9/12/78	Jean Biachot, Centre d'Etudes Nucleaires, Grenoble, France	Nuclear Charge Distributions in Fission from Gamma-Ray Spectroscopy
9/14/78	Dietmar Kolb, GSI, Darmstadt, West Germany	Superheavy Elements — A Theoretical and Experimental Challenge
9/26/78	F. Stecher-Rasmussen, Netherlands Energy Research Foundation, Petten	Nuclear Structure Studies at Petten with the (n,γ) Reaction
9/27/78	T. von Egidy, Institute Laue-Langevin, Grenoble, France	Nuclear Structure Studies with the (n,γ) Reaction
10/02/78	Philip Siemens, Lawrence Berkeley Laboratory, Berkeley, California	Dissipation and Fluctuations in Nuclear Collective Motion
10/05/78	O. Shahal, Nuclear Research Centre, Negev, Israel	Investigation of Atomic and Molecular Binding by Nuclear Resonance Scattering
10/12/78	C. E. Toepffer, University of Witwatersrand, Johannesburg, South Africa	Symmetry and Shell Effects in Light Heavy Ion Reactions
10/19/78	Thomas Bauer, CEN de Saclay, France	New Structure Information from the (p,d) Reaction at 800 MeV?
10/20/78	Paul Doll, Lawrence Berkeley Laboratory, Berkeley, California	Giant Resonance Studies with Lithium and Oxygen Scattering
10/26/78	R. G. Stokstad, Division Staff	Effect of Nuclear Deformation on Heavy-Ion Fusion
11/02/78	J. K. Bienlein, DESY, Hamburg, West Germany	Results on $T(9.46)$, $T(10.02)$ and the 10-GeV Continuum from the Doris e^+e^- Storage Ring
11/03/78	H. R. Andrews, Chalk River, Canada	Nuclear Deorientation in Vacuum and Gases
11/09/78	Roger White, Ohio University, Athens	Nuclear Structure Studies of Light Nuclei with Neutrons
11/14/78	B. Giraud, CEN de Saclay, France	Interpretations of TDHF
11/16/78	S. Gales, Michigan State University, East Lansing	Systematic Study of Inner-Neutron Hole Distributions in Heavy Nuclei
11/21/78	L. C. Feldman, Bell Laboratories, Murray Hill, New Jersey	Surface Peak Observed in Backscattering — Channeling and Its Applications
11/30/78	Niels Marquardt, Ruhr-Universität Bochum, West Germany	Excitation of Intermediate Structure Resonances in ^{24}Mg and ^{20}Ne by Non-Alpha-Particle Nuclei
11/30/78	V. E. Oberacker, Division Staff	Coulomb Fission of ^{238}U Induced by Xe, Ho, Pb, and U Projectiles
12/12/78	M. S. Pindzola, Auburn University, Auburn, Alabama	Resonant Two-Photon Ionization of Potassium
12/14/78	J. B. McGrory, Division Staff	Shell Model to Bosons to "Rotations"

COLLOQUIA AND SEMINARS PRESENTED AT OTHER INSTITUTIONS

Staff members of the Physics Division and other scientists associated with the Division frequently receive invitations to present seminars and colloquia at institutions both in the United States and abroad. Partial support for some of the requests was provided through the Traveling Lecture Program (TLP) administered by Oak Ridge Associated Universities.

Following is a list of seminars and colloquia presented in 1977-78:

- J. B. Ball - Virginia Polytechnic Institute and State University, February 9, 1978, "Holifield Heavy-Ion Research Facility"; University of Tennessee, May 8, 1978, "Status Report on the Heavy-Ion Facility at ORNL"
- C. F. Barnett - North Carolina State University, April 3, 1978, "The Complexities of Atomic Physics in Laboratory High-Temperature Plasmas"
- F. E. Bertrand - Swiss Institute of Nuclear Structure (SIN), June 3, 1977, "The New Giant Resonance"; University of Utrecht, Utrecht, The Netherlands, May 25, 1977, "The New Giant Resonances"; Max-Planck Institute für Kernphysik, Heidelberg, West Germany, June 1, 1977, "Excitation of Giant Multipole Resonances in Inelastic Hadron Scattering"; University of Tennessee, Knoxville, February, 1978, "The New Giant Resonances"; National Bureau of Standards, March 30, 1978, "Excitation of Giant Multipole Resonances by Inelastic Hadron Scattering"; Los Alamos Scientific Laboratory, March 22, 1978, "Excitation of Giant Multipole Resonances by Inelastic Scattering"; Ohio State University, June 1, 1978, "The New Giant Resonances"
- C. Bottcher - Texas A&M University, November 17, 1977, "Atomic Collisions in Lasers"; University of Windsor, Canada, February 9, 1978, "Quenching of Excited Atoms by Stable Molecules"; University of Kentucky, October 13, 1978, "Coherence Phenomena in Ion-Atom Collisions"; University of Nebraska, November 9, 1978, "Coherence Effects in Heavy-Ion-Atom Collisions"; Vanderbilt University, December 1, 1978, "Coherence Phenomena in Heavy-Ion-Atom Collisions"; TUNL, University of North Carolina, December 15, 1978, "Coherence Effects in Heavy-Ion-Atom Collisions"
- T. A. Carlson - Los Alamos Scientific Laboratory, June 27, 1977, "Electron Spectroscopy and Its Applications"; University of Uppsala, Sweden, March 22, 1978, "Angular Distribution in Photoelectron Spectroscopy"; University of Tromsø, Norway, May 30, 1978, "Angular Distribution in Photoelectron Spectroscopy"; University of Bergen, Norway, June 6, 1978, "Angular Distribution in Photoelectron Spectroscopy"; University of Helsinki, June 13, 1978, "Angular Distribution in Photoelectron Spectroscopy"; Chalmers Institute of Technology, Göteborg, Sweden, September 18, 1978, "Studies of Molecules Adsorbed on Surfaces"
- T. P. Cleary - Lawrence Livermore Laboratory, December 5, 1977, "Probing the Nuclear Surface by Means of Heavy-Ion Scattering"
- H. O. Cohn - Tohoku University, Sendai, Japan, July 5, 1978, "High-Energy Physics Research at Oak Ridge National Laboratory"; KEK-Japanese National High-Energy Physics Laboratory, Tsukuba, Japan, July 8, 1978, "High-Energy Physics Research at Oak Ridge National Laboratory"
- D. H. Crandall - Culham Laboratories, Abingdon, England, July 1, 1977, "Atomic Physics in Fusion"; University of Newcastle, Physics Dept., Newcastle upon Tyne, England, July 8, 1977, "Atomic Physics in Fusion"; Wesleyan University, September 24, 1977, "Energy Research - Fusion"; University of Oklahoma, November 11, 1977, "Atomic Physics Problems in Plasmas of Fusion and Astrophysics"; Oak Ridge National Laboratory, Chemical Physics Seminar, February 13, 1978, "Atomic Physics in Fusion"; University of Missouri at Rolla, February 23, 1978, "Atomic Physics Problems - Fusion and Astrophysics"; University of Missouri at St. Louis, February 24, 1978, "Atomic Physics Problems - Fusion and Astrophysics"; University of Kentucky, February 10, 1978, "Atomic Physics Problems - Fusion and Astrophysics"; University of East Carolina, March 17, 1978, "Atomic Processes in Problems of Fusion and Astrophysics"; North Carolina State University, October 9, 1978, "Atomic Collision Processes Involving Multicharged Ions - Unique Physics and Important Applications"; University of Virginia, October 31, 1978, "Atomic Collision Processes Involving Multicharged Ions"
- R. A. Dayras - Montreal University, May 25, 1978, "Fusion Cross Section for $^{14}\text{N} + ^{12}\text{C}$ and Angular Momentum Limit for ^{26}Al "; Laval University, May

- 26, 1978, "Angular Momentum Transfer in Deep Inelastic Scattering"
- W. B. Dress — University of Cincinnati, October 20, 1977, "Search for the Neutron's Electric Dipole Moment"; University of South Carolina, April 20, 1978, "The Electric Dipole Moment of the Neutron"
- W. B. Ewbank — American Society for Information Science, East Tennessee Chapter, Oak Ridge, Tennessee, October 12, 1978, "Report on the 1978 CODATA Meeting"; December 14, 1978, "Report from the Tennessee Conference on Library and Information Services"
- C. B. Fulmer — Institut des Sciences Nucleaires, Grenoble, France, June 16, 1977, "Recent Results Obtained with Heavy Ions at Oak Ridge"; Auburn University, January 27, 1978, "The ORNL Heavy-Ion Facility and Some Recent Heavy-Ion Experimental Results"
- R. L. Ferguson — Lawrence Livermore Laboratory, December 7, 1977, "Recent Spontaneous Fusion Experiments on ^{252}No and $^{262}[105]$ "
- J. Gomez del Campo — University of Notre Dame, November 16, 1977, "Fusion of Light Systems and Monte Carlo Calculations of the Evaporation Residues"
- C. D. Goodman — Lawrence Livermore Laboratory, October 24, 1977, "Giant $M1$, GT , and Spin-Flip Resonances in Charge Exchange Reaction"; Massachusetts Institute of Technology, February 14, 1978, "Strong Spin-Flip Transitions in (p,n) Reactions"; Indiana University, November 16, 1978, "The p,n Reaction at Intermediate Energies"; Weizmann Institute, August 23, 1977, "Strong Spin-Flip Transitions in (p,n) Reactions"
- E. E. Gross — Niels Bohr Institute, Riso, Denmark, June 14, 1977, "Nuclear Moments from Heavy-Ion Inelastic Scattering"; Kernfysisch Versneller Institute, Groningen, The Netherlands, June 22, 1977, "Nuclear Moments from Heavy-Ion Inelastic Scattering"; University of Houston, September 12, 1978, "Nuclear Moments from Heavy-Ion Inelastic Scattering"
- M. L. Halbert — University of Florida, February 23, 1978, "Effects of Angular Momentum in Nuclear Reactions"
- D. C. Hensley — Baylor University, October 25, 1978, "Experimental Physics"
- D. J. Horen — Naval Postgraduate School, Monterey, California, January 20, 1978, "Mystery of $M1$ Radiation in ^{208}Pb "; Lawrence Livermore Laboratory, January 30, 1978, "Doorway States in the p -Wave Neutron Channel Correlated with $M1$ Radiation in $^{207,208}\text{Pb}$ "; University of California, January 26, 1978, "Doorway States in the p -Wave Neutron Channel Correlated with $M1$ Radiation in $^{207,208}\text{Pb} + n$ Correlated with $M1$ Radiative Strength"; Stanford University, January 31, 1978, "Doorway States in the p -Wave Neutron Channel Correlated with $M1$ Radiation in $^{207,208}\text{Pb} + n$ Correlated with $M1$ Radiative Strength"; Duke University, October 26, 1978, "Definitive Identification of $M1$ Radiating States in Lead Isotopes by Means of High-Resolution Neutron Transmission and Scattering Measurements"; Los Alamos Scientific Laboratory, December 1977, "Doorway States in the p -Wave Neutron Channel Correlated with $M1$ Radiation Strength in $^{206,207}\text{Pb} + n$ "
- P. Hvelplund — Bell Laboratories, May 1, 1978, "Electron Capture in Atomic Collisions"; University of Connecticut, May 3, 1978, "Electron Capture in Atomic Collisions"
- C. H. Johnson — Argonne National Laboratory, May 9, 1977, "Energy Dependence of Size Resonances, 25 Years Too Late"; Georgia State University, January 30, 1978, "The First Observation of the Energy Dependence of Nuclear Strength Functions"; University of Wisconsin, February 17, 1978, "Giant Resonances below the Proton Coulomb Barrier"; University of Kentucky, October 27, 1978, "Searching for Unbound Single-Particle Neutron States in ^{41}Ca "
- Helge Knudsen — McMaster University, January 15, 1978, "Differential Scattering Cross Section"; Guelph University, January 17, 1978, "Multiple Scattering in Ordered Solids"; AEC Chalk River, January 18, 1978, "Multiple Scattering in Ordered Solids"
- I. Y. Lee — University of Rochester, November 9, 1977, "Study of High-Spin Properties of Nuclei from the Observation of Continuum Gamma Rays"
- M. W. Lucas — University of Wisconsin, November 28, 1978, "The Controversy between Charge Transfer and Wake Riding"
- J. B. McGrory — National Tsing University, Hsinchu, Taiwan, Formosa, September 12, 1977, "Nuclear Structure Calculations with Shell Model"; Panjab University, Chandigarh, India, September 15, 1977,

- "Shell Model Theory"; GSI, Darmstadt, West Germany, June 13, 1978, "Shell Model to Rotations to Bosons - Microscopic Origins of Nuclear Collective Motion"; University of Utrecht, Holland, June 15, 1978, "Shell Model to Rotations to Bosons - Microscopic Origins of Nuclear Collective Motion"; Texas A&M University, September 20, 1978, "Shell Model to Rotations to Bosons - Microscopic Origins of Nuclear Collective Motion"; Oklahoma State University, September 21, 1978, "Shell Model to Rotations to Bosons - Microscopic Origins of Nuclear Collective Motion"; Oklahoma State University, September 28, 1978, "From Shell Model to Bosons to Rotations - Microscopic Origins of Collective Motion"; University of Tennessee, October 17, 1978, "Shell Model to Rotations to Bosons - Microscopic Origins of Nuclear Collective Motion"
- P. D. Miller - State University of New York at Cortland, March 3, 1978, "Resonant Coherent Excitation of Channeled Ions"; Vanderbilt University, November 17, 1978, "Ionization by Heavy Ions"
- M. Mizumoto - Vanderbilt University, December 9, 1977, " $^{207}\text{Pb}(n,\gamma)$ Measurements"
- C. D. Moak - Argonne National Laboratory, November 10, 1978, "Resonant Coherent Excitation of Channeled Ions"
- F. E. Obenshain - Georgia State University, November 16, 1977, "Deep Inelastic Reactions with ^{20}Ne on Ti, Ni, and Zr"; Auburn University, April 10, 1978, "Energy Damping in Heavy-Ion Collisions"
- R. A. Phaneuf - Defense Research Establishment, Valcartier, Quebec, Canada, July 11, 1977, "Atomic Collision Processes for Magnetic Fusion Plasmas"; S.R.I. International Corporation, February 9, 1978, "Measurements of Electron Transfer from Hydrogen Atoms to Multiply Charged Ions"; Valdosta State College, November 2, 1978, "Atomic Physics in Thermonuclear Fusion Research"; University of Missouri at Rolla, November 9, 1978, "Role of Impurities in Magnetic Fusion Plasmas"; University of Missouri at St. Louis, November 10, 1978, "Role of Impurities in Magnetic Fusion Plasmas"
- F. Plasil - Gesellschaft für Schwerionenforschung, Darmstadt, West Germany, January 30, 1978, "Measurements of Evaporation Residue Products"; University of Maryland, November 20, 1978, "Heavy-Ion-Induced Fission and Fusion"
- S. Raman - Japan Atomic Energy Research Institute, Tokai-mura, Japan, September 14, 1977, "Search for Superheavy Elements and Research Program at ORELA"; Institute for Nuclear Study, Tokyo, Japan, September 19, 1977, "Search for Superheavy Elements and Research Program at ORELA"; University of South Carolina, November 17, 1977, "Search for Superheavy Elements in Nature"; Vanderbilt University, December 9, 1977, " $^{207}\text{Pb}(n,\gamma)$ Measurements"; University of Kentucky, January 19, 1978, "Giant M1 and E2 Resonances in ^{208}Pb " and "Search for Superheavy Elements with Synchrotron Radiation"; Texas A&M University, March 10, 1978, "Research Program at ORELA"; Middle Tennessee State University, April 23, 1978, "Superheavy Element Search"; Georgia Institute of Technology, April 19, 1978, "ORELA Research"; University of Kentucky, September 9, 1978, "Research at ORELA"
- G. R. Satchler - University of Georgia, March 10, 1978, "New Giant Resonances in Nuclei"; Institute for Nuclear Studies, Tokyo, Japan, October 4, 1978, "Hadronic Excitation of Giant Resonances"; Tokyo Institute of Technology, Tokyo, Japan, October 7, 1978, "Folded Potentials for Heavy-Ion Scattering"; University of Tsukuba, Tsukuba, Japan, October 11, 1978, "Potentials for Heavy-Ion Scattering"; Institute for Physical and Chemical Research, Tokyo, Japan, October 12, 1978, "Potentials for Heavy-Ion Scattering"; University of Tokyo, Tokyo, Japan, October 13, 1978, "Microscopic Description of Light- and Heavy-Ion Scattering"; Laboratory of Nuclear Science, Tohoku University, Sendai, Japan, October 16, 1978, "Excitation of Giant Monopole Resonance by Proton Scattering"; Physics Department, Tohoku University, Sendai, Japan, October 17, 1978, "Microscopic Description of Light- and Heavy-Ion Scattering"; Research Institute for Fundamental Physics, Kyoto University, Kyoto, Japan, October 19, 1978, "Microscopic Description of Light- and Heavy-Ion Scattering"
- G. G. Slaughter - Denison University, November 1, 1977, "Solar-Powered Houses"
- R. G. Stokstad - The Weizmann Institute of Science, Rehovot, Israel, January 19, 1978, "The Effect of Nuclear Deformation on Heavy-Ion Fusion"; The Racah Institute of Physics, Hebrew University, Jerusalem, January 20, 1978, "The Effect of Nuclear Deformation on Heavy-Ion Fusion"; Kernfysisch Versneller Instituut, Groningen, Netherlands, March 20, 1978, "The Effect of Nuclear Deformation on Heavy-Ion Fusion"; University of Giessen, Giessen, West Germany, March 28, 1978, "The Effect of Nuclear Deformation on Heavy-Ion Fusion"; Institute de Physique Nucleaire, Orsay, France, April 3, 1978, "The Effect of Nuclear Deformation on Heavy-Ion

- Fusion"; University of Munster, Munster, West Germany, April 14, 1978, "The Effect of Nuclear Deformation on Heavy-Ion Fusion"; Max-Planck Institut, Heidelberg, West Germany, April 19, 1978, "The Effect of Nuclear Deformation on Heavy-Ion Fusion"; Centre de Recherches Nucleaires, Strasbourg, France, April 28, 1978, "The Effect of Nuclear Deformation on Heavy-Ion Fusion"; Hahn-Meitner Institut, Berlin, West Germany, May 22, 1978, "The Effect of Nuclear Deformation on Heavy-Ion Fusion"; Niels-Bohr Institut, Copenhagen, Denmark, June 7, 1978, "The Effect of Nuclear Deformation on Heavy-Ion Fusion"; Stanford University, December 18, 1978, "The Effect of Nuclear Deformation on Heavy-Ion Fusion"
- C. Toepffer - Massachusetts Institute of Technology, December 6, 1978, "Isoscalar Quadrupole Giant Resonances in ^{24}Mg "; Yale University, December 7, 1978, "Isoscalar Quadrupole Giant Resonances in ^{24}Mg "
- C. Y. Wong - University of Georgia, May 19, 1977, "Schrodinger Equation Revisited - Old Wines in New Bottles"; U.S. Naval Research Laboratory, June 14, 1977, "Nuclear Hydrodynamics in Heavy-Ion Collisions"; Drexel University, February 16, 1978, "Schrodinger Equations Revisited"; Lawrence Berkeley Laboratory, February 23, 1978, "Dynamics of Nuclear Fluid"; Texas Tech University, March 10, 1978, "Superheavy Toroidal Nuclei"; University of Texas, March 14, 1978, "Dynamics of Nuclear Fluid"; Texas Christian University, March 16, 1978, "Schrodinger Equation in Fluid Dynamical Form"; Lawrence Berkeley Laboratory, November 6, 1978, "Nuclear Hydrodynamics in Heavy-Ion Reactions"

SCIENTIFIC MEETINGS SPONSORED BY THE PHYSICS DIVISION AND HELD DURING THE REPORTING PERIOD

New-Evaluator Orientation and A-Chain Mini-Review

November 7-11, 1977

R. L. Auble, Organizer

IAEA Advisory Group Meeting on Nuclear Structure and Decay Data

November 14-18, 1977

F. E. Bertrand, Organizer

Annual Meeting of HHIRF Users Group

September 28-29, 1978

R. L. Robinson, Organizer

Workshop on Future Trends in Heavy-Ion Physics

September 29-30, 1978

J. B. McGrory, Organizer

Symposium of Northeast Accelerator Personnel

October 23-25, 1978

C. M. Jones, Organizing Committee Chairman

New-Evaluator Orientation

November 13-17, 1978

M. J. Martin, Organizer

Annual Information Meeting

The 1977 Annual Information Meeting of the Physics Division was held on October 3 and 4. Members of the Advisory Committee were:

C. K. Bockelman, Yale University

J. R. Nix, Los Alamos Scientific Laboratory

A. Dalgarno, Smithsonian Astrophysical Observatory

H. E. Wegner, Brookhaven National Laboratory

H. A. Enge, Massachusetts Institute of Technology

PHYSICS DIVISION

APRIL 1, 1979