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PHYSICS DIVISION

PROGRESS REPORT

for Period Ending September 30, 1989

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INTRODUCTION

This report covers the research and development activities of the Physics Division for the 1989 fiscal year, beginning October 1, 1988, and ending September 30, 1989. The activities of this Division are concentrated in the areas of experimental nuclear physics, experimental atomic physics, and theoretical nuclear and atomic physics.

The Holifield Heavy Ion Research Facility and its operation as a national user facility continued as the single dominant activity within the Division. This year was marked by record high performances for the facility in the number of beam hours on target provided, high operating potentials for the 25 MV tandem electrostatic accelerator, and overall facility operational reliability. During this year, two new experimental devices, the Nuclear Orientation Facility and the HILI (Heavy-Ion, Light-Ion detector) were brought into full operation. In addition, this year saw the securing of funding for a state-of-the-art Recoil Mass Spectrometer for the facility and the selection of the facility by a DOE-appointed review panel as the recommended site for GAMMASPHERE. These and other highlights are summarized in Chapter 1.

The experimental nuclear physics program continues to emphasize heavy ion studies, with much of the activity centered at the Holifield Facility. The work at ultrarelativistic energies continues at the CERN SPS, but has been expanded to involve work at the Brookhaven AGS, particularly in preparation for future experiments at RHIC. Work at intermediate energies, both at Holifield and GANIL, has been significantly enhanced this year with the completion of the BaF₂ detector arrays. Results of this work are presented in Chapter 2.

The UNISOR program, since its inception, has been associated intimately with the Division and, most particularly, with the Holifield Facility. A summary of the research of this consortium is included in Chapter 3.

A second major area of experimental research for the Division is atomic physics. This activity comprises two groups: one on accelerator-based atomic physics, based primarily at the EN-tandem and the Holifield Facility; and one on atomic physics in support of fusion energy, based primarily at the ECR ion source facility. These programs also operate, respectively, the EN-tandem and the ECR Facility as "user resources." A report on these activities is given in Chapter 4.

The theoretical physics activity in the Division concentrates on the areas of atomic physics, nuclear physics, and physics at the nuclear-particle interface. These efforts represent independent studies as well as support to the experimental effort. This year has seen an expanded effort on the new initiative to establish a Center for Computationally Intensive Physics, which included sponsoring a summer school on this topic. The research of the theory activity is presented in Chapter 5.

The work on diagnostics development for the fusion program done by the Laser and Electro-optics Laboratory is discussed in Chapter 6. Also included here is a short description of calorimetry studies prompted by reports in the popular press of "cold fusion."

A small, continuing program in elementary particle physics, carried out in collaboration with the University of Tennessee, is reported in Chapter 7.

The Division operates two efforts in data compilation and evaluation. The work of the Atomic Physics Data Center and our effort as part of the National Nuclear Data Center are summarized in Chapter 8.

Our proposal for a heavy-ion storage ring for atomic physics (HISTRAP) remains a major new initiative of the accelerator-based atomic physics program and the Division. Continuing studies on optimizing the ring design and on component prototyping are described in Chapter 9.

The report concludes with general information on publications, Division activities, and personnel changes.

J. B. Ball
February 1990

1. HOLIFIELD HEAVY ION RESEARCH FACILITY

OVERVIEW

C. M. Jones and R. L. Robinson

Operation and development of the Holifield facility in this period was characterized by a record-setting year in facility operation and by a number of exciting developments in instrumentation for the experimental program.

New records were set for beam-on-target time provided for the experimental program (4829 h)¹ and for low unscheduled maintenance as a fraction of beam-on-target time (6.9%). At the same time, the tandem accelerator was operated at significantly higher terminal potentials, specifically, for about 1300 hours above 22 MV. This improved voltage capability, resulting from installation of compressed geometry acceleration tubes, allowed production of beam energies and intensities not previously possible. Some notable examples of runs with higher terminal potential were:

- 216-MeV ^{16}O ($V_{\text{term}} = 24.0$ MV) for 119 research hours.
- 500-MeV ^{90}Zr ($V_{\text{term}} = 23.2$ MV) for 132 research hours.
- 888-MeV ^{156}Ge ($V_{\text{term}} = 22.3$ MV) for 200 research hours.

The experimental capabilities of the facility were strengthened through three major developments:

The UNISOR Nuclear Orientation Facility achieved temperatures of 4.4 mK with the baffles closed to the beam line and 9 mK with the baffles opened. This system was used for the first time in on-line experiments during August.

The HILL detector array was completed through the addition of a second hodoscope of 96 plastic scintillator detectors. This system, with its combination of PPACs, multi-anode ionization chambers, and light-ion telescopes, has capabilities for characterization of nuclear events that cannot be found at any other facility in the energy range of the Holifield accelerators.

Seventy-six hexagonal-shaped BaF_2 crystals were acquired and configured into four arrays of

19 detectors. These detectors, which are considered the best means of measuring high-energy gamma rays, were used this past year in four experiments with a total of 662 research hours.

A five-year upgrade plan for increased computing capability was initiated two years ago. During this year, a clustered pair of VAX 3600 computers was acquired. The computing power of these computers is nearly a factor of four greater than the VAX 11/785 which they replaced. Also procured was a MIPS M/120 RISC computer with computing power nearly twice that of the pair of VAX 3600s. A giant step toward improved mass storage was procurement of eight Exabyte tape drives. Each tape of these units has the capacity of about twelve 6250-bpi standard tapes.

Two major events that should have a profound long-range impact on the Holifield Facility were the funding of a recoil mass spectrometer (RMS) and the selection of the Holifield Facility as the site for GAMMASPHERE. The design of the RMS allows full use of the energy range of the Holifield Facility and accommodates the GAMMASPHERE at either the target or the focal plane position. The GAMMASPHERE, which is an initiative of the nuclear physics community, will be the most important research tool over the next decade for nuclear structure studies. Its capability will be enhanced still further when combined with the RMS.

The Holifield Facility continues to serve the physics community as a national resource for both research and the training of students. During FY 1989, 190 scientists worked at the Holifield Facility. Of this group, fifty-six were graduate students. The distribution of these individuals among 50 institutions is given in Table 1.1.

1. Since beginning operation in June 1981, the Holifield facility has provided more than 30,000 hours of beam time for research.

Table 1.1. Distribution of users who participated in research programs at the Holifield during the twelve-month period between October 1, 1988, and September 30, 1989

Institutions	Number of Researchers	Institutions	Number of Researchers
U.S. UNIVERSITIES		NATIONAL LABORATORIES	
Colorado School of Mines	1	Idaho National Energy Laboratory	1
Eastern Kentucky University	1	Lawrence Berkeley Laboratory	4
East Carolina University	1	Lawrence Livermore National Laboratory	2
Furman University	2	Oak Ridge National Laboratory	34
Georgia State University	5		
Georgia Institute of Technology	5		41
Hope College	1		
Indiana University	1	NON-U.S. INSTITUTES	
JHPIR	1	BARC (India)	1
Louisiana State University	2	BHU (India)	1
Mississippi College	1	CEN/Saclay (France)	2
Mississippi State University	4	Inst. Kernphysik, Jülich (Germany)	2
Naval Academy	1	MSI, Stockholm (Sweden)	1
ORAU	4	Nazionale di Fisica Nucleare (Italy)	9
Oregon State University	4	Oxford University (United Kingdom)	1
Tennessee Technological University	4	Ruder Boskovic Inst. (Yugoslavia)	1
Texas A&I University	1	University of Copenhagen (Denmark)	1
Texas A&M University	12	University of Heidelberg (Germany)	1
University of Florida	6	University of Leuven (Belgium)	1
University of Kentucky	3	University of Seville (Spain)	1
University of Maryland	7	University of Sussex (United Kingdom)	1
University of Michigan	1	University of Mexico (Mexico)	2
University of North Carolina	1		
University of Pennsylvania	1		25
University of Pittsburgh	4		
University of Rochester	7		
University of Southern Colorado	1	Total	190
University of Tennessee	12		
Vanderbilt University	17		
Washington University	5		
Western Kentucky University	4		
Yale University	4		
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ACCELERATOR OPERATIONS AND DEVELOPMENT

OPERATIONS

G. D. Alton	C. A. Ludemann
J. A. Biggerstaff	J. A. Martin
M. R. Dinehart	R. L. McPherson
D. T. Dowling	M. J. Meigs
H. D. Hackler	G. D. Mills
C. L. Haley	S. W. Mosko
D. L. Haynes	S. N. Murray
C. A. Irizarry	D. K. Olsen
C. M. Jones	B. K. Sizemore
R. C. Juras	B. A. Tatum
S. N. Lane	S. D. Taylor
C. T. LeCroy	N. F. Ziegler

Facility operating statistics for the current reporting period, FY 1989, are shown in Tables 1.2

and 1.3. New records were set in two categories for operation in a fiscal year: an all-time-high total beam hours available for research (4829) and an all-time-low total unscheduled maintenance as a fraction of total beam hours available for research (6.9%).

A list of beams provided for research in FY 1989 is given in Table 1.4. During this period, beams of 31 ion species were provided, five for the first time. Several of these beams are especially notable in that they could not have been provided prior to the tandem accelerator voltage upgrade project. These include 216.3-MeV ^{16}O and 500-MeV ^{90}Zr for tandem-only operation and 888-MeV ^{156}Gd for coupled operation. Efforts to improve operating

Table 1.2. Tandem accelerator utilization for the period October 1, 1986, through September 30, 1989

	Hours	Percent
Beam available for research (tandem-alone and coupled operation)	4829	55
Beam available during ORIC tuning (coupled operation)	271	3
Accelerator tuning (includes scheduled startup-shutdown)	852	10
Machine studies (includes conditioning not required for specific experiments)	618	7
Total operating time	6570	75
Unscheduled maintenance	244	3
Scheduled maintenance	1191	13
Scheduled shutdown	756	9

Table 1.3. Cyclotron utilization for the period October 1, 1988, through September 30, 1989

	Hours	Percent
Beam available for research (coupled operation)	1110	13
Accelerator tuning (includes scheduled startup-shutdown and operation during tandem tuning)	285	3
Machine studies	0	0
Unscheduled maintenance	89	1
Scheduled shutdown and maintenance	7276	83

efficiency continued. The most notable achievement in this area was completion of a new, systematic, operating procedure for ORIC setup calculations. Training activities also continued with certification of one additional tandem accelerator operator and one additional ORIC operator.

Table 1.4. Beams provided for research for the period October 1, 1988, through September 30, 1989

Ion Species	Maximum Energy (MeV)	Mode†
¹ H	26	T
⁷ Li	110	T,C
¹² C	160	T
¹⁶ O	402	T,C
¹⁸ O	90	T
¹⁹ F	102	T
²³ Na*	117	T
²⁴ Mg	115	T
²⁸ Si	252	T
³⁰ Si	120	T
³² S	707	T,C
³⁴ S	160	T
³⁶ S	167	T
³⁵ Cl	169	T
⁴⁰ Ca	210	T
⁴⁴ Ca	189	T
⁴⁸ Ca	222	T
⁴⁸ Ti	916	T,C
⁵⁸ Ni	638	T,C
⁶⁰ Ni	1003	C
⁶⁴ Ni	237	T
⁷⁰ Ge*	154	T
⁷⁴ Ge	164	T
⁷⁶ Ge	169	T
⁷⁴ Se*	164	T
⁷⁶ Se*	169	T
⁷⁹ Br	934	C
⁹⁰ Zr	500	T
⁹³ Nb	334	T
¹⁵⁶ Gd*	888	C
¹⁹⁷ Au	500	T

* Provided for first time in FY 1989.

† T = Tandem alone; C = Coupled mode.

TANDEM ACCELERATOR

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J. A. Biggestaff	R. L. McPherson
D. L. Haynes	M. J. Meigs ¹
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N. F. Ziegler	

Voltage Performance

Operation of the tandem accelerator in this period has focused on exploitation for the experimental program of the improved terminal potential capability which has resulted from

installation of compressed geometry acceleration tubes.² As shown in the terminal potential distribution function presented in Fig. 1.1, this effort has resulted in a significant improvement in our

Fig. 1.1. The number of runs in 1-MV-wide intervals is shown as a function of tandem accelerator terminal potential for the period October 1, 1988, through September 30, 1989.

operational capability. During this period, the accelerator was operated for long periods at potentials up to 24 MV and for about 1300 hours above 22 MV. As indicated above, this improved voltage capability has enabled us to provide beam energies and intensities which were not previously possible.

As a result of higher voltage operation, the number of full-column sparks in the period increased to eighty. We have been pleased to note, however, that while virtually all of these sparks occurred at potentials higher than 20 MV, no significant spark-induced damage has been observed.

Operation

Reliability of the tandem accelerator continued to be excellent. Total tandem accelerator unscheduled maintenance in the period was 244 h, or 5% of the beam time provided for research. Only two unscheduled tank openings interrupted the experimental program.

Operation of the SF₆ storage and recirculation system continued to be without incident. SF₆ inventory losses for the year were about 2%. Internal inspection of the three SF₆ storage tanks revealed no problems.

Improvements and Modifications

Although our focus in this year has been more on operation, improvements to the accelerator have continued. These include installation of newly designed and fabricated auxiliary gas containment valves (described in another contribution to this report), completion of a new multitrace beam profile monitor display and integrator system, installation of new "maintenance valves" in the low-energy and high-energy tandem accelerator beam lines, and installation of aftercooler isolation valves in the SF₆ storage system.

Two minor problems with spark-induced damage were solved by modification of terminal charging system components and corona voltage grading current readout insulators. An important improvement to the facility was expansion of the tandem accelerator controlled-entry radiation safety system to four new experimental areas: T-109, C-110, C-113, and C-114. This expansion is discussed in another contribution to this report.

Ion Source Development

As described in other contributions to this report, work on development of new ion sources and techniques continued. Notable activities included detailed design of two major new sources and preliminary investigation of laser-beam-induced negative ion formation.

1. Instrumentation and Controls Division, ORNL.
2. Nucl. Instr. and Meth. in Phys. Res. A276 (1989) 413.

ORIC ACCELERATOR

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B. A. Tatum

During the 12-month period of this report, there were 13 separate heavy ion beams produced in coupled operation of ORIC and the tandem accelerator. These beams are summarized in Table 1.5. There was no stand-alone operation of the cyclotron since the internal ion source was permanently decommissioned over a year ago. ORIC was scheduled for 1484 hours of operation in FY 1989. Of this time, 1110 hours, or 75%, was available for physics research, 285 hours, or 19%, was used for tuning, and 89 hours, or 6%, for unscheduled maintenance. This division of the scheduled time continues the high operating efficiency achieved in recent years. Unscheduled maintenance was also

6% of scheduled time in both FY 1987 and FY 1988, whereas tuning time was 19% and 21%, respectively.

Table 1.5 lists the beam intensity on target for the various runs in enA. For nine of the 13 beams, the desired beam intensity was less than 1 pA. This low beam intensity is the result of the increasing use of 4 π detector systems. For most of these runs, the extraction efficiency from ORIC is not a consideration and, hence, is not listed in Table 1.5. Four of the beams were produced with the tandem accelerator operating in the 22-MV range.

A particularly noteworthy run was the $^{156}\text{Gd}^{36+}$ beam used for a spin spectrometer measurement in October 1988. About 0.4 pA of 5.6 MeV per nucleon Gd was accelerated for a five-day period with ORIC operating at $K = 105$. This run is the direct result of the careful Gd charge state measurements reported in last year's Progress Report¹ and illustrates the fact that the HHIRF can produce rare

Table 1.5. Coupled operation for research from October 1, 1988, to September 30, 1989

Date	Ion	Desired Energy (MeV)	Measured Energy (MeV)	Error (%)	Beam on Target (enA)	Tandem Voltage (MV)	Injected Charge State	Injected Energy (MeV)
10/1/88	$^{58}\text{Ni}^{22+}$	638	637.8	-0.0	8	21.1	8+	189.9
10/3/88	$^{48}\text{Ti}^{21+}$	920	916.4	-0.4	2	22.1	9+	243.2
10/7/88	$^{48}\text{Ti}^{19+}$	672	678.9	+1.0	3	21.8	8+	196.9
10/23/88	$^{156}\text{Gd}^{36+}$	875	888.3	+1.5	15	22.0	9+	218.2
2/8/89	$^{60}\text{Ni}^{24+}$	1000	1003.3	+0.3	80	20.4	9+	204.6
2/16/89	$^{60}\text{Ni}^{22+}$	800	796.4	-0.5	80	20.4	9+	204.0
4/6/89	$^{79}\text{Br}^{27+}$	930	933.8	+0.4	6	20.4	9+	204.1
4/27/89	$^{48}\text{Ti}^{21+}$	920	916.3	-0.4	1	22.1	10+	243.2
5/3/89	$^{58}\text{Ni}^{22+}$	638	634.9	-0.5	3	20.4	8+	183.7
5/16/89	$^{16}\text{O}^{8+}$	400	401.8	+0.4	2	17.7	3+	71.2
9/15/89	$^{48}\text{Ti}^{21+}$	920	912.4	-0.8	15	21.2	10+	234.0
9/15/89	$^{32}\text{S}^{15+}$	700	707.6	+1.1	40	20.5	5+	123.1
9/20/89	$^7\text{Li}^{3+}$	110	110.4	+0.4	40	9.7	1+	19.7

earth beams in the coupled mode with energies above the Coulomb barrier.

During this reporting period, an additional ORIC operator was certified.

Cyclotron Setup and Tuning

Most ORIC tuning parameters were either fixed, or tuned close to the predicted values from the setup calculations. This allowed the many beams listed in Table 1.5 to be more rapidly tuned through ORIC. This year, a rather complete procedure was written to describe the various steps required to do an ORIC setup calculation with the TCISOC, TCEQORB, TCACCEL, TCINJECT, and TCEJECT codes. This procedure provides the basis for expansion of the manpower pool capable of providing ORIC setup calculations.

Cyclotron Development

Cyclotron Control System. Software was added to the cyclotron control computer to operate the new inside coil power supply for the lower channel extraction magnet. This provides ON/OFF and INCREASE CURRENT/DECREASE CURRENT controls and output current monitoring in the cyclotron control room. Control/interlock cabling and interface logic was also installed.

A gradual renovation of the ORIC control room is continuing. A new beam line vacuum control system is being installed. Several obsolete controls and related wire and cables have been removed. New panels were installed to reorganize the remaining controls for more efficient operation.

Magnet Power Supplies. Efforts to improve or replace old or obsolete dc power supplies are continuing. The new 3000-A, 60-V power supply for the compensated magnetic channel in the extraction system, which was described last year,² was finally delivered. The supply was temporarily used for the HISTRAP prototype dipole where it demonstrated good stability and reliable operation. However, when the supply was used on the extraction magnet, it experienced serious component failures. A faulty transducer and load coupling to other voltage sources are probable causes. Repairs have been completed and corrective procedures are under way.

Beam Line Development

Beam Line Vacuum Controls. The addition of new beam line vacuum controls is under way. Items already installed include a membrane keyboard, additional digital vacuum gauge controllers, and a programmable logic controller. Software is nearly complete, and most control wiring is in place. One major obstacle encountered was the operation of a color CRT in the 10-gauss ambient magnetic field in the control room. Originally, a 19-inch CRT was planned; however, preliminary tests with an available unit demonstrated that it could not function properly without extensive magnetic shielding. Tests with other CRTs demonstrated that Trinitron technology yields a monitor that requires minimal shielding. Due to the high cost of a 19-inch Trinitron and necessary shielding, it was determined that a smaller (13-inch) Trinitron would be preferable. The CRT will be mounted atop the ORIC control console near the membrane keyboard. Installation of the CRT will proceed as soon as its magnetic shield is received from the manufacturer. The new vacuum controls will be in routine operation by mid-FY 1990.

Beam Line Vacuum Hardware. A cryo-pump station was installed on the vacuum chamber of beam switching magnet #5-2, which transports beams to the Spin Spectrometer, the 1.6-m station, and UNISOR. The pump station reduced the residual gas pressure in the chamber from approximately 5×10^{-6} torr to less than 1×10^{-7} torr. High pressure in this part of the beam transport system was believed to be a contributing cause of beam halo effects.

Work is proceeding on the replacement of the vacuum chamber in beam switching magnet #4, which transports beams from the cyclotron to the Spin Spectrometer, 1.6-m chamber, UNISOR, and the future beam line for the Recoil Mass Spectrometer, and the GAMMASPHERE. The existing chamber has had poor vacuum conditions for several years. Significant leaks are suspected, but efforts to identify their location have been unsuccessful since much of the chamber is inaccessible. The leaks are probably in welded joints between the vacuum chamber and the magnet poles where repairs would be difficult and not necessarily successful. Consequently, a new vacuum chamber

is being fabricated. The resulting vacuum system will also include a new cryogenic vacuum pump and beam viewer at the exit of the magnet.

Beam Line Upgrade AIM Project. An AIM project proposal has been submitted for the replacement of the majority of cyclotron area beam lines. The existing beam lines use equipment that, in some cases, is more than 25 years old. Existing pump stations use oil diffusion units with mechanical forepumps which are unreliable due to their age and are generally not capable of achieving the vacuum desired for heavy ions. The beam line hardware includes aluminum piping, slip flanges, and elastomer vacuum seals.

The AIM project will provide for stainless steel beam pipes, metal vacuum seals, and modern cryopumps. Beam viewers and beam stops will be replaced by diagnostic ports with new viewers, Faraday cups, and beam profile monitors which should help the operations staff reduce beam tuning time. Existing beam lines will gradually be replaced as funding becomes available.

Funding for the project is expected to begin in FY 1990 and continue through FY 1992. The total cost is expected to be \$545 K. Preliminary work is already under way, and coordination with other projects such as the vacuum control system upgrade and the RMS is being given careful consideration.

Facility Development

HHIRF Radiation Safety System. The radiation safety systems for the tandem and the cyclotron have been integrated into a single system, the HHIRF-RSS. The new RSS, an extension of the original tandem system, includes four more experiment areas with controlled access and has provision for further expansion. Three of the new controlled access areas are cyclotron experimental areas which were formerly operated in total exclusion mode. All of the controlled access areas are continuously monitored by the RSS, which will interrupt all ion acceleration if allowable personnel radiation exposure levels are exceeded or access restrictions are violated.

Transformer Failures

The HHIRF encountered two significant transformer failures on the incoming high voltage electric power system. The first failure was in the primary winding of a 750-kVA substation transformer (13.8 kV input/5-20 kV output), which is part of the anode power supply for the cyclotron rf system. The unit was repaired in the ORNL "motor shop" by rewinding the damaged coil sections.

The second failure involved the primary winding and a secondary voltage regulator in a 2000-kVA substation transformer (13.8-kV input/480-V output) which is part of the HHIRF 480-V, three-phase power distribution system. This unit was repaired in situ by eliminating the secondary voltage regulator and patching the damaged areas of the primary winding.

Both of the transformer failures involved air-cooled, dry-type units which were part of a new set of four transformers installed in 1986 to replace units with PCB cooling. The failure of the 750-kVA unit was attributed to moisture absorption during a "power off" period preceding the incident. Electric heaters were added to the transformer assembly to avoid a recurrence of this problem. The failure of the 2000-kVA unit is attributed to a configuration imbalance in the regulating VVT resulting from a slipping set screw in a contact brush positioner. The primary winding was damaged as a disintegrating cable on the VVT fell into the high-voltage electric field.

The need for line voltage regulators was reviewed as a result of the substation failure incident, and it was concluded that most, if not all, equipment at HHIRF will operate satisfactorily without regulators. Consequently, the line voltage regulators were eliminated from the 2000-kVA substation and also from two other substations.

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IMPROVED VOLTAGE PERFORMANCE OF THE OAK RIDGE 25URC TANDEM ACCELERATOR¹

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Installation of compressed geometry acceleration tubes and associated changes in the corona voltage grading system have resulted in significant improvements in voltage performance of the Oak Ridge 25URC tandem accelerator. Details of the final phase of this work and initial tests on the modified accelerator are provided.

1. Abstract of published paper: Nucl. Instr. and Meth. in Phys. Res. A276 (1989) 413.
2. Instrumentation and Controls Division, ORNL.
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OPERATIONAL EXPERIENCE WITH COMPRESSED GEOMETRY ACCELERATION TUBES IN THE OAK RIDGE 25URC TANDEM ACCELERATOR¹

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Installation of compressed geometry acceleration tubes and other associated modifications have increased the effective voltage capability of the Oak Ridge 25URC tandem accelerator by about 3 MV. Since mid-September 1988, the accelerator has been operated routinely at terminal potentials up to 24 MV and occasionally near 25 MV. In 3500 hours of full-column operation, including 1100 hours at potentials above 22 MV, no significant spark-induced damage was observed. Some considerations related to further improvements in voltage performance are discussed.

1. Abstract of paper presented at the International Conference on Electrostatic Accelerators, Strasbourg, France and Heidelberg, Germany, May 24-29, 1989. To be published in Nuclear Instruments and Methods in Physics Research.
2. Instrumentation and Controls Division, ORNL.

TANDEM ACCELERATOR AUXILIARY GAS CONTAINMENT VALVES

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In order to prevent loss of SF₆ gas in the event of SF₆ leakage into the column vacuum system, the tandem accelerator is equipped with two all-metal pancake valves which serve as primary gas containment valves. While these valves have never failed to function when required, there has been some concern that they might not close reliably with the high-velocity flow that could occur in the unlikely event of a large leak in the column vacuum system. Thus, it was decided to supplement these valves with auxiliary gas containment valves which would close reliably, even with a high-velocity flow.

In combination, the design criteria for the new auxiliary gas containment valves posed an interesting problem. Specifically, it was required that the new valves have good vacuum conductance, require no electrical interlocks and no external actuating power, and be simple, inexpensive, reliable, of all-metal construction, capable of withstanding a 110-psi pressure differential, and be remotely controllable. Figure 1.2 shows the design

Fig. 1.2. A section view of the new tandem accelerator gas containment valves.

that was developed in response to these criteria. As shown in the figure, the valve is housed in a simple spool piece, terminated with Conflat flanges. The gate is supported by a shaft and normally is held open by a helical spring at one end of the shaft. The valve is closed when the pressure in the body of the valve (outside the bellows) exceeds the pressure inside the bellows by about 1/2 atmosphere. During normal operation, the bellows interior is maintained at vacuum by a separate system which can be monitored and controlled from outside the accelerator pressure vessel. For service operations, the valve state can be controlled by changing the pressure inside the bellows.

Two valves of the type shown in Fig. 1.2 were fabricated and installed in the low- and high-energy beam lines of the accelerator just above the base of the accelerator pressure vessel.

DESIGN ASPECTS FOR A MULTIPLE-SAMPLE, CESIUM SPUTTER, NEGATIVE ION SOURCE

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J. W. Johnson

The design phase of the multiple-sample, cesium sputter, negative ion source was completed in this reporting period. Construction of this source is motivated by the desire to select and frequently change samples without extended disruption in HHIRF operation in situations where the user desires to run several samples within a short time span. In addition, this source will allow efficient use of samples with short lifetimes. Presently, samples must be manually changed, an operation which typically takes more than 30 minutes.

The source, shown in Fig. 1.3, consists of five major assemblies: (1) the target holder, (2) the

ORNL-DWG 88-5883A

Fig. 1.3. Schematic drawing of the multiple-sample cesium sputter negative ion source.

target holder chamber, (3) the sputter sample high-voltage insulator, (4) the main body of the source, and (5) the high-voltage insulator/extractor electrode assembly. The source is equipped with provisions for remotely selecting and moving into the beam position any one of sixty samples. The cylindrical sample holder holds three rings of twenty samples each, positioned circumferentially around the sample holder. Selection of a particular sample within a particular ring of samples is accomplished by rotating the selected target into the beam position by means of a software-driven stepping motor control unit. Selection of a particular ring of targets is made by a second stepping motor, which is used to move the target holder laterally by means of a cam-action rotary motion drive. Each stepping motor is equipped with an absolute shaft encoder for use in positive identification of a preselected sample position. The stepping motors will be operated at ground potential with insulating shafts for driving the rotary and lateral positioning motions. The sample holder is designed for rapid removal and exchange with a holder preloaded with the desired sample materials.

The spherical-sector cesium ionizer (38-mm-diam) used in this source has a radius of curvature of 36.5 mm, which corresponds to the distance between the ionizer and the sample surface. The heating element is made of spiral-wound coaxial tantalum wire of central wire diameter 1 mm. The ionizer surface will be formed by pressing, with a die fixture, a 1 to 1 1/2-mm-thick sheet of high-work-function material into a 38.1-mm-diam spherical sector with the 36.5-mm radius of curvature required for focusing the cesium beam onto the sample surface.

Computer-assisted techniques were utilized to design the ionizer/intermediate electrode/sample (three-electrode) system. The three-component electrode structure has a higher perveance ($8 \times 10^{-9} \text{ A/V}^{3/2}$) than the spherical-geometry, two-electrode source ($2 \times 10^{-9} \text{ A/V}^{3/2}$) described in Refs. 2 and 3, and thus produces higher positive cesium ion currents at the same potential difference. The three-electrode system also permits the sample to be independently biased relative to the ionizer and consequently, negative ion beam transmission from

the source can be improved due to extraction from the surface in a less divergent field than in the earlier spherical-geometry source.

The ionizer and cesium oven power feed-throughs are mounted diametrically opposed on the main body of the source. The cesium oven is identical in design to that of the standard geometry sources²⁻⁴ and is expected to have similar operating characteristics. The cesium ionizer heating element is a new coaxial design which has yet to be characterized. Ceramic-to-metal bonded insulators will be used throughout the source. The major components of the source target chamber, sputter probe insulator, main body, and high-voltage insulator/extraction assembly are attached to each other by means of thumb screws. Engineering drawings for this source are complete and the source will be manufactured in the near future.

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DESIGN FEATURES OF AN AXIAL-GEOMETRY, PLASMA-SPUTTER, HEAVY NEGATIVE ION SOURCE

G. D. Alton

Recent developments¹⁻⁴ have demonstrated the utility of a radial-geometry, plasma-sputter, negative ion source for producing high-intensity (several mA) pulsed beams of a wide spectrum of atomic and molecular negative ion species. This source type has shown promise also for dc beam generation at mA-intensity levels.⁵ The pulsed-mode performance characteristics of this source type are particularly well suited for use in conjunction with the tandem electrostatic accelerator when used as an injector for a heavy-ion synchrotron, while the dc mode of operation is commensurate with stand-alone tandem accelerator operation. For the synchrotron heavy-ion accelerator, high-intensity pulsed beams of widths 50-300 μs at repetition rates

of 1-50 Hz, for a wide spectrum of atomic and molecular species, are typically required. The feasibility of injecting mA beam intensities with these pulse characteristics into large tandem accelerators without deleterious effects has been demonstrated recently at the Brookhaven National Laboratory and at the University of Tsukuba.⁴ The specific need for a high-brightness source for use in conjunction with the Holifield Heavy Ion Research Facility (HHIRF) 25URC tandem electrostatic accelerator, which would serve as an injector for the proposed Heavy Ion Storage Ring for Atomic Physics (HISTRAP),⁶ was the primary motivating factor which led to the design of the source described in this report.

The high-intensity, radial-geometry, plasma-sputter, negative ion source, described in Refs. 1-4, has proved to be a reliable, stably operating source with an extremely long lifetime for pulsed-mode operation. The intensity levels obtained are often higher, by factors of 30-100, than those which can be generated in cesium sputter-type sources (such as described in Ref. 7) and yet the emittances of the

source are comparable for pulsed-mode operation.⁸ The emittances from the source match the calculated acceptances of large tandem accelerators such as the 25URC tandem accelerator at ORNL,⁹ and, in principle, ion beams from this source should be transportable through such devices. However, the radial-geometry source is not equipped with provisions for rapid sputter sample interchange such as that required for use at a research facility which operates continuously and which must provide beams from a wide spectrum of species on user demand. A radial-geometry type source also was designed for exclusive use for generation of H⁻ beams for low-duty-factor synchrotron injection applications which require no direct cooling of the discharge chamber and is, thus, improperly cooled for the high power requirements necessary for dc-mode operation. The LaB₆ filaments used to initiate and sustain the discharge are not designed for fast interchange. When they break, either as a consequence of physical erosion or mechanical stress, an extensive period of time is required for replacement. The source shown in Fig. 1.4 was designed in an

Fig. 1.4. Schematic drawing of the axial-geometry, plasma-sputter, negative ion source (top view).

attempt to overcome some of these handicaps and to provide a source which could be used for both pulsed and dc modes of operation.

The operational characteristics of the axial-geometry source are expected to be identical in almost every detail to the radial-geometry source.¹⁻⁴ The source is constructed primarily of stainless steel and utilizes metal-to-ceramic bonded high-voltage insulators and low-voltage feedthroughs. Design emphasis has been placed on the ability to rapidly change the source itself and all degradable components. The cesium oven is mounted externally, permitting easy access for servicing, while providing good thermal isolation between the discharge chamber and the oven itself. The main source can be quickly and easily disassembled for cleaning and other maintenance operations. The source assembly is composed of four major independent assemblies: (1) the sputter probe vacuum airlock assembly; (2) a freon-cooled, stainless-steel discharge chamber onto which is attached the cesium oven, discharge-gas support system, coaxial geometry LaB₆ cathodes, and SmCo and AlNiCo plasma-confinement magnets; (3) a ceramic-to-metal bonded alumina (Al₂O₃) insulator to which is attached the high-voltage extraction electrode system; and (4) the coaxial LaB₆ cathode assembly. The design of the source is complete and fabrication will commence in the near future.

PRELIMINARY LASER NEGATIVE ION BEAM GENERATION EXPERIMENTS

G. D. Alton C. C. Havener

Preliminary experiments were initiated to explore the feasibility of the use of high-power laser beams for the generation of negative ion beams from solid surfaces. The experiments were conceived (1) to test existing velocity-dependent surface ionization theories, such as that of Nørskov and Lundqvist,¹ for elemental sample materials, and (2) to evaluate the technique as a means of generating atomic negative ion beams by thermal evaporation or sublimation of metal oxide materials through processes other than surface ionization, such as polar dissociation.

These preliminary experiments were performed by mounting a standard cesium sputter, negative-ion source and a 100-W, Nd:Yag, cw laser ($\lambda = 1.06 \mu\text{m}$) in diametrically opposed positions on a 0.61-m-diam scattering chamber. Alignment of the laser beam and sample axes was accomplished by maximizing the transmitted power of the laser beam through the ion extraction aperture and onto a power meter positioned on the outside of the scattering chamber, with the sample support tube removed from the source. Secondary electron suppression was effected by placement of dipole permanent magnets on the source body and downstream of the extracted ion beam. Negative ion beams generated on the sample surface were deflected by an electrostatic deflector into a Faraday cup equipped with electron suppression.

Throughout the test and evaluation period, the sample support assembly was biased at -10 kV with respect to source housing in order to accelerate negative ion beams through the source aperture, the electrostatic deflector, and into the Faraday cup. During this period, the cesium oven temperature was operated at several discrete temperatures, ranging from 125 to 210°C. The ionizer was typically operated at a temperature (~800°C) well below the threshold for surface ionization of cesium (~1050°C), but sufficient to heat the source chamber and thereby keep the cesium ion vapor from condensing during the laser radiation period.

The concept was tested by irradiating uncleaned Cu-Li₂O, Ni, and Si samples with ~10-11 watts of

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laser power (cw) while manually turning the laser beam on and off and observing the intensity versus time of negative ion spectra generated before, during, and following sample irradiation. Figure 1.5 displays an example of the intensity-time spectra obtained from a Ni sample. The growth and fall behavior shown in this figure is similar to that for other Cu-Li₂O and Ni samples, although the magnitudes and thermal responses frequently differed. Typically, the peak intensities of the spectra reached maximum values during initial irradiation of the nascent (uncleaned) surface and decreased with further irradiation time, presumably as a result of cleaning of the surface by thermal desorption of surface adsorbates. A likely scenario for this effect is that the negative ion beam is the result of thermal desorption of electronegative surface adsorbates which become ionized either through surface ionization or through polar-dissociation of vibrationally excited molecules as they leave the low-work-function cesiated surface. Continued irradiation results in ultimately driving the negative ion signal below background level indicating that the surface has been cleaned of ionizable adsorbates and that the laser radiation actually results in beam destruction through

photodetachment processes. Similar spectra from Si samples taken under identical circumstances, in general, did not drop off with time for irradiation times exceeding twenty minutes. During irradiation of a number of samples, the cesium oven temperature was varied over a range of temperatures between 125 and 215°C with no clearly defined effect.

The results of these measurements clearly suggest that negative ion beams can be generated by laser beam desorption of electronegative atoms or molecules from solid surfaces. However, the time constants required for cleaning surfaces such as Cu-Li₂O and Ni by laser irradiation are not commensurate with those required for practical utilization of this technique for pulsed negative-ion beam generation from these materials; the magnitudes of negative ion yields from Si samples, which do not exhibit short-term decreases in intensity with increasing laser irradiation time, are also not high enough for practical use. In order to test the technique, more intense power is required in the output laser beam to enable direct sublimation of the sample material itself. The present cw laser, which produces 10-15-watt beams on the sample surface, is clearly insufficient for evaporation or

Fig. 1.5. Variation of negative ion beam intensity with time for a Ni sample with and without laser irradiation.

sublimation of the host sample material. Plans are under way to equip the laser with a Q-switch which will enable the generation of pulsed laser beams with peak power up to ~100–500 kW, 200 ns in length, and 1–25 kHz repetition rates. Instantaneous power of this magnitude will allow direct thermal evaporation of the host material and a more definitive assessment of the technique as a means for generating practically useful negative ion beams.

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IMPROVEMENTS TO THE LOW-ENERGY-REGIME MODIFIED SIGMUND SPUTTERING THEORY

G. D. Alton J. R. Olive¹

Improvements to the low-energy-regime modified Sigmund sputtering theory,² reported previously,³ have been made during this reporting period. In the earlier developments, a linear scaling technique was described which could be used to bring Sigmund theory into better agreement with experiment. While the method gave good to excellent agreement with experiment for projectile energies within the high-energy range ($1000 \text{ eV} \leq E \leq 5000 \text{ eV}$), the scaled theory often deviated substantially from experiment for projectiles with energies within the low-energy range ($E_{th} \leq E \leq 1000 \text{ eV}$) where E_{th} is the minimum energy required to effect sputtering. This threshold effect is not accounted for in either the Sigmund theory or in the scaled theory. The modified theory takes the form

$$S(E, \theta) = A_1(E) \frac{0.042 \alpha S_n(E)}{U_0 (\cos \theta)^F} \quad (\text{for } E \leq 1000 \text{ eV}) \quad (1)$$

$$S(E, \theta) = \frac{A_2 0.042 \alpha S_n(E)}{U_0 (\cos \theta)^F} \quad (\text{for } E > 1000 \text{ eV}) \quad (2)$$

where

α is a tabulated function of the ratio of the target mass M_2 to projectile mass M_1 ,

U_0 is the heat of sublimation of the target,

θ is the angle between the incident projectile and the surface normal,

F usually has values between 1 and 1.7, depending on the ratio of target to projectile mass.

$$\lambda = 4M_1M_2/(M_1 + M_2)^2,$$

$$S_n(E) = 4\pi Z_1 Z_2 e^2 z_{12} [M_1/(M_1 + M_2)] S_n(\epsilon).$$

Z_1, Z_2 are the respective projectile and target atomic number,

$$a_{12} = 0.8853a_0 (Z_1^{2/3} + Z_2^{2/3})^{-1/2}$$

a_0 is the radius of the first Bohr orbit,

$S_n(\epsilon)$ is the projectile stopping power in the target,

$$\epsilon = \frac{M_2 E (M_1 + M_2)}{Z_1 Z_2 e^2 a_{12}},$$

and A_1, A_2 are scaling parameters. (The original theory does not include such scaling factors.) In this formulation, we incorporate the following approximation for the stopping power:

$$S_n(\epsilon) = \frac{1/2 \ln(1 + \epsilon)}{\epsilon + 0.14\epsilon} \quad (3)$$

This expression, derived by Wilson,⁴ is supposed to be applicable within the high- and low-energy regimes. However, we did not find this to be the case. Good agreement between Sigmund theory and experiment, with the approximation of expression (3) used for $S_n(\epsilon)$, was found over the complete high-energy regime by linearly scaling Eq. (2) by a factor A_2 . A_2 was determined at a projectile energy $E \geq 1000 \text{ eV}$ by comparing unscaled theory with experimental data. The scaling factor A_2 , in general, was not found to depend on projectile energy E for the high-energy case. This was not the case for projectile energies $E \leq 1000 \text{ eV}$. A function $F(E)$ was found to be necessary in order to bring Eq. (1) into agreement with experiment.

For this energy regime, F was found to depend on the energy of the projectile E in the following way:

$$F(E) = a_0 + a_1 E + a_2 E^2 + a_3 E^3 + a_4 E^4. \quad (4)$$

In Eq. (4), $a_0 = -0.1067$, $a_1 = 0.4577$, $a_2 = -0.8579$, $a_3 = 0.7779$, and $a_4 = -0.2668$, where the constants a_i are averages derived from linear least squares fits to several sets of experimental data for neon, argon,

krypton, and xenon projectiles interacting with a variety of targets over the low-energy regimes $E_{th} \leq E \leq 1000$ eV. The fits were heavily weighted with an average threshold value E_{th} of 24 eV in order to

force the sputter ratio S to be zero at E_{th} , independent of projectile and target material. Figures 1.6 and 1.7 are typical of the agreement found between experiment and theory for many projectile/target

Fig. 1.6. Comparisons of calculated sputter ratios for Xe projectiles at normal incidence on Zr with the experimental data taken from Ref. 5 as a function of projectile energy. --- scaled Sigmund Theory; — unscaled Sigmund Theory; O experimental data.

Fig. 1.7. Comparisons of calculated sputter ratios for Ne projectiles at normal incidence on Pt with the experimental data taken from Ref. 5 as a function of projectile Energy. --- scaled Sigmund Theory; — unscaled Sigmund Theory; O experimental data.

combinations. The function $F(E)$ is required to have a value at 1000 eV of unity. A_2 is then used as a linear scaling factor for both the low- and high-energy regimes, so that $A_1(E) = F(E) A_2$.

1. Undergraduate student from Carson-Newman College, Jefferson City, Tennessee.
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FACILITY OPERATIONS AND DEVELOPMENT

HHIRF EXPERIMENTS

R. L. Robinson

Table 1.6 lists the experiments performed at the Holifield Facility in FY 1989. Some of these 54 experiments were performed in more than one run giving a total of 70 runs. Experiments with a prefix H denote those recommended by PAC; those with a prefix D were discretionary. Discretionary experiments accounted for 330 hours (7%) of the total 4829 hours.

Table 1.6. Experiments completed at the HHIRF during October 1, 1988-September 30, 1989

Title	Spokesman	Run No.	Target Station	Beam		Research Hours
				Type	E(MeV)	
Tandem						
Evolution Towards Mass and Charge Equilibration in Orbiting Reactions	Shivakumar (Yale U)	H202	Split-Pole Magnet	^{24}Mg	75-115	99
Sub-Barrier Inelastic and Transfer Reaction Cross Sections for $^{32}\text{S} + ^{64}\text{Ni}$	Hindi (Tennessee Technological U)	H204	Split-Pole Magnet	^{64}Ni	162,165	102
Shape Changes, Band Terminations and Transition Rates in ^{159}Lu	Garrett (ORNL)	H206	CSS (Compact Ge Ball)	^{48}Ca	209-222	129
Decay of Mass-Separated ^{177}Eu	Braga (Georgia Tech)	H217	UNISOR	^{48}Ti	250	29
Dielectronic Recombination of Cl^{17+} via $2p - 3d$ Excitation	Ditzner (ORNL)	H220	Merged Electron Beam	^{35}Cl	82-169	87
Binary-Reaction Channel Study at and Below the Coulomb Barrier	Kim (ORNL)	H226	Split-Pole Magnet	^{93}Nb	284-308	162
Decay of Mass-Separated ^{187}Au to ^{207}Pt	Schwarzenberg (Georgia Tech)	H228	UNISOR	^{12}C	160	91
Scintillation Response to Low Energy Heavy Ions	Muga (U Florida)	H233	Atomic	$^{70,74}\text{Ge}$ $^{74,76}\text{Se}$	57-164 61-126	44
Coulomb/Nuclear Excitation of ^7Li to α -t Continuum States Just Above the Binding Energy	Utsunomiya (Texas A&M)	H234	Split-Pole Magnet	^7Li	37,42,58	115
Elastic Scattering of $^{38}\text{Ni} + ^{27}\text{Al}$ at Near- and Below-Barrier Energies	Brandon (UNAM, Mexico)	H235	Split-Pole Magnet	^{38}Ni	155-220	79
Neutron Transfer Reactions in the Actinide Region	Rasmussen (LBL)	H239	Spin Spectrometer	^{237}Zr	500	132
Unpaired Band Crossings in ^{161}Er and the Single Particle Spectrum of States	Garrett (ORNL)	H241	CSS (Compact Ge Ball)	^{48}Ca	217	161
In Search of the Missing Momentum	Sohnka (Washington U)	H244	Spin Spectrometer	^{48}Ti	679,916	13

Table I.6. (Continued)

Title	Spokesman	Run No.	Target Station	Beam		Research Hours
				Type	E(MeV)	
Resonant Transfer and Excitation Investigated by Two Photon Coincidences and High Resolution	Schuch (MSI, Sweden)	H247	Atomic	^{35}Cl ^{32}S	120-160 150-225	92
Determination of α Widths for Uranium Nuclei Near $N = 130$; Search for ^{234}U , ^{225}U , and ^{226}U	Toth (ORNL)	H248	Velocity Filter	^{19}F ^{48}Ti	102 243	98
Search for Low-Spin Particle Emitting Superdeformed States in ^{184}Hg or ^{186}Hg	Akovioli (ORNL)	H249	UNISOR	^{16}O	165	81
Nuclear Orientation of ^{184}Au	Krane (Oregon SU)	H250	UNISOR	^{16}O	160	108
Conversion-Electron and Gamma-Ray Spectroscopy in ^{116}Xe and ^{126}Xe	Walters (U Maryland)	H251	UNISOR	^{32}S	145	76
Sharing of Excitation Energy in Complex Fragment Emission of $^{79}\text{Br} + ^{27}\text{Al}$ at 11 MeV/amu	Wieleczko (Saclay, France)	H252	HILI	^{16}O ^{18}Si	165 252	46
A Test of the Mass Dependence of "Rotational Shrinking" through Lifetime Measurements in ^{164}Er	Johnson (ORNL)	H253	CSS (Compact Ge Ball)	^{44}Ca	189	178
Particle-Core Coupling in ^{191}Au	Zganjar (Louisiana SU)	H254	UNISOR	^{16}O	130	74
Search for Superdeformed Shapes in $^{81,83}\text{Sr}$ Nuclei	Baktash (ORNL)	H255	Spin Spectrometer	^{30}Si ^{34}S ^{36}S	119 130 140-150	234
High-Spin Levels in Odd-Odd Ir Nuclei	Reidinger (U Tennessee)	H256	Spin Spectrometer CSS (Compact Ge Ball)	^{23}Na	105-117 94	121
Hard Photon Spectroscopy with Nearly Complete Event Characterization	Beene (ORNL)	H257	Spin Spectrometer	^1H	20,26	15
Dielectronic Recombination of Cl^{1+}	Dittner (ORNL)	H258	Merged Electron Beam	^{35}Cl	82-101	14
Direct Excitation and Resonant Dielectronic Excitation of One Electron Ions in Crystal Channels	Datz (ORNL)	H260	Atomic	^{48}Ti ^{40}Ca	242-375 210	143
Strong Deformation and Pairing Collapse in ^{72}Se and ^{72}Br	Hamilton (Vanderbilt U)	H261	CSS (Compact Ge Ball)	^{28}Si	95	82
Study of Giant Resonances in Hot Rotating Nuclei	Morsch (Jülich, Germany)	H262	Spin Spectrometer	^{16}O	160,216	186
Search for Super Deformation in ^{184}Hg	J. Hamilton (Vanderbilt U)	H263	CSS (Close Packed Ge)	^{36}S	163,167	122
Study of E0 Transitions and Intruder Structures in Xe Nuclides	Walters (U Maryland)	H265	UNISOR	^{32}S	175	83
A Search for Mixed-Symmetry States in ^{190}Pt	D. Hamilton (JHIR)	H268	UNISOR	^{12}C	150	47
High Statistics Triples Experiment for Osmium Nuclei	Lee (ORNL)	H275	CSS (Close Packed Ge)	^{36}S	152,160	166
Light Output of CsI (TI) as Function of $1/\beta$ E	Saranites (Washington U)	H278	1.6-m Chamber	^1H	21	10
Relative Electron Capture in Channelled Heavy Ions	Vane (ORNL)	H279	Atomic	^{48}Ti	250,300	70

Table 1.6. (Continued)

Title	Spokesman	Run No.	Target Station	Beam		Research Hours
				Type	E(MeV)	
Continuum Gamma Spectra in Cold Fusion Reactions	Thoennessen (ORNL/JIHR)	H280	Spin Spectrometer	^{64}Ni ^{16}O ^1H	237 82.86 29	144
Test of Dwarf Ball	Sarantites (Washington U)	D043	1.6-m Chamber	^1H	23	?
HILI Detector Development	Shapira (ORNL)	D047	HILI	^{32}S	240	70
Development of Nuclear Orientation Facility	Carter (ORAU)	D057	UNISOR	^{32}S	175	20
^{197}Au Charge State Distribution	Jones (ORNL)	D058	Beam Line C17	^{197}Au	400-500	49
Test Run to Examine Feasibility of Using Heavy Beams for Particle Decay Studies	Toth (ORNL)	D060	Velocity Filter	^{46}Ti	220	30
Development of the UNISOR Ion Source	Carter (ORAU)	D064	UNISOR	^{32}S ^{46}Ti	145 250	34
Fluorescent Light Created by Energetic ^{12}C Ions in Scintillators	Dickens (ORNL)	D071	1.6-m Chamber	^{12}C	25-100	16
Calibration and Light Guide Test of NE102/CsI Scintillators	Maguire (Vanderbilt U)	D073	1.6-m Chamber	^{16}O	200	29
Preparation of Nuclear Orientation Sources by Recoil Ion Implantation Following Direct Heavy Ion Reactions	Croft (Mississippi SU)	D074	UNISOR	^{12}C	95	12
Development of Rare Earth Production in UNISOR Ion Source	Zimmerman (U Maryland)	D075	UNISOR	^{46}Ti	250	19
Completed						
Nuclear SQUIDS, Diabolical Transfer, and Topological Phases	Guidry (U Tennessee)	H212	Spin Spectrometer	^{158}Gd	885	220
Limits to Collective Behavior at High Excitation Energies	Nasowitz (Texas A&M)	H231	1.6-m Chamber	^{60}Ni	796,1003	163
Linear Momentum Transfer and Non-equilibrium Emission in Reactions $^{32}\text{S} + \text{Te}$ at 25 MeV/Nucleon	Petit (Georgia SU)	H243	HILI	^{32}S ^7Li	707 110	139
In Search of the Missing Momentum	Sobotka (Washington U)	H244	Spin Spectrometer	^{46}Ti	679,916	168
Probing for Limiting Temperature for $^{58}\text{Ni} + ^{24}\text{Mg}$ Fusion Reactions	Maguire (Vanderbilt U)	H245	HILI	^{58}Ni	635	124
Sharing of Excitation Energy in Complex Fragment Emission of $^{79}\text{Br} + ^7\text{Al}$ at 11 MeV/amu	Wieleczko (Saclay, France)	H252	HILI	^{16}O ^{28}Si	165 252	74
Hard Photon Spectroscopy with Nearly Complete Event Characterization	Beene (ORNL)	H257	Spin Spectrometer	^{16}O	402	154
Light Output of CsI(Tl) as Function of Z and E	Sarantites (Washington U)	H278	1.6-m Chamber	^{46}Ti	912	24
Test of Dwarf Ball	Sarantites (Washington U)	D043	1.6-m Chamber	^1H	23	16
Calibration and Light Guide Test of NE102/CsI Scintillators	Shea (Vanderbilt U)	D073	HILI	^{46}Ti	916	28
						4829

The distribution of the runs is given according to the general area of physics in Table 1.7 and according to the target station in Table 1.8.

Experiments H250 (Krane) and H268 (D. Hamilton) are the first two on-line runs with the Nuclear Orientation Facility. The newly commissioned BaF₂ 19-packs were used in experiments H231 (Natowitz), H257 (Beene), H262 (Morsch), and H280 (Thoennessen).

Spokesmen from outside ORNL represented experiments utilizing 56% of the total research hours.

EXPERIMENTAL APPARATUS

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The following brief reports summarize the experimental apparatus development projects carried out over the past year. The larger projects

Table 1.7. Division of research hours by research activities for the period October 1, 1988 through September 30, 1989

Activity	Research Hours (No. of Runs)		
	Tandem	Coupled	Total
High-spin states	969(8)	220(1)	1189(9)
Superdeformation	437(4)		437(4)
Low-level properties	539(12)		539(12)
Alpha decay rate	98(1)		98(1)
Reaction mechanisms	317(5)	822(6)	1139(11)
Giant resonances	186(1)		186(1)
Quasi-elastic	458(5)		458(5)
Atomic	455(9)		455(9)
Applications	16(1)		16(1)
Test of detectors	120(6)	68(3)	188(9)
Test of apparatus	124(8)		124(8)
Total	3,719(60)	1,110(10)	4,829(70)

Table 1.8. Use of experiment target stations for the period October 1, 1988 through September 30, 1989

Target Station	Beam Line	Research Hours (No. of Runs)		
		Tandem	Coupled	Total
Spin Spectrometer	C15	751(7)	542(3)	1293(10)
Close-Packed Ge Ball	23	932(7)	na	932(7)
UNISOR	C16B	674(20)	0	674(20)
Split-Pole Magnet	33	557(6)	na	557(6)
HILI	51A/C17	139(4)	337(3)	476(7)
Atomic	35	349(6)	na	349(6)
1.6-m Scattering Chamber	C16A	39(3)	231(4)	270(7)
Velocity Filter	21	128(3)	na	128(3)
Merged Electron Beam	45	101(3)	na	101(3)
Application	17	49(1)	na	49(1)
Total		3,719(60)	1,110(10)	4,829(70)

na = not accessible to beam

are discussed in more detail elsewhere in this report.

HILI Detector System

During the past year the HILI detector was completed with the installation of the second 96-element scintillator hodoscope, and several experiments and development runs were completed at its original location on beam line 20. Based on these measurements, it was concluded that access to tandem-only beams would be highly desirable. Therefore, it was decided to remove the time-of-flight chamber, which had access to both tandem and cyclotron beams, and move the HILI system to the rotatable mount in that location. Due to limited floor space, the electronics racks had to be located downstream of the detector system. Although several runs were completed in this configuration it was clear that the congestion in the area severely limited the possibilities for using ancillary detectors. To alleviate this situation, a mezzanine was constructed over the HILI chamber to support the electronics. In addition, the scattering chamber was modified by the addition of a sliding-band seal to permit easier rotation between the two beam lines.

Nuclear Orientation Facility

The helium dilution refrigerator was reinstalled in June after almost one year of effort by the vendor to improve its performance. The system now exceeds the original temperature specifications, having attained a temperature of 4.4 mK with all baffles closed and 9 mK in the "beam-on-target" condition with baffles open. A successful on-line experiment was completed during August in which (53 sec) ^{184}Au and (11 min) ^{186}Au were oriented.

Spin Spectrometer

The program of replacement or repackaging the NaI crystals in half of the Spin Spectrometer assemblies is now nearly complete; only one more rebuilt assembly remains to be installed. In addition, nine of the original phototubes have been replaced. These measures have reduced the

pulse-height resolution for 898-keV gamma rays to 10% or better in every assembly. The resolution, averaged over all assemblies, is now about 9.2%. Further improvement is to be expected as more of the aging phototubes are replaced. The replacement of badly cracked NaI crystals has also eliminated the high-side tailing previously present in these units.

The beam-on background in the vicinity of the Spin Spectrometer was reduced by boring an 8-in.-diam hole through the downstream shield wall and burying the Faraday cup approximately three feet inside the wall.

Barium Fluoride Detectors

Testing of 76 crystals and photomultiplier tubes was completed and four "19-pack" arrays were assembled. Two stands were built to support two arrays each. Electronics procurement is nearly complete.

Compton-Suppression System

Dedicated electronics modules have been purchased or fabricated to replace modules borrowed from the electronics pool. The Ge detectors have been heavily used during the year, and 52 repairs and recoveries were required. In order to speed up recoveries involving annealing of the detectors, the Ge-recovery system was expanded to allow up to four detectors to be pumped and baked simultaneously. If the recoveries had been performed by the vendor, the estimated cost would have been in excess of \$100K.

Broad Range Spectrograph

A small scattering chamber was fabricated which can be used to place an array of gamma ray detectors around a target position located approximately two feet upstream from the center of rotation of the BRS.

Time-of-Flight Facility

The original time-of-flight chamber has been removed to make room for the HILI detector

system. However, a new flight arm has been designed and is being fabricated as a joint effort of the Holifield Facility and the University of Maryland. The new arm will be attached to the gun mount which now supports the HILI detector system, and will provide essentially the same capabilities as the original TOF facility plus the capability of being used in conjunction with the HILI detectors.

Electronics Pool

The high density NIM modules used in many experiments have often been found to exceed the power supply capacity of conventional NIM bin power supplies. High current supplies were purchased to upgrade the bins used for these modules. Four new modules were purchased, and a PC-based multichannel analyzer was acquired through cooperation with Tufts University. In addition, a large number of used NIM and CAMAC modules, NIM bins, CAMAC crates, and racks were obtained free of charge from various sources which, if purchased new, would have cost about \$150K.

Recoil Mass Spectrometer

The recoil mass spectrometer (RMS), which is a proposed major experimental device for the Holifield Facility, achieved full funding during FY 1989. The original RMS design was based on that of the University of Rochester² spectrometer with elements QQESDSEQQQ. However, it became increasingly evident that much of the science requires inverse reactions (heavy projectiles on light targets) which cannot usually be done with the Rochester-type spectrometer. Inverse reactions offer three major advantages:³ (1) Because of kinematic focussing, more recoils are transported to the focal plane of the RMS than under the same conditions for a normal reaction. (2) The greater energy of the recoils gives rise to larger Z separation in ΔE -E detectors, placed at the focal plane of the RMS, whereby Z as well as A can be obtained. (3) The greater recoil energy makes possible the use of reaction products as a secondary beam.

During the past year, Jerry Cole (INEL) and Tom Cormier (Texas A&M University) completed a new design which can accommodate essentially all inverse reactions. The design has a momentum achromat followed by the Rochester-type spectrometer with elements of QQDQSDSQQEDEQQ. The primary beam stop can be at the intermediate focus in the achromat. Cole and Cormier also incorporated into their design a distance of 75 cm between the target and first element of the RMS and between the last element and the focal plane, while still maintaining a solid angle of about 15 msr. With this distance, near 4 π detector arrays can be placed around either the target or the focal plane of the RMS. For example, only five of the 110 Ge detectors would need to be removed from the present design of the GAMMASPHERE when placed in either position.

Parameters for the present design of the RMS are given in Table 1.9.

Table 1.9. Parameters of the RMS

Solid angle	12 msr
Energy range	$\pm 10\%$
A/q range	$\pm 5\%$
Mass resolution $A/\Delta A$	>300
Electrical rigidity (E/Q)	15 MeV/q

GAMMASPHERE

GAMMASPHERE is a \$17M 4 π array of Ge and BGO detectors that has been proposed by the U.S. nuclear structure community for doing high-fold, high-resolution gamma-ray spectroscopy. Three facilities, the Holifield, the 86-Inch Cyclotron at LBL, and the ATLAS at ANL, offered to serve as the site for this major research tool. A siting panel formed by DOE to review these three locations recommended in July that the Holifield be the site for GAMMASPHERE.

A building design team has been formed to develop the optimum location for GAMMASPHERE, and also for the RMS, within the Holifield Facility. The building must meet the following special requirements:

Access to beams from both the tandem accelerator and from the coupled accelerators.

Capability to operate the GAMMASPHERE in the stand-alone mode, at the target position of the RMS, and around the focal plane of the RMS.

Provision for 8-ft-high beam line necessary to accommodate the large height of the GAMMASPHERE (the present beam line heights are 4 ft).

Availability of a counting room of adequate size nearby (approximately 800 ft²).

Options now being explored are modifications to the south annex, a new annex to the east, and accommodating the beam line height by lowering the floor 4 ft in the GAMMASPHERE/RMS target room or raising the beam line to that area by 4 ft.

-
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 2. J. D. Cole, J. H. Hamilton and A. V. Ramayya, A Proposal for a Zero Energy Dispersion Recoil Mass Spectrometer (Dec. 1986).
 3. J. H. Hamilton, A. V. Ramayya, J. D. Cole, R. L. Robinson, P. H. Stelson, H. K. Carter, and E. F. Zganjar, Supplement to a Proposal for a Zero Energy Dispersion Recoil Mass Spectrometer (Feb. 1988).

COMPUTER SYSTEMS

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Computer Facility Upgrade

The first major steps in a general five-year plan to upgrade the computing facilities of the Physics Division have been completed.

The VAX 11/785 has been replaced with a clustered pair of VAX 3600's. Each VAX 3600 is equipped with 32 MB of memory and has a computing power of 2.7 VUP (VAX Unit of Perfor-

mance), as compared to 1.5 VUP for the 11/785. The total amount of disk storage has been increased to 5 GB and is accessible from either member of the cluster. This transition from a single VAX 11/785 to a pair of VAX 3600's was extremely smooth from the user's point of view since very few changes were required, all files are accessible from either VAX, and the fact that there are two machines instead of one is nearly transparent.

Additional computing power was made available by the procurement of a MIPS M/120 RISC computer with 8 MB of memory and 600 MB of disk storage. This machine runs UNIX and has a computing power of 10 or more VUP. Several compute-intensive modeling codes have been ported to this computer with minimal difficulty. Reported performance varies from 3 to 4.5 times that of the VAX 3600 (i.e., 8 to 12 VUP) and depends on the specific program, level of optimization, etc.

The local area network has been extended to Buildings 6003 (office annex) and 6008 (Joint Institute). Since equipment previously connected to Bldg. 6003 via normal twisted pair cable had often suffered lightning damage, fiber optic cable was used for all of the long runs of this LAN extension. After correction of a few problems with some of the commercial equipment, the system is working well.

The FPS-164 Array Processor was retired earlier this year in order to eliminate the approximately \$50K yearly maintenance cost.

Exabyte Tape Status Report

An Exabyte 8-mm helical-scan data recording system was procured about one year ago for testing and evaluation on one of the HHIRF Concurrent data acquisition and processing computers. The advantage of such systems stems from the fact that one T-120 cassette can hold up to 2 GB (as much as twelve 6250-bpi standard tapes) and thus much less attention is required in processing large volumes of data or in backing up

large disks. The maximum read/write speed (248 KB/sec) is about one-third of that for a standard 125-ips 6250-bpi tape, but is adequate for our current data acquisition and processing applications. With such devices, a great deal of processing can be done overnight, which leads to a much better utilization of our limited computer and human resources. Also, the media cost per unit storage is only about 5% of that for standard tape. Although there were a number of problems initially, the device worked; and despite some inconvenience, its advantages were so great that it was put into use immediately. About 8 months ago, 5 additional drives were procured, bringing the total to 6 (2 per Concurrent CPU). Since that time they have been in almost constant (24 hours/day, 7 days/week) use for either data processing or acquisition. At this time, most of the problems have been fixed (via several PROM or software changes, and some education). We plan to acquire 6 more drives in the near future, bringing the total to 4 per Concurrent computer.

Two Exabyte drives have also been implemented on the HHIRF VAX cluster (dual VAX-3600's). This system is now working (after a few PROM changes in the Q-bus-to-SCSI interface) and is being used for backups and some processing and file copy work. Another Exabyte drive has been installed on the recently acquired MIPS M/120 and has been used for ASCII file transfer from the VAX's and for system backup.

It has been necessary to return some (2 or 3) drives to the vendor for "electronic" repair early in their life but we have yet to "wear out" one. This is a pleasant surprise, since we are almost never operating in the full streaming mode. These systems (drives and cassettes) are certainly not as robust as standard 9-track tape systems, but the advantages are such that we will continue to use them heavily until something better comes along.

DAM & SAM for VAXstations

Data manipulation and display program DAM and spectrum analysis program SAM have been

adapted for use on VAXstations running VMS. Although these are considered to be prototype versions to which features will be added, they contain essentially all of the features of earlier VAXPAK versions (plus a few) and the display is much faster. The documentation has not been completely revised to reflect the adaptation, but a supplement is available and the HELP facility does include all new or modified commands. This adaptation was made using the standard UIS graphics library and no other graphics library is involved.

Parallel Processor Development

It is desirable to be able to intercept the raw event data stream delivered by the Event Handler and impose more complex rejection tests than is possible with the Event Handler itself. It would also be beneficial to be able to make some modifications to the event (e.g., calculate new parameters, gain-match certain classes of parameters) before the data stream is recorded on tape or passed to the histogramming monitor task. To carry out such operations in real time without limiting the data acquisition rate requires substantial computing power, much more than is available with the host Concurrent 3230 computer. A development project is under way (in its early stages) to utilize a number of VME-based parallel processors for this purpose. At this time, Motorola 68020 processors (packaged into a VME module by Omnibyte) are being evaluated. A MicroVAX II computer is interfaced to the VME system and serves as a host which provides the environment (currently the ACP system developed at Fermilab) for cross compiling, linking and downloading software into the processors.

Plans for the Future

During the coming year, we will continue with the general computer upgrade plan by devoting a major portion of available resources (money and manpower) to the area of data acquisition, processing, and analysis. We plan to acquire a RISC

based DECstation 3100 (equipped with Exabyte tape drives) for development and use as an off-line data processing and analysis station. Development of the parallel processor system for data acquisition will also continue.

1. Computing and Telecommunications Division, ORNL.
2. Oak Ridge Associated Universities.

THE JOINT INSTITUTE FOR HEAVY ION RESEARCH

R. L. Robinson L. L. Riedinger¹
J. H. Hamilton²

The Joint Institute for Heavy Ion Research is a collaborative endeavor of the University of Tennessee, Vanderbilt University, and Oak Ridge National Laboratory. It is administrated by the

University of Tennessee through the Science Alliance, which is one of the State of Tennessee's Centers of Excellence. Two-thirds of the support for the Joint Institute comes from the Science Alliance; remaining funds are provided by DOE, Vanderbilt University, and ORNL. The Joint Institute is housed in two buildings adjacent to the Holifield Facility.

The purpose of the Joint Institute is to enhance and stimulate the scientific environment of the Holifield Facility to the mutual benefit of its sponsoring institutes. This is accomplished through three activities: (1) its guest program, (2) sponsorship of workshops held at the Joint Institute, and (3) operation of a dormitory facility for users of the Holifield Facility.

Table 1.10 notes guests who were, in part or fully, supported by the Joint Institute during

Table 1.10. Guest scientists at the Joint Institute for Heavy Ion Research during the period of October 1988 - September 1989

Name	Institute	Length of Appointment
S. Aberg	Univ. of Lund (Sweden)	3 months
G. Arbanas	MIT	1 month
A. Arima	Univ. of Tokyo (Japan)	6 days
S. Ayik	Tennessee Technological Univ.	6 months
J. Bardsley	Lawrence Livermore National Lab.	2 days
R. Bengtsson	Univ. of Lund (Sweden)	2 weeks
K. Bhatt	Western Kentucky Univ. and Univ. of Mississippi	4 months
M. Brandan	National Univ. of Mexico (Mexico)	2 weeks
J. Briggs	Univ. of Colorado	1 week
D. Brink	Oxford Univ. (United Kingdom)	10 days
A. Brown	Michigan State Univ.	3 days
F. Donau	Inst. for Nuclear Research (East Germany)	3 weeks
T. Dossing	Neils Bohr Inst. (Denmark)	1 month
J. Draayer	Louisiana State Univ.	3 days
R. Dreizler	Univ. of Frankfurt (West Germany)	1 month
J. Dudek	Centre de Recherches Nucleaires (France)	3 days
J. Eberth	Univ. of Köln (West Germany)	2 days
A. Eklund	Univ. of Lund (Sweden)	1 month
P. Zeijlmans van Emmichoven	Utrecht University (Netherlands)	1 year
D. Ernst	Texas A&M Univ.	2 weeks
J. Espino	Univ. of Seville (Spain)	3 months

Table 1.10. (Continued)

Name	Institute	Length of Appointment
A. Faessler	Univ. of Tübingen (West Germany)	2 weeks
D. Feng	Drexel Univ.	3 days
D. Fossan	SUNY at Stony Brook	3 days
P. Gore	Vanderbilt Univ. and UNISOR	3 months
W. Greiner	Univ. of Frankfurt (West Germany)	8 days
I. Hamamoto	Univ. of Lund (Sweden)	3 days
D. Hamilton	Univ. of Sussex (England)	1 year
K. Heyde	Univ. of Gent (Belgium)	2 weeks
W. Johnson	Univ. of Notre Dame	10 days
E. Jones	Vanderbilt Univ.	5 months
J. Kormicki	Vanderbilt Univ. and ORAU	3 days
M. Korolija	Ruder Boskovic Inst. (Yugoslavia)	1 year
G. Kyrchev	Inst. Nuclear Research & Energy (Bulgaria)	3 days
J. Lisanti	ORNL/JHIR	1 year
W. Ma	Tsinghua Univ. (China)	8 months
H. Marshak	ORAU	3 days
J. McNeill	ORNL and JHIR	1 year
A. Menchaca-Rocha	National Univ. of Mexico (Mexico)	2 weeks
P. Mohr	National Inst. of Standards (Maryland)	3 weeks
J. Mueller	Univ. of Frankfurt (West Germany)	1 year
M. Nagarajan	Daresburg Laboratory (England)	10 days
D. Napoli	Inst. Nazionale de Fisica (Argentina)	3 weeks
N. Neskovic	Boris Kidric Inst. (Yugoslavia)	2 weeks
K. Niita	Univ. of Giessen (West Germany)	1 month
P. Nolan	Univ. of Liverpool (England)	3 days
V. Oberacker	Vanderbilt Univ.	1 month
M. Ortiz	Univ. of Mexico (Mexico)	2 weeks
G. Petit	Georgia State Univ.	2 months
S. Pilotte	Chalk River Nuclear Lab. (Canada)	1 year
A. Ray	ORNL/JHIR	1 year
J. Reading	Texas A&M Univ.	8 days
M. Rhoades-Brown	Brookhaven National Lab.	8 days
M. Riley	ORNL/JHIR	1 year
P. Ring	Technical Univ. of Munich (West Germany)	3 days
M. Rosenkrantz	Univ. of Dayton	1 week
D. Rowe	Univ. of Toronto (Canada)	3 days
S. Saini	ORNL/JHIR	1 year
J. Saladin	Univ. of Pittsburgh	3 months
D. Sarantites	Washington Univ.	1 month
W. Scheid	Univ. of Giessen (West German.)	1 month
K. Schiffer	Neils Bohr Inst. (Denmark)	1 week
R. Schuch	Univ. of Frankfurt (West Germany)	10 days

Table 1.10. (Continued)

Name	Institute	Length of Appointment
M. Schultz	Univ. of Heidelberg (West Germany)	1 year
M. Schutz	Univ. of Heidelberg (West Germany)	9 months
Y. Shimizu	Kyushu Univ. (Japan)	1 month
P. Siemens	Oregon State Univ.	1 week
I. Talmi	Weizmann Inst. of Science (Israel)	6 days
K. Teh	ORNL/JIHIR	1 year
M. Thoennessen	ORNL/JIHIR	1 year
U. Thumm	Univ. of Freiburg (West Germany)	7 months
M. Tincknell	ORNL	1 year
J. Truran	Univ. of Illinois	3 days
J. Walecka	CEBAF	2 days
S. Wang	Lanzhou Univ. (China)	3 months
W. Wei	Inst. of Modern Physics (China)	1 week
H. Weidenmueller	Max-Planck Inst. (West Germany)	2 days
J. Wells	Tennessee Technological Univ.	1 month
J. Wieleczko	CEN, Saclay (France)	1 year
C. Wu	Jilin Univ. (China)	1 year
J. Wu	ORNL/JIHIR	1 year
C. Yannouleas	Neils Bohr Inst. (Denmark)	8 months
C. Yu	Neils Bohr Inst. (Denmark)	1 year
J. Zhang	Lanzhou Inst. (China)	1 year

FY 1989. The average length of appointment of the 84 guests was nearly 4 months.

Workshops sponsored by the Joint Institute are listed in Table 1.11. The Workshop on Microscopic Models provided an excellent forum for the presentation of several current theoretical approaches to

understanding nuclear structure at the microscopic level such as the Shell Model, the Fermion Dynamical Model, the Interaction Boson Model, and the Cranked HFB Model. The Town Meeting in April gave the opportunity to discuss, in an open forum, future directions in the area of high-energy

Table 1.11. Meetings sponsored by JIHIR during FY 1989

Meeting	Date	Attendance	Organizer
Workshop on Microscopic Models in Nuclear Structure Physics	October 3-6, 1988	75	M. W. Guidry
Town Meeting on High-Energy Heavy Ion Physics	April 24-25, 1989	92	G. R. Young M. Gyulassy R. L. Robinson
UNISOR Nuclear Orientation Workshop	June 20-23, 1989	55	K. Krane
Planning Workshop for GAMMASPHERE	September 21-22, 1989	92	I. Y. Lee

physics with $E/A \geq 20$ MeV/u. The results were used as input to members of the Long Range Planning Committee formed by NSAC. The UNISOR Nuclear Orientation Workshop acquainted users with the capabilities of this device and its potential contributions to nuclear structure. The purposes of the GAMMASPHERE workshop were: (1) to consider the details of the GAMMASPHERE design, (2) to define the scope and schedule for subtasks of the GAMMASPHERE and ancillary equipment, (3) to identify researchers who wish to take responsibility for or assist in specific tasks, and (4) to define organization and form working groups.

The dormitory facility can accommodate up to twelve users of the Holifield Facility. During FY 1989, there were 335 guests who stayed a total of 1913 work-days (an average of 5.7 days per guest).

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1. University of Tennessee.
 2. Vanderbilt University.

USERS GROUP ACTIVITIES

R. L. Auble

Members of the Executive Committee of the HHIRF Users Group during 1988 and 1989 are listed in Table 1.12.

The Executive Committee held four meetings during this reporting period (three via conference call) to provide input on the operation of the HHIRF. The committee's recommendations are especially important in view of the tight budget and the need to set priorities on expenditures.

Each member serves on the committee for three years. Thus, each year two members leave and two new members must be elected. The nominees are selected by a nominating committee which in 1989 was chaired by F. E. Bertrand (ORNL). Other members of the committee were: R. Phaneuf (ORNL), L. Riedinger (University of Tennessee), D. Sarantites (Washington University), and E. Zganjar (Louisiana State University).

Table 1.12. Users Group Executive Committee

<u>1988</u>
Jim Beene, Oak Ridge National Laboratory I-Yang Lee, Oak Ridge National Laboratory Joe Hamilton, ¹ Vanderbilt University Doug Cline, ² University of Rochester Richard Schmitt, Texas A&M University John Wells, Tennessee Technological University
<u>1989</u>
Doug Cline, ¹ University of Rochester Carroll Bingham, ² University of Tennessee Joe Hamilton, Vanderbilt University Ken Toth, Oak Ridge National Laboratory Richard Schmitt, Texas A&M University John Wells, Tennessee Technological University

¹Chairperson

²Chairperson elect

The annual meeting of the HHIRF Users Group was held on October 14, 1988 in conjunction with the APS/DNP meeting at Santa Fe, New Mexico. The meeting was chaired by J. H. Hamilton, and included presentations on accelerator operations and current experimental apparatus development projects.

THE PROGRAM ADVISORY COMMITTEE

R. L. Robinson

The HHIRF Program Advisory Committee meets twice a year to review proposals requesting time to perform experiments at the Holifield Facility. The members base their decisions primarily on the scientific merit of the proposals. However, they do consider other factors in the fine-tuning of their recommendations (e.g., suitability of experiment to facility, readiness of group and equipment, training of students). Members of PAC are selected from senior scientists of the nuclear and atomic physics communities and are chosen to give a broad coverage of the subdisciplines. Generally, members are chosen from among recommendations provided by the Executive Committee of the Holifield Users Group.

Statistics on the past two PACs and on the PAC that will meet this coming October 30 are given in Table 1.13. Numbers for PAC-12 and PAC-13 are more representative of PACs which have met since 1984. However, PAC-14 has an unusually large number of requested research hours with the result that only about 55% of these can be recommended for approval. This is to be compared to an average recommended-to-requested ratio of 76% for the past six PACs.

Members of the PACs are given in Table 1.14. Other nonparticipating attendees of the PAC meetings were: an observer from DOE (L. S. Schroeder), the chairman of the Executive Committee of the Users Group (D. Cline), the HHIRF Users Liaison Officer (R. L. Auble), and the

Physics Division Director (J. B. Ball). The meetings are chaired by R. L. Robinson.

Table 1.14. Members of PAC-12, PAC-13, and PAC-14

Member	Institute	PAC
R. Betts	ANL	14
C. L. Cocke	Kansas State University	14
R. M. Diamond	LBL	12,13,14
D. H. Feng	Drexel University	12,13,14
S. Landowne	ANL	12,13
J. B. McGrory	ORNL	14
J. B. Natowitz	Texas A&M University	12,13,14
R. A. Phaneuf	ORNL	12,13
P. J. Siemens	Oregon State University	12
P. H. Stelson	ORNL	12,13,14

Table 1.13. Information on PAC-12, PAC-13, and PAC-14

	Meeting Date	Hours Requested	Hours Recommended	Rec/Req.
PAC-12	Nov. 1, 1988	2488	2024	81%
PAC-13	April 4, 1989	2704	1848	68%
PAC-14	Oct. 30, 1989	3888	~2100	~55%

2. EXPERIMENTAL NUCLEAR PHYSICS

The Spin Spectrometer not only continues to yield a wealth of nuclear structure information on nuclei at high spin, as well as on nuclear reaction mechanisms, but it continues to be used in innovative ways. Using this device to extract particle- γ correlations has proven to be sensitive to static quadrupole moments of low lying 2^+ states and such correlations have provided additional support for the nuclear orbiting picture for the strongly damped $^{28}\text{Si} + ^{12}\text{C}$ reaction. In another experiment, the Spin Spectrometer was operated in coincidence with an inner $\sim 4\pi$ "dwarf ball" to detect and identify light fragments, 3 packs of 19 BaF_2 arrays to detect high energy γ -rays, and a position-sensitive Breskin detector to detect heavy recoils. The almost 1000 parameters per event severely taxed the HHIRF data acquisition system and is now presenting a challenge in data reduction. First results from the HILL detector also face the same data reduction and analysis problems. Progress in the development of a multi-microprocessor farm to process data tapes from the WABO relativistic heavy-ion experiment is the bright hope to unjam this data reduction bottleneck. The relativistic heavy-ion program is moving in the direction of more γ -ray coverage to improve π^0 and n acceptance at low p_t as well as to improve mass resolution. This effort is also expanding its base of operations from CERN to BNL where a program has begun to develop detectors for dimuon measurements at PHIC. The giant resonance program, using the heavy ion beams at GANIL and at HHIRF, also continues to produce interesting results on the microscopic structure of these resonances.

NUCLEAR STRUCTURE STUDIES VIA ELASTIC AND INELASTIC SCATTERING

^{24}Mg NUCLEAR MOMENTS FROM ^{24}Mg (200 MeV) + ^{208}Pb SCATTERING¹

D. C. Hensley	F. E. Bertrand
E. E. Gross	G. Yourvopoulos ²
M. L. Halbert	D. L. Humphrey ²
J. R. Reene	T. VanCleve ²

Differential cross sections for exciting the low-lying states in ^{24}Mg by heavy-ion inelastic scattering were measured with a new technique that uses a 4π γ -ray detector in coincidence with charged-particle detectors. The resulting data were subjected to a coupled-channels analysis to obtain a set of E2 and E4 matrix elements for exciting the $2_1^+(1.37 \text{ MeV})$, $4_1^+(4.12 \text{ MeV})$, and $2_2^+(4.24 \text{ MeV})$ states of ^{24}Mg as well as the interconnecting and self-coupling matrix elements for these states. Our results disagree with electron scattering measurements for the charge shape of ^{24}Mg . The data on the $2_2^+(4.24 \text{ MeV})$ state is not well accounted for by the asymmetric rotor model.

EXTRACTION OF COMPLETE ALIGNMENT TENSORS FROM SPIN SPECTROMETER DATA ON INELASTIC SCATTERING

D. C. Hensley E. E. Gross
J. R. Reene

The spin alignment tensors for the first 2^+ state of ^{24}Mg have been determined by measuring the angular correlation of the emitted gamma ray in the Spin Spectrometer. The state was excited in the inelastic scattering of ^{24}Mg on ^{208}Pb at 200 MeV. Because the state is very strongly excited and because the energy of the gamma ray is sufficiently unique, it was possible to obtain accurate data for all 70 detectors over the full range of the charged particle angular distribution.

If the Z axis is chosen to be in the reaction plane, then the gamma ray angular correlation for a $2^+ \rightarrow 0^+$ transition can be described in the following way:¹

$$Z_{kq}^n = \frac{\iint Y_{kq}(\theta, 0) (2 - \delta_{q0}) \cos(q\phi) \delta_n(\alpha, \phi) \sin(\alpha) d\alpha d\phi}{\sqrt{A_n(2k+1)}} \quad (1)$$

1. Abstract of paper to be published in Physical Review C (November 1989).

$$\text{Yield}_n = \epsilon_n \sum_{k,q} A_{kq} Z_{kq}^n \quad \begin{matrix} k = 0, 2, 4 \\ q = 0, \dots, k \end{matrix} \quad (2)$$

$$t_{kq} = \frac{A_{kq}}{F_k \cdot A_{00}} \quad t_{00} = F_0 = 1 \quad (3)$$

The integral in Eq. 1 is defined to be in the rest frame of the ^{24}Mg ; however, the $\delta_n(\theta, \phi)$ selects the integration to be over the face of detector n . These integrals were numerically evaluated, and the relativistic transformation from the ^{24}Mg rest frame to the lab (v/c is about 13%) was included. A gamma angular correlation is sensitive only to even k tensor elements and $q = 0, \dots, k$, so that there are just 9 (k, q) combinations.

The delta function $\delta_n(\theta, \phi)$ has the value 1 if (θ, ϕ) lies within the NaI detector n and is 0, otherwise. This function, which was not previously available, was calculated from the tabulated center of weights for each detector, assuming that all detectors have the same geometrical efficiency.

In Eq. (2), Yield_n is the yield of 1.37-MeV gamma rays seen in detector n , ϵ_n is the relative photopeak efficiency for that detector, and the A_{kq} are the coefficients to be evaluated. A_{00} is essentially a normalization which is proportional to the differential cross section. In Eq. (3), the t_{kq} are the spin alignment tensors, and F_k are tabulated angular correlation coefficients. Since there are nine A_{kq} coefficients to be determined and there are 70 measured yields, the A_{kq} coefficients were determined by a least squares fitting procedure.

The spin alignment tensors were determined for 35 different angles of scatter of the ^{24}Mg from $\theta_{\text{cm}} = 21.5^\circ$ to 55.5° and are shown in Figs. 2.1-2.4. In the figures, the dashed lines correspond to predictions of the coupled channels program ECIS, based solely on the charged particle angular distribution data. It was encouraging that the shapes of the distributions were generally well described, but there was clearly a problem with the magnitudes. The next paper² in this report will discuss the attenuation of the theoretical alignment and the effects of including the spin alignment tensor data into the coupled-channels fitting procedure.

Fig. 2.1. Spin alignment tensors for the first 2^+ state in ^{24}Mg on ^{208}Pb reaction. The dashed line refers to the initial, uncorrected prediction of the coupled channel analysis for this reaction.

Fig. 2.2. t_{20} and t_{21} spin alignment tensors for ^{24}Mg .

The yields of the 1.37-MeV gamma ray corresponding to the first 2^+ state of ^{24}Mg were determined by a gate on the 1.37-MeV peak, corrected by a similar gate just above the peak, and subject to the additional requirements that the energy of the scattered ^{24}Mg lie within a 2.1-MeV-wide gate and that the spectrometer

Fig. 2.3. t_{40} and t_{42} spin alignment tensors for ^{24}Mg .

Fig. 2.4. t_{41} and t_{43} spin alignment tensors for ^{24}Mg .

detected just one gamma-ray cluster. The yields in each detector were the cluster sum yields so that Compton scattering out of a particular detector was largely corrected for.

It was possible by examining the internal consistency of the data to determine that the Spin Spectrometer was rotated by about 1.5 degrees in ϕ with respect to the charged particle detectors. This is most likely due to the

difficulty of accurately positioning the charged particle detectors in the small scattering chamber. A similar examination of θ for the position of the spectrometer showed no need for a correction to θ .

It should be noted that at 34° the measurement of the scattered ^{24}Mg shifted from the left to the right side of the spectrometer,³ but there is no apparent discontinuity in the spin alignment tensors at that angle. This implies that the reaction plane coordinant system has been correctly defined and that there is no left/right discrepancy in the analysis of the data. The following paper² will demonstrate the excellent agreement between the experimental results and the theory, particularly in the Coulomb excitation dominated regime from 20° to nearly 40° .

1. S. Steadman et al., Phys. Rev. Lett. 33, 499 (1974).
2. E. E. Gross et al., "Gamma-Ray Angular Correlation for ^{24}Mg 2_1^+ Recoil into Vacuum," this report.
3. D. C. Hensley et al., Phys. Div. Prog. Rep. for Period Ending Sept. 30, 1987, p. 60.

GAMMA-RAY ANGULAR CORRELATION FOR $^{24}\text{Mg}(2_1^+)$ RECOIL INTO VACUUM

D. C. Hensley E. E. Gross
J. R. Beene

As previously reported,^{1,2} the 4π γ -ray capability of the Spin Spectrometer was used to obtain differential cross sections for elastic and inelastic scattering to states in ^{24}Mg from ^{24}Mg on ^{208}Pb at 200 MeV. A coupled-channels analysis was made to determine the optical potential and the transition matrix elements by a least squares fit to those differential cross-section data.² The alignment tensors represented by that fit to the cross section data are compared with the measured tensors (shown as dashed curves) in Figs. 2.1 through 2.4 of the previous contribution to this report.³ There are three features to be noted about this comparison. First, the calculation reproduces the general trends of the measured alignment tensors. Second, for tensors with large values, such as t_{22} and t_{44} (see Fig. 2.1 of

Ref. 3), the calculated values are noticeably larger than the measured values in the Coulomb dominated region. Third, in spite of the excellent coupled-channels fits to the differential cross sections, there is considerable room for improvement in the predicted behavior of the alignment tensors at large angles, where Coulomb-nuclear interference effects are important.

The second point is understandable when it is recognized that the calculated alignment tensors represent unperturbed values, whereas the experimental tensors contain the effects of the precession of nuclear spin by the hyperfine interaction before the γ -rays are emitted. We determine the G_2 and G_4 attenuation coefficients by comparing the calculated and measured alignment tensors in the Coulomb dominated region, $\theta_{CM} < 35^\circ$. Determining G_2 and G_4 independently in this way, we obtain $G_2 = 0.90 \pm 0.01$ and $G_4 = 0.69 \pm 0.01$. These attenuation coefficients bring the calculated alignment tensors into excellent agreement with the measured values in the Coulomb dominated region, $\theta_{CM} < 35^\circ$. This is shown for the t_{22} and t_{40} alignment tensors by the dotted curves in Fig. 2.5. However, the discrepancy at the larger angles

Fig. 2.5. Comparison of the experimental alignment tensors with coupled channels calculations which have been adjusted to account for the effects of the precession of the nuclear spin by a hyperfine interaction. The significance of the dashed and solid lines is discussed in the text.

remains since here there is a disagreement in shape as well as in magnitude. Sensitivity of the alignment tensors to the nuclear optical potential was investigated by calculations using the shallow and the deep potentials of Ref. 2. Both potentials give identical alignment tensors. Sensitivity of the alignment tensors to the $M(E4;0_1^+ \leftrightarrow 4_1^+)$ matrix element was also investigated. For values $41 \text{ efm}^4 < M(E4;0_1^+ \leftrightarrow 4_1^+) < 142 \text{ efm}^4$, there is no sensitivity provided $M(E2;0_1^+ \leftrightarrow 2_1^+)$ is adjusted to maintain the fit to the 2_1^+ differential cross section. This range of $M(E4;0_1^+ \leftrightarrow 4_1^+)$ covers the range of reported values.

All the sensitivity to the large-angle alignment tensors appears to reside in the 2_1^+ reorientation matrix elements $M(E2;2_1^+ \leftrightarrow 2_1^+)$ and $M(E4;2_1^+ \leftrightarrow 2_1^+)$. These matrix elements were searched on to obtain a minimum χ^2 fit to the alignment tensors, the elastic, the 2_1^+ , the 4_1^+ , and the 2_3^+ differential cross sections in a coupled-channels, rotational-model calculation using the program ECIS.⁴ The 2_1^+ reorientation matrix elements strongly affect the predicted differential cross sections at large angles. Therefore, the nuclear optical potential parameters V , W , a , and a' were also allowed to vary, so as not to prejudice the fit by the optical potential. Furthermore, because of the strong coupling between $M(E2;0_1^+ \leftrightarrow 2_1^+)$ and $M(E2;2_1^+ \leftrightarrow 2_1^+)$ matrix elements noted previously,² this search procedure was repeated for various values of $M(E2;0_1^+ \leftrightarrow 2_1^+)$ until a simultaneous χ^2 minimum condition was obtained for both matrix elements. The resulting χ^2 surfaces are shown in Fig. 2.6. Figure 2.6a reveals that χ^2 for a fit to the 2_1^+ cross section alone is both a strong function of the E2 reorientation matrix element, $M(E2;2_1^+ \leftrightarrow 2_1^+)$, expressed as a static quadrupole moment Q_2 , and of $M(E2;0_1^+ \leftrightarrow 2_1^+)$, the basic matrix element exciting the state. A value of $Q_2 \approx +20 \text{ efm}^2$ is favored as reported in Ref. 2. Figure 2.6b shows that the alignment tensors prefer $Q_2 \approx +32 \text{ efm}^2$, irrespective of the value of $M(E2;0_1^+ \leftrightarrow 2_1^+)$. Figure 2.6c indicates that a good compromise between fitting the 2_1^+ differential cross section and the alignment

Fig. 2.6. χ^2 searches on Q_2 for values of ME2 of 20.44, 20.60, and 20.75 efm² (triangle, circle, and square, respectively). The results are shown for (a) the angular distributions only, (b) the spin alignment tensors only, and (c) a weighted average of both data sets.

tensors is $Q_2 = +30$ efm². The alignment tensors predicted by these matrix elements are indicated by the solid curves in Fig. 2.5 for the t_{22} and t_{40} tensor alignment components. In addition to providing an excellent account of the 2_1^+ γ -ray angular correlation, these matrix elements provide a fit to the 2_1^+ differential cross section that is hard to distinguish from the fit shown in Ref. 2. The E2 reorientation matrix element represents a static quadrupole moment, Q_2 , of $(+30 \pm 4)$ efm². This value is ~60% larger than the rigid rotor model and would pose a problem for shell-model, Hartree-Fock, and potential-energy surface model calculations.

1. D. C. Hensley, E. E. Gross, and G. Vourvopoulos, Phys. Div. Prog. Rep. for Period Ending Sept. 30, 1987, ORNL-6420, p. 60.
2. D. C. Hensley et al, Phys. Rev. C, to be published.
3. D. C. Hensley, E. E. Gross, and J. R. Beene, "Extraction of Complete Alignment Tensors from Spin Spectrometer Data on Inelastic Scattering," this report.
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HEAVY-ION EXCITATION AND PHOTON DECAY OF GIANT RESONANCES IN ²⁰⁸Pb¹

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We have determined the ground state photon decay probability and the branching ratios to a number of low-lying states as a function of excitation energy in ²⁰⁸Pb up to ~15 MeV. Results for the giant quadrupole resonance at 10.6 MeV include determination of a ground state electromagnetic transition strength $B(E2)_{gs} = 5300 \pm 1600$ e²fm⁴ and observation of strong suppression of the E1 transition from the resonance to the 3^- state at 2.6 MeV. These results confirm the common assumption of the predominately isoscalar character of the 10.6-MeV resonance. Ground-state gamma coincidences enable us to isolate the isovector giant dipole resonance, which is too weak to be seen in singles, and to test models for its excitation in heavy ion scattering.

1. Abstract of published paper: Phys. Rev. C 39, 1307 (1989).
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HEAVY-ION COULOMB EXCITATION AND PHOTON DECAY OF THE GIANT DIPOLE RESONANCE IN ²⁰⁸Pb¹

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The excitation and electromagnetic decay of the giant resonance region (8-15 MeV) in ²⁰⁸Pb have been measured with the ²⁰⁸Pb(170,170')

reaction at 84 MeV/nucleon. The study of coincidences between scattered ^{170}O ions and photon decays to the ^{208}Pb ground state, including angular correlations, serves to isolate the isovector giant dipole resonance and enable us to investigate the mechanisms of its excitation and decay in detail. The angular correlations and yields are accounted for quantitatively by a pure Coulomb excitation model of the reaction process.

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COMPOUND AND PRECOMPOUND EFFECTS IN PHOTON DECAY OF THE GIANT DIPOLE RESONANCE¹

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We have investigated the excitation and ground-state photon decay of the giant resonance region in ^{208}Pb and ^{209}Bi due to inelastic scattering of 84-MeV/nucleon ^{170}O . The inelastic spectra are dominated by the isovector giant dipole resonance. The spectra of ^{208}Pb and ^{209}Bi are almost identical in the giant resonance region. We conclude that the resonance strength functions are very nearly the same for these nuclei. Significant differences are found, however, in the distribution of ground-state decay photons from the two nuclei. These differences appear to be due to a large contribution from decay of fully-damped compound states in ^{208}Pb .

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SEARCH FOR HIGH-ENERGY TARGET EXCITATIONS WITH HEAVY-ION INELASTIC SCATTERING

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Inelastic scattering experiments with heavy ions are used to study giant resonances built on the ground state of the target nuclei. One difficulty in analyzing these data is the high-energy continuum forming a background under the resonance peaks. The measured energy loss of the projectiles is plotted as excitation energy in the target, under the assumption that the full energy is deposited in the target. Whether the events of the high-energy continuum really correspond to inelastic target excitations or to more complex processes, such as pickup-breakup reactions, has been studied using charged particle or neutron coincidence experiments.^{8,9} The measured proton or neutron spectra in these experiments can originate from both the highly excited target as well as from pickup-breakup processes.

Pickup-breakup reactions, however, produce at most a small excitation energy in the residual nuclei; therefore a coincidence measurement with high energy γ rays discriminates against these processes. The emission of γ -rays from highly excited targets or projectiles is very similar to the decay of the compound nuclei following heavy-ion fusion-evaporation reactions. The γ decay of the giant dipole resonance (GDR) built on excited states should be observable. The underlying assumption is that the system equilibrates and the decay can be treated statistically. The observation of the

GDR with a resonance energy corresponding to the target is therefore an indication of high excitation energy deposited in the target through inelastic scattering.

In a recent experiment at GANIL, a 3-mg/cm²-thick ²⁰⁸Pb target was bombarded with an 84-MeV/nucleon ¹⁷⁰ beam. Inelastic scattered particles were detected in the magnetic spectrograph SPEG in coincidence with high-energy γ rays in three packs of 19 and five packs of 7 BaF₂ detectors, in order to study the decay of giant resonances built on the ground state of the target. The very low neutron separation energy of ¹⁷⁰ (~4 MeV), reduces the probability of detecting a highly excited projectile. The details of the experiment are described elsewhere.^{10,11} Only one 7-pack positioned at 110° and two 19-packs (110° and 138°) could be used for this analysis, limiting the accumulated statistics.

We performed an analysis of these data in terms of high-energy γ rays in coincidence with the high-energy continuum in order to search for high-energy target excitations. Neutrons and γ rays were identified and separated by two-dimensional energy/time-of-flight gates applied to the BaF₂ spectra.

Even without any calculations, conclusions about target excitations can be drawn, by carefully examining the coincidence data. Figure 2.7a shows the particle spectra plotted in terms of excitation energy in the target. The singles data (solid curve) show a peak at about 12 MeV, containing the GDR and the GQR built on the ground state of ²⁰⁸Pb. At higher energies, the continuum slowly decreases up to the highest measured energy of 60 MeV. The dashed curve shows the particle spectrum in coincidence with γ rays above 5 MeV. This coincidence spectrum shows structures associated with the neutron evaporation thresholds. The γ -ray multiplicity increases with excitation energy in the target. However, at excitation energies where single- or multiple-neutron evaporation becomes energetically possible, the neutron decay probability dominates. At these threshold

Fig. 2.7. (a) Spectrum of inelastically scattered 84 MeV/nucleon ¹⁷⁰. The singles data (dashed curve) were downscaled during the experiment. In the γ -coincidence data (solid curve) the neutron evaporation thresholds are clearly visible. (b) In the difference spectrum (coincidences minus singles), even the 5n threshold at 40 MeV appears.

energies the γ -ray multiplicity is reduced, creating the bumps shown in Fig. 2.7a. Folding this effect into the spectrum results in a shift of the GDR/GQR peak to slightly higher energy. In addition, the bumps corresponding to the three neutron evaporation thresholds are clearly visible, indicating excitations of the target up to at least 25 MeV. Even higher neutron evaporation thresholds are observable by subtracting the singles spectrum from the coincidence spectrum as shown in Fig. 2.7b. The 4n and even the 5n bumps show up, giving evidence for target excitations up to 40 MeV.

With the assumption of an equilibrated highly excited target, the statistical model code CASCADE was used to calculate the γ spectra as well as the total number of neutrons for different excitation energy bins. Standard statistical model parameters were adjusted for ^{208}Pb . The GDR built on highly excited states was included in the calculation; and the resonance energy ($E_{\text{GDR}} = 13.5$ MeV) and width ($\Gamma_{\text{GDR}} = 4.0$ MeV) were chosen close to the ground state values. The entrance channel populations for the calculations were extracted from the singles particle spectrum, assuming a triangular distribution of the angular momentum with a mean value of 5 $\hbar$.

Figure 2.8 shows experimental values (solid points) and CASCADE calculations (open points) for the total number of neutrons as a function of target excitation energy in bins of 4 MeV. The calculations were folded with the neutron response function of the BaF_2 detectors and normalized to the data at 20 MeV. The absolute number of neutrons increases with the excitation energy but the cross section of the particle spectra decreases, therefore yielding an

Fig. 2.8. Total number of evaporated neutrons in coincidence with the spectrograph (closed circles) and the predictions from CASCADE (open circles). The calculations were normalized to the data at about 20 MeV.

approximately constant curve. The data agree with the calculation up to about 40 MeV. Even up to 60 MeV, a large contribution of the cross section can be explained with a statistical decay of an excited target.

The γ -ray spectra in coincidence with the particles summed over a wide range of excitation energies (36-60 MeV) is shown in Fig. 2.9a. Although the statistics in this experiment is not sufficient to extract GDR parameters, a bump around 12 MeV, where the GDR of ^{208}Pb is expected, is clearly visible. The calculations are normalized to the data at 7 MeV and are not folded with the response function of the BaF_2 . Figure 2.9b,c show the same data subdivided into smaller energy bins. Assuming that the lowest energy bin (36-44 MeV) corresponds to 100% target excitation, results in the second (44-52 MeV) and third (52-60 MeV) energy bins indicate target excitation fractions of 82% and 63%, respectively. This again indicates that above

Fig. 2.9. Gamma-ray spectra in coincidence with the inelastic scattered 170 summed over one large energy bin covering 36-60 MeV (a), which is subdivided into three smaller bins: (b) 48-60 MeV, (c) 36-48 MeV and (d) 28-36 MeV.

40 MeV the full cross section cannot be attributed to target excitations.

The analysis of the γ -ray spectrum is consistent with the neutron data analysis. Even up to 60 MeV a substantial fraction of the total cross section can be accounted for by target excitations. At about 40 MeV, pickup-breakup reactions start to contribute.

In conclusion, the particle- γ -ray coincidence measurements of the high energy continuum can be used to study high-energy target excitations. The cross section up to 60 MeV should still be large enough to extract the GDR parameters. This opens up an interesting alternative to the study of the GDR built on highly excited states through heavy-ion fusion reactions, since it is possible to study a wide range of excitation energies within one experiment. In contrast to heavy-ion fusion reactions, where the highly excited fused system has a high average angular momentum, only states with low angular momenta are populated in small angle ($<5^\circ$) inelastic scattering. Thus, the excitation energy dependence of the GDR parameters can be studied without the influence of high angular momenta.

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MEASUREMENT OF M_n/M_p FOR THE GQR IN ^{118}Sn

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Elastic and inelastic scattering of 84-MeV/nucleon ^{170}O ions by ^{118}Sn have been measured using the SPEG spectrometer at GANIL. The objective of this work is to investigate the ratio of neutron and proton excitation matrix elements, M_n/M_p , for the GQR of ^{118}Sn , which, based on pion scattering data,³ has been reported to deviate considerably from the value $N/Z = 1.35$ expected for a "pure" isoscalar resonance. A similarly large value for M_n/M_p , compared to the N/Z value, had been reported⁴ for pion scattering on ^{208}Pb . Our previously reported heavy-ion scattering results⁵ on ^{208}Pb contradicted those pion scattering results⁴ and showed that GQR data could be well represented by calculations using the deformed optical potential model for exciting an isoscalar resonance.

Measurements were made with the spectrometer set at an angle of 2.7 deg, which provided data from 0.7 to 4.7 deg in the laboratory frame. The target was a 1.83-mg/cm², self-supporting foil of ^{118}Sn . Some data were also obtained for targets of ^{112}Sn , ^{124}Sn , ^{90}Zr , ^{92}Zr , ^{94}Zr and ^{96}Zr . Preliminary analysis of the data has commenced. Whereas for ^{208}Pb there are clear differences between angular distributions calculated using M_n/M_p for a pure isoscalar GQR and assuming the value from pion scattering in the angular region 2 to 4 deg, the major differences for ^{118}Sn are localized near 1.5 to 2 deg. This effect has resulted in the need for more careful calibration of the absolute scattering angles and solid angles than was needed for ^{208}Pb . A further difficulty in the analysis arises because the GQR in ^{118}Sn is spread over a wider energy interval ($\Gamma_{\text{FWHM}} = 3.8$ MeV) than that for ^{208}Pb ($\Gamma_{\text{FWHM}} = 2.0$ MeV).

The results of a first analysis have indicated some problems with fits to the elastic scattering data which are as yet not completely understood. Although the inelastic data suggest

that M_n/M_p for the GQR is closer to N/Z than reported in Ref. 3, a final conclusion on its isospin character must await a final analysis of the data.

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EXCITATION AND FISSION DECAY OF ^{238}U USING THE $(^{17}\text{O}, ^{17}\text{O}')$ REACTION

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The inelastic scattering of 375-MeV ^{17}O projectiles was used to study the giant resonance region in ^{238}U . The energy, width, and strength of the giant quadrupole resonance (GQR) were extracted from singles spectra; and fission probabilities were deduced from singles and coincidence data. Angular correlations between fission fragments and inelastically scattered particles were measured to search for evidence of K-conservation in the fission decay of the GQR.

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ELASTIC AND INELASTIC SCATTERING OF 280- AND 489-MeV PROTONS FROM ^{58}Ni

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Nonrelativistic and relativistic collective deformed potential models have been used to

study the excitation of seven states in ^{58}Ni by 280- and 489-MeV unpolarized protons. Optical model potentials were determined at each energy by fitting elastic scattering data using both of the models. Deformation lengths were also obtained using both models; and no dependence on incident energy was observed for either model. The average value of the hadronic deformation lengths, along with the charge deformation lengths, were used to calculate neutron-to-proton multipole matrix elements (M_n/M_p). Five transitions, 2_1^+ , 1.45-MeV; 2_3^+ , 3.04-MeV; 2_4^+ , 3.26-MeV; 4_1^+ , 2.46-MeV; and the 4_3^+ , 4.75-MeV states were determined to be isoscalar, i.e. $M_n/M_p = N/Z$. The 4_2^+ , 3.63-MeV state was observed to be a protonlike transition with $M_n/M_p = 0.43 \pm .18$. At small scattering angles the relativistic model gave consistently larger cross sections than the nonrelativistic model. This effect was much larger at 280 MeV than at 489 MeV.

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ELASTIC SCATTERING OF $^{58}\text{Ni} + ^{27}\text{Al}$ AT ENERGIES NEAR THE COULOMB BARRIER

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Preliminary measurements of the elastic scattering of ^{58}Ni on ^{27}Al were done at 160, 170, and 210 MeV and were reported previously.² The analysis of the data showed that, in order to unequivocally establish the threshold anomaly in elastic scattering near barrier energies, it is necessary to measure detailed angular distributions with about 5% accuracy.

The required complete measurements were carried out at four ^{58}Ni bombarding energies: 160, 170, 185, and 220 MeV. The ^{58}Ni beams were obtained from the HHIRF tandem accelerator and

were used to bombard an Al target. The elastic ^{58}Ni , as well as the recoiling ^{27}Al nuclei, were momentum analyzed by an Enge split-pole magnet followed by a detection system able to measure focal plane position, energy losses, and total energy. These parameters permit the identification of the detected ions and the calculation of their kinetic energies.

Figure 2.10 shows the results from a preliminary analysis of the data. The curves are drawn to guide the eye. The measurements shown at the most backward angles might contain a non-negligible contribution from inelastic scattering. The complete analysis is presently in progress.

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Fig. 2.10. Elastic cross sections given as a ratio to Rutherford (σ_R), for the $^{58}\text{Ni} + ^{27}\text{Al}$ system. The lines are present to guide the eye.

NUCLEAR STRUCTURE STUDIES VIA TRANSFER AND CAPTURE REACTIONS

THERMAL-NEUTRON SCATTERING LENGTHS AND CAPTURE BY EVEN CALCIUM ISOTOPES¹

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Neutron-diffraction patterns have been measured for isotopically enriched powder samples of calcite using both steady-state and pulsed-neutron techniques. Greatly enhanced precision over previous work has been achieved for ^{40}Ca and ^{44}Ca , while the results for ^{42}Ca , ^{43}Ca , and ^{48}Ca represent new data. The coherent scattering lengths deduced from these measurements have been employed in a more definitive analysis of primary electric-dipole gamma rays from thermal-neutron capture. In three cases (^{40}Ca , ^{42}Ca , and ^{48}Ca) the estimates from a spherical optical-model formulation of the direct-capture mechanism are in agreement with the experimental cross sections. In ^{44}Ca the theory overestimates the measured cross sections on average by about 60%; this divergence can be explained by considering the modifications to the theory due to collective vibrations of the ^{44}Ca core.

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VALENCE CAPTURE MECHANISM IN RESONANCE NEUTRON CAPTURE BY ^{13}C ¹

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The partial radiation widths of three (two electric dipole and one electric quadrupole) primary γ transitions in ^{14}C subsequent to

neutron capture by the 153-keV, 2^+ resonance in ^{13}C have been remeasured. Both electric dipole transitions, accounting for more than 80% of the total radiation width, can be explained as valence neutron transitions. The deduced total radiation width of $0.215^{+0.08}_{-0.035}$ eV for this resonance disagrees with the previous value of 2.4 ± 0.9 eV and significantly affects the production of $A \geq 14$ nuclei in primordial nucleosynthesis.

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POPULATION OF HIGH SPIN STATES IN THE PLUTONIUM ISOTOPES BY HEAVY ION TRANSFER REACTIONS

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Coulomb-excitation and heavy-ion neutron-evaporation reactions have traditionally yielded the most information on high-spin states in nuclei. One- and two-neutron transfer reactions recently have proven to be valuable probes into the single particle and pairing effects respectively of nuclei.^{4,5} In addition, because of the "cold" transfer mechanism, the method is useful for studying nuclei for which Coulomb-excitation reactions are difficult because targets would be unstable or difficult to handle, as in the actinide region.⁶

The heavy-ion, one-neutron pickup reaction $^{239}\text{Pu}(^{90}\text{Zr}, ^{91}\text{Zr})^{238}\text{Pu}$ and the Coulomb-excitation reaction $^{239}\text{Pu}(^{90}\text{Zr}, ^{90}\text{Zr}')^{239}\text{Pu}$ ($E_{\text{lab}} = 500$ MeV) were used to study the rotational level schemes of ^{238}Pu and ^{239}Pu , respectively. The experiment was performed in the Spin Spectrometer at ORNL's Holifield Heavy Ion Research Facility.

Fig. 2.11 shows the γ -ray spectra integrated over grazing angle and gated on neutron multiplicity 0. (A) Total γ -ray spectrum.

Fig. 2.11. The γ -ray spectra integrated over grazing angle and gated on neutron multiplicity 0. (A) The total γ -ray spectrum. (B) The twofold γ -ray spectrum gated on three ^{238}Pu transitions, showing the ground rotational band of ^{238}Pu .

(B) The twofold γ -ray spectrum gated on three known ^{238}Pu transitions of 305.7 keV ($12^+ \rightarrow 10^+$), 348.7 keV ($14^+ \rightarrow 12^+$), and 389.0 keV ($16^+ \rightarrow 14^+$), which were clearly separated from any ^{239}Pu transitions. Rotational transitions in ^{238}Pu can clearly be identified up to the $26^+ \rightarrow 24^+$ 543-keV transition. Additionally, transitions up to the $\frac{49}{2}^+$ level in ^{239}Pu were observed. There is no initial evidence for backbending in either nucleus. Data analysis is still in progress.

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SEARCH FOR A NUCLEAR SQUID IN $^{206}\text{Pb} + ^{156}\text{Gd}$ TRANSFER REACTIONS

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Nikam and Ring have used Hartree-Fock-Bogoliubov theory in the rotating frame to calculate the two-neutron transfer amplitude $\langle A+2 | (a^\dagger a^\dagger) L=0 | A \rangle$ between rotating superfluid deformed nuclei.⁴⁻⁶ A new and unexpected behavior was found. Their calculation indicated that the transfer matrix element is proportional to the pairing gap only for very small angular momentum. At higher angular momentum the matrix element falls dramatically, goes through zero, and changes sign. These regions where the matrix element vanish were called regions of diabolic pair transfer. After the first zero the transfer matrix element has negative values. In some cases there exist more than one such diabolic region and the matrix element oscillates around zero for high angular momentum. This oscillating behavior of the pair transfer matrix element as a function of the angular momentum is similar to the oscillation of the amplitude of an electric direct current in a Superconducting Quantum Interference Device (SQUID) as a function of the magnetic field.

The experiment was carried out using 888-MeV ^{156}Gd ions bombarding a $512\text{-}\mu\text{g}/\text{cm}^2$ ^{206}Pb target in the Spin Spectrometer combined with the Compton Suppression Spectrometer System of the Holifield Heavy Ion Accelerator. The detector arrangement consisted of 55 NaI and 15 Ge Compton suppressed detectors. A particle-

particle- γ coincidence technique was utilized. Both the scattered ion and the corresponding recoil were detected in kinematic coincidence by 3 pairs of position-sensitive, parallel-plate avalanche counters in coincidence with the detection of γ rays by the Ge detectors.

Fig. 2.12 shows the γ -ray spectrum integrated over the grazing angle and gated on neutron

Fig. 2.12. The total γ -ray spectrum for the reaction $^{156}\text{Gd} + ^{206}\text{Pb}$. The two-neutron pickup and stripping channels are marked.

multiplicity 0. The two-neutron pickup and stripping channels are observed up to $12+ + 10+$. Analysis is currently under way to determine the angular momentum dependence of the transfer cross sections in these channels.

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PAIRING EFFECTS ON TRANSFER REACTIONS

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Within the past five years we have developed experimental techniques to study heavy-ion transfer reactions. These methods have been turned into a quantitative tool to assess the influence of collective excitation on single-particle and pairing structure.

Experiments for $^{161,162}\text{Dy} + ^{116}\text{Sn}$ and $^{161,162}\text{Dy} + ^{58}\text{Ni}$ were performed at Oak Ridge National Laboratory (ORNL) using the Spin Spectrometer.^{3,4} Beams of 637-MeV ^{116}Sn , 285-MeV and 345-MeV ^{58}Ni were produced by the Holifield Heavy Ion Research Facility (HHIRF). The targets were 500-600 $\mu\text{g}/\text{cm}^2$ self-supporting foils. Four position-sensitive, parallel-plate avalanche counters, covering laboratory angular ranges of $\pm 8^\circ$ to 76° and $\pm 104^\circ$ to 162° , were placed inside the Spin Spectrometer to detect scattered projectilelike and targetlike ions. Particle-particle- γ coincidence data were taken with the requirement that at least one γ ray be detected in a Ge detector; in addition, scaled-down particle singles were stored.

We wish to restrict attention to quasielastic reactions which can be described by Rutherford-like trajectories, since we would like to extract structure information with as little interference from complicated reaction dynamics as possible. In all the data to be discussed we have imposed the following conditions. (1) Beam energies are near the Coulomb barrier. (2) Only data in a range of scattering angles where the total cross section still looks like Rutherford are used in any quantitative analysis. (3) All data are gated on the quasielastic peak in the energy-loss spectrum and on zero neutron multiplicity. (4) Total γ -ray energy and multiplicity information from the Spin Spectrometer is used to restrict events to those populating states within 1-2 MeV of the ground states of the nuclei produced in the reaction.

An enhancement factor for two-neutron transfer can be defined in the case of semi-classical conditions as $F = P_{2n}/P_{1n}^2$ where the one- and two-neutron transfer probabilities are denoted by P_{1n} and P_{2n} , respectively. This definition ignores possible differences in the ground state Q-value and the number of states involved, but it should be some measure of how strong two-neutron transfer is relative to that expected from sequential transfer of two uncorrelated neutrons.

The enhancement factors of separated ground-band and two-quasiparticle band populations for ^{116}Sn and ^{58}Ni experiments are shown in Fig. 2.13. We find two components in this population, with very different enhancement factors.

Fig. 2.13. Enhancement factors defined for one- and two-neutron transfer reactions as a function of classical separation between (spherical) surfaces: $D_{55} = D - 1.25(A^{1/3} + A^{1/3})$, classical separation of centers at closest approach for Rutherford trajectories.

The bulk of the reaction, >80%, populates two-quasiparticle bands with $F = 8-12$ for the ^{116}Sn experiment and $F = 6-11$ for the ^{58}Ni experiment. However, the transfer to the ground band is found to have enhancement factors $F = 70-500$ for the ^{116}Sn experiment and $F = 30-100$ for the ^{58}Ni experiment, suggesting very large pairing effects in the transfer to the ground state band of ^{160}Dy .

During the past year, we completed our investigation of high-spin states in ^{172}Os using γ - γ coincidence studies. These states were populated by the $^{14}\text{N}d(^{32}\text{S},4n)$ reaction using 162-MeV ^{32}S ions from the HHIRF tandem accelerator. Gamma-gamma coincidence measurements were made with the Oak Ridge Compton Suppression Spectrometer System incorporated into the Spin Spectrometer. The yrast band was observed through the 30^+ state, and four sidebands were deduced from γ - γ coincidence relationships. A band identified as belonging to ^{173}Os was also observed. Results were interpreted using average-nuclear-field calculations which incorporated the deformed Woods-Saxon potential with its "universal" parametrization, a cranking approximation, and the Hartree-Fock-Bogoliubov method. The calculations indicate the presence of strongly interacting quasiparticle band crossings for $0.2 < \hbar\omega < 0.3$, in semiquantitative agreement with experiment.

Some interesting conclusions from the present study are as follows: (1) The nuclei considered possess rather unusual alignment properties resulting from their characteristic structure in terms of excited quasiparticles. This structure is dominated by strong interactions in the $i_{13/2}$ neutron quasiparticle crossings (AB, BC, and AD) and by the fact that they appear very close in terms of rotational frequencies. (2) There are two low-frequency anomalies in the yrast-sequence moment of inertia and the first of these has been interpreted in terms of the nearly degenerate crossings. (3) The nearby anomaly at $\hbar\omega = 0.26$ MeV results from the AB crossing. (4) The $h_{9/2}$ proton-induced alignment could not be identified in the present study. Theoretical arguments indicate its possible onset at $\hbar\omega = 0.45$ MeV. (5) The experimentally determined alignment gains are consistent with the above interpretations. (6) The calculations suggest a strong reduction in the neutron pairing gap over the frequency range $\hbar\omega = 0.22$ - 0.28 MeV. It is deemed significant that this reduction in the neutron pairing gap occurs

in the same region as does the unusually low BC band crossing.

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TRANSITION QUADRUPOLE MOMENTS OF HIGH SPIN STATES IN ^{172}W

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Transition quadrupole moments from lifetime measurements of states with spins up to ~ 20 in collective bands near the yrast line have proved to be a valuable tool for tracing changes in nuclear shape that occur from Coriolis and centrifugal forces. A reduction of collectivity at $I > 14$ has been observed in several $N = 90$ nuclei.⁸⁻¹⁰ This effect is understood qualitatively in terms of the cranked-shell-model theory¹¹ as a result of rotation alignment of two $i_{13/2}$ neutrons. The reduction of collectivity is due to the driving forces of the aligned neutrons with low- Ω orbitals, i.e., the Fermi level lies low in the $i_{13/2}$ shell. The predicted potential-energy surfaces are very shallow, especially in the γ degree of freedom; therefore, the deformation driving forces of the aligned neutrons cause the nucleus to change from prolate shape at low spin (small rotational frequency) to a triaxial shape with reduced collectivity at high spin.

The calculated systematics¹² of triaxial shape-driving orbitals suggest that the collectivity should not decrease at higher neutron number around $N = 98$, where the aligned $i_{13/2}$ orbitals are situated near the middle of the shell. By the use of the method of Recht et al.¹³, Bengtsson and Xing¹⁴ substantiated these general predictions by a full cranked-shell-model calculation for ^{172}W using a deformed Woods-Saxon potential. To test these ideas, we carried out lifetime measurements on this nucleus by the Doppler-shift recoil-distance method. In an earlier account of this work,¹⁴ we reported a reduction of the transition quadrupole moments by about 15% for spins ≥ 12 compared to the values in the ground-state band. This could be understood if the rotation-induced structure change is due not only to $i_{13/2}$ neutrons but also to $h_{9/2}$ protons.

More recently Raman et al.¹⁵ questioned the large transition quadrupole moment Q_t value of 7.62 ± 0.24 eb for the $2^+ \rightarrow 0^+$ transition extracted from our lifetime measurements and, hence, the need for aligned $h_{9/2}$ protons to interpret the results. To investigate factors which could have caused a decrease in the extracted lifetimes, we reanalyzed the "total-projected" data (TP-type data) with a focus on the normalization of the γ -ray spectra at different target-stopper distances. With the new normalization factors, there are significant changes in the normalized intensities for the decay of the 2^+ and 4^+ states at the larger recoil distances. The revised value¹⁶ of Q_t is 7.05 ± 0.30 eb for the $2^+ \rightarrow 0^+$ transition, which is 8% smaller than the value in Ref. 14. We have now completed the reanalysis of the other types of data ["sum-gated-above" (SGA) and "sum-gated-below (SGB)"] for ^{172}W .

The portion of the ^{172}W level scheme¹⁷ for which we were able to extract lifetime data is shown in Fig. 2.15. Decay curves were extracted for those transitions with an asterisk on the transition energy. The relative transition intensities from our measurements are also given in Fig. 2.15. Figure 2.15 also illustrates the modeling to handle the complexity of the unknown

side feeding in the TP-type data and the SGB-type data. Two-step cascade side feeding was modeled into each level of a sequence of levels under consideration. In all cases, a rotational band was used to model the feeding into the top level of the sequence. A summary of the results obtained from the lifetimes of states in the yrast band are given in Table 2.1. Experimental transition quadrupole moments, Q_t , were obtained from the reduced E2 transition probabilities by the relationship

$$B(E2, I \rightarrow I-2) = \frac{5}{16\pi} \langle I20 | I-2 0 \rangle^2 Q_t^2.$$

The Q_t values in columns 3, 4, and 5 are mean values of the results from each data type as indicated by the column heading.

In Fig. 2.16 the transition quadrupole moments deduced from the lifetime results for the yrast band of ^{172}W are presented as a function of the rotational frequency. The solid curve shows the results of a cranked Hartree-Fock-Bogoliubov (HFB) model calculation. Theoretical deformations for the yrast band of ^{172}W were calculated using the pairing-self-consistent-cranking model without particle number projection. The calculations are based on the Woods-Saxon potential with the set of potential parameters given in Ref. 18. In these calculations the total Routhian is minimized with respect to the deformation parameters (β_2, β_4 , and γ) for a number of rotational frequencies up to 400 keV. The deformations (β_2, γ) from these calculations were converted to Q_t using

$$Q_t = \frac{6ZeA^{2/3}}{(15\pi)^{1/2}} r_0^2 \beta_2 (1 + 0.360 \beta_2) \cos(30^\circ + \gamma).$$

The solid curve corresponds to $r_0 = 1.20$ fm. At low spin ($I < 8$), the Q_t values are all near a constant value of 7.0 eb. However, the error bars do not rule out the ~8% increase in collectivity from centrifugal stretching. The dashed curve shows the results of a cranked-HFB-model calculation¹⁹ with constant pairing, i.e., 75% of full-strength neutron pair correlations and 100% of full-strength proton pair correlations. For states with $I > 10$ the Q_t values are all near a constant value of 6.75 eb. This is,

Fig. 2.15. Portion of the level scheme for ^{172}W . Decay curves were obtained for those transitions with an asterisk. The relative transition intensities are given for each transition. The modeling to handle the complexity of the unknown side feeding is also illustrated.

of course, the trend predicted by the cranked-HFB-model calculations and by the calculated systematics² of triaxial shape-driving forces which originate from the aligned $13/2$ orbitals around $N = 98$. Therefore, it is no longer necessary to invoke the simultaneous alignment of $h_{9/2}$ protons and $13/2$ neutrons to explain the transition quadrupole moments for the yrast states of ^{172}W .

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Table 2.1. Summary of the results obtained from lifetimes of states in the yrast band of ^{172}W

State	$E_\gamma(\text{keV})$	TP	TP Plus Side Bands	SGA and SGB	$\tau(\text{ps})$	Best Value
		$Q_t(\text{eb})$	$Q_t(\text{eb})$	$Q_t(\text{eb})$		$Q_t(\text{eb})$
2^+	123.4	7.06 ± 0.30		6.93 ± 0.41	1061 ± 93	7.00 ± 0.30
4^+	254.0	6.86 ± 0.24		7.10 ± 0.45	48.6 ± 3.4	6.98 ± 0.24
6^+	350.7	6.79 ± 0.38	6.57 ± 0.26	7.37 ± 0.68	9.77 ± 0.93	6.91 ± 0.32
8^+	419.6	6.95 ± 0.44	6.93 ± 0.60	7.14 ± 1.0	3.77 ± 0.4	7.01 ± 0.44
10^+	470.7	6.35 ± 0.50	6.97 ± 0.29	7.00 ± 1.0	2.23 ± 0.34	6.77 ± 0.50
12^+	513.0	7.01 ± 0.70	6.33 ± 0.50		1.48 ± 0.23	6.67 ± 0.50
14^+	549.9	6.40 ± 0.80			1.12 ± 0.30	6.40 ± 0.80
16^+	576.0	6.58 ± 0.90		7.55 ± 2.3	0.72 ± 0.19	7.07 ± 0.90
18^+	598.3			7.17 ± 1.20	0.58 ± 0.21	7.17 ± 1.20
20^+	645.5	6.7 ± 0.9			0.45 ± 0.13	6.7 ± 0.9

Fig. 2.16. Transition quadrupole moments for the yrast sequence of ^{172}W as a function of rotational frequency ($\hbar\omega = E_\gamma/2$). The solid and dashed curves show the results of cranked HFB model calculations.

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THE HIGH SPIN COLLECTIVITY OF ^{164}Yb AND NEIGHBORING EVEN-A ISOTOPES

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The collectivity of ^{164}Yb at high spins has been studied by measuring the lifetimes of the $J^\pi = 20^+ - 32^+$ states using the Doppler-broadened line-shape technique. Ytterbium-164 was populated by the $^{124}\text{Sn}(^{44}\text{Ca}, 4n)$ reaction using a 189-MeV ^{44}Ca beam from the 25 MV tandem accelerator of the Holifield Heavy Ion Facility. The targets were 1 mg/cm² of enriched ^{124}Sn deposited on 10 mg/cm² Au backings. The line shapes were measured in the four most forward (45 degrees) and four most backward (135 degrees) detectors of the compact array of 20 Compton-suppressed germanium detectors. The remaining

12 detectors located near $\theta = 90^\circ$ were used (together with the four forward and four backward detectors) to select the decay sequence of interest with minimum background. A total of about 150×10^6 triple gamma-ray coincidence events were collected and analyzed off-line. A shorter run of about 75×10^6 triple gamma-ray coincidence events, collected using two "stacked" self-supporting 0.5-mg/cm^2 ^{124}Sn targets, was used to extend the level scheme^{4,5} of ^{164}Yb .

The lifetimes were extracted by fitting gamma-ray line shapes in summed, clean spectra gated on transitions below the levels of interest. The Monte Carlo program DSAMFT^{6,7} was used in fitting the line shapes for a determination of lifetimes. Side feeding was taken into account by assuming a feeding cascade with constant $J(2)$ moment of inertia and transition quadrupole moments, Q_5 , for each level. The resulting transition quadrupole moments, Q_t , for the $20^+ - 32^+$ states are shown in Fig. 2.17.

Fig. 2.17. Plot of the transition quadrupole moments for the yrast states of ^{164}Yb as a function of angular momentum. These values were extracted from Doppler-broadened line shapes measured using the $^{124}\text{Sn}(^{40}\text{Ca}, 4n)$ reaction.

The loss of collectivity (decrease in Q_t values) at high spin is qualitatively similar to that observed⁷ for the neighboring isotope, ^{166}Yb . This loss of collectivity can be understood as a rotationally-induced deoccupation of strongly shape-polarizing anti-aligned high-j configurations⁸ (i.e., those in which the nucleons move in the opposite direction with respect to the nuclear rotation). The energy of such configurations, that have a negative component of the intrinsic angular momentum on the rotational axis j_x , increases with increasing rotational frequency ω . The Coriolis plus centrifugal term in the nuclear Hamiltonian is $-\omega j_x$. This loss of collectivity can be reproduced⁸ by state of the art self-consistent calculations of the nuclear shape.

A loss of collectivity also is observed^{9,10} for the lighter ytterbium isotopes, $^{160,162}\text{Yb}$, but at much smaller angular momentum. It is difficult to understand the abrupt change between ^{162}Yb and ^{164}Yb in the angular momentum where the change of collectivity takes place. This anomaly may be associated with a less stable shape of the lighter ytterbium isotopes. Lifetime measurements for these lighter isotopes at higher spins are planned.

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THE OBSERVATION OF DIABOLICAL POINTS IN RAPIDLY ROTATING NUCLEI

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A "diabolo point" is a singularity where different eigenenergy surfaces of the same quantum mechanical hamiltonian have identical values (i.e. they touch). Of course, the crossing of such surfaces is forbidden² in a quantum system. The datum of zero interaction between configurations of rotating superfluid nuclei differing by two quasiparticles formally meets the requirements for such a "diabolo point".³ These points are simply the minimum interaction band crossings (sharp "backbends") considered several years ago.^{4,5} Recently, it has been suggested³ that these singularities can be identified as closely-spaced constant-N contours in the (λ_n, ω) plane.

Experimental contours of constant neutron number in the (λ_n, ω) plane are shown for erbium and ytterbium isotopes in Fig. 2.18. The empirical determination of λ_n and ω from experimental quantities is discussed in Ref. 6. In order to obtain data for each neutron number, an analysis is made for both the even-spin, positive-parity yrast sequence in even-even isotopes, labeled $(\pi, \alpha) = (+, 0)$, and the lowest negative-parity decay sequence in odd-mass isotopes $(-, 1/2)$. Band crossings associated with the excitation of pairs of $i_{13/2}$ quasineutrons should be identical in these decay sequences. Such a plot is the experimental analog of Fig. 1 of Ref. 3.

A predicted feature of the diabolical points, an increased density of single-particle levels associated with a vanishing interaction between states differing by two quasiparticles, is observed experimentally (see Fig. 2.18). Specifically, a "bunching" of experimental levels is observed at $\hbar\omega = 0.27$ MeV for both $N = 90-92$ and $96-97$. Likewise, the observed bunching of experimental levels for $N = 90-92$ at $\hbar\omega = 0.42$ MeV could be associated with a second band crossing based on the excitation of either two additional $i_{13/2}$ quasineutrons or another

Fig. 2.18. Empirical contours of constant neutron number, N , as a function of λ_n and ω . For reference, the observed frequencies of the lowest $i_{13/2}$ quasineutron band crossings in the even-even yrast sequences are indicated by the horizontal dashed lines labeled $\hbar\omega_c$. The experimental data sources are summarized in Refs. 6 and 11.

pair of quasineutrons (e.g., negative-parity quasineutrons of mixed $h_{9/2}$ and $f_{7/2}$ character). The band crossing observed at $\hbar\omega = 0.42$ MeV has been associated with the excitation of a pair of $h_{11/2}$ quasiprotons⁷ with a strong interaction between zero- and two-quasiproton levels. No increased density of quasineutron states should be associated with such a quasiproton band crossing. Therefore, the physical basis for this increased density of quasineutron states at high rotational frequency is not known. Short reports of this work are given in Refs. 8 and 9,

and a comprehensive analysis of constant neutron contour plots for rare earth nuclei is under way, see, e.g., Ref. 9.

The phase change of the wave function, Berry phase, when a diabolical point is circumscribed, a nuclear analogue of the Aharonov-Bohm Effect, is of considerable current interest.^{3,10} It may be possible to observe consequences of this phase change in the next generation of Coulomb excitation and/or Coulomb excitation plus transfer experiments.

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A NEW TECHNIQUE FOR OBTAINING EMPIRICAL PROTON-NEUTRON INTERACTIONS

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The proton-neutron interaction, which is predicted to be the dominant long-range interaction,³ has long been considered an important ingredient of nuclear deformations, see e.g. Refs. 4 and 5. Techniques have been developed to obtain empirical estimates of this interaction both for shell-model states in spherical nuclei⁶ and for quasiparticles in deformed nuclei.⁷

This contribution presents empirical proton-neutron interactions for deformed rare-earth nuclei based on a new technique⁸ for extracting average interaction energies between the pair of protons and the pair of neutrons nearest to the

respective Fermi levels. This interaction is given by:

$$V_{pn} = [\lambda_n(Z+1, N, \omega) - \lambda_n(Z-1, N, \omega)]/2.$$

The empirical extraction of $\lambda_n(Z, N, \omega)$ from experimental quantities is described in Ref. 9. Note that V_{pn} is half the separation of neighboring isotonic chains at constant $\hbar\omega$ on gauge-space alignment or constant-N contour plots. Examples of these plots are shown in Ref. 9 and the preceding contribution.

Values of the proton-neutron interaction, extracted for the yrast configurations of neighboring even-even isotopes and isotones with $Z = 68-78$ and $N = 90-108$, are shown in Fig. 2.19 as a function N for various values of Z and $\hbar\omega$. The average value of this interaction, $\langle V_{pn} \rangle = -240$ keV, is reasonable — the nuclear potential for a nucleus with $A = 170$ is about -50 MeV, or about -290 keV/A. The N and Z dependence of V_{pn} usually are qualitatively preserved independent of the rotational frequency; however, the variations are larger for increased $\hbar\omega$. The larger variations in V_{pn} for larger rotational frequencies apparently is associated with the loss of pair correlations with increasing $\hbar\omega$. That is, at small rotational frequencies the extracted values are quasiproton-quasineutron interactions; whereas, at the largest frequencies they are proton-neutron interactions between the last pair of protons and the last pair of neutrons that couple to spin zero and positive parity. Therefore, at small values of $\hbar\omega$ the pair correlations "smear" the effects of fluctuations in the spacings of single-proton and single-neutron levels, which apparently are associated with the larger variations of V_{pn} at large values of $\hbar\omega$. The observed pattern of, for example, a more attractive interaction between the 71st and 72nd protons and the 91st and 92nd, the 97th and 98th, and the 99th and 100th neutrons than for the 71st and 72nd protons and the 93rd and 94th and the 95th and 96th neutrons is not completely understood. However, it may be associated with the energy differences of the

EMPIRICAL ESTIMATES OF RESIDUAL PROTON-NEUTRON INTERACTIONS

Fig. 2.19. Plot of V_{pn} as a function of N , Z , and f_{12} , corresponding to the lowest even-spin, positive-parity configurations of even-even deformed rare-earth nuclei. A datum at $N = 95$ in the $Z = 71-72$ plot denotes the average proton-neutron interaction between the 95th and 96th neutrons and the 71st and 72nd protons.

relative overlap of these proton and neutron orbits.

Such an analysis, when extended to other configurations and to odd-mass nuclei, can provide a wealth of detailed information on the interactions associated with a variety of nuclear configurations.

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THE STABILITY OF NUCLEAR SHAPE CORRELATIONS

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The number of constituent nucleons makes the nucleus a unique quantum system — not too few for correlations, not too many for single-particle effects. This analysis establishes empirical criteria for determining the stability of nuclear correlations and applies them as a function of N , Z , and I , in different mass regions. By comparing low- and high-spin data, where pair correlations are strong and weak respectively, information can be obtained regarding the relative sensitivity of pair and shape correlations to the number of nucleons in

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the nucleus. An independent analysis of the particle-number dependence of the stability of pair correlations is also discussed in the following contribution.

Nuclear energy levels of deformed nuclei are fit to the second order rotational expression:

$$E(I) = E_0 + A I(I+1) + B I^2(I+1)^2.$$

Values of the constants E_0 , A , and B are obtained as a function of N , Z , and I for con-

secutive values of $I - 2$, I , and $I + 2$. The ratio of B/A is taken to be a measure of how good a rotor the nucleus is or of the stability of the nuclear correlations. Such an analysis has been made for the yrast decay sequences of the even-even isotopes of $Z = 34-40$ and $Z = 56-78$ and for the superdeformed decay sequences. Sample plots of $\log |A/B|$ are shown as a function of I for the Gd, Dy, Er, and Yb isotopes in Fig. 2.20 and for the superdeformed decay

Fig. 2.20. Plot of $\log |A/B|$ as a function of angular momentum, I , for the even-spin, positive-parity states of even-even isotopes of gadolinium, dysprosium, erbium, and ytterbium. A and B are the fitted coefficients of $I(I+1)$ and $I^2(I+1)^2$ respectively, see text. The ratio A/B is negative except for those denoted by a + sign.

sequences in Fig. 2.21. Large values of $\log |A/B|$ denote stable correlations.

These data indicate how well the simple rotational formula works. For midshell nuclei the ratio of the coefficients of the first and second terms in the expansion varies from three orders of magnitude at low spin to, in the best cases, more than five orders of magnitude at high spins. Few concepts in nuclear physics are so precise! Nuclei become better rotors with

increasing angular momentum (due to the loss of pair correlations) and as the middle of the shell is approached. Whereas, the complete analysis indicates a sizable increase in $\log |A/B|$ with increasing mass at low spin, the best rotors in different mass regions appear to be nearly equally stable. Such systematics seem to indicate that pair correlations are less stable and more dependent on the nuclear mass than shape correlations. This feature is not

Fig. 2.21. Plot of $\log |A/B|$ as a function of angular momentum, I , for a variety of superdeformed decay sequences. The angular momentum was taken as the most likely value given in the experimental references. Changes of spin by up to four units do not alter the conclusions of the text. See also the caption to Fig. 2.20.

surprising. Pair correlations involve only a few pairs of particles near the Fermi level (see the following contribution), whereas all the valence-shell nucleons are associated with the nuclear shape.

The excellent stability of superdeformed ^{152}Dy (the ratio A/B is systematically greater than 10^5 for $I > 30$) both with respect to other superdeformed nuclei and to normally deformed nuclei is shown in Fig. 2.21. This added stability presumably is associated with sizable gaps in both the single-proton and the single-neutron spectrum of states at this large deformation (deformed shells). Superdeformed ^{152}Dy replaces rapidly rotating, midshell, rare-earth nuclei³ and the fission isomers⁴ (low-spin, superdeformed actinide nuclei) as the best nuclear rotor. At the highest spins it approaches the best diatomic molecular rotors⁵ ($10^4 < A/B < 5 \times 10^6$) as nature's most stable rotating quantum system.

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THE STABILITY OF NUCLEAR PAIR CORRELATIONS

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Pair correlations are a well-known property of medium and heavy deformed nuclei. Because of the small number of nucleons associated with this degree of freedom, even in the best of cases this correlation might be expected to be marginal. Indeed, it is known to be unstable with respect to rotation, see e.g. Ref. 3. The present contribution discusses the mass dependence of the stability of pair correlations.

For some time it has been known that band crossings based on the excitation of a pair of high- j quasiparticles are sensitive to pair correlations.⁴ The situation is very simple when the Fermi level, λ , is near the low- Ω

orbitals of the aligning quasiparticles. In this limit $(\epsilon - \lambda)^2 \ll \Delta^2$, and the expression for the quasiparticle energy for the highly-alignable, high- j , low- Ω orbitals reduces to

$$E = \sqrt{(\epsilon - \lambda)^2 + \Delta^2} = \Delta.$$

Then the band crossing occurs at that rotational frequency, $\hbar\omega_c$, where the rotational (Coriolis plus centrifugal) forces, $= -\hbar\omega_c j_1$, compensate the effects of pair correlations for the pair of quasiparticles excited at the band crossing. This interpretation is reinforced by the nearly constant (standard deviation of 6 %) empirical ratio of $\hbar\omega_c j_1 / \Delta_{pe}$ for all nuclei ($A = 80-235$) with the Fermi levels among the lower half of the Ω values of the aligning quasiparticles (see Fig. 6 of Ref. 5). The odd-even mass parameter, Δ_{pe} , is calculated from the most recent mass table.⁶

In this limit the lowest crossing frequency can be interpreted very simply. It is how rapid the nucleus must be rotated to unpair the first pair of quasiparticles. Therefore, the decrease in the pair gap, $\delta\Delta$, associated with the occupation of a single-particle orbital (not associated with the band crossing) can be estimated from the shift in the band crossing frequency between ground-state configuration in the even-even nucleus and the appropriate single-particle configuration in the odd- A neighbor, $\delta\hbar\omega_c$. That is, we assume:

$$\delta\Delta/\Delta = \delta\hbar\omega_c/\hbar\omega_c.$$

The average of the empirical values of $\delta\hbar\omega_c/\hbar\omega_c$ for $i_{13/2}$ quasineutrons and $h_{11/2}$ and $g_{9/2}$ quasiprotons are given in Table 2.2.

Pair correlations are expected to scale like the number of single-particle levels in the pair gap. Thus the decrease in pairing for the occupation of a single level near the Fermi level is a measure of the number of levels in the effective pair gap $[= 1/(\delta\hbar\omega_c/\hbar\omega_c)]$. The empirical estimates of these values are compared in Table 2.3 with the number of single-particle orbits within 2Δ for the appropriate mass region. Theoretical values are given for comparison based on average values for the whole

Table 2.2. Average values of δh_{ω_c} and $\overline{\Delta_{oe}}$ for various aligning quasiparticles

Aligning Quasipart.	No. Cases	δh_{ω_c} (MeV)	δh_{ω_c} $\langle h_{\omega_c}(e-e) \rangle$	$\overline{\Delta_{oe}}$ (MeV)
$\nu i_{13/2}$	10	0.038 ± 0.006	0.14 ± 0.02	1.12 ± 0.04
$\pi h_{11/2}$	4	0.111 ± 0.015	0.30 ± 0.04	1.33 ± 0.02
$\pi g_{9/2}$	5	0.18 ± 0.08	0.32 ± 0.11	1.66 ± 0.11

Table 2.3. Comparison of empirical and theoretical estimates of the number of effective levels involved in pair correlations

Aligning Quasipart.	$1/\delta h_{\omega_c}$ h_{ω_c}	No. Orbits in 2Δ	
		Shell Av.	Nilsson
$\nu i_{13/2}$	$7.1^{8.3}_{6.2}$	6.6	8.0
$\pi h_{11/2}$	$3.3^{3.8}_{2.9}$	5.3	7.6
$\pi g_{9/2}$	$3.1^{4.8}_{2.3}$	3.8	5.4

shell and from Nilsson model calculations for the appropriate particle number. The empirical estimate for the $i_{13/2}$ neutron alignments in $A = 165$ nuclei within statistical uncertainty agrees with the predicted number of nucleons in the effective pair gap. In contrast, the empirical estimates are too small for the alignment of both $h_{11/2}$ and $g_{9/2}$ quasiprotons in the $A = 130$ and 80 mass regions, respectively. (Note, however, that the estimate for the $g_{9/2}$ case is not very well determined!) In lighter systems the occupation of a single configuration near the Fermi level apparently causes the pair correlations to decrease more rapidly than expected, indicating that the pair correlations are not only marginally stable in these light systems, but are also very sensitive to the number of nucleons in the system.

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ROTATIONAL LEVEL STRUCTURE IN THE ODD-ODD NUCLEUS ^{166}Lu and PROTON-NEUTRON RESIDUAL INTERACTIONS

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With the present large arrays of Compton-suppressed Ge γ -ray detectors, it has been possible to investigate the structure of nuclei up to quite high spins ($I > 40$) via heavy-ion-induced reactions. Of particular interest in high-spin studies are the prolate deformed nuclei which behave as good rotors. Most analyses in past years have been performed on the even-even and odd- A rotors; however, there are several interesting questions which can be addressed by high-spin studies of odd-odd nuclei.

One such question is the residual interaction between the unpaired proton and the unpaired neutron. An empirical estimate of this interaction can be extracted as the difference between the experimental energy of the quasiproton-quasineutron configuration in the odd-odd nuclei and the corresponding states constructed from single-quasiproton and single-quasineutron states in neighboring isotones and

isotopes.³ Recent estimates of such interactions for odd-odd lanthanum and praseodymium isotopes yield large values that seem to be dependent on the spatial overlap between the orbits of the quasiproton and the quasineutron.⁴ Such analyses, however, also are sensitive to the polarization of the nuclear shape by the unpaired quasiproton and quasineutron.

Therefore, it seems crucial to make such a study in the most stably deformed nuclei possible. For this study we have chosen ^{166}Lu . Not only should the deformation of this midshell rare-earth nucleus, with 71 protons and 95 neutrons, be stable, but states based on very different proton orbits are known in the neighboring odd-mass lutetium isotopes. The quasiprotons based on the $1/2[541]$ Nilsson orbital should have a large spatial overlap with the low- Ω $i_{13/2}$ quasineutrons, and those based on the $9/2[514]$ orbital should have a small overlap with the low- Ω $i_{13/2}$ quasineutrons.

Recently in-beam γ -ray experiments have been performed, at the Holifield Heavy-Ion Research Facility, using the compact array of 20 Compton-suppressed Ge γ -ray detectors to study the rotational level structure of ^{166}Lu . The reaction $^{123}\text{Sb} + 217\text{-MeV } ^{48}\text{Ca} \rightarrow ^{171}\text{Lu}^* + ^{166}\text{Lu} + 5n$ was used. In one experiment, an unbacked target was used to permit observation of discrete γ rays at quite high spins. In another experiment, a Pb-backed target was used to achieve good γ -ray resolution at low energies and to obtain decay lifetimes at high spins by using the Doppler Shift Attenuation Method. In both experiments, a detector that is sensitive to low energy gamma rays was used to observe transitions between nearly degenerate two-quasiparticle states. The data analysis is presently in progress, but we have observed the blocking effects of the two unpaired nucleons concerning proton and neutron alignments. With regard to the two quasiparticle states and proton-neutron residual interactions, further data analysis is needed.

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IS THE STRUCTURE OF RAPIDLY-ROTATING COLD NUCLEI ORDERED OR CHAOTIC?

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Recently, it has become increasingly fashionable to consider the information content of the spectrum of eigenstates for quantal systems in terms of general statistical concepts. The very rich spectrum of nuclear states provides an excellent opportunity for such analyses. For some time it has been known² that the distribution of the spacing of nuclear states at the neutron and proton threshold can be described by random-matrix theory. This theory describes quantum mechanical analogues of classically chaotic systems. More recently, these analyses have been extended^{3,4} to lower excitation energies where rather complete spectroscopic information exists for low-spin states from a variety of experimental probes (especially from (n,γ) studies). To obtain sufficient data for such analyses at lower excitation energy, it is necessary to sum over levels in a variety of nuclei³ and/or a large range of excitation energies and angular momenta.^{3,4} Therefore, the conclusions (often that even the low-lying levels behave "chaotically") are not specific to a particular class of nuclei³ or nuclear states.^{3,4} Indeed, in deformed nuclei often several members of a rotational band, based on a single intrinsic nuclear state, are included in the analysis in order to improve statistics. Is this valid?

Several interesting questions can be addressed by extending such "nearest neighbor" analyses to high spin. Among these are the spin dependence of the density of, and the interactions between, single-particle states and the persistence of known, and the possibility of new, correlations at high spin. However, at the present time it is impossible to extend such an analysis to high spin adopting the "standard"

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criteria. Not enough high spin levels of a specific spin and parity are known in the same nucleus to establish a meaningful average value. In the best cases, only four high spin levels of the same spin and parity are known. The more typical number is only one or two levels. As an alternative, we have chosen to confine our analysis to a limited range of spins in a group of nuclei where nuclear properties are known to be stable, and to form the average spacing of neighboring levels, d , from the total ensemble. This procedure has the advantage of being specific to a particular range of nuclei, spins, and excitation energies and of having an average spacing constructed from a sizable number of levels. Its disadvantages are: (i) a bias toward smaller level spacings [if the excitation energy of the next decay sequence of similar spin and parity is large it would not be populated by the (heavy ion, xn) reaction]; and (ii) the problem of missing levels is worse than at low spin where more levels of the same spin and parity are known in each nucleus.

A nearest neighbor analysis of fifty-nine level spacings for $I = 19$ and 20 states (19.5 and 20.5 states in odd-A nuclei) from deformed nuclei with $A = 155-184$ is shown in Fig. 2.22, and the distribution of these data with respect to the nuclear quantum numbers is given in Table 2.4. This range of mass and spin was chosen because the nuclear properties are known to remain rather constant, see, e.g., Ref. 5. Though the conclusions derived from this analysis are limited by the statistics of the sample, rather definite conclusions can be derived from the average spacings tabulated. The significantly larger average spacing of the 20^+ states in even-even nuclei is a result of the special correlations of these states. Two-thirds of the 20^+ spacings are between the S band (based on a pair of aligned $1_{1/2}$ quasineutrons) and the extension of the ground-state band above this band crossing. Therefore, these states, which account for the excess probability for large spacings shown in Fig. 2.22, are not characteristic of the spacing of single-particle states. The lack of level spacing information

Fig. 2.22. Comparison of empirical level spacing distributions for fifty-nine $I = 19$, 19.5, 20, and 20.5 spacings in deformed rare earth nuclei with $A = 154-184$ with Wigner and Poisson distributions.

Table 2.4. Distribution of data

	No. of Cases	Average Spacing (MeV)
<u>Even-even</u>		
19^+	0	-
20^+	20	0.346
19^-	12	0.194
20^-	7	0.194
<u>Odd-N</u>		
19.5^+	0	-
20.5^+	0	-
19.5^-	6	0.284
20.5^-	8	0.201
<u>Odd-Z</u>		
19.5^+	0	-
20.5^+	0	-
19.5^-	3	0.256
20.5^-	3	0.286
<u>Total</u>	59	0.263

for the positive-parity levels in odd- N nuclei is attributed to a lower density of positive-parity single-particle states. There are seven positive-parity and 15 negative-parity Nilsson states in the $N = 82$ -126 shell. In several cases, two or more positive-parity states are observed in odd- Z nuclei; however, the relative energies of the corresponding decay sequences are not established. Similar problems exist for odd-odd nuclei, where generally the experimental data is of poorer quality.

In summary, the spacings of low-lying high-spin states of rare earth nuclei are neither described by Wigner ("chaotic") nor Poisson ("ordered") distributions. The deviations can be explained by the residual correlations and the variations of single-particle levels in this mass region. The planned new instrumentation, e.g., the GAMMASPHERE, will greatly increase the possibility for this type of analysis for high spin data.

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EXOTIC $N = 82$ NUCLEI ^{153}Lu AND ^{154}Hf AND FILLING OF THE $\nu_{11/2}$ SUBSHELL¹

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Microsecond isomers in the very proton-rich $N = 82$ nuclei ^{153}Lu and ^{154}Hf have been identified by γ -ray spectroscopy following mass analysis of $^{102}\text{Pd} + 245\text{-MeV } ^{54}\text{Fe}$ reaction products using the Daresbury Recoil Separator. The ionization chamber located at the end of the Separator was replaced with an aluminum catcher foil, which was surrounded by a low energy photon spectrometer and four large Ge γ -ray detectors. The isomers in ^{153}Lu and ^{154}Hf are

interpreted as $(\nu_{11/2})^n$ states, and the $B(E2)$ values observed imply that the $\nu_{11/2}$ occupation numbers for these nuclei are in fact somewhat less than $Z-64$. The overall $B(E2)$ results for the $(\nu_{11/2})^n$ isomers in the $N = 82$ isotone series, Fig. 2.23, indicate that the half-filling of the $\nu_{11/2}$ subshell occurs just below $Z = 71$.

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Fig. 2.23. Measured E2 transition rates for $v = 2$ and $v = 3$ isomeric transitions in $N = 82$ isotones as a function of $Z-64$. Where error bars are not shown, they lie within the plotted point.

SHAPE COEXISTENCE AND DISAPPEARANCE OF PAIRING CORRELATIONS IN ^{82}Sr

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According to both the experimental systematics and theoretical calculations, the mass $A = 80$ nuclei with $N = 44$ have a transitional character and display a rich pattern of shape coexistence and shape transition, due to their soft potential energy surfaces. Moreover, recent calculations by Nazarewicz et al.⁸ have revealed that for $N, Z = 38, 42$, and 44 particle numbers, the single-particle energy spectra develop significant gaps at large deformations which survive up to high angular frequencies. As a result of the reinforcement of these gaps, superdeformed shapes are expected to set in at high spins in $^{81-83}\text{Sr}$ and $^{83-85}\text{Zr}$ nuclei.

In our current studies, we have concentrated on the investigation of ^{82}Sr and its odd neighboring isotopes. The fusion-evaporation reaction $^{52}\text{Cr}(^{34}\text{S}, 2p2n)$ at a beam energy of 130 MeV was used to populate the high-spin states in ^{82}Sr . The experimental setup consisted of the ORNL Compton Suppression Spectrometer System (18 Ge), Spin Spectrometer, and the 4 π CsI Dwarf Ball of Washington University. This system provided for both high-resolution γ -ray spectroscopy, and complete exit-channel selection. In addition to light charged-particle identification, the 72 elements of the Dwarf Ball also provide angular-distribution and particle-energy information for the emitted particles. This information will be used to obtain the anisotropy of the charged particles in the center-of-mass frame and, thereby, to deduce the deformation of the parent compound nucleus.⁹

In the off-line analysis of these data, we generated a 3000 $\times$ 3000 channel γ - γ coincidence matrix, subject to the requirements that: (1) the Dwarf Ball detect at least one proton; and (2) the total coincidence fold from the Spin

Spectrometer exceed a minimum value of $K = 7$. These conditions resulted in spectra that were dominated by γ rays from ^{82}Sr . Figure 2.24 shows a partial level scheme for ^{82}Sr , which was constructed using the above data. In addition to establishing two new bands, we have extended four of the previously known¹⁰ bands to spins that range from 20 to 27 $\hbar$. Together, they represent the most extensive high-spin band structure obtained in a medium-heavy nucleus.

A theoretical analysis of the above bands in ^{82}Sr was carried out using the Woods-Saxon model of Refs. 8,11. The pairing gap was computed selfconsistently at zero rotational frequency and then assumed to be a smoothly decreasing function of ω . The results of these calculations indicate coexistence of prolate, oblate and triaxial shapes in this nucleus (Fig. 2.25). The predicted band-crossing frequencies, aligned angular momentum and g -factors agree very well with the experimentally observed values.

While the absolute energy minimum for the ground state corresponds to a spherical shape, prolate shapes and collective rotation rapidly set in at higher spins. For example, the deformation of the ground state band is predicted to be $\beta = 0.34$ at spin $I = 8$. The continuation of the ground-state band closely resembles that of the prolate ground state band in its ^{82}Sr isotope. They both consist of aligned $g_{9/2}$ protons at spin $I = 8$, followed by gradual alignment of a pair of $g_{9/2}$ neutrons at $\hbar\omega = 0.75$ MeV.

The calculations also predict the existence of an oblate minimum, which gives rise to the positive-parity yrast band at higher spins. The minimum arises from almost simultaneous alignment of $g_{9/2}$ neutrons and protons which, together, polarize the core toward collective oblate deformations. The reported measured g -factors for the states with spin $I = 8$ in these two positive-parity bands are in very good agreement with the calculated values.

At spins $I > 32 \hbar$, a large prolate deformation ($\beta > 0.42$) is predicted to set in as the lowest $h_{11/2}$ orbital becomes occupied (see Fig.

Fig. 2.24. Partial decay scheme for ^{82}Sr . Fig. 2.25. Shape evolution of the rotational bands in ^{82}Sr .

2.25). The experimental gamma-gamma energy correlation map shows a weak ridge-valley structure with a width that corresponds to a dynamical moment of inertia of $J(2)/K^2 = 26.7 \text{ MeV}^{-1}$ that corresponds to $\beta = 0.55$ for a deformed rigid rotor. However, apart from the known transitions, and largely due to lack of sufficient statistics, we have not been able to identify any discrete band that could be identified with this ridge-valley structure.

The odd- and even-spin negative-parity bands are predicted to consist of 2-quasiproton configurations with triaxial deformations. At higher spins, the odd-spin negative-parity band assumes an oblate shape. Experimentally, this band crosses the positive-parity band and forms the yrast line. This behavior may be reproduced in calculations with very small pairing correlations. Loss of pairing correlations at high spins in this nucleus is a natural consequence

of (1) presence of large gaps at $N = 44$ and $Z = 38$; and (2) the multi-quasiparticle nature of the bands at large rotational frequencies.

Several papers in the past few years have reported the onset of rigid-rotor (RR) behavior ($J^{(1)} = J^{(2)} = J_{\text{rig}}$) at high spins in the $A = 80$ (e.g., ^{84}Zr , $^{76,78}\text{Kr}$, ^{72}Se ...) and $A = 160$ (e.g., ^{160}Hf , $^{165,168}\text{Yb}$...) mass regions. This behavior was then interpreted to imply loss of pairing correlations in these nuclei. It is worthwhile to note that, far from showing a rigid-rotor behavior, the $J^{(2)}$ moments of inertia in the NP bands gradually decrease at frequencies above $\hbar\omega = 0.7$ MeV. (This is because collective rotation at oblate shapes becomes energetically more expensive as the angular momentum approaches the maximum value of $I = 31$ that can be generated without involving the $h_{11/2}$ intruder orbitals.) The fact that high-spin bands in ^{82}Sr show no rigid-rotor behavior, even if their properties are well described in calculations without pairing, is a clear indication that loss of static pairing need not necessarily be accompanied by a rigid-rotor behavior. Conversely, since in addition to pairing correlations the moments of inertia reflect and are sensitive to other properties of the band (e.g., shape parameters and alignments), their behavior cannot be indicative of the evolution of the pairing strength alone. Thus, inferences regarding the superfluid-to-normal phase transition should not be based on the evolution and behavior of the moments of inertia.

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A 35- μs ISOMER IN THE EXOTIC $N = 83$ NUCLEUS ^{154}Lu

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In proton-rich $N = 82$ isotones ^{149}Ho , ^{151}Tm , and ^{153}Lu , $27/2^-$ isomers of $\pi h_{11/2}^n v = 3$ character occur at ~ 2.7 MeV.⁸⁻¹⁰ As Z and the $\pi h_{11/2}$ occupation number increase, the observed $B(E2, 27/2^- \rightarrow 23/2^-)$ decreases sharply, reaching a value of only $0.45 e^2\text{fm}^4$ (or 0.01 W.u.) in ^{153}Lu , where the $\pi h_{11/2}$ subshell is approximately half-filled.¹⁰ Corresponding $(\pi h_{11/2}^n \nu f_{7/2}) 17^+$ isomers have been located^{8,11} in the $N = 83$ neighboring nuclei ^{150}Ho and ^{152}Tm . Echoing the trend in the $N = 82$ series, the $B(E2, 17^+ \rightarrow 15^+)$ diminishes from ^{150}Ho to ^{152}Tm , and, by extrapolation, a 17^+ half-life much longer than $1 \mu\text{s}$ has been predicted¹¹ for the ^{154}Lu isotone, which has not been studied up to now.

In a recent experiment^{10,12} designed to search for μs isomers in proton-rich $N = 82$, 83 nuclei, the product recoils from the reaction $^{102}\text{Pd} + 240\text{-}245 \text{ MeV } ^{54}\text{Fe} \rightarrow ^{156}\text{Hf}^*$ were mass analyzed using the Daresbury Recoil Separator and deposited on an aluminum catcher foil behind the separator focal plane. Gamma-ray measurements were performed with several Ge detectors and a Low Energy Photon Spectrometer (LEPS) surrounding the catcher. The strongest isomeric species observed was the $2p_n$ evaporation product $15\text{-}\mu\text{s}$ ^{153}Yb , for which a detailed decay scheme has already been reported.¹² The next strongest family of γ rays was observed in the $A = 154$ mass window and was found to be coincident with Lu X rays. Therefore these γ rays are assigned to the p_n product ^{154}Lu . The isomeric half-life was determined to be $35 \pm 3 \mu\text{s}$. Although the yield of the ^{154}Lu isomer at the catcher foil was only 4% of the ^{153}Yb isomeric yield, the

parent level should be isomeric, but the measurements revealed no intermediate isomers in the level scheme. A further difficulty would be the implied $15^+ \rightarrow 13^-$ assignment for the 520-keV transition. The most plausible solution is indicated in Fig. 2.27, where an unobserved low-energy $15^+ \rightarrow 14^+$ M1 transition is followed by 350-keV $14^+ \rightarrow 13^+$ and 520-keV $14^+ \rightarrow 13^-$ decay branches in a manner consistent with the coincidence results. In the corresponding portion of the ^{153}Lu level spectrum, the $\pi h_{11/2}^n 23/2^-$ state is isomeric, even though the $21/2^-$ state lies below it;¹⁰ this happens because the $23/2^- \rightarrow 21/2^-$ M1 transition is forbidden within the $\pi h_{11/2}^n$ configuration. However, in ^{154}Lu the $15^+ \rightarrow 14^+$ transition between $\pi h_{11/2}^n$ $\nu f_{7/2}$ states can be fast, and may thus carry the entire decay intensity.

While the level scheme shown on Fig. 2.27 may not be correct in all details, there seems little doubt about the interpretation of the 130-keV E2 γ ray as the expected $17^+ \rightarrow 15^+$ isomeric transition. The measured half-life gives

$$B(E2, 130 \text{ keV}, ^{154}\text{Lu}) = 0.19(2) \text{ e}^2\text{fm}^4,$$

much smaller than the values 182(18) and 44(2) e^2fm^4 determined for the analogous $17^+ \rightarrow 15^+$ decays in ^{150}Ho and ^{152}Tm . Following Ref. 11, we plot in Fig. 2.28 the isomeric E2 transition

Fig. 2.28. Transition amplitudes $\sqrt{B(E2)}$ for isomeric E2 transitions in $N = 82$ and 83 isotones as a function of Z , assuming a sign change in ^{153}Lu only.¹⁰ Where error bars are not shown, they lie within the plotted point.

amplitudes, $\sqrt{B(E2)}$, for $N = 82, 83$ nuclei as a function of Z , with the assumption that the amplitude has changed sign only in ^{153}Lu .¹⁰ The variation of $\sqrt{B(E2)}$ with Z is seen to be approximately linear for each set of isotones. The shift between the $N = 82$ and $N = 83$ lines in Fig. 2.28 may be attributed¹¹ to the $(\pi h_{11/2}^n)_{27/2^-} \nu f_{7/2}$ components of the 15^+ states, which give rise to similar contributions to the $17^+ \rightarrow 15^+$ transition amplitudes in each of the $N = 83$ isotones. As mentioned above, this result has been anticipated in Ref. 11, where a $B(E2, 17^+ \rightarrow 15^+)$ very close to zero was predicted for ^{154}Lu . Furthermore, a recent β -decay study¹³ suggests that the ^{154}Lu ground state is a 7^+ , but any highly converted, low energy $(\pi h_{11/2}^n \nu f_{7/2}) 9^+ \rightarrow 7^+$ transition would not have been observed.

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ROTATIONAL BAND STRUCTURES IN ^{175}Re

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To continue the systematic studies of high-spin states in Ir and Re nuclei, we performed two experiments at the Holifield Heavy Ion Research Facility recently. The reactions $^{156}\text{Gd}(^{23}\text{Na}, x)$ and $^{161}\text{Dy}(^{23}\text{Na}, x)$ (both at 111 MeV) were used for studying the γ rays in ^{175}Re and ^{180}Ir , respectively. Twenty Ge detectors of the Compton Suppression Spectrometer System were loaded in the compact array with a close distance to the target center (~ 12 to 14 cm) to allow the collection of γ -ray triples events. Since there was no previously known information on either nucleus, excitation functions were performed at three different beam energies preceding the major experiments. Both backed and unbacked targets were used in the ^{180}Ir run; a Pb-backed target was used in the ^{175}Re run.

A preliminary analysis of the ^{175}Re data has been carried out, and three band structures have been assigned. Based on the systematics of the known bands in the neighboring odd-A Re nuclei,⁴ two decoupled bands, strongly populated in the reaction, are identified as the proton $1/2^-[541]$ (or $\pi h_{9/2}$) and $1/2^+[660]$ (or $\pi i_{13/2}$) structures. The presence of band crossings can be seen from the usual plot of aligned angular momentum versus rotational frequency in Fig. 2.29. A sharp backbending occurs at $\hbar\omega \sim 0.3$ MeV and is believed to be due to the alignment of the usual ($\nu i_{13/2}$) pair (a common feature throughout this rare-earth region). A smooth increase in the alignment in the $\pi i_{13/2}$ band is also observed, as is also found in other light Ir⁵ and Re⁶ nuclei. This feature can be explained by the large deformation driving property of the $1/2^+[660]$ orbital as indicated in our Total Routhian Surface calculations.

A strongly coupled band, based on the $5/2^+[502]$ configuration, also has been observed in ^{175}Re . Another strongly coupled band seen in

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Fig. 2.29. The aligned angular momentum versus rotational frequency in ^{175}Re .

the data probably results from the $\pi h_{11/2}$ excitation. Detailed analysis is still in progress.

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LIFETIMES OF ROTATIONAL STATES IN ^{186}Pt

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The nucleus ^{186}Pt is known to exhibit shape coexistence,⁶ and in addition it is proposed that there is a structure transition between ^{186}Pt and ^{188}Pt .⁷ Detailed Total Routhian Surface (TRS) calculations performed here indicate that, even at the ground state, ^{186}Pt has

significantly larger γ and hexadecapole deformations than other Pt isotopes. Extensive spectroscopic investigations of Ir-Pt-Au nuclei^{6,8-11} have led to the question of how Pt nuclei change from those with dominant prolate shape at $A < 184$ to those with oblate shapes at $A > 190$. In question is whether the transition point is at $N = 108$ or 110.

To attempt to answer these questions, we have performed lifetime measurements on states in ^{186}Pt . High-spin states were populated by the reaction $^{154}\text{Sm}(^{36}\text{S},4n)^{186}\text{Pt}$ at a beam energy of 165 MeV using the Holifield 25 MV tandem accelerator. The recoil-distance plunger was surrounded by a Compton-suppressed Ge detector (BGO shield) at 0° and six Ge detectors at 90° . Only γ rays at 0° in coincidence with any of six Ge(Li) detectors at 90° were recorded as an event. The thickness of the enriched ^{154}Sm target was $1.0 - 1.2 \text{ mg/cm}^2$. Data were taken at 20 separations between target and stopper, varying from 8.5 to 1508.5 μm . The shortest distance was determined by the pulser-capacitance technique.

The presence of γ rays from the 5n and 6n reaction products made the spectra complicated, and required a coincidence acquisition of the data. Both total projections and spectra gated by certain yrast lines have to be used to get lifetimes. Almost two-thirds of the acquired events were found to be triples due to the closer distances of the Ge counters: 5.9 cm for the detectors at 90° and 9.7 cm for the detector at 0° . Normalization factors were determined from the $2^+ \rightarrow 0^+$ transition in total projections after corrections. The standard peak-fitting program SAM was used to extract areas of the γ -ray peaks. The recoil velocity of ^{186}Pt was determined to be $v/c = (1.71 \pm 0.04)\%$ from separations of shifted and unshifted peaks [$\Delta E = E_0(v/c \cos \theta)$].

Two ways were used to extract lifetimes from the data: (1) Unshifted and shifted peaks from the total projections were used to extract lifetimes for the highest and lowest spins that are within our window of measurement. (2) Unshifted peaks from spectra gated by transitions above or

below that of interest were used for the whole region, especially for intermediate spins due to doublets occurring in total projections.

The recoil-distance data were analyzed with the computer program LIFETIME. The level scheme measured by Pilotte¹² is used. For the feeding to the top member of the measured yrast sequence, a rotational band with three or four levels was used. Both a two-level side feeder and two one-level side feeders were used separately. Parameters were grouped and fixed, level after level, from top to bottom for both the total projected and gated data to determine an initial set of lifetime values. Finally, all of these values were allowed to vary in the program MINOS to assign the final values and their uncertainties. The application of this technique to the data gave rather large uncertainties in general. The corrections involved are for the apparent solid angle of the γ -ray detector, attenuation of the angular distribution of the γ rays, line-shape broadening, and branching ratios.

There are sidefeedings from isomers in ^{186}Pt .^{6,8} Three ways were used to deal with their influences: (1) Subtraction of long lifetime tails were made. The background was taken from spectra at large distances, except for the 2^+ transition, in which case the tail was calculated from published lifetimes of isomers in addition to the known relative intensities. (2) Original decay curves were analyzed and some parameters calculated from published data. The parameters were fixed in parameter files before running. (3) Original decay curves and parameters were determined. Two side bands were fit to extract them. Then these parameters were fixed in input parameter files for running.

A summary of the mean lifetimes τ_m and transition quadrupole moments Q_t from experiment is presented in Table 2.5. The $Q_t(\text{exp})$ is calculated from τ_m in the traditional way:

$$B(E2; I \rightarrow I-2) = \frac{5}{16\pi} \langle I2K0 | I-2K \rangle^2 Q_t^2(\text{exp}). \quad (1)$$

The $Q_t(\text{theory})$ was calculated from the deformation parameters (B_2, γ, B_4) of the TRS calculations as follows:

Table 2.5. Experimental results for the yrast band in ^{186}Pt

Spin	E_γ (keV)	τ_m (ps)	$Q_t(\text{exp})$ (eb)
2^+	191.4	320 ± 40	$5.86^{+0.40}_{-0.34}$
4^+	298.9	24 ± 7	$6.72^{+1.26}_{-0.8}$
6^+	387.2	6 ± 2	$6.87^{+1.55}_{-0.92}$
8^+	465.6	$2.3^{+0.9}_{-0.8}$	$6.68^{+1.6}_{-0.9}$
10^+	515.4	$1.5^{+0.8}_{-0.7}$	$6.56^{+2.4}_{-1.3}$
12^+	478.0	$2.4^{+1.1}_{-0.8}$	$6.24^{+1.13}_{-1.11}$
14^+	489.2	$3.0^{+1.5}_{-1.0}$	$5.21^{+2.2}_{-0.9}$
16^+	571.1	$1.0^{+0.5}_{-0.3}$	$6.18^{+1.56}_{-1.13}$
18^+	658.0	$< 1.$	

$$Q_t(\text{theory}) = \frac{6}{(15\pi)^{1/2} B_2} (1 + 0.36 B_2 + 0.967 B_4 + \frac{0.328 B_4^2}{B_2}) \times \cos(\gamma) Z R_0^2 A^{2/3} \quad (2)$$

where $R_0 = 1.2 \text{ fm}$.

The only previous measurement of lifetimes of the ground-state band in ^{186}Pt came from recoil-shadow conversion-electron spectroscopy.⁶ Our lifetime of the 2^+ state is consistent with that result.

The $Q_t(\text{exp})$ values are plotted as a function of spin in Fig. 2.30. The "large" uncertainties result not from an insufficient quality of the data, but rather from the complex sidefeeding present in ^{186}Pt (involving isomeric bandheads) and the difficulty of finding a unique set of sidefeeding conditions to model these bands. For comparison, the values extracted from the deformation parameters calculated in the TRS model are overlaid in Fig. 2.30. The agreement

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Fig. 2.30. Transition quadrupole moments Q_t as a function of spin for the yrast band of ^{186}Pt . Also shown are the TRS predicted values for the AB (neutron $i_{13/2}$) and EF (proton $h_{9/2}$) configurations.

between experiment and theory is quite good throughout. The TRS results indicate a "stretching" in the ground band from $I = 2$ to $I = 8$. The measured values tend to show the same pattern, although the uncertainties also allow a constancy in the $Q_t(\text{exp})$ in the ground band. The calculations indicate a drop in $Q_t(\text{exp})$ at $I = 10$ and above due to the alignment of a pair of either $i_{13/2}$ neutrons (AB) or $h_{9/2}$ protons (EF). The measured Q_t values cannot differentiate.

A comparison of measured $Q_t(\text{exp})$ values in ^{186}Pt with those known in other Pt nuclei is shown in Fig. 2.31. The experimental values in the region $176 < A < 188$ (except ^{180}Pt) show the same trend of increasing Q_t as a function of spin before the first backbend (present in the TRS prediction shown in Fig. 2.30). In fact, these experimental curves can be divided into two groups, according to the behavior at low spins: (1) those with large quadrupole moments and increasing values as a function of spin, which indicates a shape softness below $A = 186$, and (2) the others with smaller and more constant quadrupole moments, indicating perhaps

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Fig. 2.31. $Q_t(\text{exp})$ as a function of spin in the Pt isotopes. The ^{186}Pt values were measured here, while the results of the other nuclei come from the literature.¹²⁻¹⁸

less soft shapes for Pt nuclei above $A = 190$. This transition in the nature of the collectivity in the Pt nuclei appears to occur at $N = 110$. This conclusion is supported by the systematic study of low-spin levels in the Pt isotopes, as deduced from radioactive decay work.¹¹ That is, the energy difference between corresponding levels for two neighboring even- A Pt isotopes is the largest between ^{186}Pt and ^{188}Pt . Also, the second 2^+ levels come down in energy and remain constant for $A > 188$.

The trend in the Q_t values with A for the Pt nuclei is shown more clearly in Fig. 2.32. It is true from our measurement, compared to that of Garg et al.,¹³ that the $Q_t(\text{exp})$ values are very similar for ^{186}Pt and ^{184}Pt , whereas the TRS calculations predict a 5% decrease in Q_t in ^{186}Pt compared to ^{184}Pt . But, overall the experimental trend agrees rather well with the TRS calculations. Both indicate that the maximum collectivity at $I = 2$ occurs for ^{180}Pt ,

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Fig. 2.32. $Q_t(\text{exp})$ as function of mass number for Pt.

although there are no measured values on ^{182}Pt to better define the experimental trend.

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HIGH-SPIN STATES IN $^{179,181}\text{Ir}$

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Gamma rays from high-spin states in the light Ir nuclei were measured via the reactions $^{156,158}\text{Gd}(^{27}\text{Al}, ^4\text{n})^{179,181}\text{Ir}$ at 134 MeV. These measurements were performed at the Holifield Heavy Ion Research Facility, using the Spin Spectrometer loaded with 19 Compton-suppressed Ge counters. About 10^8 γ - γ coincidence data were collected for ^{181}Ir and 8×10^7 for ^{179}Ir . Earlier studies³ of levels in ^{181}Ir have been extended up to $53/2 \hbar$, while in ^{179}Ir we make the first measurements up to $57/2 \hbar$. Four rotational bands in each nucleus are associated with configurations: $\pi h_{9/2}$, $\pi i_{13/2}$, $\pi d_{5/2}$, and $\pi h_{11/2}$. A $\nu i_{13/2}$ quasiparticle alignment is found to occur around $\hbar\omega = 0.3$ MeV in the $\pi h_{9/2}$ band, but at lower frequencies in the $\pi d_{5/2}$ and $\pi h_{11/2}$ bands (due to differences in shape). The alignment of the $\pi i_{13/2}$ band increases smoothly, which could indicate a larger deformation associated with this orbital.

NUCLEAR STRUCTURE STUDIES VIA RADIOACTIVE DECAY

DECAY OF $^{149}\text{Er}^{g+}$ BY POSITRON AND DELAYED PROTON EMISSION AND BY ELECTRON CAPTURE¹

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In this study the decay of $^{149}\text{Er}^{g+}$ by positron emission, electron capture, and β -delayed proton emission was investigated. Gamma rays associated with $^{149}\text{Er}^{g+}$ decay were placed in a decay scheme on the basis of $\gamma\gamma$ and $x\gamma$ coincidences and half-life. We assigned 120 γ rays de-exciting 91 levels in ^{149}Ho to 8.9 ± 0.2 s $^{149}\text{Er}^{g+}$ decay. The $\pi s_{1/2}$ single-particle state in ^{149}Ho was observed to occur at 49.0 keV above the $\pi h_{11/2}$ ground state. A $(3.5 \pm 0.7)\%$ isomeric transition decay branch and a $(0.18 \pm 0.07)\%$ β -delayed proton decay branch were determined for $^{149}\text{Er}^{g+}$ decay. Three additional γ rays were assigned to 4 ± 2 s $^{149}\text{Er}^g$ decay and a $(7 \pm 2)\%$ β -delayed proton decay branch was determined. Measured EC/ϵ^+ ratios to proton emitting states in ^{149}Ho resulted in a $(Q_{\text{EC}} - S_p) = 7.0 \pm 0.5$ MeV for $^{149}\text{Er}^g$ decay and an $S_p = 1.4 \pm 0.8$ MeV for ^{149}Ho .

The ^{149}Er β -delayed proton spectrum (see Fig. 2.33a) consists of a highly structured component superposed on one that is essentially structureless. As in the case³ of another $N = 81$ precursor, ^{151}Yb , the intense peaks were found to be associated with proton emission from a region (4-5 MeV excitation) of low density of levels in the $N = 82$ daughter ^{149}Ho that are populated by the Gamow-Teller β decay of the $s_{1/2}$ ^{149}Er ground state. The levels can de-excite via $L = 0$ proton decays to the ground state of ^{149}Dy . Thus, proton emission becomes important near 4.0 MeV of excitation in ^{149}Ho . Conversely, $L = 0$ proton emission from levels fed by the $h_{11/2}$ $^{149}\text{Er}^{g+}$ beta decay populates levels near 2 MeV in ^{149}Dy , and $L > 4$ is required for the transition to the ground state of ^{149}Dy . In this case, proton emission does not become significant until higher excitation energies in ^{149}Ho where the level density is

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Fig. 2.33. Delayed protons emitted following the β decay of ^{149}Er : (a) singles spectrum, and (b) spectrum measured in coincidence with positrons.

~ 100 times greater. Therefore, the decay of $^{149}\text{Er}^m$ is the primary contributor to the structureless, or statistical, portion of the delayed-proton spectrum. In Fig. 2.33b we show protons observed in coincidence with positrons.

This positron-coincident spectrum emphasizes proton emission from lower-lying levels in ^{149}Ho that are fed principally by β^+ rather than by electron-capture decay. Indeed, one notes in Fig. 2.33b that the structureless distribution

seen in Fig. 2.33a, which arises from high-lying levels in ^{149}Ho , is greatly suppressed.

1. Summary of a published paper: Phys. Rev. C 39, 219 (1989).
2. Lawrence Berkeley Laboratory, Berkeley, CA 94720.
3. K. S. Toth et al., Phys. Lett. B 178, 150 (1986).

IDENTIFICATION OF ^{145}Er AND ^{145}Ho ¹

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On-line mass separation and K x-ray coincidences were used to identify the β decays of ^{145}Er and ^{145}Ho . While only β -delayed proton emission was observed for ^{145}Er ($T_{1/2}=0.9 \pm 0.3$ s), a total of 16 γ rays were assigned to the β decay of ^{145}Ho ($T_{1/2}=2.4 \pm 0.1$ s). A ^{145}Ho decay scheme (see Fig. 2.34) was constructed which incorporates 13 γ -ray transitions and 10 excited levels in ^{145}Dy , including the $\nu_{11/2}$ isomeric level which is located at 118.2

keV. The low-lying neutron-hole structure in ^{145}Dy is compared to level systematics in even- Z nuclei with $N = 77, 79$, and 81.

1. Summary of a published paper: Phys. Rev. C 39, 1972 (1989).
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DOORWAY STATE FORMATION AND STRUCTURE IN β -DELAYED PROTON DECAY¹

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β -delayed proton decay in deformed heavy nuclei is characterized by high level densities in the proton emitter, giving rise to almost featureless proton energy spectra. This situation is expected to change near closed shells where reduced level densities and nuclear structure may affect the spectra. Pronounced peaks in delayed proton spectra have indeed been observed, first, near the $Z = 50$ closed shell⁵ and more recently near $N = 82$.⁶ The question arises whether these narrow resonances are the result of nuclear structure or predominantly a fluctuation phenomenon of the Porter-Thomas type that can be interpreted within the context of a statistical model.

To shed light on this question we investigated an isotonic sequence of six β -delayed proton emitters with $N = 82$ and $65 < Z < 70$ with the on-line isotope separator facility OASIS⁷ at the Berkeley SuperHILAC. The proton spectra of the odd- Z , $N = 81$ precursors ^{148}Ho , ^{150}Tm , and ^{152}Lu are featureless, which is characteristic of proton decay from regions of high level density in the emitter, and are adequately described⁸ by a statistical model. In contrast, the proton spectra of the even- Z , $N = 81$ precursors ^{147}Dy , ^{149}Er , and ^{151}Yb exhibit pronounced structure (Fig. 2.35) which has been shown⁹ earlier to be associated with the decay of the low spin ($1/2^+$) ground states. (Delayed protons connected with the $11/2^-$ isomeric states, because of angular momentum considerations, originate from levels at high excitation energies in the β -decay daughters and give rise to a structureless spectrum.) Gamma-ray decay studies,

Fig. 2.34. Partial decay scheme of ^{145}Ho . Excitation and γ -ray energies are given in keV; relative γ -ray intensities are based on a value of 100 for the 339.8-keV γ ray.

Fig. 2.35. Beta-delayed proton spectra of $N = 81$ precursors. In (a) and (b) protons were recorded in coincidence with positrons, while (c) is a singles spectrum. The positron coincidences select preferentially decays from the $s_{1/2}$ ground states of the precursors and suppress decays from the $h_{7/2}$ isomers; the latter giving rise to smooth ("statistical") spectra (for details see Ref. 6). In the decay of ^{147}Dy (c) the statistical component is very weak.

β -strength function measurements, and calculations of state densities and Gamow-Teller strength distributions, lead us to suggest that some of the observed structure near $N = 82$ arises from the preequilibrium decay of doorway states populated in β^+/EC decay, and that it can be understood within the framework of a simple doorway-state model based on the original work by Bloch and Feshbach.¹⁰

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DIRECT AND β -DELAYED PARTICLE DECAYS NEAR CLOSED SHELLS¹

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We have been involved in the investigation of nuclear structure properties of nuclei close to the proton drip line. In these studies we have used on-line isotope separators at Oak Ridge (UNISOR) and Berkeley (OASIS), the ORNL velocity filter, and a fast helium-gas-jet transport system at the LBL 88-Inch Cyclotron. We describe briefly three areas of our research that have dealt with particle decays: (1) α decay in medium-weight nuclei, (2) α -decay rates for even-even isotopes, and (3) β -delayed-proton decay of $N = 81$ precursors.

1. Summary of a published paper: Nucl. Instrum. Methods B40, 447 (1989).

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DECAY PROPERTIES OF ^{153}Yb AND ^{153}Tm ; EXCITATION ENERGIES OF THE $s_{1/2}$ AND $h_{11/2}$ PROTON STATES IN ^{153}Tm ¹

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The decay properties of ^{153}Yb and ^{153}Tm , produced in ^{64}Zn bombardments of ^{92}Mo , were investigated following on-line mass separation. A decay scheme, incorporating 34 transitions and 25 levels in ^{153}Tm (see Fig. 2.36), was constructed for ^{153}Yb . It establishes the $s_{1/2}$ proton level in ^{153}Tm to be isomeric at an excitation energy of 43.2 keV. The α -decay branch

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Fig. 2.36. Proposed β -decay scheme for ^{153}Yb .

of the $h_{11/2}$ ^{153}Tm ground state was determined to be $91 \pm 3\%$. In addition, a partial decay scheme was put together for the $9\% \beta^+$ branch. About 66% of this β^+ decay proceeds to the $h_{9/2}$ neutron state located at 299.3 keV in ^{153}Er . Only one transition, 266.5 keV, could be assigned to the β^+ decay of the ^{153}Tm $s_{1/2}$ isomer; it is suggested that the γ ray de-excites the $p_{3/2}$ neutron level to the $f_{7/2}$ ^{153}Er ground state. Based on the intensity of this 266.5-keV γ ray, the isomer's α branch was estimated to be $\sim 93\%$.

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IDENTIFICATION OF ^{153}Lu β Decay

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We have been investigating the decay properties of $A = 153$ nuclides with the use of the OASIS isotope separator on-line at the Lawrence Berkeley Laboratory SuperHILAC. Part of our investigation included a search for the so-far unreported isotope ^{153}Lu . This nuclide is predicted to be proton unbound and its β decay is

expected to feed single-neutron levels in ^{153}Yb . A 1.85-mg/cm² molybdenum foil, enriched in ^{92}Mo to 97.4%, was bombarded with 285-MeV ^{64}Zn ions. The $A = 153$ products were selected by an analyzing slit in the focal plane of the separator, transported ionoptically to a fast cycling tape system, and periodically (cycle times of 1.28, 4.0, and 12.8 s were used) positioned between an array of γ -ray and particle detectors. Coincidences between particles, γ rays, X rays, and positrons were recorded in an event-by-event mode. Singles γ -ray data were acquired with all three Ge detectors.

A low production yield was anticipated for the $^{92}\text{Mo}(^{64}\text{Zn}, p2n)$ channel and indeed there was no obvious indication of Yb K X rays. Observation of their presence was severely hampered by the much more intense K α and K β X rays of elements with $Z < 69$. However, ^{153}Yb levels have recently been studied² via in-beam γ -ray spectroscopy. In addition to high-lying, high-spin states, the authors² located the $h_{9/2}$ and $i_{13/2}$ neutron levels at 567 and 1202 keV, respectively. The $h_{9/2}$ state should be the most intense; populated by the decay of the $11/2^-$ ($h_{11/2}$ proton orbital) ^{153}Lu ground state. An examination of our data showed the presence of a weak 566.5-keV γ ray in spectra accumulated during the 1.28- and 4.0-s counting cycles; it was obscured by the longer-lived radioactivities in the 12.8-s spectra. Gating on the 566.5-keV γ ray revealed Yb K X rays in coincidence. Based on this evidence, we conclude that we have identified the decay of the new isotope ^{153}Lu . From the decay data of the 566.6-keV transition, we determined the ^{153}Lu half-life to be 0.9 ± 0.1 s. The half-life estimated from the gross theory³ of β decay is 3.9 s.

In addition to the 566.5-keV transition, we assign two other γ rays to the decay of ^{153}Lu ; all three γ rays were observed in-beam by McNeill et al.² From their ^{153}Yb level scheme we then constructed the ^{153}Lu decay scheme shown in Fig. 2.37. Bearing in mind that there must be unobserved γ rays, we calculate a logft limit of >4.0 for the β transition feeding the 566.5-keV level. Our data thus support the

Fig. 2.37. Partial decay scheme proposed for ^{153}Lu . Relative γ -ray intensities are enclosed in parentheses; they are based on a value of 100 for the 566.5-keV transition.

$h_{9/2}$ assignment to this state since the parent level, as shown in Fig. 2.38, is most probably an $h_{11/2}$ single-proton state.

In Fig. 2.38 we show the energies of $h_{9/2}$ and $i_{13/2}$ states in even- Z nuclei above europium with neutron numbers of 83, 85, and 87. The 566.5- and 1202.0-keV ^{153}Yb levels fit well into the overall systematics. In Ref. 4, single-neutron levels in $N = 83$ nuclei from ^{137}Xe to ^{149}Dy were considered. It was noted that the $h_{9/2}$, $p_{1/2}$, $p_{3/2}$, and $f_{5/2}$ orbitals increase in excitation energy with respect to the $f_{7/2}$ ground states as Z increases up to 64 (gadolinium) and then decrease as Z increases further (see Fig. 2.38). Also, we note in Fig. 2.38 a compression of the $h_{9/2}$ level energies as the neutron number becomes larger. The $i_{13/2}$ orbital behaves differently; its energy decreases with increasing Z , reaches a minimum at $Z = 64$, and then increases (Fig. 2.38). Its behavior with N also differs from that of the $h_{9/2}$ orbital. The evidence is that the $13/2^+$ levels are not pure single-particle states; they are mixed with 3^- octupole collectivity.

Fig. 2.38. Systematics of known $h_{9/2}$ and $i_{13/2}$ neutron states in Gd, Dy, Er, and Yb nuclei whose neutron numbers are 83, 85, and 87.

Direct proton emission from ^{153}Lu to ^{152}Yb was not seen. This decay mode, because of angular momentum considerations, should be much more probable for the $s_{1/2}$ isomer than for the $h_{11/2}$ ground state. However we were unable to observe any evidence of the $s_{1/2}$ β decay and a limit on the proton branching ratio could not be determined.

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IDENTIFICATION OF ^{181}Pb IN ^{40}Ca IRRADIATIONS OF ^{144}Sm

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The isotope ^{181}Pb was identified in ^{40}Ca irradiations of ^{144}Sm via its α -decay properties: $E_\alpha = 7.044 \pm 0.015$ MeV (see Fig. 2.39), and $T_{1/2} = 50 \pm 35$ ms. The assignment was based on excitation-function and cross-bombardment ($^{39}\text{K} + ^{147}\text{Sm}$ and $^{40}\text{Ca} + ^{147}\text{Sm}$) information and on decay-energy systematics. Also, in the course of the $^{40}\text{Ca} + ^{147}\text{Sm}$ measurements, two

Fig. 2.39. Alpha-particle spectrum measured in bombardments of ^{144}Sm with 201-MeV ^{40}Ca . Energies shown for α peaks are given in keV. The 7044-keV peak is assigned to the α decay of the new isotope ^{181}Pb .

α groups that have not been reported previously were assigned to ^{183}Pb α decay. The observation of these α groups necessitates a correction to the adopted mass of ^{183}Pb .

1. Summary of a published paper: Phys. Rev. C 39, 1150 (1989).
2. Lawrence Berkeley Laboratory, Berkeley, CA 94720.

SUPERALLOWED $^{42}\text{Sc}(\beta^+)^{42}\text{Ca}$ DECAY¹

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The neutron-separation energy of ^{42}Ca and the proton-separation energy of ^{42}Sc have been measured accurately via the $^{41}\text{Ca}(n,\gamma)^{42}\text{Ca}$ and $^{41}\text{Ca}(p,\gamma)^{42}\text{Sc}$ reaction, respectively. The measured values imply a Q -value of 6425.92 ± 0.19 keV for the total β -decay energy of ^{42}Sc .

If the conserved vector-current hypothesis is valid and the electromagnetic corrections are made properly, the ft values of superallowed $0^+ \rightarrow 0^+$ β -decays should all be the same. The ft values for the superallowed ^{42}Sc and ^{14}O decays were found to be equal to better than 13 ± 18 parts in 10^4 , in agreement with the expectations.

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1. Abstract of published paper: Nucl. Phys. A496, 429 (1989).
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HEAVY-ION REACTION MECHANISM STUDIES, FUSION AND FISSION

INVESTIGATION OF THERMAL AND ANGULAR MOMENTUM EFFECTS IN THE GIANT DIPOLE RESONANCE DECAY OF HOT RARE EARTH NUCLEI¹

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Recoil- γ coincidences have been measured in the reaction $^{160}\text{Gd} + ^{159}\text{Tb}$ at beam energies of 300 and 400 MeV. In the γ -ray spectra corresponding to excitation energies above 140 MeV a split giant dipole resonance is observed with widths substantially smaller than at somewhat lower excitation energy, and comparable to those found for the giant resonance built on the ground state. The possible influence of excitation energy and angular momentum on this effect are discussed. The intensity ratio of the two dipole resonance components is found to change with excitation energy, indicating a transition of the nuclear shape from prolate towards oblate.

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HARD PHOTON SPECTROSCOPY WITH NEARLY COMPLETE EVENT CHARACTERIZATION

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High energy photons, unlike hadronic probes, emerge from the collision zone in a heavy-ion reaction almost completely undisturbed by interactions with surrounding nuclear matter. Therefore these photons ($E_\gamma > 20$ MeV) are potentially an extremely useful tool for probing reaction mechanisms of intermediate-energy heavy ions.

A substantial effort, both experimental and theoretical, has gone into the study of high-energy photon production over the past few years. An excellent review of the experimental data was provided recently by Metag.³ Several models have been proposed to explain the data, but the incoherent nucleon-nucleon bremsstrahlung picture is currently the most widely accepted. In this model, high-energy photons arise from first proton-neutron collisions in the initial phase of the reaction. Calculations employing this basic picture explain qualitatively — and in many cases quantitatively — a large body of data. Unfortunately the data, with very few exceptions, are inclusive, or nearly inclusive, measurements which do not offer unambiguous verification of the model. Furthermore, while many features of the available body of inclusive data are consistent with the incoherent first collision picture, there is evidence for a different mechanism: thermal (i.e., multiple collision) effects playing a role in low-energy, heavy-ion collisions⁴ and even preliminary reports of coherent effects seen with 175-MeV α particles⁵ on heavy targets.

A disturbing feature of the data reviewed in Ref. 3 is the scarcity of data on nucleon-nucleus collisions below 100-MeV bombarding energies. The only reliable data available is for 72-MeV protons, and it has the remarkable

property of lying precisely on the heavy ion systematics.

In July 1989 we initiated a series of experiments in which high-energy photons are studied together with as complete as possible characterization of the reaction. The initial experiments were done at HHIRF using an asymmetric system $^{160}\text{O} + ^{100}\text{Mo}$ at 25 MeV/nucleon. One reason for beginning with this reaction was the rather extensive body of data on breakup-fusion (incomplete fusion) with ^{16}O induced reactions, and the possibility of identifying particular incomplete fusion channels with relatively well-defined impact parameter ranges, and hence mapping photon yield as a function of impact parameter. Events were characterized experimentally by determination of the recoil velocity of heavy residues, the multiplicity and energy of evaporated light-charged particles, neutrons and low-energy γ rays. In addition, essentially all nonequilibrium p , d , t and α were detected and identified for emission angles $\theta > 10^\circ$. Projectilelike fragments were detected and Z -identified for angles $\theta \sim 4^\circ$ to 35° . These data will enable us to characterize events in terms of impact parameter by determination of linear momentum transfer (from heavy-recoil time of flight) and by identification of specific incomplete fusion channels. Further, it will be possible to make independent estimates of the total energy and angular momentum deposited in the residues from evaporated particle and γ -ray multiplicities and energies. We also hope to investigate correlations between high-energy photon emission and forward-nucleon emission with this data.

The experimental setup which made possible so detailed an investigation of low probability events was based on two concentric, almost 4π , devices surrounding the target; the Spin Spectrometer (SS) and the Dwarf Ball/Wall. The SS was used for detection of γ rays and neutrons, with the forward ring of NaI elements ($\theta < 35^\circ$) removed and replaced by a conical scattering chamber to make room for charged particle detectors. Neutrons and gamma rays were identified and separated by time of flight. The

relatively poor timing (~ 2 ns) and short flight path to the SS detectors limit the effectiveness of this separation to neutron energies below ~ 7 MeV and means that the NaI detectors in the forward hemisphere are not useful for high energy γ -ray detection. Three packs of nineteen 6.5×20 cm BaF_2 scintillators of the ORNL BaF_2 array were used as the principal tool for high energy γ -ray detection. They were positioned at angles $\theta = 23^\circ$, 63° , and 116° , facing the target through gaps in the SS made by removing individual NaI elements. This experiment was the first large scale use of our new BaF_2 array.

Light charged particles were detected in the Dwarf Ball/Wall (DB/W) which consists of 104 plastic-CsI phoswich detectors covering the angular range $\theta = 4^\circ$ to 165° . The most forward segments of the DB/W were removed on one side to allow a 6×9 cm x-y position-sensitive Breskin detector to view the target and detect heavy recoils after a flight path of 40 cm.

This experiment, which generated a data stream with a total of almost 1000 distinct parameters, and required three separate (but coordinated) CAMAC readout processors, stressed the existing HHIRF data acquisition capabilities nearly to its limits. The data also presents a prodigious data-reduction task. We have completed preliminary processing and calibration of data from the individual subsystems (SS, BaF_2 , DB/W). We hope to implement the next processing step on a prototype data-reduction station based on a RISC/UNIX workstation, as part of the development of the next stage of the HHIRF data-reduction system.

This experiment is the first of a series that we plan to carry out at HHIRF and other facilities in a study of high-energy photon emission in relatively low energy heavy-ion reactions (up to ~ 50 MeV/nucleon). We also intend to acquire data with proton and α beams to add to the body of data needed as input to theoretical calculations.

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ANGULAR MOMENTUM EFFECTS IN SUBBARRIER FUSION OF $^{64}\text{Ni} + ^{100}\text{Mo}$

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Angular-momentum distributions σ_L for the compound nucleus ^{164}Yb were deduced from measurements of γ -ray multiplicity for all significant evaporation residues from fusion of ^{64}Ni and ^{100}Mo . At the lowest bombarding energies the σ_L extend to higher L values than do predictions of barrier-penetration models that include coupling of the principal inelastic channels, even if the coupling strengths are increased to match the experimental excitation function. Likewise, σ_L from a real potential with an energy-dependent shape fitted to the excitation function fails to reproduce the experimental σ_L distribution. Better success is achieved with models in which fusion occurs at large distances.

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CONTINUUM γ -RAY SPECTRA IN NEAR-BARRIER FUSION REACTIONS

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Many interesting effects have been uncovered in the study of heavy-ion fusion reactions near and below the Coulomb barrier. One of the most surprising results concerns the decay of fused systems formed at the same excitation energy

and spin with entrance channels having different mass asymmetries. Experiments at Argonne and Heidelberg^{3,4} have been interpreted as demonstrating that $^{156}\text{Er}(E^* = 47 \text{ MeV})$, emits, on the average, more neutrons when formed in the $^{12}\text{C} + ^{144}\text{Sm}$ reaction than when formed in the $^{64}\text{Ni} + ^{92}\text{Zr}$ reaction. An almost identical result has been reported by the same group for $^{160}\text{Er}(E^* = 53 \text{ MeV})$ formed in ^{16}O - and ^{64}Ni -induced reactions. A similar experiment with ^{164}Yb as a compound nucleus performed with the Spin Spectrometer, however, showed no significant entrance-channel-dependent effect.⁵

One possible explanation is related to reaction dynamic effects. The symmetric reaction channel results in fusion near the Coulomb barrier, so that the relative radial velocity of the reactants is almost zero as they pass over (or through) the barrier. For relatively large partial waves (30 $\hbar$), this could lead to dinuclear (quasi-molecular) configurations, which might evolve into the mononuclear compound system over a time scale comparable to the neutron emission lifetime. However, this explanation should not depend strongly on the nuclear structure of the final compound system; thus it seems to be contradicted by the ^{164}Yb result.

As this effect takes place during the early stages of the compound system decay, high-energy γ rays from the decay of the giant dipole resonance (GDR) built onto highly excited states provide a good probe to study this effect. The γ rays are emitted during the earliest steps of the decay cascade and their energy and angular distributions can be sensitive to the shape of the nuclear system in which the giant dipole vibration occurs. Calculations with the statistical model code CASCADE for ^{160}Er at $E^* = 53 \text{ MeV}$, assuming normal deformation ($\beta = 0.3$, solid line) and a large deformation ($\beta = 0.65$, dashed line) are shown in Fig. 2.40. The latter deformation is used to characterize the dumbbell-shaped quasi-molecule in the more symmetric entrance channel. The difference in the spectra results from the large splitting of the GDR strength in the quasimolecular system. The

Fig. 2.40. The calculated high-energy γ -ray spectra for the decay of ^{160}Er at $E^* = 53$ MeV for a normal deformation (solid) and for a quasi-molecular shape (dashed).

values for the GDR energies and widths are given in the figure.

With a direct comparison of the two high-energy γ -ray spectra from the same compound nucleus formed with the two different entrance channels, we should be able to distinguish a possible quasi-molecular configuration from the normal deformed compound system. We therefore performed one experiment populating ^{160}Er at $E^* = 53$ MeV with the reactions $^{160}\text{Nd} + ^{144}\text{Sm}$ and $^{64}\text{Ni} + ^{96}\text{Zr}$ and in another one we formed the compound nucleus ^{164}Yb at $E^* = 49$ MeV with $^{160}\text{Gd} + ^{148}\text{Sm}$ and $^{64}\text{Ni} + ^{100}\text{Mo}$.

The experiments were performed in the Spin Spectrometer and the high-energy γ rays were measured with the new BaF_2 detector array. The array consists of four 19 packs of detectors positioned at 21° , 63° (two packs), and 117° . In addition, five NaI crystals of the Spin Spectrometer were replaced by small BaF_2 crystals mounted in "anticompton" shields. Two NaI crystals were removed to insert Ge detectors in order to measure the final cross-section distribution. The total coverage with γ -ray detectors was large enough to determine

the entrance channel angular momentum distribution.

The experiment was successful and sufficient statistics were collected for all measured systems. The data are presently under analysis.

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SPIN ALIGNMENT AND DENSITY MATRIX MEASUREMENT IN $^{28}\text{Si}+^{12}\text{C}$ ORBITING REACTION¹

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Gamma-ray angular correlations have been measured using the ORNL Spin Spectrometer for the strongly damped reactions $^{12}\text{C}(^{28}\text{Si}, ^{12}\text{C})^{28}\text{Si}$ between $\theta_{\text{cm}} = 120^\circ$ and $\theta_{\text{cm}} = 160^\circ$ for $E_{\text{cm}} = 43.5$ and 48 MeV. Density matrices for the $^{12}\text{C}(2^+)$ and $^{28}\text{Si}(2^+)$ states have been deduced from the observed angular distribution of 4.44-MeV and 1.78-MeV γ rays emitted from the de-excitation of $^{12}\text{C}(2^+)$ and $^{28}\text{Si}(2^+)$ states, respectively. We find that the density matrices are symmetric with respect to the direction of motion of the particle rather than normal to the reaction plane and, as a result, spin alignments with respect to the normal to the reaction plane are much smaller than those expected from statistical compound nucleus or sticking model calculations. The measured density matrices and spin alignments are consistent with the picture of formation of a long-lived dinuclear complex undergoing orbiting and bending motions.

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HAUSER-FESHBACH CALCULATIONS FOR THE EMISSION OF COMPLEX FRAGMENTS IN FUSION REACTIONS

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ORNL-DWG 39-18470

Traditionally, the Hauser-Feshbach formula has been used to compute the decay of compound nuclei formed in complete fusion reactions when most of the energy is released in the form of light particles, essentially n, p or α 's.^{3,4} However, it also has been known for some time that other than $Z = 1$ or $Z = 2$ nuclei are emitted in statistical fashion, in agreement with Hauser-Feshbach predictions. The situation for emission of complex nuclei of $Z > 2$ is not well-studied. Motivated by the measurements of Ref. 5, a series of studies of complex fragments has been initiated in many laboratories. Recently, we have developed a large Hauser-Feshbach code BUSCO^{6,7} that is able to predict total cross sections, angular distributions, and energy spectra of emitted fragments with Z as large as Ca. Results of these calculations have been given for the $^3\text{He} + ^{109}\text{Ag}$ (ref. 6), $^{12}\text{C} + ^{109}\text{Ag}$ (ref. 6), and $^{58}\text{Ni} + ^{58}\text{Ni}$ (ref. 7) systems up to emitted fragments of $Z = 14$, for which experimental measurements exist. The dependence in excitation energy, however, was not studied. In this report we show results on the energy dependence for the $^3\text{He} + ^{109}\text{Ag}$ system in the energy regime that has been measured up to now.^{5,8} Details on the statistical model parameters and optical model transition coefficients have been given previously.^{6,7}

Figure 2.41 shows the comparisons between the experimental data (symbols) of Refs. 5,8 and the Hauser-Feshbach calculations (lines); Fig. 2.41a shows the comparisons for emitted fragments of even Z , and Fig. 2.41b for those of odd Z . The value of the critical angular momentum used in the calculations varied from 16 $\hbar$ for the lowest energy to 19 $\hbar$ for the highest energy. The highest-energy point corresponds to the measurements of the Indiana group⁸ and only the part corresponding to equilibrium emission has been included. As can be seen from Fig. 2.41, the agreement is excellent and shows that these calculations offer an alternative way

Fig. 2.41. Comparisons between the experimental cross sections (symbols) of Refs. 5 and 8 and Hauser-Feshbach calculations (lines). Fig. 1a shows the comparisons for even- Z fragments and Fig. 1b shows those for odd- Z .

to interpret data on complex fragment emission. Another successful model used to analyze these data is the asymmetric fission model of Moretto,⁹ which conceptually differs from the Hauser-Feshbach formula in the sense that the decay probability depends on the density of levels at the saddle point rather than on the level densities of the fragments at infinite separation. Clearly, this conceptual difference is irrelevant for nucleon decay since the level density at the saddle point is identical to the level density of the residual nuclei. However, for heavier fragments this difference may be more important and will certainly be most important for the case of symmetric fission, for which the Hauser-Feshbach description is probably not valid. Nevertheless, for the case shown in Fig. 2.41, and up to $Z = 10$, the

Hauser-Feshbach description gives results that are as good as those of the asymmetric fission model. Good agreements have also been found for other heavy-ion combinations like $^{58}\text{Ni} + ^{58}\text{Ni}$ using values of critical angular momenta that are consistent with fusion systematics. For cases such as $^{58}\text{Ni} + ^{58}\text{Ni}$, it will be interesting to study the emission of fragments close to symmetry splitting, for which important differences between the Hauser-Feshbach description and the fission model may be seen.

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**POPULATIONS OF EXCITED STATES OF COMPLEX
FRAGMENTS EMITTED IN $^{58}\text{Ni} + ^{58}\text{Ni}$ COLLISIONS
AT 11 MeV/NUCLEON**

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Complex fragments of $Z = 4-20$ were measured for collisions of ^{58}Ni on ^{58}Ni at a bombarding energy of 630 MeV. The fragments were measured with five solid-state surface barrier counter telescopes, placed inside the 30-cm scattering chamber of the ORNL Spin Spectrometer; and coincident γ -rays were detected with 62 NaI detectors and 8 hyperpure Ge detectors equipped with BGO Compton-suppression shields. The data acquired were γ and neutron multiplicities, populations of excited states of the ejectiles, and differential cross sections for the emitted fragments. Results for fragment cross sections and populations of excited states using the NaI detectors have been published.³ In this report

we present data taken with the Ge detectors relevant to the population of excited states.

One of the important observations given in Ref. 3 is that the measurements of angular distributions, energy spectra, and populations of excited states for ejectiles of $Z < 10$ are consistent with emissions from the compound nucleus formed in a complete fusion reaction. Fragments of $Z > 9$ have mixed sources. Figure 2.42 shows the angle-integrated cross sections for fragments up to $Z = 20$. The hatched histograms, are the results of Hauser-Feshbach calculations, which assume complete fusion and equilibrium decay. As can be seen from the

Fig. 2.42. Angle-integrated cross sections for fragments up to $Z = 20$. The calculations (hatched histograms) correspond only to the complete-fusion reactions.

figure, the calculations agree very well with the data up to $Z = 9$. At higher Z -values the experimental cross sections are much larger than predicted. Further insight into this discrepancy can be gained by studying the population of the excited states of these nuclei. In Fig. 2.43, we show several angular distributions ($d\sigma/d\Omega$) for ground states, as well as excited states of carbon (a) and of sodium (b) nuclei. These cross sections were extracted by measuring the γ rays of the excited states using the Ge detectors and by identifying the masses of the various isotopes with the solid-state-counter telescopes. Fig. 2.43a shows the cross sections for ground and excited states of ^{12}C and ^{13}C and, as can be seen, the angular distributions are isotropic as expected for a complete fusion and equilibrium decay process. However, the angular distribution for the ground state of

^{23}Na is not isotropic (see Fig. 2.43b) and an anisotropy of about a factor of two is observed. A smaller anisotropy is seen for the 0.44-MeV transition of ^{23}Na , and the population of the 2.1-MeV state is isotropic. These changes observed for ^{23}Na are very interesting and they have not been reported. The measurement of populations of excited states clearly indicates that different sources contribute to the emission of ^{23}Na nuclei in this reaction. The ground state transition corresponds mostly to a direct emission process, like projectile splitting in a deep-inelastic scattering process.⁹

Using simple statistical analysis,³ effective temperatures can be extracted from the measured cross sections of excited states. In Fig. 2.44, we show the effective temperature for ejectiles ranging from ^7Be to ^{24}Mg . The solid circles are the experimental values and the open ones correspond to theoretical predictions. These calculations contain two components: (1) the usual complete-fusion component, and (2) a deep inelastic-like component introduced to simulate the emission of nuclei with $Z > 9$. For the complete-fusion case, the initial temperature is 4 MeV and the effective experimental and calculated temperatures for nuclei with $Z < 9$ are both about 2 MeV. These differences in temperatures are due to the sequential emission

Fig. 2.43. Angular distributions ($d\sigma/d\Omega$) for ground and excited states of carbon (a) and of sodium (b) isotopes.

Fig. 2.44. Effective temperatures (T_{eff}) extracted from measurements of cross sections of excited states. The various nuclei studied are indicated in the figure. The Hauser-Feshbach calculations are given by the solid points.

process as indicated in Ref. 3. For nuclei with $Z > 9$ all the extracted temperatures are rather small, indicating that the primary reactions producing these fragments do not produce sources of high temperature and, although the calculations (closed circles) do reproduce the correct trend of the data, they are too high by about a factor of two. Clearly, further studies of complex fragments with large- Z values need to be carried out.

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LIQUID-DROP EFFECTS IN SUBBARRIER TRANSFER REACTIONS¹

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A threshold behavior is observed in back-angle yields of multinucleon transfer products in quasielastic reactions between ^{50}Ti and ^{93}Nb at near barrier energies. A variety of nuclidic species that require transfers of up to five nucleons are observed to emerge suddenly as the threshold is crossed. The internuclear separation distance where the multinucleon transfer products first emerge coincides with the closest approach distance of the experimentally established fusion threshold energy, indicating a common origin for the fusion enhancement and multinucleon transfer reactions.

1. Abstract of paper to be submitted to Physical Review.
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FUSION OF $^{58}\text{Ni} + ^{24}\text{Mg}$ AT 10.9 MeV/NUCLEON

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Evaporation residues, fission fragments, and coincident light- and intermediate-mass charged particles have been measured inclusively and in coincidence for reactions of 630-MeV ^{58}Ni incident on a ^{24}Mg target. The reaction products were measured in the HILL (Heavy Ion Light Ion) detector system which covers the forward cone from 2.5° to 20° . By adding the new (BC400 fast plastic scintillator/CsI (Tl)) ring detector⁶ to the HILL detector system the angular coverage was extended to 27° .

The position signals from the gas detector were calibrated with particles that penetrated the hodoscope array. The edges of the 192 discrete scintillator counters served as fiducials for the calibration. The energy spectra obtained in the ionization chamber were calibrated by means of elastic scattering.

As a first step, we analyzed the inclusive heavy-fragment data, focusing our attention on the evaporation residues in the ionization chamber. In Fig. 2.45 showing energy spectra of products with $Z = 29$ to $Z = 32$ at 5.5° , one sees a significant discrepancy in the centroids and in the asymmetry of the spectra between the data and the LILITA⁷ prediction for the complete-fusion evaporation process. This suggests that incomplete fusion took place. Fig. 2.46 shows combined energy spectra for $Z = 30$ at 5.5° . The centroid of the LILITA calculation matched the experimental data after a 60% complete fusion component was combined with 40% incomplete fusion. This amount of incomplete fusion is consistent with the systematics suggested by H. Mogenstern et al.⁸

Analysis of light-particle heavy-fragment coincidence data is now in process.

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Fig. 2.45. Energy spectra of products with $Z = 29$ to $Z = 32$ at $\theta = 5.5^\circ$. The solid lines are experimental data. The open circles are LILITA calculations for complete fusion multiplied by a factor of 0.6.

ENERGY SPECTRA FOR $Z=30$ AT $\theta=5.5$

Fig. 2.46. Combined energy spectra for $Z = 30$ at $\theta = 5.5^\circ$. The open circles are the LILITA calculations for complete fusion with a factor of 0.6, the open squares are the LILITA calculations for incomplete fusion with a factor of 0.4, and the open triangles are the sum of the two components.

6. Accompanying contribution to this annual report.

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8. Phys. Rev. Lett. 52, 13 (1984).

FUSION CROSS SECTIONS FOR $^{46,50}\text{Ti} + ^{90}\text{Zr}$, ^{93}Nb AND SOME SYSTEMATICS OF HEAVY-ION FUSION AT BARRIER AND SUBBARRIER ENERGIES¹

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Measurements of the fusion cross sections in the barrier and subbarrier regions are presented for the four heavy-ion systems $^{46,50}\text{Ti} + ^{90}\text{Zr}$, ^{93}Nb . The measured cross sections varied from 0.04 to 400 mb. The evaporation residues were detected by the use of a velocity filter. Procedures are described for extracting fusion cross sections from such measurements. The observed differences in the subbarrier fusion cross sections for the ^{90}Zr and ^{93}Nb nuclei, both of which have small collectivity, have led us to question the view that excursions of the strong nuclear force due to collective motions of the colliding nuclei are the primary enhancement mechanisms for the observed heavy-ion subbarrier fusion cross sections. A simple formula is presented, based on a flat distribution of barriers, which is applied to the near-barrier region (10 to 200 mb). This formula states that the quantity $\sqrt{\sigma E}$ vs E is linear in the near-barrier region with a zero intercept defining a threshold energy for fusion. These threshold values reflect variations in the binding energies of the valence neutrons. We also point out that the far-subbarrier region (<10 mb) shows large variations in fusion cross sections and that these variations reflect differences in the collectivities of the colliding nuclei (especially noticeable differences are seen between permanently deformed nuclei and "vibrational" nuclei). These systematics of heavy-ion subbarrier fusion suggest that neck formation is playing an important role. The barrier for neutron transfer vanishes at distances typically 1.5 fm beyond the typical barrier distance and this distance could vary with the binding energy

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of the valence neutrons. The presence of neutrons in the region between the nuclei could promote neck formation, which provides a force strong enough to overcome the Coulomb force. The collective properties of the colliding nuclei are then interpreted as a modulation of the threshold for neck formation and thereby reflect the large observed differences in the far-subbarrier cross sections. Formulas are presented for σ_L , which result from a flat distribution of barriers. These formulas predict a broad bell-shaped spin distribution and are compared to the measured distribution in the subbarrier region for the system $^{64}\text{Ni} + ^{100}\text{Mo}$.

1. Abstract of paper submitted for publication in Physical Review C.

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RELAXATION OF ANGULAR MOMENTUM IN FISSION AND QUASIFISSION REACTIONS¹

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Binary reaction products from reactions of a ^{238}U beam at energies 5.4, 5.9, 6.7, and 7.5 MeV/nucleon with targets of ^{16}O , ^{26}Mg , ^{27}Al , ^{32}S , ^{35}Cl , ^{40}Ca , ^{48}Ca , and natZn have been measured with a kinematic coincidence method at GSI. The gamma-ray multiplicities were measured with NaI detectors and are presented as a function of the fragment mass. The results indicate that all aligned and statistically excited spin modes of the fragments are fully populated in compound-nucleus fission reactions. In quasi-fission reactions the relaxation process seems to terminate before full statistical spin equilibrium is reached. The results were analyzed and are discussed in terms of different relaxation mechanisms with different characteristic relaxation times. The influence of various terminal freeze-out shapes was also investigated.

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EMISSION OF LIGHT IONS, NEUTRONS, PIONS, AND PHOTONS IN HEAVY-ION REACTIONS

TWO-PARTICLE CORRELATIONS FROM HEAVY-ION COLLISIONS

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Light particles have been measured in coincidence with heavy fragments resulting from collisions of ^{58}Ni with ^{58}Ni and with ^{12}C nuclei at 850 MeV incident energy. The data were taken at RHIRF using the HILI detection system. The Z-separation, energy, and vertical position of the heavy fragments were obtained from a position-sensitive ionization chamber. Light charged particles were measured using an array of 96 ΔE -E phoswich scintillator detectors.

The influence of the geometry of the experimental setup on the light-particle correlation function can be seen in Fig. 2.47 where two-proton and two-alpha correlation functions for two different geometric cuts are shown. The two-proton correlation function from the $^{58}\text{Ni} + ^{12}\text{C}$ reaction seems to be dominated by lifetime effects and long-range Coulomb interaction between light particles and the emitting source.⁵ For comparison, theoretical calculations⁶ for the "source dimension" $R_x = R_y = 3.4$ fm and $R_z = 30$ fm are also shown. The two-proton correlation function for $^{58}\text{Ni} + ^{58}\text{Ni}$ reaction shows stronger correlation when all particles are detected on the same side with respect to the beam axis. At present, it is not quite clear whether this is a true effect or just a consequence of different contributions to the correlation function from an ensemble average.⁷ (The data shown include contributions over the whole range of light particle and heavy

Fig. 2.47. Two different experimental setups for light-heavy ion coincidence measurement (top). Thin solid lines depict light particles and thick lines are used for heavy fragments. Symbols used in the bottom part correspond to the geometry shown in the top part.

fragment energies.) In particular, that may be the reason why the two-proton correlation function for $^{58}\text{Ni} + ^{58}\text{Ni}$ reaction increases for very small relative momenta.

The two-alpha correlation function is, within experimental errors, quite independent of the reaction and of detection geometry. It can be easily explained as resulting from the decay of ground state of ^8Be and of excited states of ^9Be (Ref. 8).

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5. P. A. DeYoung, et al., Phys. Rev. C 39, 128, (1989).
6. T. S. Awes, et al., Phys. Rev. Lett. 61, 2665 (1988).

7. M. Gyulassy, Phys. Rev. Lett. 48, 454 (1982).

8. J. Pochodzalla, et al; Phys. Rev. C 35, 1695 (1987); Phys. Lett. 161B, 275 (1985).

CORRELATIONS BETWEEN LIGHT PARTICLES AND EVAPORATION RESIDUES FOR THE $^{79}\text{Br} + ^{27}\text{Al}$ REACTION AT $E(^{79}\text{Br}) = 930$ MeV

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Evaporation residues (ER), intermediate mass fragments (IMF) of $Z > 2$, and $Z = 1$ and $Z = 2$ particles have been measured for the $^{79}\text{Br} + ^{27}\text{Al}$ reaction at $E(^{79}\text{Br}) = 930$ MeV. Measurements were made with the large detector array, HILI, capable of registering coincidences between the light particles and the ER's or the IMF's. Coincident events between the IMF, the heavier partners of the IMF, and the light particles have also been measured and will help in the determination of the primary energy partition in the IMF-emission process. The present report is concentrates on the correlation between the light particles and the ER's.

Figure 2.48 shows energy spectra (open circles) of fragments of $Z = 38$ integrated over all angles covered by the detector (about 2.8° to 20°). These data were obtained with the ionization chamber of the HILI detector. Figure 2.48a shows coincidence data corresponding to events determined by any hodoscope element firing in coincidence with the ionization chamber, which indicates mostly coincidences between $Z = 38$ and any light particle (primarily n, p, or α). Due to the very large particle multiplicities (for $Z = 38$, ten charges are already missing from the total compound nucleus charge), the spectrum of Fig. 2.48a is essentially identical to a singles spectrum. Figure 2.48 shows the fragment spectrum with the additional requirement that only one α is present in the hodoscope and spectrum, Fig. 2.48c with the requirement that only two α 's are present. As can be seen from the figure, the spectrum changes as a function of the coincidence requirement.

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Fig. 2.48. Energy spectra of $Z = 38$ fragments from the $^{79}\text{Br} + ^{27}\text{Al}$ at 12 MeV/A. Fig. 2.48a gives the spectrum in coincidence with any light particle. Fig. 2.48b depicts the spectrum in coincidence with 1a, and Fig. 2.48c shows the spectrum in coincidence with 2a.

To describe the data in Fig. 2.48, it is necessary to include the physical limitations of the detector. We have used the code LILITA to simulate the energy spectra of the ER, incorporating the geometrical constraints imposed by HILI. The calculations are of Monte Carlo

Hauser-Feshbach type, except that they are performed in an event-by-event mode, and processed with a second code, which takes the HILI geometry into account. Constraints due to energy threshold are also included (8 MeV for p's and 20 MeV for α 's).

Results of these calculations are shown in Fig. 2.48 by solid circles. The calculations correspond to the complete-fusion reaction of $^{79}\text{Br} + ^{27}\text{Al}$ using a critical angular momentum of 65 $\hbar$, consistent with current systematics. From the comparisons shown in Fig. 2.48a, it is evident that the predicted spectrum (solid points) falls off more rapidly than the data at the higher energies, which is a clear indication of the presence of incomplete-fusion reactions. It is particularly interesting, however, to see the evolution of the spectrum with higher-fold coincidences (Fig. 2.48b and c). For the case of 1a-fold (Fig. 2.48b), the agreement between the complete-fusion calculation and the data is good, and it is nearly perfect for the case of the 2a-fold coincidences (Fig. 2.48c). These comparisons show a unique way in which the ER components can be isolated in cases where there is strong competition with incomplete-fusion reactions. Furthermore, the changes seen in Fig. 2.48 can be understood qualitatively, since the incomplete-fusion reactions produce lower α multiplicities and, consequently, much lower coincidence probabilities.

The data set obtained with the HILI systems is so large and varied that it is desirable to focus on smaller subsets. In the case of light-particle correlations with the ER's, which includes in- and out-of-plane correlations, as well as energy spectra, nucleon multiplicities, and nucleon correlations, it is instructive to look for global quantities which may reveal interesting and unexpected effects. One such effect is shown in Fig. 2.49 for the total p-to- α ratio (p/α) obtained in coincidence with a fragment of given Z characteristic of ER ($Z > 33$). Two kinds of triggers were applied in this study of p/α . Fig. 2.49a shows the ratio obtained for the case of 1a-fold coincidences and Fig. 2.49b shows the ratio corresponding to

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Fig. 2.49. Ratio of p/a measured by the HILL detector as a function of the Z of the residual fragment. Fig. 2.49a shows the ratio corresponding to 1a-fold coincidences. Fig. 2.49b gives the ratio corresponding to 2a-fold coincidences. The calculations (curves) are explained in the text.

2a-fold coincidences. Because 1a-fold coincidences may contain large amounts of incomplete fusion, the 2a-fold curve should be more appropriate in analyzing the p/a ratio in terms of complete fusion. The various calculations shown in Fig. 2.49b are attempts to explain the measured ratios. The first feature to be noted in Fig. 2.49 is the difference in slope between the 1a- and 2a-fold data (Fig. 2.49a vs 2b). This difference clearly indicates, once again, the contributions of incomplete fusion, and for $Z < 35$, contributions of peripheral processes, since both types of processes will produce more coincident p's than a's. Furthermore, the calculation labeled CF (complete fusion) performed for 65 $\hbar$ shows a slope that is in

agreement with the 2a case and not with the 1a case.

Concerning the absolute values of the p/a ratios (see Fig. 2.49b), it is necessary to point out that the CF calculations with 65 $\hbar$ or 75 $\hbar$ fail to reproduce the experimental values. The calculation labeled IF (incomplete fusion) also cannot account for the data. We feel that other effects must be present that may explain the observed p/a ratios. One possibility is the effect of the temperature-dependence on the level-density parameter a . It has been pointed out in a recent paper⁵ that the level-density parameter decreases with increasing temperature. For our present compound nucleus of mass 106, using the equation of Ref. 5 we have estimated about a 30% reduction in the level-density parameter a from 4.4 MeV (for initial compound nucleus temperature) to 1 MeV. The calculation labeled $a(T)$ in Fig. 2.49b is the result of this variation, and was performed for a maximum angular momentum of 65 $\hbar$. As can be seen, it yields a much better account of the observed p/a ratio than any of the other calculations shown in the figure. Other effects, such as deformation at high excitation energies, have to be explored before drawing conclusions about the $a(T)$ -dependence, but it is clear that a traditional CF calculation alone cannot account for the observed p/a data.

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5. W. E. Ormand et al. Phys. Rev. C 40, 1510 (1989).

EXTENDED EMISSION SOURCES OBSERVED VIA TWO-PROTON CORRELATIONS¹

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	H. M. Xu ³

Two-proton correlations were measured as a function of the total energy and relative momentum of the protons. The correlation is analyzed

for different orientations of the relative momentum, which allows information on the size and lifetime of the emission source to be extracted. The most energetic particles are emitted from a short-lived source of compound nucleus dimensions while the lower energy protons appear to be emitted from a source considerably larger than the compound nucleus.

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NEUTRON EMISSION FROM PRODUCTS OF STRONGLY DAMPED REACTIONS $^{58}\text{Ni} + ^{165}\text{Ho}$ AT 930 MeV¹

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Neutron time-of-flight spectra have been measured for emission from products of reactions between ^{58}Ni and ^{165}Ho at a bombarding energy of 930 MeV. Neutrons were detected in coincidence with projectilelike fragments from strongly damped reactions using a heavy-ion ΔE -E telescope which permitted the total kinetic energy loss to be extracted for each event. The neutron spectra were separated into 25-MeV-wide total kinetic energy loss bins over the total kinetic energy loss range from 0 to 450. Moving source fits were made to the neutron spectra to determine emission temperatures, multiplicities, velocities, and angles for the projectilelike fragment, targetlike fragment, and nonequilibrium emission sources as a function of the total kinetic energy loss. The extracted temperature of the projectilelike fragment is found to be larger than that of the targetlike fragment source at all total kinetic energy losses, approaching that of the targetlike fragment only at the largest total kinetic energy losses. The results suggest an equal division of the available excitation energy at small total kinetic

energy loss with a thermal energy division occurring only at the largest total kinetic energy losses. The velocity of the nonequilibrium source is found to remain constant at approximately one-half of the beam velocity, independent of the final projectilelike fragment velocity. This result supports models of non-equilibrium emission in which nucleon emission is isotropic in the nucleon-nucleon center-of-mass system, as opposed to models in which the nonequilibrium emission occurs isotropically from the heavy fragments along their reaction trajectories.

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NUCLEAR PHYSICS WITH ULTRARELATIVISTIC PROJECTILES

MEASUREMENTS OF SOFT PHOTONS EMITTED IN RELATIVISTIC PROTON-NUCLEUS COLLISIONS¹

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A proposal to make a systematic study of low-energy photon production in proton nucleus collisions has been prepared and submitted to the AGS PAC. The proposal has been approved for six weeks of running, and beam time is scheduled for March 1990. This study will measure photon production down to very low P_t (~few MeV/c) and look for new sources of "soft" photons in excess of those produced by nuclear decays and hadronic bremsstrahlung. We plan to use two arrays of barium fluoride crystals to measure low energy photons with excellent energy resolution and good timing resolution to suppress neutral background. We will use the beam line of experiment E814 as the host for this experiment. If successful, these measurements will be

extended to study soft photon production in heavy ion collisions.

1. Approved AGS experiment # E855.
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**TRANSVERSE MOMENTUM DISTRIBUTIONS
OF NEUTRAL PIONS
FROM CENTRAL AND PERIPHERAL $^{16}\text{O} + \text{Au}$ COLLISIONS
AT 200 A GeV¹**

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G. Clewing ³	S. Persson ⁵
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R. Glasow ³	R. Santo ³
H. A. Gustafsson ⁵	H. R. Schmidt ²
H. H. Gutbrod ²	T. Siemiarczuk ²
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B. W. Kolb ²	E. Stenlund ⁵
P. Kristiansson ⁵	G. R. Young

The production of neutral pions by the interaction of 200 A GeV protons and ^{16}O projectiles with an Au target has been studied in the pseudorapidity range $1.5 < \eta < 2.1$. Transverse momentum spectra have been measured between 0.4 and 2.8 GeV/c, and their dependence on the centrality of the collision has been investigated. The data show a high degree of similarity to $p + p$ and $\alpha + \alpha$ data from the ISR. The peripheral-collision spectra display a marked change of slope with a hard component starting at about 1.8 GeV/c, in contrast to central-collision data.

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**TRANSVERSE ENERGY PRODUCTION
IN THE TARGET FRAGMENTATION REGION
IN ^{16}O -NUCLEUS REACTIONS AT 60 AND 200 A GeV¹**

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Charged pion yields and transverse energies of baryons are measured for the reaction $^{16}\text{O} + \text{Cu, Ag, Au}$ at 60- and 200-A-GeV bombarding energy in the target fragmentation region employing the Plastic Ball detector. Only little dependence of the measured quantities on the bombarding energy is found. The data are compared with the Multi-Chain Fragmentation Model of Ranft. As a result, it turns out that a leading order formation zone cascade is not sufficient to explain the baryon yield and the transverse energies of baryons in the target fragmentation region.

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GLOBAL AND LOCAL FLUCTUATIONS IN MULTIPLICITY AND TRANSVERSE ENERGY FOR CENTRAL ULTRARELATIVISTIC HEAVY-ION INTERACTIONS¹

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G. R. Young	

We present results from a comparison between experimental data and model calculations, in this case represented by the FRITIOF model, regarding global and local fluctuations in the distributions of transverse energy and charged-particle multiplicity. The results indicate that the observed fluctuations originate predominantly from the distribution of sources, i.e., either the number of participating nucleons or the number of binary collisions. The apparently larger widths of the distributions observed in restricted regions of phase space are explained to be of purely statistical nature. As a result of the analysis, the cross section for events with energy densities much larger than the typical value for a central collision is limited. The results of the analysis are essentially independent of whether or not intermittency is of importance in the reactions. The very small scales, normally associated with studies of intermittent behavior, are not within the scope of this paper.

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A NEURAL-NETWORK APPROACH TO THE PROBLEM OF PHOTON-PAIR COMBINATORICS¹

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A neural-network approach is applied to the problem of correctly pairing photons from π^0 , n , and higher resonance decays in the presence of a large background of photons resulting from many simultaneous decays. The method uses the full information of the multiphoton final state to suppress the selection of false photon pairs which arise from the many combinatorial possibilities. The method is demonstrated for simulated high-photon-multiplicity events under realistic experimental conditions. The applicability and limitations of this method, or similar methods which use the full event information, are discussed.

1. Abstract of published paper: Nucl. Instrum. Methods Phys. Res. A276, 468 (Apr. 1989)

TRANSVERSE RADIUS OF AN EXPANDING HADRONIC SYSTEM AT FREEZE-OUT TIME¹

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A simple, analytical model has been constructed for both the longitudinal and transverse expansion of an interacting hadronic system. This model explicitly assumes that the particle rapidity distribution is not boost-invariant, and specifically includes an initial transverse dimension. It employs standard assumptions about the delayed formation of produced particles and the correlation between longitudinal position and rapidity. No particular dynamical scenario is assumed for the early stages of the system's expansion, but rather the last stage, freeze-out, is tied to the particle rapidity distribution. The observed multiplicity and width of the rapidity distribution control the transverse size and time when the system freezes-out. The model predicts a transverse

radius at freeze-out and its dependences on rapidity and multiplicity, which are very similar to those obtained by pion interferometry. This analysis can be used with different event classes to correlate changes in the multiplicity and width of the rapidity distribution with changes in the size, shape, and lifetime of the system at freeze-out.

1. Abstract of published paper: Phys. Rev. C 40, 2107 (Nov. 1989).

CALORIMETRY RESULTS FROM WA80

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The main purpose of the Midrapidity Calorimeter (MIRAC) in the WA80 setup is to provide a reliable measure of the transverse energy, E_T , generated in high-energy nuclear collisions. E_T is an approximate Lorentz-invariant quantity defined as

$$E_T' = \sum_n E_n \sin \theta_n,$$

where E_n and θ_n are the energy and scattering angle of the n 'th particle. The sum runs over all produced stable particles. Since hadronic calorimeters in high multiplicity environments are not able to resolve individual particles, the usual experimental approach has been to extract E_T as

$$E_T = \sum_i c_i E_i,$$

where E_i is the total energy recorded in the i 'th subsection of the calorimeter and c_i is a

coefficient adjusted from simulations; so $\langle E_T \rangle = \langle E_T' \rangle$. c_i will typically be close to $\sin \theta_i$, where θ_i is the azimuthal angle of the i 'th subsection. In MIRAC the smallest unit is the phototube.

It is, however, not only the total integrated E_T impinging on the calorimeter which is of interest. In addition, the more detailed information concerning the angular distribution of the produced transverse energy and its division between hadrons and "electromagnetic" (EM) particles (= electrons + photons and photons from the decay of neutral pions) is of considerable interest. This information can conveniently be expressed in terms of the pseudorapidity distributions, $dE_T/d\eta$, for both hadrons and EM particles.

Considerable effort has been invested in investigating different procedures for extracting $dE_T/d\eta$ from the MIRAC data. Most of the work has gone into methods based on various unfolding techniques. If α is an index running over a suitable set of pseudorapidity η -bins for both hadrons and EM particles, and if i runs over all 720 tubes of MIRAC, then the average signal S_i in the i 'th tube can be expressed as

$$S_i = \sum_{\alpha} R_{i\alpha} E_{\alpha}, \quad (1)$$

where E_{α} is the energy carried by particles in η bin α and $R_{i\alpha}$ is the η -response function of MIRAC. The matrix R can be calculated from simulation of MIRAC's parameterized response to various particles. This response to single particles is known from extensive calibration measurements at CEPN. In matrix notation, Eq. (1) can be written

$$\underline{S} = \underline{R} \underline{E},$$

and the $dE_T/d\eta$ distribution can therefore, in principle, be found either by directly inverting R ,

$$\underline{E} = \underline{R}^{-1} \underline{S},$$

or by utilizing various linear unfolding techniques. The outcome of these investigations, however, has been negative in the sense that no unfolding algorithm was able to produce reasonable $dE_T/d\eta$ distributions when applied to the experimental data.

A more conventional and conservative approach, which is based on reproducing the average behavior of the data, has therefore been selected. The core of the method consists of creating the η -distribution coefficients, $D_{\alpha i}$, defined as the fraction of the calibrated signal in tube i which, on the average, originates from the η interval α . $D_{\alpha i}$ is calculated as

$$D_{\alpha i} = \frac{\langle E_{\alpha i} \rangle_{\text{events}}}{\langle S_i \rangle_{\text{events}}},$$

where the average is taken over a large number of simulated events from a Monte Carlo event generator (in our case either FRITIOF or VENUS). S_i is the calibrated signal in the i 'th tube, and $E_{\alpha i}$ is the energy in the i 'th tube originating from η -interval α .

$dE_T/d\eta$ can now be calculated as

$$\frac{dE_T}{d\eta}(\alpha) = \frac{\sin \theta_K}{N_K \Delta \eta_K} \sum_j D_{\alpha j} S_j$$

on an event-by-event basis. θ_K is the scattering angle corresponding to η -interval α ; $\Delta \eta_K$ is the η -width of that interval; and finally, N_K is the fraction of the total energy emitted in α recorded by MIRAC. N_K will vary from 5-10% at $\eta = 1.6-2.0$ to 100% at $\eta = 3.0-4.0$.

A potential disadvantage of this method using the distribution function D is that the results might be sensitive to the event topology of the event generator. The algorithm has, therefore, been tested for several different event topologies. It was found that different distribution functions had to be used for 50- and 200-A-GeV reactions, but distribution functions for various projectile-target-event-generator cases did not differ much at a fixed bombarding energy.

In Fig. 2.50 is shown a comparison between the input $dE_T/d\eta$ distributions from FRITIOF and the extracted $dE_T/d\eta$ distribution based on the above-described algorithm. Note that both the overall shape and the partition of electromagnetic and hadronic energy is nicely reproduced.

Figure 2.51 shows a preliminary $dE_T/d\eta$ distribution for 200-A-GeV $^{16}\text{O} + ^{197}\text{Au}$ based on WA80 minimum-bias data. Note the differences in the centroids for the electromagnetic and hadronic energy. With this new $dE_T/d\eta$ algorithm,

Fig. 2.50. Comparison between $dE_T/d\eta$ distributions for 200-A-GeV $^{16}\text{O} + ^{197}\text{Au}$ from FRITIOF (dashed lines) and the distributions extracted from the η -distribution algorithm applied to simulated MIRAC events. The upper pair of histograms shows the total $dE_T/d\eta$; whereas, the center pair and the lower pair show the hadronic and electromagnetic energy, respectively.

a complete rescan of the WA80 calorimeter data will be performed. Preliminary tests show that already-published E_T distributions will not change appreciably, but we will, for the first time, be able to study in detail the systematics of the $dE_T/d\eta$ distributions and the division between electromagnetic and hadronic energy.

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Fig. 2.51. Preliminary results from WABO minimum-bias data for $dE_T/d\eta$ for 200-A-GeV $^{160} + ^{197}\text{Au}$. Three histograms shown from the top and down: total, hadronic, and electromagnetic $dE_T/d\eta$. Statistical and systematic errors are being evaluated.

STATUS OF WABO DIRECT PHOTON MEASUREMENTS AND NEW BGO PHOTON CALORIMETER

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Recent results of ultrarelativistic heavy-ion collisions at 200 GeV/A suggest that the energy densities attained in central $^{160} + \text{Au}$ reactions

may be sufficiently high to result in a phase transition from normal nuclear matter to a deconfined quark-gluon-plasma state. Thermal, directly radiated photons ($p_T < 3 \text{ GeV}/c$) are considered to be a promising signal of quark-gluon-plasma formation since they are little influenced by the dynamics of the hadronization process due to their electroweak interaction.⁷

The lead-glass detector SAPHIR⁸ of the CERN WABO experiment measures photons, and the data can be used to reconstruct π^0 and η mesons from their decay photons with modest efficiency and resolution. The photons which are detected result dominantly from such meson and baryon decays. By calculating the percentage of those "trivial" photons by means of Monte Carlo simulations, the ratio of direct photons to neutral pions can be estimated by:

$$\frac{\gamma}{\pi^0} = \frac{N_{\gamma, \pi^0}}{N_{\pi^0}} \frac{A_{\pi^0}}{A_{\gamma}} - (R_{\pi^0} + R_{\gamma} + R_X) \quad (1)$$

Here N_{γ, π^0} denotes the measured γ, π^0 distribution; A_{γ, π^0} , the geometrical acceptance folded with the photon detection probability and R_i , the ratio of photons from the decay of particle i to the π^0 spectrum. It has been found⁹ that the following 4 decays contribute most to the γ/π^0 background: $\pi^0 \rightarrow \gamma\gamma$, $\eta \rightarrow \gamma\gamma$, $\omega \rightarrow \pi^0\gamma$ and $\eta' \rightarrow \gamma\gamma$. Whereas the π^0 distributions are known in the p_T region $0.4 < p_T < 3 \text{ GeV}/c$, the p_T distributions from the other 3 mesons have to be calculated by the following m_T scaling law^{10,11}:

$$f[m_T(X)] = f[m_T(\pi^0)] \quad (2)$$

with $m_T = \sqrt{m^2 + p_T^2}$, where $X = \eta, \omega, \eta'$ and m denotes the respective rest masses. The η mesons have been reconstructed for 200-A-GeV $^{160} + \text{Au}$ reactions in a limited p_T region, and the result agrees with the values given below. The values in the table are taken from pp reactions and served as normalization points for Eq. (2).

	$p_T \text{ (GeV}/c)$	Value	Reference
η/π^0	5.0	0.55	12
η'/π^0	5.0	1.0	13
ω/π^0	5.0	1.0	13

In Fig. 2.52 the γ/π^0 ratio is shown for central and peripheral 200-A-GeV $^{160} + \text{Au}$ reactions

Fig. 2.52. The ratio γ/π^0 of the inclusive photon cross section to the π^0 cross section is shown as a function of the transverse momentum p_T for central and peripheral collisions of ^{160}Au at 200 A GeV. The open squares represent the experimental results with associated uncertainty. The shaded histograms show the results with uncertainty of the Monte Carlo calculation of the photon contribution resulting from hadronic decays. The difference between the open points and histogram yields the photon contribution which may be attributed to direct photon radiation.

as a function of p_T . The histograms denote results of the Monte Carlo calculation of the contribution of decay photons, whereas the data are represented by the open squares. Within the limits of the uncertainties, all of the observed photons can be accounted for by the known hadronic decays. With the present level of systematic uncertainty, the data now set an upper limit of $\sim 15\%$ for the direct photon percentage γ/π^0 over this p_T range. With better statistics, a limit of $\sim 5\%$ appears feasible.

The photon results at very low p_T are most interesting since the direct photon radiation from possible quark-gluon-plasma formation is expected to yield photons with p_T dominantly in

the region of up to several times the plasma temperature of about 200 MeV. However, the extraction of the π^0 and η cross sections at low p_T is most difficult, due to the necessary requirement of a large acceptance in relative photon angles $\Delta\phi$, and hence, a large acceptance detector is required. Also, the background from the combination of false photon pairs increases for decreasing p_T , necessitating a detector with very good mass resolution for the π^0 and η . In the next period of WABO running with sulfur beams, it is anticipated to triple the present coverage with lead-glass detectors and, therefore, significantly improve the π^0 and η acceptance at low p_T . In addition, an array of approximately 550 BGO modules will be used to determine whether the expected improvement of a factor of 4 to 5 in mass resolution can be obtained in the environment of high multiplicity present in ultrarelativistic heavy-ion reactions. Such an improvement in mass resolution will be necessary for a possible photon experiment with Pb beams at CERN in order to cope with the expected increase in the combinatorial background resulting from the higher photon multiplicity.

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STATUS OF INTERMITTENCY STUDIES

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It was suggested recently^{1,2} that the investigation of fluctuations in phase-space densities can provide deep insight into the multiparticle production processes. Enhanced fluctuations in very small rapidity intervals have been observed³⁻⁵ in a variety of reactions at high energy, ranging from e^+e^- , pA to nucleus-nucleus collisions. Most of the excitement in such studies stems from the viewpoint that large fluctuations are expected to accompany the phase transition from a quark-gluon phase to the hadronic matter. Several alternative theoretical interpretations for the origin of these fluctuations have been suggested, namely, that they may be due to cascading or branching processes with scale invariant branching structure,^{1,6} formation of blobs of cold quark-gluon plasma,⁷ hadronic Cerenkov radiation,⁸ or due to other collective phenomena such as Bose-Einstein correlations.⁹

A flurry of activity in this field has been stimulated by the method of scaled factorial moments to investigate nonstatistical fluctuations in the rapidity density distributions recently proposed by Bialas and Peschanski.^{1,2} This method has the advantages that (a) it allows one to reduce considerably the effect of statistical fluctuations, which are always present due to finite multiplicity of the event, and (b) it allows one not only to detect large nonstatistical fluctuations but also to investigate the characteristic scale of these fluctuations, which then could lead to an interpretation of their origin.

For an analysis in pseudorapidity space, the pseudorapidity interval $\Delta\eta$ is divided into M partitions of width $\delta\eta = \Delta\eta/M$. The scaled factorial moment F_i of order i for a particular partition width $\delta\eta$ for the analysis of inclusive events is given by^{1,2}

$$\langle F_i(\delta\eta) \rangle = \frac{1}{M} \sum_{m=1}^M \frac{\langle C_m(C_m - 1) \cdots (C_m - i + 1) \rangle}{\langle C_m \rangle^i} \quad (1)$$

where $\langle \rangle$ denotes the average over the event sample analyzed, C_m is the contents of the m 'th

bin, and $\langle C_m \rangle$ is the average multiplicity in the m 'th bin. Note that all particles are treated on an equal footing. It has been shown^{1,2} that the factorial moments F_i , when averaged over many events, are equal to the moments of the primary distribution of the particle density in the phase-space. Also, if the fluctuations are purely of statistical nature, no variation of $\langle F_i \rangle$ with $\delta\eta$ is expected. The observation of such a variation then indicates the presence of nonstatistical fluctuations of physical origin. The values of $\delta\eta$ for which these changes occur correspond to the characteristic size S of the observed fluctuations. Intermittency, a term borrowed from the hydrodynamics of turbulent flow of fluids, means that the phenomena are characterized by the presence of fluctuations at many different scales. In such a situation, the factorial moments will show variations at all scales, e.g., unlimited growth.

Fluctuations of a scale S give moments which depend on bin width (or resolution), $\delta\eta$, only when $S < \delta\eta$. The moments are independent of $\delta\eta$ when $S > \delta\eta$. Fluctuations which are intermittent, on the other hand, result in a power law behavior of the moments,

$$\langle F_i \rangle = \left(\frac{\Delta\eta}{\delta\eta} \right)^{k_i}; \quad (2)$$

$$\ln \langle F_i \rangle = a_i - k_i \ln(\delta\eta). \quad (3)$$

It has been suggested by Ochs and Wosiek⁶ that if the observed growth of factorial moments with decreasing bin width $\delta\eta$ in the one-dimensional analysis in the pseudorapidity space is, indeed, driven by clusters of strongly collimated particles, further subdivision of the phase-space by partitioning the azimuthal angle should considerably enhance the effect. A two-dimensional analysis in the pseudorapidity η and azimuthal angle ϕ then may help to distinguish between different model interpretation of these fluctuations.

We have carried out a factorial moment analysis in two-dimensional phase-space of pseudorapidity η and azimuthal angle ϕ . Unlike the one-dimensional analysis, where each partitioning

of the pseudorapidity space is unique, a bin of certain area in two-dimensional (2D) analysis can be obtained by partitioning 2D phase-space in more than one way. Bialas and Peschanski^{1,2} point out that the factorial moments are independent of the way the phase-space is partitioned. We chose to partition the phase-space in such a way that we reach the experimental limits of resolution for η and ϕ simultaneously. For a given bin size in pseudorapidity space,

$$\delta\eta = \frac{\Delta\eta}{M_\eta}$$

we chose $M_\phi = 3M_\eta$, so that $\delta\phi = 2\pi/M_\phi$, where M_η and M_ϕ are the number of partitions in the η and ϕ directions, respectively. The factorial moments were calculated using Eq. (1) with number of 2D bins $M = M_\phi M_\eta$ and bin size $\delta W = \delta\eta\delta\phi$. We also calculated the factorial moments with $M_\phi = M_\eta$ and $M_\phi = 2M_\eta$. It was comforting to note that in a plot of $\ln\langle F_i(\delta W) \rangle$ vs $-\ln(\delta W)$, the curves for three different ways of partitioning the 2D phase-space were indistinguishable within the

statistics. Very preliminary results from such an analysis of the multiplicity data from NA80 collaboration show that, unlike the case for a one-dimensional analysis in the pseudorapidity space,⁴ $\ln\langle F_i \rangle$ does not show a linear dependence on $-\ln(\delta W)$. In fact, the factorial moments for the 2D analysis grow much more rapidly with decreasing bin size than did the factorial moments for the 1D analysis. We find that an exponential function of the type

$$\ln\langle F_i \rangle = a_i \exp[-B_i \ln(\delta W)] \quad (4)$$

gives a reasonably good fit to the moments shown in Fig. 2.53. It can be argued that the one-dimensional analysis in pseudorapidity space is equivalent to a 2D analysis with just one partition in the azimuthal direction. It is, perhaps, not surprising to note that the one-dimensional factorial moments, when plotted as a function of 2D bin size given by $\delta W = 2\pi\delta\eta$, lie almost on top of the curves shown in Fig. 2.53. We have also done the one-dimensional analysis in azimuthal space without partitioning the

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2D ANALYSIS WITH FACTORIAL MOMENTS

200AGeV $^{16}\text{O}+\text{Au}$ $2.4 \leq \eta \leq 4.0$

Fig. 2.53. $\ln\langle F_i \rangle$ are plotted as a function of $-\ln(\delta W)$. For the 2D analysis, the numbers in the brackets represent the number of η bins (M_η) to the number of ϕ bins (M_ϕ) ratio.

pseudorapidity phase-space. The factorial moments from this analysis, when plotted as a function of the 2D bin size given by $\delta W = \Delta\eta\delta\phi$, also lie very close to the results from the 2D analysis. It shows that Eq. (4) gives a more general relationship than Eq. (3). The left-hand side of Eq. (4) can be expanded to give

$$\ln\langle F_i \rangle = \left\{ \alpha_i 1 - \beta_i \ln(\delta W) + \frac{[\beta_i \ln(\delta W)]^2}{2} - \dots \right\}, \quad (5)$$

where only the first two terms are significant when $\ln(\delta W)$ is small, as in the case of the one-dimensional analysis in the pseudorapidity space, and is identical to Eq. (3) with $\alpha_i \beta_i = k_i$. However, for larger values of $\ln(\delta W)$, higher order terms become important and give nonlinear growth. Equation (4) can be rewritten as

$$\ln\langle F_i \rangle = \alpha_i (\delta W)^{-\beta_i}; \quad (6)$$

$$\langle F_i \rangle = \exp[\alpha_i (\delta W)^{-\beta_i}]. \quad (7)$$

It is interesting to find that it is the parameter α_i which determines the growth rate and hence scales like the slope parameter k_i of Eq. (4), whereas the parameter β_i varies very little.

It should be noted here that the results of Fig. 2.53 were obtained using a cluster-finding software that had some serious deficiencies. At present, the cluster routines, which do multi-hit correction and do track association for the hits on the multiplicity detectors MIRAM1 and MIRAM2 in the WA80 setup, are undergoing major revision. This is to provide an improved rejection against fake tracks (detector noise), which becomes very important for a pair of very close tracks (one-pad separation). The ability to reject fake tracks is particularly very important for fluctuation analysis at small bin sizes. Preliminary results of the 1D fluctuation analysis in the pseudorapidity space using the improved cluster software show that the rate of growth of factorial moments is much weaker than indicated by the previous analysis. However, a complete analysis remains to be done before any conclusions can be drawn. It also remains to be seen if the general trend of nonlinear growth seen in the 2D analysis (Fig. 2.53) persists in the new analysis.

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STATISTICAL MOMENTS OF TRANSVERSE ENERGY, CHARGED-PARTICLE MULTIPLICITY, AND FORWARD ENERGY DISTRIBUTIONS

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One of the main goals of the WA80 experiment is to have nearly 4π coverage for an ultrarelativistic heavy-ion event. The WA80 experiment measures the forward energy (E_{ZDC}) close to the beam ($\eta > \bar{\eta}$, $\eta = -\ln[\tan(\phi/2)]$), the charged-particle multiplicity (CPM) between $1.7 < \eta < 4.0$, and the transverse energy (E_T) between $2.4 < \eta < 5.5$.

In several publications⁷ correlations between E_{ZDC} and E_T , E_{ZDC} and CPM, or E_T and CPM have been shown. (The latter should give a measure of the average p_T per particle.) Narrow correlations are observed among these quantities. If

these three quantities are related, it seems reasonable to study a simultaneous analysis of all three. This can overcome certain shortcomings of analyzing them only in pairs. For example, if the CPM is analyzed as a function of E_{ZDC} and the width of the CPM distribution is measured, one, in effect, takes slices parallel to the E_{ZDC} axis from the 3-D ellipsoid of E_{ZDC} vs CPM vs E_T and projects the distribution onto the CPM axis. If the E_{ZDC} window is wide, this slicing can disturb the tails of this projection, resulting in wrong interpretations of the data. Several 2-D projections from a 3-D point distribution of CPM, E_T , and E_{ZDC} are shown in Fig. 2.54. Each event is represented there by a point. A nice correlation is visible, as expected, from the "standard" 2-D correlation plots.

Preliminary results of an analysis measuring the widths of the ellipsoid are presented using the information from all three variables simultaneously. The range $2.4 < n < 4.0$ is covered for CPM and E_T . This analysis was stimulated by recent claims⁸ that the widths of the CPM and E_T distributions seen in heavy-ion collisions are

too wide to be explained by an independent source model and that, therefore, coherence has to be assumed. However, detector effects such as inefficiencies, resolutions, and limited angular coverage were not taken into account in the analysis described in Ref. 8. Inclusion of these effects significantly modifies the conclusions drawn. In addition, a more detailed analysis by the WA80 collaboration⁹ shows that this effect is not as large as predicted by Ref. 8 and can be, within the present limits, understood by "string" models without assuming coherent effects.

The analysis described here takes the full information of all three variables simultaneously and analyzes the widths of the ellipsoid by an eigenvector analysis and compares the results to the Monte Carlo code FRITIOF. For simplicity, in the following, CPM is referred to as X , E_T as Y , and E_{ZDC} as Z . The total number of events analyzed in the sample is called N . After the dataset is transformed into its "Center of Gravity,"

$$c_a = \bar{x}_a = \frac{1}{N} \sum_{i=1}^N (x_i)_a, \quad a = x, y, z.$$

A dispersion matrix D is constructed by:

$$D = \begin{pmatrix} \frac{1}{N} \sum_{i=1}^N x_i x_i & \frac{1}{N} \sum_{i=1}^N y_i x_i & \frac{1}{N} \sum_{i=1}^N z_i x_i \\ \frac{1}{N} \sum_{i=1}^N x_i y_i & \frac{1}{N} \sum_{i=1}^N y_i y_i & \frac{1}{N} \sum_{i=1}^N z_i y_i \\ \frac{1}{N} \sum_{i=1}^N x_i z_i & \frac{1}{N} \sum_{i=1}^N y_i z_i & \frac{1}{N} \sum_{i=1}^N z_i z_i \end{pmatrix}$$

This matrix is then transformed into diagonal form, where the elements in the diagonal, which are now eigenvalues, are labelled λ_i . These values represent the variance of the point distribution along these new axes. The correlation observed among the new coordinates are minimal. The direction of these axes are given by the eigenvector equation,

$$\vec{D} \cdot \vec{\delta}_i = \lambda_i \vec{\delta}_i, \quad i = 1, \dots, 3.$$

The eigenvalues are ordered so that $\lambda_1 > \lambda_2 > \lambda_3$. Then the a_1 axis represents the direction

Fig. 2.54. 2-D projections from a 3-D point distribution viewed from different angles.

in which the variance (λ_1) of the point distribution is largest.

The point distribution is then transformed into the new coordinate system, and the width of the new distribution along the a_2 and a_3 axes is analyzed by making four slices along the first axis. Figure 2.55 shows the transformed distribution in its three major projections. The

Fig. 2.55. Projections of the point distribution after transformation into eigenvector space.

distribution is observed to deviate from a symmetric ellipsoid at both extremes along the a_1 axis, as seen in the upper two plots. This is due to trigger cuts for large values of E_{ZDC} for large values of the a_1 coordinate. The enlarged fluctuations observed for small values of the a_1 coordinate are due to limited detector acceptance on the low end.

In order to understand the width of this distribution, it is compared to FRITIOF simulations. Figure 2.56 shows the average and "standard deviations" (σ) of the ellipsoid along axis a_2 and a_3 for the four cuts made along axis a_1 . On the left are the results from FRITIOF without detector effects; in the middle are the results from FRITIOF with those effects included; and on the right are the data from the WABO experiment. These diagrams show that the

Fig. 2.56. Average and standard deviation of the point distribution for "pure" FRITIOF (left), FRITIOF including detector effects (middle), WABO data (right).

global fluctuation in the minimum-bias data can be reproduced when taking the detector effects into account. The analysis will be continued for different projectile and target combinations. It will finally tell us more about the correlations involved in the measured quantities.

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7. See, e.g., "Proceedings of Quark Matter 87," Z. Phys. C 38, 3-14; or "Proceedings of Nucleus-Nucleus Collisions III," Nucl. Phys. A488, 651c-644c (1988); or Phys. Lett. B 199, 297-303 (Dec. 1987); or Phys. Lett. B 202, 596-602 (Mar. 1988).
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9. "Global and Local Fluctuations in Multiplicity and Transverse Energy for Central Ultrarelativistic Heavy-Ion Reactions," R. Albrecht et al., submitted to Zeitschrift fuer Physik C.

ENERGY-DENSITY ESTIMATES FROM ^{16}O - AND ^{32}S -INDUCED REACTIONS

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Although energy-density estimates ultimately will be made based on models which reproduce the observed results and include the space-time development of the heavy-ion collision,⁷ it might be expected that reasonable estimates may be obtained based on the measured E_T , since this should directly reflect the amount of thermalized energy. The major source of uncertainty is then to obtain a reliable estimate of the volume over which the observed energy was initially available. The most commonly used method to estimate the energy density is the following relationship, first suggested by Bjorken,⁸

$$\epsilon = \frac{1}{F\tau} \left. \frac{dE_T}{dn} \right|_{n_{\max}}, \quad (1)$$

in which the differential transverse energy $dE_T/dn|_{n_{\max}}$ observed at midrapidity is associated with a differential volume of transverse area F corresponding to the area of nuclear overlap and thickness τ related to the particle formation time. This estimate has the feature of being a Lorentz invariant, valid for the local cm frame regardless of whether or not the nuclei are stopped completely. The main disadvantage is that the presently unknown formation time τ is simply assumed to be 1 fm/c.

An alternative method is motivated by the observation that, for central collisions, the total transverse energies observed account for a

large fraction of the energy available in the center of mass, and therefore indicate a large degree of nuclear stopping. In this case an integral estimate of the energy density may be made as

$$\epsilon = \frac{1}{FL} \int dn \frac{1}{\sin\theta_{\text{cm}}} \frac{dE_T}{dn}, \quad (2)$$

where the total available energy has been obtained by integrating a gaussian dE_T/dn distribution fitted to the forward n region. The total volume in the center of mass is given by the transverse area F times L , the total Lorentz contracted length of the stopped system, as seen in the center-of-mass frame. Most estimates have assumed that the initial conditions are such that the smaller projectile is stopped within the target volume^{9,10} as suggested many years ago by Landau,¹¹ and have assumed L to be the contracted target length. Alternatively, one may imagine initial conditions as suggested by Bjorken⁸ in which, as in the capacitor-plate analogy, after passing through one another, the receding nuclei are nearly stopped due to the energy stored in the intervening color fields. In this case the appropriate total length might be the sum of projectile and target lengths plus the intervening stopping distance L_S .

The systematic dependence of these various energy-density estimates on the total nucleon thickness $A_p^{1/3} + A_t^{1/3}$ is shown in Fig. 2.57. It is seen that estimates based on the assumption of Landau-stopping, in which the projectile is completely stopped within the target volume, give densities roughly 3-6 times larger than estimates based on the Bjorken-type initial conditions. Moreover, the fact that the energy density decreases with increasing thickness of the system is difficult to interpret, given that the stopped energy fraction is observed to be nearly constant but less than one. On the other hand, it is observed that the integral and differential estimates assuming Bjorken-type initial conditions show a systematic increase with increasing thickness of the system, as might be expected for overlapping color strings. A stopping distance of $L_S = 4$ fm gives values consistent with those obtained for a 1 fm/c

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Fig. 2.57. Energy-density estimates by various methods for 200-GeV/nucleon 160 - and 32 S-induced reactions as a function of the total thickness of the interacting system. The Pb + Pb points are based on an extrapolation of the observed E_T scaling.

formation time at about $2\text{--}3 \text{ GeV/fm}^3$ for the heavy systems. This is similar to recent calculations.⁷ It also may be observed that the average energy density is not expected to increase significantly for reactions of Pb + Pb; however, the core energy density and volume is expected to increase substantially.

In addition to the observation that the total E_T /participant is constant when integrated over the forward pseudorapidity region $2.4 < \eta < 5.5$, it is similarly found that $dE_T/d\eta|_{\eta_{\text{max}}}$ /participant is also constant with a value of about 1 GeV/participant for all systems and impact parameters. Using this information we may generalize upon Eq. (1) and calculate the radial energy density profile according to the participant nucleon profile. The result is shown in Fig. 2.58 for zero-impact-parameter collisions of O, S, and Au on Au at 200 GeV/nucleon. The comparison between the different systems is now much more dramatic than the volume average comparison in that one expects a 30% higher central energy density for Au projectiles. In fact, it is seen that if the energy density necessary for the phase transition corresponds to 3 GeV/fm^3 on the indicated scale, then reac-

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Fig. 2.58. The estimated energy density profile for zero-impact-parameter collisions of O, S, and Au on Au at 200 GeV/nucleon based on Eq. (1) and the observed scaling of the transverse energy.

tions of Au on Au would provide a cylindrical volume about 10 fm across, significantly above the critical energy density while the other projectiles would fall below the critical energy density.

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PROPOSAL FOR A JOINT NA35/WA80 EXPERIMENT WITH LEAD BEAMS AT CERN¹

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The first round of experiments with CERN/SPS beams of ^{16}O and ^{32}S has shown that energy densities in the vicinity of those needed for the production of the quark-gluon plasma may have been reached. In order to produce more extended plasma volumes than those that currently may

be achievable, and in order to produce higher central-core energy densities,²¹ CERN is investigating the possibility of providing SPS beams of very heavy nuclei such as Pb and Au. To exploit the availability of such beams, the NA35 and WA80 collaborations have filed a joint letter of intent¹ proposing a large-acceptance hadron detector associated with a high resolution photon detector.

The proposed experimental layout is shown in Fig. 2.59. The target is placed at the upstream field fringe of the vertex magnet currently used in NA35. This magnet assures the necessary dispersion of charged particles in the horizontal plane, with a transverse momentum "kick" of about 1.2 GeV/c, resulting in a distribution of charged-particle products into a "butterfly" along the deflection plane as shown in Fig. 2.60.

The proposed array of tracking detectors, consisting primarily of time-projection chambers (TPCs) and ring-imaging Cerenkov chambers (RICHs), is deployed so as to take advantage of the butterfly deflection pattern. Charged particles with laboratory momenta exceeding about 2 GeV/c (midrapidity for pions) and ranging up to 100 GeV/c will be measured and momentum analyzed. The butterfly deflection pattern is particularly advantageous for the placement of proposed BGO photon detectors, since it is possible to take advantage of regions that are relatively free of the large number of charged particles produced in reactions between very heavy nuclei (see Fig. 2.60). The photon detectors will cover the angular interval $2.8^\circ < \theta < 8.6^\circ$, corresponding to a rapidity range $2.6 < y < 3.7$. A set of downstream calorimeters will cover the region $0^\circ < \theta < 2.8^\circ$ (pseudorapidity $\eta > 3.7$). A segmented ring calorimeter, currently used by NA35, will cover the domain $3.7 < \eta < 5.5$, and a zero-degree calorimeter will provide an active beam stop for $\eta > 5.5$.

In an initial reaction to the letter of intent, the SPS Committee has expressed some reservations regarding the scale of the proposed experiment and the feasibility of the photon measurements. It is hoped that the WA80 photon-measurement production runs with sulfur ions,

Fig. 2.59. Layout of the proposed joint NA35/NA80 large-acceptance hadron detector and associated photon detector. TPCs indicate time projection chambers and Rs indicate ring-imaging Cerenkov chambers.

scheduled for 1990 and 1991, will resolve the latter issue.

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21. See "Transverse Radius of an Expanding Hadronic System at Freeze-Out Time," M. L. Tinknell, this report.

Fig. 2.60. Active area of the central and lateral TPCs, RICH detectors (dashed), and BGO photon detectors as projected onto a plane 10 m downstream of the vertex magnet center, superimposed on the "butterfly" charged-particle hit pattern.

CALORIMETER/ABSORBER OPTIMIZATION FOR A RHIC DIMUON EXPERIMENT

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We are studying the feasibility of mounting a dimuon experiment at the proposed Relativistic Heavy Ion Collider (RHIC). The work⁷ that we have proposed to carry out at Brookhaven National Laboratory (BNL) involves detector development in several different areas. They are: (1) a determination of the level and characteristics of the background behind the hadron calorimeter/absorber in a dimuon experiment, (2) the development of tracking chambers suitable for use in a dimuon experiment at RHIC, and (3) the development of a muon identifier for use behind the tracking section of a dimuon spectrometer. The results will be of use for designing hadron calorimeter/absorbers and muon identifiers for the various experiments in which they have been proposed for RHIC. The ultimate goal of the present effort is to be able to design a workable, dedicated, dimuon spectrometer for RHIC. A dimuon experiment is particularly attractive for studying the formation of the J/ψ and of higher-mass vector mesons as a probe of the quark-gluon plasma.⁸

The possibility of performing dimuon measurements at RHIC has been studied at the three RHIC detector workshops.⁹⁻¹¹ Massive photons have been proposed as a probe to detect the existence of a quark-gluon plasma and, subsequently, a diagnosis of its properties has been discussed in Refs. 9 and 10 and in other papers referenced therein. Possible designs of dimuon detectors were also given in Refs. 9 and 10. It is the purpose of the present work to obtain basic information about backgrounds involved in a dimuon experiment. This information will be used in the actual design of such a detector.

It is fully expected that this future design will evolve considerably from the schematic designs presented in the earlier studies.

The four central issues that determine the feasibility of dimuon detection in relativistic heavy-ion collisions are acceptance, dynamic range, resolution, and background level. The goal is to detect dimuons over a reasonably broad range of masses and transverse momenta. The general softness of the spectrum of secondaries produced at midrapidity at RHIC makes it feasible to consider a thin absorber, although detailed information on the spectrum of punch-through products is lacking, particularly for the low incident hadron energies that will be encountered in the central region at RHIC. Appropriate measurements will be made, and the data will be compared with the output of the computer calculations. The purpose of these absorber studies is to obtain a sufficient database on the characteristics of the shower leakage so that the design codes can be verified or improved. The knowledge gained of the details of the hadronic showers will not only provide important information for improvements in the calorimeter design codes, but also will allow the use of these codes in the optimization procedures leading to the choice of the absorber in a RHIC dimuon experiment.

It is important to know how calorimeters made of materials with a low ratio of interaction length to radiation length behave. Such a calorimeter would be an attractive active absorber for a muon experiment because of the minimal multiple scattering it would cause for the muons transversing it. There is little information on the behavior of sampling calorimeters with low-Z materials, such as aluminum, as the inert layer.

We were funded in FY 1989 to proceed with detector R&D for RHIC. The specific projects proposed were: (1) a study of shower development in and leakage behind the calorimeters for different incident particle types and energies, and (2) a study of the behavior of a few novel types of calorimetry at low energies characteristic of RHIC central-rapidity particles.

The calorimeter studies were a continuation of a project started with internal seed-money funds at ORNL. We have constructed several different kinds of electromagnetic detectors in an effort to study the low-energy response (chiefly resolution and linearity) of different calorimeter types and in order to experiment with different readout ideas.

We have constructed a section of an electromagnetic calorimeter from scintillating optical fiber ribbon. The ribbon was made by glueing 200- μ^2 optical fibers together to form 10-cm-wide ribbon. The ribbon was then glued between 800- μ -thick lead sheets. This results in a lead-scintillator ratio of 4:1, as proposed by Wigmans for a compensated calorimeter. The completed module was 10 x 10 x 15 cm in active volume. Resolution tests were made for this detector with a single 3-in.-diam photomultiplier for readout. A resolution of about $\Delta E/E = 9-10\%/ \sqrt{E}$ was measured for 1- to 10-GeV electrons. When shower radius and position resolution tests are made with this device during the upcoming AGS cycle, the readout will consist of nine photomultipliers in a 3 x 3 array giving a granularity of just over 3 x 3 cm.

We have made energy resolution measurements for an electromagnetic calorimeter constructed by a group at the University of Illinois. This module was constructed from 1-mm scintillating optical fibers and grooved lead sheets. The fiber is placed in a hexagonal pattern in a lead matrix. The volume composition of the device is approximately 40% lead, 50% fiber, and 10% glue. The resolution of this detector was about 7.5%, somewhat better than the 200-micron ribbon. This was expected, based on GEANT calculations. The sampling fluctuations are more severe for the fiber-ribbon device because a rather small fraction of the shower is seen in the active medium.

A second electromagnetic calorimeter was constructed at ORNL with conventional techniques but on a miniature scale. This calorimeter was built from 4 x 4 x 0.1 cm lead and 4 x 4 x 0.3 cm

plastic scintillator sheets arranged in an 11 x 11 tower array. The towers are read out with conventional wavelength shifter plates that are coupled to photodiodes. Each tower is divided into four depth segments, two each 24 cells deep followed by two each 48 cells deep. (A cell is defined as a lead-scintillator combination.) The advantages of this arrangement are twofold: (1) we can characterize the shower profile, and (2) the metal composition may be changed easily. The first 9 towers (3 x 3) of this device have only recently been completed and have not been tested in a beam.

One of our goals is to measure the ratios of electron-to-hadron responses (e/h ratios) for the above devices at energies between 1 and 10 GeV/c. To avoid having to build several devices, each long enough to contain hadronic showers, we decided to build a small, portable hadronic calorimeter to back up the test calorimeters, which could then be designed to contain only electromagnetic showers. We, thus, constructed and instrumented a copper-scintillator detector, based on the design of our WABO Zero-Degree Calorimeter. We scaled the drawings by one-half and substituted copper plates for the uranium plates. This calorimeter gave an energy resolution of $\Delta E/E = 60\%/ \sqrt{E}$ for pions between 1 and 10 GeV/c. It was then used behind the EM calorimeters described above. Measurements were made with electrons and pions of 1 to 6 GeV/c to measure the e/h ratio of the EM calorimeters. These results are being analyzed.

We have designed an absorber/calorimeter which, when installed in the A2 beam line at BNL, will allow us to study the shower development and leakage from various materials as a function of beam energy. The absorber/calorimeter will be constructed from 120 x 120 x 2.5 cm steel plates and 1-cm-thick sheets of plastic scintillator. There will be two different scintillator plate designs: (1) The first design will consist of 11 slabs, each 120 x 10 x 1 cm, with photomultiplier readout on each end. The strips are stacked up along their 120-cm sides,

forming, in effect, a hodoscope between two sheets of steel. (2) The second type of scintillator plate will be 120 x 120 x 1 cm in size with a total of 4 photomultipliers used to read out two opposing sides of the scintillator (two photomultipliers per side).

The absorber/calorimeter will be assembled such that steel plates will alternate with scintillator plates, and every fourth scintillator position will be of the hodoscope type, as described above. In addition, successive hodoscope layers will be rotated by 90 degrees with respect to each other. The total length of the assembly is variable, to a maximum of three meters. This structure was developed to keep the cost of the readout to a minimum while providing periodic information on the transverse profile of the shower, in addition to information on the depth at which the shower starts. Even with this arrangement, the structure requires about 350 photomultipliers and ADC channels. Each tube will have the gain stabilized with the light from a pulsed laser system. The laser system is quite similar to one which we use in the CERN NA80 experiment. The laser has been delivered and is presently being brought into service. The frame to hold the scintillator and absorber material has been designed and built; it is ready for shipment to BNL. The scintillator has been purchased, and the individual panels are being assembled with light guides and photomultiplier tubes here at ORNL.

The first set of tracking chambers to be used will be obtained from BNL experiment E734. These are 4 x 4 m proportional drift tube arrays. We will use four double planes of these tubes. Each plane has an x and a y layer. A new support structure has been designed for these chambers and will be built early in FY 1990. Commissioning work to bring the planes back into operation will also take place then. The custom electronics associated with the chambers will be used and have been checked recently. A new readout interface is being implemented to form the data into Ethernet packets which will then be sent to the

VALET-Plus on-line system. Software development for this has begun.

Four hodoscope arrays are under construction. Two of the arrays are being constructed using an existing hodoscope array from an earlier experiment at LLNL. The other two arrays are being built partly from existing paddles from Riverside and partly from the new scintillator purchased for this project. They will use the same photomultiplier tubes and laser plus light-fiber calibration system as will the absorber/calorimeter readout, so that the whole system can be tested and pulsed from the same source.

A number of issues related to the background for a muon measurement behind the hadron calorimeter/absorber will be investigated using this setup. These include: (a) What are the punch-through probabilities for pions, kaons, and protons with incident momenta in the range of 0.3 to 10 GeV/c striking a specific absorber? (b) How do these probabilities vary as a function of the absorber composition, e.g., carbon, aluminum, steel, copper, lead, when interleaved with a second material which is suitable active material for a sampling calorimeter? How do the results vary with absorber thickness? (c) What fraction of the exiting particles can penetrate a second shield and cause a "muon" trigger? How many of the punch-through particles will be rejected by position and angle cuts appropriate to a muon-finding analysis program?

In the first measurements, the interest will be in determining the number and spatial distribution of the leakage particles, with little or no information on the momenta or particle type. This phase will be accomplished using the detector equipment whose preparation was begun in FY 1989. It includes a segmented absorber which is read out by scintillator "slats," which are in production. A set of existing proportional drift tubes (PDTs) from E734 will be placed behind the absorber to serve as tracking chambers in order to determine the spatial distribution and direction cosines of the leakage particles at the back of the absorber. In this

phase the ratio $R = (\text{number of particles exiting absorber}) / (\text{number of incident particles})$ will be investigated as a function of the momentum of the incident particles (ranging from 0.5 to 150 GeV/c) and as a function of the thickness and composition of the absorber material. Initial tests will be made with a steel-scintillator sandwich absorber/calorimeter. Further tests will be made varying the inert absorber/scintillator thickness ratio and the type of inert absorber (steel, carbon, aluminum, lead). These studies will indicate whether the Monte Carlo calculations made using GEANT or CALOR provide reliable first-order estimates of the leakage and whether the dimuon measurement appears at all feasible at RHIC.

DATA-SUMMARY-TAPE PRODUCTION USING THE ACP FARM

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The research in ultrarelativistic heavy-ion collisions naturally implies large experiments which produce a huge amount of information which must then be processed to correlate the information from the different detector components. The first step in analyzing the experimental data is to process the RAW information, such as ADC and TDC channels numbers, in order to produce so-called data summary tapes (DSTs). These DSTs contain the information from the event in terms of calibrated physical quantities. This information can then be used for further analysis without having to repeat the time-consuming first step of transforming the information from RAW to DST format.

For the WABO sulfur data, we currently need around 15 hours of cpu time on a VAX 8650 to process one 6250-bpi tape of ³²S + Al data. Heavier targets need even more cpu time. Given that we have over 200 RAW tapes from the sulfur run alone, and given the high costs of cpu time on VAX clusters, such as the STC VAX 8650 cluster at ORNL or the 8650 cluster at Berkeley, the processing of the experimental data becomes quite expensive. Because every event is independent of the previous or the following one, parallel processing of events is an obvious computer architecture to investigate. We have started to use a multi-microprocessor farm of

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6. Adjunct research participant from the University of Tennessee, Knoxville, Tennessee 37996.

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the type developed by the Advanced Computer Program (ACP) at Fermi National Laboratory. Each node of such a farm is a one VME-board computer, in our case based on a Motorola 68020 32-bit cpu with a 68881 or 68882 floating point coprocessor. Each node has 2 MByte of on-board memory with an optional extension to 6 MByte via an external card. Each node has the processing power of about 0.8 of a VAX 11/780 or 0.13 of a VAX 8650. The nodes are accessed from a host computer, in our case a DEC VAXstation II/GPX, by a special backbone bus (Branch Bus).

Figure 2.61 shows the setup currently used by the WABO group. A VAXstation II/GPX workstation with graphics terminal and two 8-mm tape drives for data input and output is connected by a QVI interface card to the VME Branch Bus Controller (BBC). From here the information is transferred

to the different VME crates by the Branch Bus. Each crate contains a VME Resource Module (VRM) to allow bus arbitration and the Branch Bus VME Interface (BVI). Within a crate, the information is transferred using the VME buses.

The full setup at ORNL currently consists of 76 cpu's (56 from ORNL and 20 from GSI, Darmstadt, F.R.G.) and 38 4-MByte extension cards (18 from ORNL and 20 from GSI). Thirty-five of these cpu's with full memory are used for the DST production. A diagram of this part of the setup is shown in Fig. 2.61. The rest of the nodes are connected to another VAXstation II/GPX for program development, running of Monte Carlo event generators, and other analysis.

Several modifications had to be made in our analysis program to make it compatible with the ACP farm. The first obvious change is a split

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Fig. 2.61. Artist's view of the current ACP Farm setup to produce DST tapes from WABO RAW data. Key: BBT = Branch Bus Terminator, BBC = Branch Bus Controller, VRM = VME Resource Module, CPU = ACP CPU, BVI = Branch Bus VME Interface

of the program into a HOST and a NODE part. The HOST part handles reading the RAW data from tape, accessing information from on-line data-bases, transferring the data after some short data-integrity checks to the next available node, and collecting results from the nodes. The NODE part handles processing the data and transforming the RAW information into physical quantities. Because of the limited Fortran compiler running on the nodes, the NODE programs had to be changed to standard Fortran 77 and all "Common Blocks" that need to be transferred from the VAXstation to the nodes had to be separated into ones containing real or integer variables.

Estimates based on a limited DST production done last year at the 8650 cluster at Berkeley show that about 9300 hours of 8650 cpu time would be required to process only the WABO sulfur data. Assuming \$30 for a nonprime cpu hour (i.e., nights and weekends) at the STC cluster, this adds up to \$280K. This does not include renting disks and analyzing the produced DST tapes. Further assuming an availability of around 100 cpu hours a week, the whole DST production would have taken 92 weeks of continuous processing on the STC VAX 8650 cluster at ORNL.

The part of current ACP Farm setup that is dedicated to DST production is equivalent to 28 VAX 11/780s or 4.6 VAX 8650s. It is accessible to us all the time. We found that new cluster routines which are much more consumptive of cpu time had to be installed in part of the code to improve the physics analysis. In spite of this, we will be able to produce all DST tapes in less than 20 weeks.

Figure 2.62 shows two control spectra produced on the Farm from a typical S + Al run at $E/A = 200$ GeV. The upper graph shows the number of events processed per node, indicating that all nodes, on average, process the same number of events. We noticed that with the older 68881 floating point coprocessor, the number of events processed per node is about 20% less than with the new 68882 processor for a given elapsed clock time.

The lower graph shows the cpu time per node per event. The spike at small cpu times corre-

Fig. 2.62. Control spectra from an $E/A = 200$ -GeV S + Al run. The upper graph shows the number of events processed per cpu and the lower one illustrates the cpu time in seconds needed per node per event.

sponds to events which are rejected by cuts on trigger detectors and other data-integrity checks. These are done first in the program to avoid processing further events which do not pass them. On average, the nodes spend about 70 seconds per S + Al event.

With the Farm fully operational now, we are not only able to process our DST tapes but also to analyze the data afterwards, and produce high statistic Monte Carlo runs needed for comparison with our data.

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EVENT-GENERATOR CODES FOR HIGH-ENERGY HEAVY-ION COLLISIONS

T. C. Awes S. P. Sorensen¹

The work on Monte Carlo codes for high-energy nuclear collisions that was started at the Joint Institute Workshop in September 1988 has continued in 1989. For most of the codes, we have received and implemented new versions. In most

cases the changes were due either to errors in the codes located during the workshop or to improvements inspired by our discussions.

The standardized Monte Carlo code interface has been improved. All codes are now running on the IBM 3090/200E at The University of Tennessee Computing Center, and several codes have been rewritten and implemented on the ACP parallel computer system in the ORNL Physics Division.

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KOBA-NIELSEN-OLESEN SCALING, INTERMITTENCY, AND STATISTICS

T. C. Aves

The field of multiparticle production received a great deal of early motivation by the suggestion of Koba, Nielsen, and Olesen (KNO)¹ that, based on Feynman and geometric scaling, the scaled particle multiplicity distribution $\psi(Z) = \bar{n}P(n)$, where $Z = n/\bar{n}$ is the ratio of the particle multiplicity to the average particle multiplicity, should have an energy-independent asymptotic form. A revival of interest in the topic of multiparticle production has occurred within the last few years, driven partly by the experimental results from the CERN Sp $\bar{p}$ S collider, which have indicated large KNO scaling violations.^{2,3} More recently, intense interest has been generated by the suggested analyses of the scaled factorial moments of the particle multiplicity distribution in rapidity intervals⁴ of decreasing size. These analyses have shown an unexpectedly large increase of the scaled factorial moments⁵⁻⁸ which has been interpreted as an indication of cascading in the particle production process, analogous to the development of turbulence in hydrodynamics, also referred to as intermittency.⁹

A particle multiplicity scaling distribution has been derived with no a priori assumptions on the actual production mechanism itself. The only necessary assumption is that the observed multiplicity distribution is the result of many similar independently contributing production

sources. For concreteness, the production sources might be viewed as segments of the fragmenting strings in a string model picture. The final result for the "statistical" KNO distribution is given here without derivation as

$$\psi(Z) = \frac{1}{Z/2\sigma^2} \exp \frac{-(\ln Z + 1/2 \sigma^2)^2}{2\sigma^2} \quad (1)$$

It involves a single parameter σ^2 which is the scaled variance about the mean. To paraphrase the derivation of this result, in essence, a central limit theorem argument is used to obtain a gaussian distribution; as expected, however, not in the variable Z distributed on $[0, \infty]$ with a mean of 1, but in the quantity $\ln Z$ which is distributed on $[-\infty, \infty]$ with a mean value of 0.

In Fig. 2.63 the statistical KNO function of Eq. (1) is shown evaluated with $\sigma^2 = 1/12$ and $\sigma^2 = 1/4$, which give quite reasonable agreement with results from PEP and UA5, respectively. Our intention is not necessarily to reproduce experimental results in detail, but rather to understand more clearly which features of the experimental results arise from (uninteresting) statistical effects and which are indicative of the more interesting underlying physical processes. The fact that the statistical KNO function provides a reasonably good description of the observed KNO distributions would seem to give some validity to the assumption of many independent production sources, and even suggests the general nature of the KNO functional form, which, in this case, required essentially no assumptions on the dynamics.

The scaled moments of the multiplicity distributions may be calculated directly from the statistical KNO function as

$$C_q \equiv \langle Z^q \rangle = \exp \left[\frac{1}{2} q(q-1) \sigma^2 \right] \quad (2)$$

We also would like to obtain an expression for the scaled factorial moments of the derived statistical KNO distribution. To do this we simply note that the normalized variance about the mean is given by $\sigma^2 = C_2 - 1$. Therefore, we may use the general result that $C_2 = F_2 + 1/\bar{n}$ and replace $\sigma^2 = C_2 - 1$ to obtain the desired relation for the scaled factorial moments,

Fig. 2.63. KNO scaled multiplicity distributions $\varphi(Z) = \bar{n}P(n)$. The data shown are for $p\bar{p}$ collisions at $\sqrt{s} = 546$ GeV from UAS (Ref. 3) (open points) and for e^+e^- collisions at $\sqrt{s} = 29$ GeV from the HRS at PEP (Ref. 14) (solid points). The KNO function, $\varphi_{\text{KNO}}(Z) = 45.1 Z^{3.07} \exp(-2.63 Z - 0.61 Z^2)$, fit to multiplicity distributions from nonsingle-diffractive events at energies below $\sqrt{s} = 62$ (Ref. 3) is shown by the solid curve. Two examples of the statistical KNO distribution obtained by Eq. (1) with $\sigma^2 = 1/12$ and $\sigma^2 = 1/4$ are shown by the long-dashed and short-dashed curves, respectively. Note that φZ of Eq. (1) has been multiplied by a factor of 2 to agree with the experimental normalizations, which result from charge conservation.

$$F_q \equiv \langle Z(Z-1)\dots(Z-q+1) \rangle = \exp\left[\frac{1}{2} q(q-1)\sigma^2\right]. \quad (3)$$

Recently, Bialas and Peschanski⁶ have proposed to study the behavior of the scaled factorial moments of the experimental multiplicity distributions as the total rapidity interval Δy is divided into bins of decreasing size according to $\delta y = \Delta y/M$ with, for example, $M = 2^v$; $v = 0, 1, 2, \dots$. The scaled factorial moments of the experimental multiplicity distribution corresponding to the bin size δy averaged over all M bins are then calculated according to

$$F_q(M) = M^{-1} \sum_{m=1}^M \frac{n_m(n_m-1)\dots(n_m-q+1)}{(\bar{n}_m)^q}, \quad (4)$$

where n_m is the observed multiplicity in the m^{th} bin.⁹ The average $\bar{n}_m$ is usually evaluated for inclusive distributions as $\bar{n}_m = \langle ND \rangle / M$ where $\langle ND \rangle$ is the average total multiplicity for the full-rapidity interval. The scaled factorial moments of Eq. (4) are calculated for each event and averaged over all events to obtain $\langle F_q(M) \rangle$. Recent experimental results^{5,8} have indicated that the scaled factorial moments increase approximately as a power of the decreasing bin size according to

$$\langle F_q \rangle = b_q [\Delta y / \delta y]^{\phi_q} \quad (5)$$

or equivalently,

$$\ln(\langle F_q \rangle) = a_q - \phi_q \ln(\delta y). \quad (6)$$

The increase in the F_q with decreasing bin size observed experimentally is greater than predicted by current hadronization models. This apparent deficiency in our understanding of the hadronization process has prompted a great deal of theoretical activity. It has been shown that such a power-law dependence can arise from a self-similar cascading or branching process similar to the phenomena of intermittency in the field of turbulence.⁹ The observed power-law dependence of the moments has been interpreted as evidence for cascading⁹ or scale-invariant branching,¹⁰ as a simple Bose-Einstein effect,¹¹ and also as a signature of emission from quark-matter droplets.^{12,13} It was also predicted that for the case of a cascading process with a large number of steps, the exponents ϕ_q for the higher moments should be related to that of the second moment according to Ref. 9,

$$\phi_q = \frac{1}{2} q(q-1)\phi_2. \quad (7)$$

This relationship appears to be confirmed by experimental results.⁷

We wish to study the expected behavior of the scaled moments $C_q(M)$ of Eq. (2) and of the scaled factorial moments $F_q(M)$ of Eq. (3) for decreasing rapidity intervals utilizing the assumption that the particle production is the result of many independent sources. To do this, it is only necessary to replace σ^2 with the scaled variance about the mean for the bin size under consideration, $\sigma^2(M) \equiv [D_2(M)/\bar{n}_m]^2$. This

is immediately evaluated as $\sigma^2(M) = M\Delta_0^2/\langle N \rangle$, where we have used the fact that $\bar{n}_M = \langle N \rangle/M$ and $D_2(M) = \sqrt{\bar{n}_M \Delta_0}$ with Δ_0 constant according to the assumption of independent sources and approximately according to observation. Similarly, $\sigma^2(M) = \sigma^2(M) - 1/\bar{n}_M = M(\Delta_0^2 - 1)/\langle N \rangle$. We may now evaluate the scaled factorial moments for the statistical distribution in bins of size δy as given by

$$F_q(M) = \exp\left[\frac{1}{2} q(q-1)(\delta y)^{-1}\phi\right], \quad (8)$$

where $\phi = (\Delta_0^2 - 1)/\langle \rho \rangle$ with the average particle rapidity density written as $\langle \rho \rangle = \langle N \rangle/\Delta y$. For small $(\delta y)^{-1}\phi$, Eq. (8) may be expanded as

$$\ln[F_q(M)] = \frac{1}{2} q(q-1)\phi - \frac{1}{2} q(q-1)\phi \ln(\delta y). \quad (9)$$

This is seen to be in exactly the form of Eq. (6) with the identification that $\phi_q = 1/2 q(q-1)\phi$ with $\phi_2 = \phi$, which also shows that the relationship between the moments of Eq. (7) is immediately satisfied.

Although the result of Eq. (8) is general and applicable for any case of many independent particle-producing sources, it is of interest to evaluate the dependence expected for a source which produces particles according to a distribution of the negative-binomial form. In this case, $\Delta_0^2 = [1 + \bar{n}/k]$, from which it follows that

$$\phi = \langle \rho \rangle^{-1} \bar{n}/k. \quad (10)$$

For a Poisson production process, $\bar{n}/k = 0$; and we obtain the exact result $F_q(M) \equiv 1$ expected for a Poisson distribution. For e^+e^- reactions it is observed that $\bar{n}/k = 0.1-0.2$, and since $\langle \rho \rangle = 2-3$, it is expected that $\phi = 0.05-0.1$, in reasonable agreement with observations.⁵ For hadron-hadron collisions the value for ϕ is expected to be similar, since the fragmentation process is presumably the same and since the average particle rapidity densities are similar. Also, as observed, the value of ϕ is clearly expected to decrease in hadron-nucleus and nucleus-nucleus collisions⁶ due the large increase in the density of produced particles, especially for small impact parameters.⁷ Since $\langle \rho \rangle$ increases only slowly with energy, it is to

be expected that ϕ should show only a moderate decrease with increasing energy.

Since the result of Eq. (8) is approximate, in the sense that it was derived under the assumption of a large number of similar sources which are only characterized by their variance, it is of interest to compare the expected results with those of a Monte Carlo calculation in which one samples from a known distribution. A Monte Carlo calculation has been performed in which multiparticle events were created with particles distributed into an array of 1024 bins. The "experimental" average scaled factorial moments were calculated from the Monte Carlo results according to Eq. (4) in bins of decreasing width from $w = 1$ to $w = 1/1024$ in factors of 2. For each event, particles were created by sampling from a parent distribution of negative-binomial form in each of the 1024 bins. The results of the Monte Carlo calculations are shown in Fig. 2.64, in which $[1/2 q(q-1)]^{-1} \ln F_q$ is plotted against $-\ln w$. In Fig. 2.64 the results for a negative-binomial parent distribution are shown for F_5 (solid triangles) and also for F_2 (open triangles) and are compared with the result expected from Eq. (8) (solid line) with the corresponding value of $\phi = 1/1024$. The simulation results are seen to be in good agreement with expectation and also show the expected relation of Eq. (7) between the moments. Also shown in Fig. 2.64 are the results from a Poisson production source calculation (solid and open circles), which is similar to the negative-binomial calculation with the exception that, rather than sampling from the parent distribution once for each of the 1024 bins, the parent distribution is sampled 1024 times but randomly distributed into any of the 1024 bins. In this case the distribution for the full interval is strictly Poisson and the average multiplicity in each bin is $\bar{n} = 100/1024$, but the fluctuations in the smaller bins are larger than Poisson since multiple samplings may fall into the same bin. It is interesting that this purely Poisson production source calculation with "rapidity fluctuations"

Fig. 2.64. Results of a Monte Carlo calculation of particle production. The scaled factorial moments F_q are calculated from the Monte Carlo results according to Eq. (4). The quantity $[1/2 q(q-1)]^{-1} \ln F_q$, which should be q -independent [see Eq. (8)], is plotted against $-\ln w$, where w is the bin width. The solid points show the results for F_5 , and the results for F_2 are shown by the open points. For each set of results, 10^5 events have been produced with an average multiplicity of 100 particles per event. Results are shown for (1) a negative-binomial with $k = 1$ by triangles ($\sigma_T^2 = 111.0$); the solid line shows the result expected according to Eq. (7); (2) a fluctuating Poisson by circles ($\sigma_T^2 = 100.3$); and (3) a cascading process by squares ($\sigma_T^2 = 173.2$). For $-\ln w > 4$ it is found that $\ln F_5 < 0$ for the cascading process calculation.

can give rise to an apparent negative-binomial multiplicity distribution with an effective value of $\phi = 1/1024$ when studied in small intervals. In general, the effect of such "rapidity fluctuations" is to increase the multiplicity fluctuations within a bin and hence to increase ϕ whether the sampled parent distribution is binomial, Poisson, or negative-binomial. The slope of the solid line corresponds to the w^{-1} dependence expected for uncorrelated w bins.

In Fig. 2.64 the square points show the results for a cascading process according to the so-called α -model of Ref. 4. The result of the random cascading calculation shows a much different behavior than the other calculations. In this case the relative fluctuations on the entire interval are large, but as smaller intervals are analyzed, the relative fluctuations first increase and then decrease as the distribution

becomes smoother, even binomial in nature, at the smallest bin widths. The initial power-law dependence of the scaled factorial moments on the bin size, observed in general for the cascading process, is weaker than the exponential rise observed for statistically independent processes. The observation of large fluctuations occurring on the full-rapidity interval and the weaker power-law dependence therefore provide a clear signature with which to discriminate a cascading fragmentation process from fragmentation arising from many independent subprocesses. It is interesting to note that the higher moments can be related to the second moment according to Eq. (7) to a good approximation for both the cascading process and the statistically independent subprocesses. This result implies that neither the observed increase of the scaled factorial moments nor the observation of scaling according to Eq. (7) provide conclusive evidence for a cascading process.⁹

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SPACE-TIME DEVELOPMENT OF THE ENERGY DENSITY IN HIGH-ENERGY NUCLEAR COLLISIONS

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A central question in the field of high-energy nuclear collisions is the magnitude of the attained energy densities. Conventional wisdom, based on lattice QCD calculations, tells us that a phase transition between a hadron gas and the deconfined quark-gluon plasma takes place around 2 GeV/fm^3 with theoretical uncertainties as large as a factor of 2 in both directions. Unfortunately, the energy density is not a direct observable, but has to be inferred indirectly from measurements of, for example, transverse and forward energy distributions. Usually the so-called Bjorken's formula has been used to relate the transverse energy rapidity density at midrapidity, $dE_T/d\eta|_{\text{max}}$, to the energy density $\epsilon = 1/(\tau_0 \pi R^2) dE_T/d\eta|_{\text{max}}$, where πR^2 is the transverse area of the projectile and τ_0 is the crucial formation time. This formula is derived under a number of assumptions which seem only to be fulfilled at much higher c.m. energies than obtainable at the SPS accelerator at CERN.

In order to obtain a more realistic estimate of the energy density, we have constructed a space-time model for the development of the energy density. The model contains the same fundamental assumptions as most nuclear collision string models, such as the LUND model or the Dual Parton Model, but without specific reference to discrete nucleon-nucleon collisions: (a) Each volume element of the projectile (target) produces energy at a rate which decreases exponentially with the traversed path length in the target (projectile). The overall energy production is governed by the momentum degradation length λ . (b) In the rest frame of the produced field energy, it takes the time τ_0 before the energy materializes and contributes to the energy density of strongly interacting particles. During this time the field energy is expanding only longitudinally. (c) After their formation, the produced particles are free-streaming with an exponential pT

distribution (characterized by the inverse slope T) and a Gaussian rapidity distribution (characterized by the width σ_Y).

Three of the four free parameters can be fixed by comparison to the WA80 experimental data: (1) The SAPHIR pT spectra of π^0 's give $T = 0.2 \text{ GeV/c}$. (2) The width of the $dE_T/d\eta$ spectra from MIRAC fixes σ_Y to 1.0 and 1.2 at 60 A and 200 A GeV, respectively. (3) The value of λ is determined to be around 4 fm from the measured values of $dE_T/d\eta|_{\text{max}}$ in central collisions. The formation time can either be viewed as a free parameter or estimates can be obtained from other sources. Experimental and theoretical estimates range from 1/3 to 2 fm/c.

In Fig. 2.65 is shown the time dependence of the energy density averaged over a cylindrical volume of 50 fm^3 at the space-center of the collision of $^{16}\text{O} + ^{197}\text{Au}$ at 15, 60, and 200 A GeV. The formation time has been assumed to be 1 fm/c. The energy density attains a maximal value around 1 GeV/fm^3 for 200 A GeV, in contrast to the Bjorken estimate which is slightly above 2 GeV/fm^3 . The main reason for this difference is that, in contrast to the Bjorken model where all the energy is released instantaneously, this model takes into account the gradual conversion

Fig. 2.65. Time dependence of the energy density averaged over a cylindrical volume of 50 fm^3 for $^{16}\text{O} + ^{197}\text{Au}$ at 15, 60, and 200 A GeV.

of kinetic beam energy into field energy as the nuclear overlap develops. Since the size of the target is of the order of 1 fm in the c.m. system, the formation time and the collision time are of the same magnitude. At higher energies the energy densities will be dominated by the formation time, whereas at lower energies the slower collision time will dominate the space-time development of the energy density. The maximal volume-averaged energy density at 60 A GeV is only around 0.6 GeV/fm³, and at 15 A GeV it is reduced to 0.25 GeV/fm³. At the lowest beam energy, several assumptions in the model are, however, questionable; and a more realistic estimate of the total hadron energy density, including the energy densities of the colliding baryons, will give larger values of ϵ .

The dependence of the energy density ϵ_{max} at the center of the collision on τ_0 is illustrated in Fig. 2.66 with a slightly different set of parameters (λ , σ_T , and $\langle p_T \rangle$). The inverse dependence from the Bjorken formula is also seen here, but a reduction of τ_0 by a factor of 2 only increases ϵ by approximately 1.7. Finally, Fig. 2.67 illustrates the projectile-target

Fig. 2.66. Time dependence of the maximum energy density for three different formation times τ_0 .

Fig. 2.67. Projectile-target dependence of the energy density.

dependence of ϵ . The increase of ϵ in going from 200 A GeV $^{16}\text{O} + ^{197}\text{Au}$ to $^{208}\text{Pb} + ^{208}\text{Pb}$ is approximately a factor of 2.

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MISCELLANEOUS TOPICS

DATA COMMUNICATIONS AND COMPUTER NETWORKING

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Computer networking, with both local-area networks (LAN) and wide-area networks (WAN), is an essential "tool" for the conduct of nuclear physics and indeed for all of the research activities conducted in the Physics Division. A conscious recognition of the importance of data communications and wide-area networking to nuclear physics research by funding agencies has been achieved and a forthcoming report¹ has documented this important dependence.

For the DOE Office of Energy Research, of which the the High Energy and Nuclear Physics

Program Office (HENP) is a part, an "umbrella" networking venture called the Energy Sciences Network, ESnet, is evolving to meet the requirements of all of the OER programs. The networks originally initiated to meet specific individual programmatic needs will be incorporated within ESnet and this includes the large DECnet network traditionally used by High Energy and Nuclear Physics. The ESnet concept will provide superior networking capabilities for all of the DOE/OER programs. It will provide interconnectivity to other large U.S. research networks such as NASA's Space Physics Analysis Network (SPAN) and the NASA Science INTERNET, to the National Science Foundation backbone network (NSFnet), and to others; and it will provide shared international connectivity. The merging and coalescence of U.S. research networks is being implemented in stages as part of the implementation of the National Research and Education Network (NREN), an as yet unfunded program to eventually provide a shared research network operating at gigabit-per-second trunk speeds.

For the ORNL Physics Division, improvements in both LAN and WAN speed, connectivity, interoperability and efficiency have continually been made over the past few years. Currently, the Physics Division, and all of the OER-supported programs at ORNL, have WAN DECnet connectivity to the ESnet/DECnet at 56 kbps. This allows network connections to over 17,000 globally distributed nodes/hosts and interconnectivity with most of the worlds DECnets used for research purposes. Improvements, as a result of the ESnet implementation at ORNL, will allow connections at T1 trunk speeds (1.544 Mbps) on a dual-protocol ESnet trunk. The ESnet protocols are DECnet and the DOD Internet protocol, IP.

To further the WAN capability of the Physics Divisions computing resources, most of the main computers in the Division have implemented software that allows the TCP/IP protocol suite to be used, in addition to the usual DECnet protocols. The TCP/IP implementation allows more straightforward connections to/from the Physics Division

by many outside university users of the HHIRF, most of whom use WAN connections connected to the NSF regional networks. This IP connectivity, by virtue of ORNL's connections to the NSF regional network, SURAnet, currently operates at T1 speeds and will be improved by the ESnet implementation.

1. "Report of the Nuclear Physics Panel on Computer Networking," DOE Energy Research Report, Nuclear Physics Program Office, to be published, September, 1989.

INSTRUMENTATION

GAMMASPHERE R&D

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Experiments using the GAMMASPHERE are expected to produce a very high data rate (up to 10,000 events per second with up to 200 bytes per event). The data acquisition system will collect data from multiple sources, build the events, and distribute them to members of a parallel computer system. The parallel processor system will examine, modify, and select the data and direct an event-data stream and a histogram-address stream to a host processor with tape drives, large memory, and disks. A prototyping system, as shown in Fig. 2.68, is designed to test hardware and software options. It consists of a RISC host processor with a work station, disk, and tape drives. A VME-bus-based parallel processor system with fast event readout hardware is connected to the host.

The design of the mechanical support of the GAMMASPHERE is shown in Fig. 2.69. This design derived from considering the mechanical stress and the method of assembly and installation of the detectors. Six supporting assemblies, each with four rods separated so that a Ge detector can fit inside, are used. The assemblies are supported by kinematic mounts which allow for position adjustment. The design of a platform for accessing detectors located on the upper part of the sphere has also been studied.

Fig. 2.68. Conceptual block diagram of prototype data-acquisition/processing system.

Fig. 2.69. The mechanical support of the GAMMASPHERE.

The inner ball of the GAMMASPHERE will have 240 elements, placed in front of the BGO anti-Compton shields. It will protect the BGO suppressor elements from direct gamma-ray hits which cause false veto of the Ge signal. In the current design, BaF₂ was used for the inner

ball. The light output from BaF₂ has two components with wavelengths centered at 210 and 315 nm, respectively. The rise time of the 210 nm component is extremely fast, and a good timing signal can be derived from it. Therefore, the BaF₂ inner ball can further provide an event trigger pulse and distinguish gamma rays from neutrons by time-of-flight measurements.

Since the inner ball is located inside the shell of Ge and BGO detectors, it has restricted access ports, which makes the light collection a challenging problem. Several options are being investigated: (1) use a quartz light guide to transmit the UV light to a phototube located outside the shell; (2) use small (1-cm-diam) phototubes fitted inside the BGO shield; and (3) use a wavelength shifter together with photodiodes. It should be noted that if efficient wavelength shifting is achieved, it could be employed to eliminate the need for a quartz PMT in options (1) and (2) above.

While primary R&D efforts are devoted to investigations directly related to the standard honeycomb design described in the GAMMASPHERE proposal, it is prudent, even at this stage, to consider options. A property crucial to the performance of an array like GAMMASPHERE is the total photopeak efficiency of the array, conventionally denoted by the product $Nq\epsilon$, where N is the number of Ge detectors in the array, q is the solid angle subtended by each Ge, and ϵ is the photopeak efficiency of each individual Ge element. For the proposed GAMMASPHERE design $Nq\epsilon = 0.09$ ($N = 110$, $q = 0.00421$, so $Nq = 0.46$, and $\epsilon = 0.2$). In principle, dramatic improvements in ϵ can be made by using larger-diameter Ge detectors. In practice, there are many problems with this approach, the overriding one being that Ge detectors of the GAMMASPHERE design with radii significantly greater than the 3.5 cm are not likely to be available in large numbers for some time. Many of the benefits of larger Ge detectors can be obtained, however, by grouping smaller detectors together in closely packed clusters and using them in an "add-back" mode, where, under appropriate conditions, the output from neighboring detectors is added.

This is illustrated in Table 2.6 where the photopeak efficiency is tabulated for ideal clusters of cylindrical 3-cm-radius and 7-cm-long Ge detectors as a function of the number (n) of crystals in the cluster for 1.33-MeV photons emanating from a point 27 cm from the face

Table 2.6. Total photopeak efficiencies for various close-packed Ge configurations, as a function of the number of Ge detectors, n.

n	ϵ
1	0.178 (3)
2	0.209 (6)
3	0.217 (3)
4	0.256 (7)
7	0.296 (3)

of the cluster. These results were obtained with the simulation code GEANT3. It might appear from Table 2.6 that an ideal array would be made entirely of close-packed Ge detectors. However, if other effects, such as crystal-to-crystal scattering from non-nearest neighbors, true hits on adjacent detectors, etc. are considered, it is found advisable to limit clusters to approximately 7 detectors, with adjacent clusters separated by an active high density material (e.g. BGO). Two things should be noted about Table 2.6. First, the clusters consist of cylinders with no taper. Use of hexagonal detectors improves ϵ to about 0.31 for the 7 cluster, while tapering the Ge crystals can give further improvements in excess of 10%. The second point is that even the untapered cylindrical geometry of Table 2.6, with its zero crystal-to-crystal separation, cannot be obtained from manufacturers at present, much less the hexagonal or tapered configurations mentioned above.

We have thus concluded that it is not practical to consider construction of a truly high performance array based on Ge clusters on the timescale of the GAMMASPHERE project. We next considered a more limited option, namely, can we develop a design which can take advantage of close-packed cluster geometry when the Ge tech-

nology permits? In the search for such a design, we established the following ground rules: (1) The initial (un-upgraded) implementation will feature performance at least equal to the standard design. (2) The cost of the initial implementation should be comparable to the standard design. (3) The initial implementation must be realizable with current technology. (4) The upgrade cost (to the extent that it can be foreseen) must be within range of reasonable funding expectations.

The four points outlined above seem to us to require that a design that will be able to take advantage of close-packed clusters of exotically shaped Ge crystals when they become available, will have to be based on a cluster concept from the beginning, even though the initial implementation of the clusters will be far from optimal. In particular, the initial clusters will have to be based on cylindrical untapered Ge of modest size, in separate conventional cans, which will require relatively large crystal-to-crystal spacing. The basic structural subunit of such a design is shown in Fig. 2.70. It is based on a hexagonal arrangement of BGO surrounding a 7-detector Ge cluster. At each corner of the basic hexagon a large hexagonal BGO piece is inserted to be shared between three cluster units. The front of this piece is covered with BaF₂ (inner ball), which extends to the outside through a large-diameter cylindrical hole in the BGO corner piece. There are various ways to realize a full array with these subunits. The ones which are practical for our purposes are based on the 32-element or 42-element geodesics consisting of 20 and 30 hexagonal units, respectively. Both contain 12 pentagonal units which would look similar to Fig. 2.70, but would hold only 3 Ge clusters (if only a single Ge size were used). The 32-unit arrangement would therefore contain 170 Ge crystals (assuming two pentagons used for beam entrance and exit), and the 42-unit version would require 240 detectors. The geometries of the subunits are not very different for these two options. One possibility would be to build units for the 42-detector version but arrange them initially (imperfectly) in

Fig. 2.70. Cross sectional views of the detector arrangement used in the sample cluster simulation. The diameter of the Ge detectors is 6 cm. The location of the plane of each cut is indicated by the dotted line on the other cut.

a 32-unit design. The performance of an array of this sort is documented in Table 2.7, based on Ge detectors of 3-cm-radius and 7-cm length. Table 2.7 gives the results of simulations (1.33-MeV γ ray) on the value of ϵ for a single hexagonal 7-Ge unit, as a function of the detector-to-can gap (crystal-to-crystal separation is twice this). Also shown is the target-to-central detector-face distance d for the 42-detector implementation and the total array values of N_0 and $N_{0\epsilon}$ for the full array. Note that the values for the full array include 10 pentagons with 3-detector clusters and assume two empty pentagons.

We see from Table 2.7 that in order to meet the first criterion above, a crystal packing with a detector-to-detector spacing of (approx-

mately 5 mm (gap = 2.5 mm) would have to be achieved. The ultimate upgraded performance of the 42-element version, assuming tapered hexagonal detectors with a gap of 1.5 mm, would be $N_{0\epsilon} = 0.25$. While this design meets the basic criteria listed above (if it were initially implemented in a 32-element version), it represents a radical departure from the proven technology of the standard design, and, at best, must be considered a high-risk option. The principal virtue is that it is potentially upgradable to an array of much better performance in a simple stepwise way without major reconfiguration.

1. CERN document, GEANT3 CERN-DD/EE/84-1.

THE BaF₂ PROJECT

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Detection of high-energy γ rays now plays a major part in many experiments carried on by ORNL physicists and their collaborators, both at the HHIRF and other facilities. Over the past two years we have designed and assembled an array of BaF₂ detectors and associated mounting hardware and electronics, which can vastly improve the quality of high-energy γ -ray data in such experiments. Our goal was to provide a portable, flexible, easily reconfigurable array optimized for detection of the 10- to 200-MeV γ rays, and a self-contained electronics package, including freestanding setup, control, and monitoring capabilities. The large neutron background and very low yield of high-energy

Table 2.7. Properties of the seven detector close-packed configuration as a function of the gap parameter

Gap (cm)	$\epsilon(7\text{-det.})$	$d(42)$	$N_0(42)$	$N_0(32)$	$N_{0\epsilon}(42)$	$N_{0\epsilon}(32)$
0	0.296	31.46	0.547	0.529	0.156	0.149
0.1	0.280	32.4	0.514	0.498	0.139	0.133
0.2	0.279	33.35	0.486	0.470	0.130	0.124
0.3	0.277	34.30	0.458	0.444	0.122	0.117
0.5	0.260	36.18	0.411	0.398	0.103	0.099

γ rays in heavy-ion reactions make n - γ separation a major problem in most experiments. BaF_2 scintillators make excellent high-energy γ -ray detectors for heavy-ion physics, primarily because their excellent timing performance and relative insensitivity to neutrons greatly improves this separation. A more complete discussion of the advantages of BaF_2 over other scintillators and the details of the detector shapes and of the array has been given in previous reports.³

The BaF_2 array will be used primarily to investigate extremely small cross-section processes. Because of this, and because of the simple modular geometry of the array, the size of the completed array is open-ended, essentially determined by financial considerations. These considerations limited the current stage of the array to 77 elements (6.5 cm x 20 cm hexagonal crystals). This initial stage has now been completed. This is sufficient to build four stacks of 19 close-packed detectors with one spare. All detectors have been extensively tested; only eight of the 56 detectors delivered this year were rejected, due to poor timing and transmission performance. Six of these remain to be replaced. The performance of the detectors in terms of energy resolution was better than expected. The average resolution at 662 keV was 10.4%, ranging from 9.1 to 11.7%. These values are well below the specifications set at 12%. The resolution varies for all detectors accurately with $1/\sqrt{E}$ and reaches, on the average, 4.2% at 4.4 MeV. The low internal α count rate of ~ 140 cts/s above 1 MeV is insignificant for the current uses of the array. The time resolution was measured with a setup similar to the actual experimental conditions using a ^{60}Co source. The average time resolution (FWHM) was below 500 ps.

In addition to the crystals, 86 photo-multipliers were delivered, tested, and accepted. The time resolution of these Hamamatsu R2059 quartz window photomultiplier tubes was on the average 350 ps.⁴ The detectors will be predominantly used in stacks of 19. Cans for four

stacks have been built, which can be mounted in two height and angle adjustable stands. Mounts are also available to allow stacks of 19 BaF_2 detectors to substitute for single elements of the Spin Spectrometer, thus making possible high-energy γ -ray detection in coincidence with the detailed information on low-energy γ rays and neutrons which this 4 π array can provide.

The electronics sufficient for the four stacks is also essentially complete, including three types of modules developed specifically for this project. These include a high-density ECL logic delay which provides up to 600 ns of adjustable delay with a time jitter of less than 100 ps, and computer-controlled linear and logic multiplexors. A separate data acquisition system, based on the MacVEE system⁵ developed by the UAI experiment at CERN, is being assembled. This system will be used to set up, monitor, and control the array and its electronics, independent of the primary data acquisition computers. All the necessary hardware has been purchased, and the system already performs basic data acquisition in the CAMAC environment.

In February 1989, the first set of 19 detectors was successfully used in an experiment measuring the limits of collectivity in hot nuclear matter. In May, three 19 packs were used in a complex experiment in coincidence with the Spin Spectrometer, the Dwarf Ball/wall, and a PPAC, studying nuclear bremsstrahlung photons emitted from heavy ion collisions. The final setup of four packs was installed in the summer for two experiments measuring the giant dipole resonance (GDR) built on highly excited states in heavy ion fusion reactions.

Further tests to investigate possible performance improvements are under way. The slow scintillation component of BaF_2 , containing most of the total light output, is strongly temperature dependent. In order to measure this effect, one crystal was cooled well below room temperature. Figure 2.71a shows a strong pulse height decrease as a function of temperature. The linear fit to the data corresponds to about

Fig. 2.71. Pulse height (a) and the resolution (b) of a ^{137}Cs source as a function of temperature. (Note from the values in (b) that these data were obtained with a crystal with very poor energy resolution, which was not accepted as part of the array.

1.9% per °C at 20°C. Currently we have no electronic gain correction or temperature stabilization system available. At present we attempt to deal with this effect by monitoring the temperature in each detector pack electronically, and storing its value in the event-by-event data stream. Although the fluctuations of the room temperature (~21°C) during the recent experiments were slightly above 2°C, the temperature

inside the packs could be kept to within 1°C at a constant value of ~24°C.

The increase of pulse height (PH) with decreasing temperature offers the possibility to improve the resolution by lowering the operating temperature of the packs as shown in Fig. 2.71b. The solid curve represents a dependence of the resolution proportional to $1/\text{PH}$. Further tests of the feasibility of operating the detectors during an actual experiment at temperatures well below room temperature will be investigated.

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2. Instrumentation and Controls Division, ORNL.
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4. J. L. Blankenship, Phys. Div. Prog. Rep. for Period Ending Sept. 30, 1987, ORNL-6420, p. 123.
5. B. G. Taylor, CERN technical report, CERN-EP/88-67.

AN ORGANIC/INORGANIC SCINTILLATOR RING DETECTOR

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A 16-element $\Delta E/E$ (BC400 fast plastic scintillator/CsI (Tl) scintillator) phoswich ring detector, spanning from 20° to 27°, has been built to complement data taken with the HILI (Heavy Ion Light Ion) detector system. This addition should enhance the probability for full-event description of central collisions in inverse-kinematic heavy-ion reactions. The ΔE detector is a thin plastic scintillator about 100 microns thick. The thickness of the CsI(Tl) detector is about 1.5 cm. The front face is about 2 x 2 cm. The ring elements are positioned 14 cm away from the target inside the HILI scattering chamber.

Three particle identification modes have been used: $\Delta E/E$ mode, pulse-shape discrimination mode, and the time-of-flight mode. Fig. 2.72 shows the Z-spectrum from reactions of 320-MeV ^{32}S with ^{27}Al . Using data from the fast (thin)

Fig. 2.72. Z-Spectrum from 320-MeV $^{32}\text{S} + ^{27}\text{Al}$ reactions using the $\Delta E/E$ poswich technique, charged particles from $Z=1$ to $Z=16$ are well-resolved.

plastic scintillator for energy-loss measurements, one can identify all Z 's from 1 to 16 without any difficulty. By using the difference in the decay time of the CsI scintillation light for different particles, two different time gates (Q_2 : earlier and shorter gate, Q_3 : later and longer gate) were used to further identify light particles according to mass. In Fig. 2.73 the new parameter ratio, Q_2/Q_3 , plotted vs Q_2 , shows a good separation between protons and alpha particles. One can also see the separation between protons, deuterons and tritons. A good time pick-off signal ($\text{FWHM} = 135\text{ps}$) can help in identifying some of the slow particles stopped in the ΔE detector using energy and time-of-flight information (time-of-flight for $E/A = 1$ is ~ 10 ns).

Fig. 2.73. Light-particle identification from pulse-shape discrimination. Q_2 is the earlier and shorter (400 ns) time gate; Q_3 is the later and longer (1500 ns) time gate.

CALIBRATION AND GAIN MATCHING SCHEME FOR THE HILI HODOSCOPE

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Experience has shown that proper calibration of all 192 HILI hodoscope elements requires several months. We have therefore developed a scheme wherein the overall gains of all elements can be fixed prior to data taking and monitored during acquisition.

The hodoscope elements are arranged in 16 vertical stacks. We detect the passage of fast muons through a vertical stack and use their energy loss as reference for gain setting.

A block diagram of the hodoscope trigger is shown in Figure 2.74. The muon trigger is provided by requiring that the scintillators fire in at least six rows, whether on- or off-line. Events associated with this trigger are processed immediately. This criterion is adequate to select muons which penetrate the whole stack. Subsequent examination of the hit pattern can select cases where the muons travel vertically. Figure 2.75 shows muon spectra with and without vertical selection. Prior to the experiment all

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Fig. 2.74. Signal processing logic for hodoscope trigger.

Fig. 2.75. Typical muon spectra with (right) and without (left) selection of vertical penetration.

the detector gains are set to place the muon peak in a predetermined channel (~ 100). This procedure fixes the overall gain of the system; and calibration data measured with this setup can be used in the analysis of future data.

THE MIDRAPIDITY CALORIMETER FOR THE RELATIVISTIC HEAVY-ION EXPERIMENT¹

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G. R. Young	

A sampling calorimeter designed for use at midrapidity in the relativistic heavy-ion experiment WA80 at CERN is described. Calibration and performance results are presented. Over the energy range of 2 to 50 GeV, the response of the midrapidity calorimeter was linear, and its energy resolution σ/E was found to be given by $0.014 + 0.11/\sqrt{E}$ and $0.034 + 0.34/\sqrt{E}$ for electromagnetic and hadronic showers, respectively. Signal ratios of 1.2 and 1.4 were obtained for the e/h ratio of the lead-scintillator electromagnetic section and the iron-scintillator hadronic section, respectively. The calorimeter provided an accurate transverse energy trigger. The response and resolution for high-energy heavy ions were slightly better than anticipated on the basis of the low-energy calibrations.

1. Texas A&I University, Kingsville, Texas.
2. Rudjer Boskovic Institute, Yugoslavia.
3. Joint Institute for Heavy Ion Research.
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1. Abstract of published paper: Nucl. Instrum. Methods Phys. Res. A279, 479 (July 1989).

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THE ZERO-DEGREE CALORIMETER
FOR THE RELATIVISTIC HEAVY-ION EXPERIMENT WA80
AT CERN¹

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Calibration and performance results are presented for a sampling calorimeter designed for use as a beam calorimeter at zero degrees in the relativistic heavy-ion experiment WA80 at CERN. This uranium-scintillator zero-degree calorimeter (ZDC) was found to have a linear response to heavy ions over the range 60 to 6400 GeV and an in-beam hadronic resolution ranging from $\sigma/E = 0.013 + 0.33/\sqrt{E}$ at low intensities to $\sigma/E = 0.02 + 0.67/\sqrt{E}$ at higher intensities. The e/h ratio of the electromagnetic section was measured to be 1.12 at 135 GeV. The ZDC operated reliably with incident beams of 3.2-TeV oxygen and 6.4-TeV sulfur at intensities of over 10^6 nuclei per spill. It provided a trigger both for minimum bias events and for violent central collisions.

1. Abstract of published paper: Nucl. Instrum. Methods Phys. Res. A279, 503 (July 1989).

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VALET-PLUS SYSTEM FOR ON-LINE DATA ACQUISITION

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The VALET-Plus² is a microcomputer system developed at CERN for use in equipment testing and control and for data acquisition. It consists of a Motorola M680x0-based VME module connected to a personal computer or other computer via an RS-232C link and/or Ethernet. Application software and ROM-resident libraries

execute in the M680x0 module, which has direct control of the VME bus and, through interface modules in the VME crate, of CAMAC, FASTBUS, or other equipment. The connected computer provides display, keyboard-control, and file-server functions.

We have set up a VALET-Plus primarily for use in our RHIC detector research and development work. Our initial implementation, which utilized an M68000 processor, has been used in making measurements of optical properties of scintillator materials and in studies of prototype detectors at the BNL AGS.

A measure of the data acquisition/on-line monitoring performance of this system was obtained as follows. The CERN-provided software/firmware package SPIDER was used to take data from CAMAC modules consisting of a TDC and an ADC. Three parameters, one from the TDC and two from the ADC, were histogrammed with HMINI, a CERN package which is essentially a subset of HBOOK and which is resident in the VALET-Plus ROM. The one 2K- and two 1K-channel spectra were plotted on the screen of a Macintosh Plus, which was connected to the VALET-Plus by an RS-232C cable and which performed the server functions. The system was driven by interrupts that were derived from the CAMAC graded LAM signal generated when the TDC was started and stopped by signals from a constant-repetition-rate pulser, and the system digitized and histogrammed pulser-derived signals. All data were analyzed (SPIDER analysis priority was set to 1), and no event-by-event data were written to tape. Figure 2.76 indicates the dead-time related losses in the system. The total number of counts in any of the spectra divided by the measured number of trigger pulses from the pulser (Counts/Triggers) is plotted versus the pulser repetition rate (Trigger Rate). The steps in the data imply that the system as tested was capable of analyzing ~650 events per second.

The system was used at the AGS without the SPIDER package to take data during tests of prototype detectors. The acquisition/analysis

Fig. 2.76. Performance of VALET-Plus system. Ratio of total number of counts analyzed to number of triggers delivered is plotted versus the trigger rate. Steps can be seen in the data that indicate when the system is busy and unable to accept a following event. This implies that the maximum data rate under these conditions (see text) is ~650 per second.

program, which was written in PILS,³ read an initialization file that defined the CAMAC setup and specified gating, histogramming, and parameter-calculation requirements for the on-line analysis. The program included a wait loop in which a CAMAC input register, used as a trigger module, was tested for the presence of a LAM. When this was detected, all parameters were read out and analyzed. Event-by-event data were transferred via Ethernet to the disk of a

VAXStation 2000 for storage. When this disk was filled the data were moved over the HEPNet to a larger disk on a MicroVAX at ORNL. The system operated in this way, with 45 one-dimensional and 4 two-dimensional histograms, was able to process ~5 events per 1.4-second spill at an AGS cycle time of 2.2 seconds.

We have recently upgraded our VALET-Plus by substituting an M68020/M68881-based processor for the M68000-based processor, which is reported to improve its speed by a factor of ~3 (Ref. 4). The system is presently being used in the evaluation of several hundred photo-multiplier tubes that will be used in new detectors for the RHIC detector R&D program. Plans for the VALET-Plus include using it as an event builder in runs at the AGS, in which it will read out data for some detectors from CAMAC modules, combine these data with other detector data transmitted over Ethernet, and then pass the assembled event over Ethernet to a MicroVAX for analysis.

1. Science and Engineering Research Semester Participant from University of Miami.

2. T. Berners-Lee et al., IEEE Trans. Nucl. Sci. NS-34, 835 (Aug. 1987).

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3. THE UNISOR PROGRAM

The University Isotope Separator - Oak Ridge is a cooperative venture of universities, Oak Ridge Associated Universities, Oak Ridge National Laboratory, the U.S. Department of Energy, and the State of Tennessee. The primary purpose of the UNISOR consortium is to investigate the structures and decay mechanisms of rare, short-lived atomic nuclei which are prepared by means of a magnetic isotope separator coupled to the accelerators in the Holifield Heavy Ion Research Facility. The accounts which follow describe work at the UNISOR facility or work associated with UNISOR research performed principally by investigators outside the Physics Division. Research and development activities at UNISOR by Physics Division staff members are included in the Nuclear Physics Section.

SEPARATOR DEVELOPMENT

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The UNISOR version of the FEBIAD-B2 ion source has successfully been in operation at UNISOR since April, 1987. Table 3.1 shows the variety of reaction products produced using different projectiles. Efforts during the past year have been toward improving the reliability of the carbide targets and extending the useful range of targets toward lower melting points. The use of carbides for targets is, in principle, a very useful technique since they have high melting points. Also, the targets can be made rather simple by using a small amount of material--which is especially important for rare, expensive isotopes or those for which thin foils are difficult to prepare. However, it was

found that the carbide targets were nonuniform and tended to burn out rapidly. We found that by preparing the carbide compound outside of the ion source and placing it on the graphite felt, a more uniform target was achieved. Also, the target holder was modified in order to provide some heat shielding, thus lowering the target temperature, which increased the carbide target lifetime by approximately a factor of 3.

The principle failure mode of the ion source has been the evaporation of the filament support. A new design was constructed and tested whereby the threads were moved to a cooler position. This has resulted in much greater filament lifetimes. In addition, some of the parts can now be reused, saving on construction costs.

The rare-earth isotopes are difficult to extract and ionize at the temperatures at which the FEBIAD-B2 source operates; therefore, the efficiency for these elements has been significantly lower than for some of the other elements. Since the spectroscopy of the rare earth elements is an important area of research, two programs to improve the efficiency have been undertaken. The first was to retry a very old technique whereby CCl₄ is introduced into the ion source. More than ten years ago, this technique produced poor results and also resulted in rapid ion source failure. By improving the control of the quantity of CCl₄ and using very small amounts, significant enhancement of production of samarium has been

Table 3.1. Reaction products with the corresponding targets obtained with the UNISOR FEBIAD-B2 ion source.

Target	Product
Mo	Cs, Sm, Eu, In
W, ¹⁸⁰ W-carbide	Pb, Tl, Hg
Ta	Au
Re	Pb
Pt	Po
Hf-carbide	Tl
Fe	As, Sn, In

achieved. In addition, the ion source lifetime was not affected for as long as the experiment lasted, 24 hours. Figure 3.1 shows the relative intensities of the 163-keV gamma transition from ^{137}Sm decay versus the current of mass 35 measured in the separator collection chamber. We took the current at mass 35 (^{35}Cl) to be a measure of the amount of CCl_4 introduced into the ion source. A factor of 18 improvement in efficiency has been found in three separate experiments. Carbon tetrafluoride (CF_4) has also been tested, with inconclusive results. It should be more reactive and less harmful to ion source parts; thus tests will continue.

The second approach to improving rare earths' efficiencies has been to modify the GSI design⁷ of the thermal ion source for the UNISOR separator. During this year, a source was built and off-line tests were made. Temperatures up to 2300°C have been achieved. The design permits temperatures up to 3000°C , although problems associated with the on-line separation of heavy-ion-induced recoils generally limits the temperature to about 2500°C . On-line runs should yield ionization for rare earths such as Pr, Nd, Pm, Sm, and Eu.

The current tape transport system has been in operation at UNISOR since 1981. A relatively

Fig. 3.1. Production of Sm as a function of quantity of CCl_4 introduced into the FEBIAD-B2 ion source.

minor problem has been tape slippage at the capstan. Since the tape position is determined by the number of steps of the stepping motor, any slip at the capstan will cause an inaccuracy in the tape position. While this occurs infrequently, it is difficult to predict and prevent; thus a more positive method for locating the tape was developed. The new system utilizes holes punched in the tape at the correct distances. A circuit was tested which takes a signal from the computer that starts the stepping motor. A LED senses when the next hole has moved into position and stops the stepping motor. In tests in which slippage was purposefully introduced, a positioning of better than 0.5 mm was achieved. While the new system has less flexibility in the distance the tape can be moved in practice, this does not seem to be a drawback.

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5. UNISOR, Oak Ridge Associated Universities, Oak Ridge, Tennessee and Vanderbilt University, Nashville, Tennessee.
6. University of Maryland, College Park, Maryland.
7. R. Kirchner, K. H. Burkard, W. Muller, O. Klepper, Nucl. Instrum. and Meth. 186, 295 (1981).

OPERATION OF THE ^3He : ^4He REFRIGERATOR

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The ^3He : ^4He dilution refrigerator was reinstalled by the vendor in June this year and operated successfully during two long run periods in July and August. During the first, a series of tests were made, and in the second, on-line and off-line experiments provided additional information on the performance.

A base temperature of 4.4 mK was indicated by a $^{60}\text{CoQ}(\text{sc})$ thermometer when all radiation

shields were closed. This is the coldest temperature that, to our knowledge, any on-line system reaches.

Heat loads were applied and the base temperature was measured. These measurements provide an indication of cooling power of the unit and the minimum temperatures that might be expected under various operating conditions (Fig. 3.2).

Fig. 3.2. The cold-finger temperature, given by a $^{60}\text{Co}/\text{G}(\text{sc})$ thermometer, is shown for different heat loads.

During ion implantation, the 4 K shield and the iris must be open. The opening of the iris is critical since this controls the amount of room-temperature radiation reaching the cold finger. A series of measurements were made, but their precision was not high because it took several hours to reach equilibrium conditions. They did indicate that under normal operating conditions, i.e., with a 6-mm-diam opening, a base temperature of 10 ± 1 mK would be attained.

A lead plug 6-cm-long, with a 1-cm-diam central hole, was located -30 cm below the 4 K shield and in good thermal contact with the 4 K beam tube. The purpose of the plug was to stop scattered thermal radiation from reaching from the cold finger and also to absorb γ rays from any activity that had been deposited on the iris. The γ -ray shielding appeared to work well, as indicated by a radiation survey along the length of the beam tube. No tests were made without the plug due to difficulty in mounting

it, but, purely on arguments based on the geometry of the baffles, we expect it to have a very beneficial effect.

The reproducibility, the base temperature, and the ease of carrying out a cyclic set of measurements were well demonstrated by the off-line run using a ^{72}Se source. The temperature was cycled between 1 K and -5 mK (Fig. 3.3). A $^{57}\text{Co}/\text{Fe}$ thermometer indicated the base temperature. These changes were highly reproducible and made data analysis and the comparison of different data sets much easier. These results also provide confidence that such cycling can be carried out easily and efficiently. The temperature stability within the cold-count period is excellent. It should be noted that the refrigerator was undisturbed during this period since liquid He and N_2 were added only at the beginning of the cooling period.

Two on-line experiments using separated ^{144}Au and ^{146}Au have been completed. During the ^{146}Au

Fig. 3.3. The change in count rate of the 136 keV transition in a $^{57}\text{Co}/\text{Fe}$ thermometer mounted on the refrigerator cold finger. Data are shown for detectors at 90° and 180° relative to the orientation axis when the source is successively warm (4.2 K) and cold (-5 mK). Data were recorded every hour, and the figure indicates that the temperature and measuring conditions were stable throughout the measurement.

measurement, a 3-mm-diam opening in the iris was used, and despite its small diameter, no problems were experienced. This indicates that the overall stability of the beam, apart from occasional and minor retuning, was good.

Confusion over the axis of the magnetic field, and hence the positioning of detectors, has been removed by determining an axis through the source and at right angles to the field direction. This axis is well determined by the openings in the coil former, and it can be transferred to the laboratory frame of reference. The solid angles available at the different measuring positions have also been determined and the location of these positions, relative to the laboratory frame of reference, has been established.

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DEVELOPMENT OF A LASER ION SOURCE

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Tests have been made using the prototype laser ion source⁴ at Colorado State University. The purpose of these tests was to determine the combined efficiency obtainable with this concept that involves transport of the ions in a He-jet followed by laser vaporization, laser ionization, and formation of a pulsed ion beam. The He-jet portion of the project was begun at Mississippi State University to investigate the possibility of He-jet transport without the contaminating aerosols used in the typical system.

The He-jet system consists of a vacuum system with two chambers: (1) a source chamber maintained at about 1 atmosphere pressure with helium and (2) a target chamber kept at pressures of 0 to 2 torr. A tungsten ribbon filament containing a measured quantity of ¹¹⁵InCl₃ was placed in the source chamber. The filament was heated to vaporize the indium, which was then carried with the helium gas through a brass capillary tube to the target chamber. An aluminum target was placed 1 cm from the exit of the capillary in the target chamber to catch the indium. After the system was vented to atmospheric pressure, the target was measured using a NaI detector to determine the efficiency of transport of indium from the filament to the target. The experiment was repeated for a range of capillary lengths. The targets used in the laser ion source experiments were prepared with ⁶⁷Ga instead of indium to provide a better match for the laser system in use at Colorado State University.

Transport efficiencies ranging from 10% to 60% were measured, with the highest efficiency occurring with a capillary length of 15 cm. The target chamber pressure was 1.7 torr for this condition. Two targets, Ga-1 and Ga-2, used in later ion source experiments, were created with transport efficiencies of 26% and 50%, respectively. The targets contained about 90% of the ⁶⁷Ga within a 3-mm-diam spot.

This high-transport efficiency was obtained with only the normal impurities present in the commercial grade helium and some trace aerosols present, due to our filament vaporization technique. Further work is planned to investigate different He-jet geometries and to measure transport efficiency from a heavy-isotope beam from the UNISOR facility.

The two gallium targets prepared at Mississippi State University were sent to Colorado State University for a laser ion source test using the time-of-flight mass spectrometer system. The intention was to use the copper vapor laser to vaporize the sample followed by resonance ionization using a combination of 589 nm (yellow) and 294 nm (frequency doubled)

from a Nd:YAG pumped dye laser. However, since the copper vapor laser was not working at the time of the experiments, we chose the (probably) less efficient 532-nm (2 x Nd:YAG frequency) beam for the vaporization step. This not only gave us a less uniform intensity distribution on the target, but contributed considerably more nonresonant signal than was expected from the copper vapor laser.

The Ga-1 target was ablated, using a moderately strong 532-nm beam to visibly remove the surface layer from the target. The laser was manually scanned in a pattern across the target to ensure removal of the largest fraction of the ^{67}Ga . After removing the Ga-1 target, our measurements showed that 89% of the gallium had been removed by the laser. The ionization/transport efficiency of the gallium removed by the laser to the time-of-flight detector was 0.35%.

The Ga-2 target was ablated by a much weaker 532-nm beam and, for a portion of the time, a resonant dye laser beam. A significant enhancement of the mass 67 peak in the time-of-flight spectrum was observed when the dye laser was tuned to resonance. However, almost all of the ablation was done by the 532-nm beam. When the target was removed, 23% of the gallium had been ablated by the laser. Of the gallium removed, the ionization/transport efficiency was 0.65%.

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PREPARATION OF IMPLANTED REACTION-PRODUCT SOURCES FOR NUCLEAR ORIENTATION MEASUREMENTS

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Nuclear orientation may be achieved when the nuclear magnetic moment μ experiences a large

magnetic field B at a temperature T . The orientation condition is satisfied when the energy splitting between the m -state components given by $\mu B/l = kT$, the Boltzman energy; thus high fields and low temperatures are required. The low temperature may be provided by a dilution refrigerator and the high field is obtained through the hyperfine interaction when nuclei are implanted in a ferromagnetic host. A relatively small external field is sufficient to produce the polarization of the atoms and hence the nuclei through the hyperfine interaction.

An essential requirement is that the nuclei experience the full hyperfine field. This implies that they must lie deep within the host ferromagnet and also must be widely distributed, so that their near neighbors are those of the host. This condition is easily satisfied by diffusing the radioactive impurity into the host. High-temperature diffusion and subsequent cooling leads to an annealed sample; experience shows that the full hyperfine interaction is experienced.

This procedure takes several hours and is usually limited to cases when the solubility is good. An alternative and "brute force" method is to implant the recoils following a reaction. These typically have energies of several MeV, and much greater than those that can be obtained with a conventional mass separator. They also have a wide energy spread due to the target thickness. It is thus possible to place catcher foils behind a target to receive the recoils. The catcher foils may also be directly activated by the degraded beam, and some of these recoils may remain within the catcher. By using thin catchers, this source of unwanted activity may be kept to a minimum and the activity from very short-lived isotopes, $T_{1/2} < 1$ h, is not a serious problem.

We have carried out a series of experiments to show the viability of the technique and, in particular, to demonstrate that sufficient activity with few impurities can be prepared. We have further shown that the direct implantation of high-energy recoils produce sources that may be oriented without further processing.

In our measurements, we formed ^{72}Se ($T_{1/2} \approx 8.4\text{d}$) in thin iron foils (3 mg cm^{-2}). The source spot was $\sim 3\text{ mm}$ in diameter and a disc of the foil measuring 1 cm in diameter was soldered to the cold finger. A ^{57}Co thermometer source was then soldered on this disc, i.e., the source foil was sandwiched between the copper and the thermometer.

Large anisotropies, close to the maximum expected value, were observed for many transitions. The measurements were repeated with a second source foil, which was annealed at 800°C for three hours. No significant change in anisotropy was observed and it would appear that our sample procedure was satisfactory. This is contrary to what might be expected--thin foils can be difficult to magnetize while heavy ion stopping within the foil may be expected to produce dislocations and an unsatisfactory environment for the implanted ions. We believe that the beam heating of the target-catcher-foil stack effectively annealed the iron catcher, while the disc geometry of the foil, lying parallel to the field lines, led to a saturated condition. It would appear that, although several "good practices" have been violated, we have succeeded in preparing satisfactory nuclear orientation samples. The method is a general one and our search of the nuclear chart indicates that it has a wide applicability for isotopes with $T_{1/2}$ greater than a few hours.

Data analysis to date indicates that the experiment was successful; and the observed large anisotropies will allow even the weakest transitions to be analyzed.

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NUCLEAR ORIENTATION OF ^{186}Au

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We are searching for evidence of shape coexistence in the $E2/M1$ multipole mixing ratios of transitions connecting coexisting bands in even-even nuclei in the mass 180-190 region. Simultaneously, improved knowledge of the $E2/M1$ ratios will permit unambiguous analysis of electron conversion data to obtain $E0$ multipoles, which also serves as a probe of the mixed bands.

The decay of ^{186}Au (53 s) is among the shortest-lived decays possible using nuclear orientation techniques and represents a severe test of the new on-line refrigerator at UNISOR. We performed the orientation experiment in August 1989, implanting the activity into an Fe target at the UNISOR Nuclear Orientation Facility and observing the gamma rays with six detectors located in a symmetric configuration around the sample. The data were taken in the fully on-line mode at temperatures at or below 8 mK . The results (Fig. 3.4) of the preliminary data analysis show a reasonable amount of anisotropy for the $(4^+ \rightarrow 2^+)$ 273 keV transition.

In preparation for the refrigerator run, approximately four shifts of spectroscopy data

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Fig. 3.4. Anisotropy (count ratio $0^\circ/90^\circ$) for the 273-keV transition ($4^+ \rightarrow 2^+$) of ^{186}Au .

were taken. The level scheme of the ^{186}Pt daughter is not well established, and the lack of detailed knowledge of the decay scheme makes analysis of the nuclear orientation data difficult. We have obtained and analyzed spectroscopy results consisting of gamma singles, electron singles, multiscale data and gamma-gamma and electron-gamma coincidence data. The preliminary analysis of these data indicate a number of new levels; and they provide gamma intensities that are critical in analyzing the nuclear orientation data.

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THE DECAY OF ORIENTED ^{186}Au AND ^{186}Ir

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Mass separation of the $A = 186$ component from the products of the reaction $140 \text{ MeV } ^{12}\text{C}$ on tantalum was made using the UNISOR facility, which provided copious amounts of ^{186}Au isomers. The ^{186}Au ions were implanted with an accelerating potential of 50 keV into a cooled iron foil attached to the cold finger of the $^3\text{He}^4\text{He}$ dilution refrigerator. The on-line operation gave a base temperature of -10 mK and data were collected when the implanted nuclei were

oriented (-10 mK) and random (4 K). A series of runs, each of 10-minute duration, were made and the "warm" and "cold" conditions were maintained for periods of approximately three hours during a total run time of 26 hours, excluding periods when the beam was not available. A high statistical precision was obtained and transitions up to -3.5 MeV were identified. Many of the weak γ rays displayed large anisotropies.

Following the ^{186}Au - ^{186}Pt on-line experiment, measurements were made on the daughter products, and transitions from $186\text{mIr}(T_{1/2} = 2 \text{ hours})$ and $186\text{Ir}(16.6 \text{ hours})$ to levels in Os were measured in the off-line mode. For these experiments, the "cold" temperature was typically less than 5 mK . Data were collected over a period of 36 hours and again excellent statistical precision was obtained and large anisotropies, sometimes exceeding 100%, were observed.

The two sets of measurements demonstrated very well the capability of the nuclear orientation facility for obtaining data that are dependent on level spins and on the multipolarity of transitions linking them.

We expect the data analysis to be completed within the next several months.

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ON THE DISCREPANCIES IN PREDICTED M1
TRANSITION STRENGTHS FOR TRANSITIONS
BETWEEN INTRUDER STATES IN ^{195}Tl

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In the previous report, we reported data concerning the levels of ^{195}Tl based on the low-lying $9/2^-$ state, which is generally believed to be a single particle state resulting from the intrusion of the $h_{9/2}$ level from above the $Z = 82$ shell closure.³ Calculations of a particle-core coupling model, utilizing a triaxial rotor model description for the ^{194}Hg core, were compared with the observed energy levels and gamma-ray transition intensities between the various negative parity states. The necessary parameters for this model can be estimated from the properties of the Hg core, and, in this case, could be determined quite precisely from a few of the observed states in ^{195}Tl . In particular, the Fermi level λ is fixed by the position of the $I = 7/2, K = 7/2$ band head, the asymmetry parameter γ by the $I = 5/2, K = 5/2$ band head, and the magnitude of the quadrupole deformation is constrained very tightly by the known quadrupole moment of the $I = 9/2, K = 9/2$ band head. The energies of the remaining observed states, as well as the gamma-ray transition rates, can be regarded as predictions of the model. The energies are well described, but surprisingly large discrepancies remain for the mixed M1/E2 intraband relative transition intensities. Specifically, the relative intensities for I to $I - 1$ compared with I to $I - 2$ transitions (from the same initial state) within the $K = 9/2$ band are underpredicted by a factor of about 5-8. Analysis of the E2/M1 mixing ratios for these I to $I - 1$ transitions indicate that the M1's are systematically underpredicted, resulting in calculated mixing ratios that are too large by a factor of roughly 5. A related discrepancy is that the calculated magnetic moment of the $I = 9/2$ band head is too low (3.3 nm), compared to 4.0 nm, measured recently at UNISOR⁴ for $^{199-195}\text{Tl}$. It is important to emphasize that these are serious discrepancies because the parameters of the model are tightly

constrained by other considerations; the M1 calculation is standard for particle-core (particle-rotor) models; and these calculations were done on the deformed single-particle basis (thereby obtaining a realistic description of the single-particle wave functions). The form for the M1 operator used here (and standard for these models) is: $M1 = (3/4\pi)^{1/2} * (g_l + g_s + g_R)$, where l and s are the orbital and spin angular momentum of the odd particle, and R is the core collective angular momentum. For an odd proton coupled to a collective core, the standard g-factors are $g_R = Z/A$, $g_l = 1.0$, and $g_s = (0.7 \text{ or } 0.6) * g_s(\text{free})$, where $g_s(\text{free}) = 5.58$ for a proton. The need for an effective g_s factor is understood as the result of residual spin-spin interactions which are not treated explicitly.⁵ Instead, these interactions are roughly included by using the renormalized spin operator to calculate M1 properties. Such effective operators have been used extensively for shell model nuclei, and indeed the $9/2^-$ ground state of ^{209}Bi (mainly proton $h_{9/2}$ single-particle configuration) has long been known to have an anomalous magnetic moment, corresponding to an effective spin g-factor of only $0.36 * g_s(\text{free})$.

If the effective g_s -factor is allowed to vary outside the normal range, we find that the magnetic moment of the $I = 9/2$ band head can be reproduced with a value of $0.3 * g_s(\text{free})$, and at the same time the discrepancies of the calculated and experimental E2/M1 mixing ratios are reduced to 1/2 the discrepancies with $g_s = 0.7 * g_s(\text{free})$. The discrepancy concerning relative intensities is improved by about a factor of 2, but the I to $I - 1$ transition intensity is still underpredicted in the calculations. Very similar results are obtained if the effective orbital and spin g-factors are chosen according to values derived for shell model nuclei near ^{208}Pb as given in Ref. 6 [namely, $g_l = 1.09$, and $g_s = 0.385 * g_s(\text{free})$], or in Ref. 7. In either case, the main result is the same: the effective g-factors required to describe the magnetic dipole properties of a proton in the $h_{9/2}$ orbital are considerably

different from those generally used for other orbitals. Evidently, the effect of unsaturated nucleon spins remains as important here as it is for ^{209}Bi .

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DECAY OF MASS-SEPARATED ^{193}Bi AND ^{193}Pb

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In the previous progress report, the decay experiment to study the level structure of ^{193}Pb and ^{193}Tl was discussed.⁵ Data were accumulated in two different bombardments of W and Re targets, respectively, with ^{16}O . The $13/2^+$ isomer of Pb was produced largely with the W target, while the low-spin ($3/2^+$) isomer was produced with almost equal probability as the $13/2^+$ when the Re target was used. The experimental arrangement was discussed in the earlier report.⁵ Also, in the bombardment of the Re target, ^{193}Bi was produced and several transitions in ^{193}Pb were observed. During the last year, analysis of these data has proceeded; we can now show the decay schemes deduced for ^{193}Bi and the additions to the previous decay scheme for the decay of ^{193}Pb .⁶

As stated in the earlier report, the experiment was designed to maximize the amount of data acquired on the decay of ^{193}Pb , and hence, the transitions due to the decay of ^{193}Bi were weaker in our spectra than those due to the daughters. Nevertheless, through analysis of

the gamma-gamma coincidence data and the rate of decay of the singles peaks, a partial decay scheme for ^{193}Bi has been obtained. It is shown in two parts in Figs. 3.5 and 3.6. The two parts feed the two long-lived isomers of ^{193}Pb which have spins of $13/2^+$ and $(3/2^+)$, and on the basis of systematics one would be the ground state and the other would be at very low excitation. In preparing the figures, we assumed that the low-spin isomer, shown in Fig. 3.5, is the ground state and that the $13/2^+$ state, shown in Fig. 3.6, is at excitation energy E. The scheme has many features similar to the one obtained for the decay of ^{195}Bi earlier.⁶ The analysis of the conversion electron data is in progress and should enable the assignment of additional spins and parities, and perhaps show the occurrence of shape coexistence in ^{193}Pb .

The primary motivation of the experiment was to search for shape coexistence in ^{193}Tl through study of the decay of ^{193}Pb . This experiment

Fig. 3.5. The portion of the decay scheme of ^{193}Bi feeding the low-spin isomer of ^{193}Pb . The energies and relative intensities are given above each transition. Dots on the transitions indicate their placement by coincidence data.

Fig. 3.6. The portion of the decay scheme of ^{193}Bi feeding the $13/2^+$ isomer of ^{193}Pb (see caption from Fig. 3.5).

Fig. 3.7. The portion of the decay scheme of ^{193}Pb feeding the ground state of ^{193}Tl . The energies and relative intensities from the decay of the low-spin/high-spin isomers of ^{193}Pb are given above each transition.

was designed to search for the low-spin states in the decay scheme, which had been missed in the earlier decay study.⁷ The success of the experiment is demonstrated in Fig. 3.7, the portion of the decay scheme which decays to the $1/2^+$ ground state of ^{193}Tl . In this analysis, we observed 21 transitions between 14 states in this portion of the decay scheme, as compared to 6 transitions between 5 states in the previous scheme. During this experiment, the intensity of the 365.4-keV transition was close to 100 times as strong as any other transition, which was a result of strong production and separation of the $9/2^-$ isomer in ^{193}Tl and its strong branch for isomeric decay. Because of this isomeric decay through the 365.4-keV level, a relative intensity due to the decay of the Pb isomers for the 365.4-keV transition could not be reliably obtained from these data.

The portion of the decay scheme decaying to the $9/2^-$ isomer of ^{193}Tl was also improved through the addition of 7 new transitions and 5 new levels. The five strongest transitions to

the level, believed to be the $h_{11/2}$ level, have now been observed, and perhaps give the location of the states populated by exciting the core of this single hole state to its 2^+ level. The five transitions to the $h_{11/2}$ state are within 90 keV of each other, indicating that the core is essentially spherical. In contrast, the band built on the $h_{9/2}$ intruder state displays a strong coupling rotational character. We have observed the $K = 9/2$ rotational band up to $l = 17/2$ and the start of the $K = 7/2$ band associated with this single particle state. We are still searching the data to locate the $K = 5/2$ band as was seen in the decay of ^{195}Pb . When the data analysis is complete, the bands based on the $h_{9/2}$ intruder state (energy levels and relative gamma-ray intensities) will be compared with calculations coupling a single particle to a triaxial core as discussed in Ref. 5 for the analogous levels in ^{195}Tl .

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LOW-ENERGY-LEVEL STRUCTURE OF ^{193}Hg

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In a recent experiment, data were taken on ^{193}Bi and ^{193}Pb decay.⁷ However, ^{193}Tl decay turned out to be the decay of highest count-rate. Previous data taken on ^{193}Tl decay had only 1/20 the counts of the present data, and also lacked conversion-electron data; the present data supply the lacking information. During the last year, the gamma and electron singles, gamma-gamma, and gamma-electron data were analyzed. Also, low-lying energy levels were compared with particle-core coupling model calculations.

The details of the experiment were discussed in an earlier progress report.⁷ Briefly, sources were created by bombardment of a stacked-foil target of Re/Mo alloy with 165-MeV ^{16}O . The UNISOR mass separator was then used to select the proper isotope to be collected on a tape transport system, which carried the deposited sources to two different detector stations. The data collected were gamma-ray and conversion electron multiscaled-singles spectra and gamma-gamma-t and e-gamma-t coincidence data.

These data, once analyzed, were used to check a previous ^{193}Tl -decay scheme;⁸ this scheme was elaborate and had many tentative placements/levels. Using the present data, these tentative placements were confirmed or denied. Up to now about 10 new levels were found, and several others tentatively placed. The search for new

levels, as well as conversion-electron analysis (which will give spin-assignment of levels), is continuing.

Preliminary calculations have been made for both the positive and negative parity states found at low energy in ^{193}Hg . At this stage of the investigation, the goal is to determine whether or not a sensible interpretation of the data is possible within a particle plus triaxial rotor model, in which all the model parameters are taken at their standard values. In the version of the model used here, the single-particle part of the calculation is made with a deformed modified oscillator potential, with 9 major (N-) shells included. Thus, there is no limitation to only one or a few j-shells, and by using the standard K, μ parameters for this potential, along with a standard BCS pairing calculation, the positions and properties of the low lying states are predictions of the model, and not fitted results. From our study of the negative parity states of ^{193}Tl , we expect that the shape parameters used there to describe the ^{194}Hg collective core ($\epsilon = -0.14$, $\gamma = 22$ deg) should also be appropriate for ^{193}Hg . Two axially-symmetric shapes ($\epsilon = +0.14$, $\gamma = 0$, prolate and $\gamma = -0.14$, $\gamma = 0$, oblate) are also considered below for comparison.

The positive parity states within 600 keV of the $13/2^+$ band head are shown in Fig. 3.8, along with the electric quadrupole and magnetic dipole moments for the $13/2^+$ state.^{9,10} The "standard" triaxial rotor calculation seems to describe the data quite well (the same number and ordering of states are found in the calculations as in the data, and the moments are adequately reproduced), but the result of the calculation with an oblate axially symmetric rotor is not very different from the "standard." However, the theoretical results using the prolate deformation is significantly different; in this case, the sequence of states ($13/2^+$, $15/2^+$, $17/2^+$) suggests a slightly perturbed strong-coupled band, while for the triaxial or oblate rotors, the calculated band has the decoupled ordering ($13/2$, $17/2$, $15/2$). It is

Fig. 3.8. Low-lying positive parity energy levels of ^{193}Tl decay in comparison with the predictions of particle-core coupling calculations employing three different shapes for the core. Predictions for the magnetic dipole and electric quadrupole moments of the $13/2^+$ state are also compared with the experimental values.

interesting to note that the calculated moments are nearly identical in the three cases. The magnetic moment simply reflects the high- j orbital that the odd neutron occupies. The constancy of the calculated electric quadrupole moment is a result of the position of the Fermi level, which lies slightly above the neutron $i_{13/2}$ j -shell. For the prolate shape, this is closest to the $\Omega = 9/2, 11/2$ intrinsic orbitals, while for the oblate shape the $\Omega = 5/2, 3/2$ intrinsic orbitals are nearest. In the strong coupling approximation and for axially symmetric shapes, the quadrupole moment is given by $Q = (3K^2 - I(I+1)) Q_0 / (I+1)(2I+3)$. Both factors in the numerator are positive for the prolate shape, and both are negative for the oblate shape. Thus, in this case, the sign of the quadrupole moment does not determine the nuclear shape.

For the negative parity states, shown in Fig. 3.9, again the "standard" calculation gives results which agree reasonably well with the data, and again the calculation using an oblate shape does about as well. Both predict $3/2^-$, $5/2^-$, and $1/2^-$ band heads at very low energy, and a cluster of four states (an extra $5/2^-$ compared to the data) around 300 keV; and both predict moments for the $3/2^-$ state in agreement with the observed values.^{9,10} Also, the calculated results with a prolate rotor are again notably worse in terms of the energy spectrum produced, but here the moments for the $3/2^-$ also clearly disagree with the data. In all three of the calculations the $3/2^-$ state is mainly $K = 3/2$, and so the first term in the strong-coupling expression for the quadrupole moment is positive. Thus, the sign of the calculated moment does reflect directly the sign

Fig. 3.9. Low-lying negative parity energy levels of ^{193}Tl decay in comparison with the predictions of particle-core coupling calculations employing three different shapes for the core. Predictions for the magnetic dipole and electric quadrupole moments of the $3/2^-$ state are also compared with the experimental values.

of the intrinsic quadrupole moment, and hence the sign of the quadrupole deformation. The calculated magnetic moments have opposite signs because the nature of the dominant intrinsic orbital is changing; i.e., the direction of the neutron spin vector relative to the orbital angular momentum is different in the two cases.

Thus, at the semiquantitative level presented here, the particle plus triaxial rotor model provides an adequate description of both positive and negative parity low-lying states in ^{193}Tl . A more detailed comparison between experiment and theory will provide a better determination of the appropriate nuclear shape parameters, and will also help identify any shape-coexistent states that might be present at low energy in this nucleus. Such states will be outside the assumed model space and should be

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SPECTROSCOPY IN THE DECAY OF ^{189}Pt TO ^{189}Ir

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The decay of odd-mass Pt to Ir has been the subject of considerable interest ranging from basic nuclear spectroscopy to tests of super-symmetry schemes. We have proposed to use the decay of ^{189}Pt , oriented at low temperatures, as a test of the geometry of the UNISOR Nuclear Orientation Facility. The spin-3/2 parent state gives identically vanishing A_4 terms in the angular distribution of gamma rays in the decay of ^{189}Pt . Thus, the analysis using the 45°-detector positions will be put to a severe test to determine whether our facility and our analysis techniques do indeed give vanishing A_4 terms.

To refine the analysis and simultaneously to improve the spectroscopy of this decay, we performed gamma and electron singles and coincidence studies at UNISOR. The spectroscopy data is being analyzed to yield an improved decay scheme, which can then be used to analyze future nuclear orientation data. Gamma and electron singles data have been analyzed, time planes have been completed, and coincidence data are being analyzed. Preliminary results show a considerable improvement on the previous decay scheme, based on 1972 spectroscopy data.¹¹ We have already identified several new levels and can reduce the ambiguity of spin assignments to existing levels. This information will be critical for the interpretation of nuclear orientation data on this decay.

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SEARCH FOR STRONGLY COUPLED BANDS IN ^{187}Au

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An extensive data set on the $^{187}\text{Tl} \rightarrow ^{187}\text{Hg} \rightarrow ^{187}\text{Au}$ and $^{187}\text{Hg} \rightarrow ^{187}\text{Au}$ decays, emphasizing conversion-electron and gamma coincidence measurements, has been obtained and is under intense analysis. The data were obtained using the UNISOR facility at the Hollifield Heavy Ion Research Facility with the $^{176}\text{Hf}(^{19}\text{F}, 8n)^{187}\text{Hg}$ and $^{176}\text{Hf}(^{16}\text{O}, 5n)^{187}\text{Hg}$ reactions. The first reaction enables one to enter the low-spin states of Au since the ^{187}Tl beta decay preferentially populates the $3/2^+$, ^{187}Hg (2.4-m) ground state. The second leads to a much greater population of the ^{187}Au high-spin states since the heavy-ion reaction preferentially populates the $13/2^+$, ^{187}Hg (1.7-min) isomer.

We have preliminary evidence for strongly coupled bands (deformed) arising from the $\pi h_{11/2}^- \otimes ^{186}\text{Hg}$ and $\pi d_{3/2}^- \otimes ^{186}\text{Hg}$ core-particle couplings. Similar structures were observed⁴ in ^{185}Au . The detailed analysis of such structures in several adjacent odd-mass Au isotopes will enable one to determine if, indeed, this is a new type of degree-of-freedom in odd-mass nuclei.

We are extracting these shape isomers from the spectroscopic data using the technique of locating E0 enhanced transitions as fingerprints⁴ for transitions between shape-coexisting structures.

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STUDY OF HIGHLY CONVERTED TRANSITIONS IN ^{183}Pt AND ^{183}Pt

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Having obtained data of high statistical quality for the decay of ^{183}Au and ^{183}Pt , we have been able to do a systematic survey of very converted transitions in this region. Numerous transitions with $\alpha_K(\text{expt.}) > \alpha_K(\text{M1})$ have been found and have been identified as having an electric monopole component. Some of these do not permit an accurate measure of the conversion coefficient due to the total absence of gamma rays. This is remarkable as pure monopole transitions are only expected, from selection rules, to occur between pairs of states of spin 0 (thus excluding all odd-mass nuclei). Previously, only two of these transitions have been observed and were interpreted as abnormally converted M1 transitions.^{3,4} So far, twelve highly converted transitions have been found in ^{185}Pt and three in ^{183}Pt . The rapid change in E0 strength between these neighboring nuclei is of significant interest. The relationship of monopole transitions and shape coexistence in this mid-shell region is being explored.

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DECAY OF MASS-SEPARATED ^{183}Au

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Neutron-deficient ^{183}Au nuclei were produced using the Holifield tandem beam and UNISOR facilities. The reaction $^{181}\text{Ta}(^{12}\text{C}, 10n)$ yielded 42-s ^{183}Au which was subsequently mass-separated and deposited onto a tape transport. Two detector stations were used to give gamma-gamma and conversion-electron-gamma coincidences and spectrum-multiscaled singles. Data of high statistical quality (8 M coincidence events) were obtained and proved to be sufficient to give extensive decay schemes of ^{183}Pt and ^{183}Ir . Previously, a limited scheme for ^{183}Pt has been published and a preprint of a more detailed study has recently appeared.^{3,4} Our data, through the gamma-electron coincidences, yield valuable information on very-converted transitions which are numerous in this region. To date, three transitions with $\alpha_K(\text{expt.}) > \alpha_K(\text{M1})$ have been seen in ^{183}Pt .

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DECAY OF MASS-SEPARATED ^{137}Eu

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The study of the decay of ^{137}Eu to levels in ^{137}Sm is part of a continuing investigation of neutron-deficient rare earth nuclei with $N < 82$ and $Z > 50$. The expected large deformations for nuclei in this region are predicted⁵ to come close enough to the line of stability in the neutron-deficient Sm and Pm isotopes that the possibility of producing and studying their structures exists.

Activities of ^{137}Eu were produced by bombarding stacked foils of ^{92}Mo targets with ^{40}Ti

beams from the 25-MeV tandem accelerator at HHIRF with on-line separation at UNISOR. The experiments consisted of γ - γ -t coincidence and γ -ray singles spectrometry.

Initial analysis has established levels in ^{137}Sm at 209, 541, and 765 keV, populated by the decay of ^{137}Eu . This level sequence is in agreement with the $9/2^-$ (g.s.), $11/2^-$ (209 keV), $13/2^-$ (541 keV), $15/2^-$ (765 keV) band structure seen in an in-beam γ -spectroscopic study of ^{137}Sm .⁶ Also, from our study, a half-life of 6 ± 1 seconds for the decay of ^{137}Eu has been obtained compared to the previously reported value of approximately 9 seconds.⁷

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TRANSITIONAL NUCLEI: $^{130,132}\text{Ce}$ AND $^{132,134}\text{Nd}$

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An investigation of low-lying energy levels of $^{130,132}\text{Ce}$ and $^{132,134}\text{Nd}$, has been made via β decay, especially of those levels in the 2^+ gamma band in the even-even nuclei. The radioactive parent nuclei were produced by $^{92}\text{Mo}(^{46}\text{Ti}, \text{xpn})$ and $^{112}\text{Sn}(^{28}\text{Si}, \text{xpn})$ reactions. The UNISOR isotope separator enabled $A = 134$ mass separation. Level schemes of these four nuclei were constructed. The β -decay half-lives of the parent nuclei, ^{130}Pr , ^{132}Pr , ^{132}Pm , and ^{134}Pm were determined to be 40 ± 4 , 96 ± 18 , 8.8 ± 0.8 and 23 ± 2 , respectively. The gamma-soft character of ^{130}Ce , ^{132}Ce , ^{132}Nd , and ^{134}Nd is supported by the comparison of relative reduced

transition probabilities from experiments with IBA-2 predictions.

IBA-2 calculations were made for the primary objective of extracting E2 transition rates to use in forming the relative E2 transition rates for comparison with experimental data for the available cases where there are two or more γ rays emitted from a given level. It was assumed that the γ -ray transitions are purely E2 transitions, for the purposes of these comparisons.

$B(E2)$'s for the Xe, Ba, and Ce nuclei were calculated by Puddu, Scholten, and Otsuka,⁷ in an IBA-2 model. They adopted a smoothly varying set of IBA parameters (dependent on neutron number) and did not attempt to fit each nucleus individually. Our IBA-2 calculations have used their parameters as a starting point. The program "NPBOS" was used.⁸ The Hamiltonian parameters ϵ_d , κ , χ_ν , ξ_{11} , ξ_{12} , and ξ_{13} were adjusted for each nucleus to give wave functions which reproduced the experimental energy levels of that nucleus.

The effective charges of the neutron and proton bosons must be entered into the computation of the transition probabilities. For lack of data, the $e_\nu^{(2)}$ and $e_p^{(2)}$ were set equal to each other and adjusted for a given nucleus to enable the known $B(E2; 0_g^+ \rightarrow 2_g^+)$ of that nucleus to be reproduced. These effective charges were then used in the computation of E2 transition probabilities for that nucleus. The $B(E2; 0_g^+ \rightarrow 2_g^+)$ were all fitted with effective charges which fell in the narrow range from 0.120 to 0.134 eb.

The results as ratios of the calculated $B(E2)$'s were compared with the experimental ratios.⁹ The experimental ratios are in general agreement with the calculated values.

Additional support for the use of the perturbed IBA-2 model is given by a comparison with the criterion of Davydov and Filippov¹⁰ for a triaxial nucleus which rotates without changes in its internal states; namely, that level energies are expected to obey $E(2_g) + E(2_g) = E(3_g)$. In Table 3.2, for the nuclei of this study, are given the ratios

Table 3.2. Davydov and Filippov⁷ predict that for the gamma band in a rotating triaxial nucleus, $E(3_1) = E(2_1) + E(2_1)$. For the available data in this region this expression is shown, normalized and as a percentage. Note that for equal numbers of neutrons, the values are almost identical, except for ^{144}Sm and ^{146}Gd .

Number of Neutrons	$[E(2_1) + E(2_1) - E(3_1)] / [E(2_1) + E(2_1)]$, as %			
72	^{138}Ce -8.2	^{132}Nd -7.8		
74	^{140}Ce -4.5	^{134}Nd -3.9	^{136}Sm -6.6	
76	^{142}Ce -0.58	^{136}Nd +0.41	^{138}Sm +0.80	^{140}Gd -2.6
78	^{144}Ce +5.5	^{138}Nd +5.4	^{140}Sm -5.1	

$(E(2_1) + E(2_1) - E(3_1)) / (E(2_1) + E(2_1))$ normalized and expected to be equal to zero for the ideal nucleus. We see that the ratios are zero within $\pm 10\%$. The similarity of the ratio for each N indicates again the strong dependence of the shape on neutron number. The small ratios for the N = 76 nuclei suggest that there is little mixing of the 2, and 3, states with other spin 2 and spin 3 states. It has been evident for several years that the ground-state rotational bands for nuclei with Z near 58 and N < 82 indicate increasing deformation with decreasing neutron number, with only a weak dependence on the proton number. This is illustrated in Fig. 3.10.

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Fig. 3.10. A comparison of the ground state and gamma bands in neutron-deficient Ce, Nd, and Sm.

DECAY OF ^{134}Sm AND LEVELS OF ^{134}Pm

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Gamma-ray spectra were collected with the mass separator at A = 134 using the $^{92}\text{Mo}(^{46}\text{Ti}, xnyp)$ reaction with beam energy of 230 MeV. The observation of X-ray lines of Pm, singly and in coincidence with the previously known 118.0-keV γ ray, confirmed the previous identification of the β decay of ^{134}Sm . Additional coincidence spectra collected by use of the He-jet technique at beam energies of 190,

220, and especially 250 MeV supported the assignments and relative intensities and enabled somewhat better determinations of the energies. Through use of the γ -ray singles intensities and the γ - γ coincidence relationships, the partial energy level diagram of Fig. 3.11 was constructed. The 112.2-keV γ ray decays with the same half-life as the 110.2-keV γ ray. Since it is in coincidence with the 218.8-keV γ ray, but not with the 118.9-keV γ ray, it has been placed tentatively as a transition to the ground state. The γ rays in Fig. 3.11, and some others which we did not observe, were recently reported.⁴

The half-life for the β decay of ^{134}Sm , measured by the intensity of the 118.9- and 161.3-keV γ rays, is 9.3 ± 0.8 s, in agreement with the previous 12 ± 3 s⁵ and 10.3 ± 0.5 s.⁴ An approximate log ft of 5.2 was calculated with

Fig. 3.11. A partial level scheme for the β decay of ^{134}Sm to ^{134}Pm . The size and sign of ϵ are not known.

the use of the systematic value of the maximum positron energy, 6 MeV, and of the deduced 23% β feeding to the 118.9-keV level. Allowed β decay to the 118.9-keV level is indicated, and this suggests that this level has spin-parity 1^+ because $0^+ \rightarrow 0^+$ β decay is rare (allowed β decay is assumed). A reasonable choice for the lowest level of Fig. 3.11 is $1^+ = 2^+$, which requires an M3/E4 transition to or from a probable 5^+ isomeric level and which has elsewhere been proposed as the level which β decays to ^{134}Nd (Ref. 6). It is not known which level is the lower in energy, the presumed 2^+ which is connected to other levels of the decay scheme, or the presumed 5^+ which appears to be produced directly by the $^{92}\text{Mo}(^{46}\text{Ti}, 3pn)$ reaction.

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0(6) STRUCTURE IN ^{126}Xe

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In a UNISOR experiment, the gamma ray and conversion-electron singles and coincidence spectra were measured for the decay of 1^+ 1.6-min ^{126}Cs to levels of ^{126}Xe . The results were marked by the identification of a new E0 transition from 0^+ level at 2553 keV, and the overall absence of any significant E0 transition intensity for any other transitions. A large number of new levels have been identified, and when combined with published in-beam work makes possible a rather complete set of levels in ^{126}Xe below 2.5 MeV. These levels are described quite well below 2 MeV by

calculations using the $O(6)$ limit of the Interacting Boson Model-2.

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BUFFER ORBITALS IN THE ODD-MASS Xe NUCLIDES WITH $N < 82$

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In a UNISOR experiment the gamma ray and conversion-electron singles and coincidence spectra were measured for the decay of $1/2^+$ 32-h ^{129}Cs to levels of ^{129}Xe and $1/2^+$ 6.2-h ^{127}Cs to levels of ^{127}Xe . From these data, it has been possible to identify a number of new low-spin levels in ^{127}Xe up to 2 MeV. The data support the notion that the excited states of ^{127}Xe can be described by the rather weak coupling of the $s_{1/2}$, $d_{3/2}$, and $g_{7/2}$ single-neutron states with the ^{126}Xe core. When combined with available in-beam measurements for higher-spin levels in ^{127}Xe and other Xe nuclei, it is possible to observe that the structure of the low-energy levels in the odd-mass Xe nuclides changes very little from $N = 71$ through $N = 81$. This resistance to change, in spite of the addition of 10 $h_{11/2}$ neutrons, can be interpreted as indicating that these neutron orbitals play only a minor role in governing the structure of these Xe nuclei. Their principal role would be to serve as a buffer and absorb the additional neutrons without significantly affecting the occupancies of the active positive parity neutron orbitals. This is the role that is predicted for the $h_{11/2}$ neutrons by the Fermion Dynamical Symmetry Model (FDSM).

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IDENTIFICATION OF A FULL 2-PHONON VIBRATIONAL INTRUDER IN ^{129}Xe

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In a UNISOR experiment, the gamma ray and conversion-electron singles and coincidence spectra were measured for the decay of the 2^+ and 8 60-s isomers of ^{129}Cs to levels of ^{129}Xe . Analysis of the data has revealed the presence of a number of E0 transitions and E0 components admixed with M1/E2 transitions. These data indicate strong mixing between the more-deformed 6-particle 2-hole intruder levels and the normal 4-particle intruders. In the level scheme shown in the Fig. 3.12, these transitions form a

rotational pattern of levels based on the ground state. These levels may be compared to the structure of isotonic ^{114}Cd , where it is the rotational structure that forms the excited band and the vibrational structure that is built on the ground state.

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4. EXPERIMENTAL ATOMIC PHYSICS

ATOMIC PHYSICS FOR FUSION PROGRAM

ELECTRON CAPTURE IN $O^{3+} + H(D)$ AND $O^{4+} + H(D)$ COLLISIONS USING MERGED BEAMS

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Experimental investigations of electron capture resulting from low-energy collisions of multiply charged ions with neutral $H(D)$ have continued. Measurements for O^{3+} and $O^{4+} + H(D)$ in the energy range from 1 to 1000 eV/amu were performed at the ORNL-ECR Multicharged Ion Research Facility using the ion-atom merged beam apparatus. We are able to obtain such low collision energies by merging a relatively fast (~ 9 -10 keV) multicharged ion beam with a ground-state neutral H beam traveling at nearly the same velocity. The primary objective is to obtain a better quantitative understanding of such collisions at energies where the inter-nuclear motion is slow, compared with the orbital motion of the active bound electrons in the system. A quasi-molecular description of the interacting system is appropriate for this study. Our recently published experimental data for $O^{3+} + H$ show an unexpected enhancement at low energies, which may be due to the ion-induced dipole attraction modifying the trajectories of the reactants.² No such enhancement, though, was found in subsequent measurements for $H^{3,4,5+} + H$.³

To continue these studies, cross sections have been measured for electron capture for the collision systems $O^{3+} + H(D)$ and $O^{4+} + H(D)$. The data are presented along with other experimental and theoretical results in Figs. 4.1-4.3. For collisions with both O^{3+} and O^{4+} , the merged-beams data join smoothly with other measurements⁴ at the higher energies based on ion-beam - gas-target methods and verify the normalization methods used for the latter. In the $O^{3+} + H$ case, the measurements lie significantly below theoretical calculations^{5,6} at

Fig. 4.1. Comparison of merged-beams data for $O^{3+} + H(D)$ with other measurements (Ref. 4) and theoretical calculations (Refs. 5,6). The solid curve is from Ref. 5, the dashed curve from Ref. 6.

Fig. 4.2. Comparison of merged-beams data for $O^{3+} + H(D)$ with theoretical calculations (Ref. 5) for capture into the 3s and 3p states.

energies below 100 eV/amu, where significant contribution from capture to the 3p state is predicted. The measured cross section is in fact consistent with the calculation⁵ for capture to the 3s state down to 10 eV/amu, and suggests that this calculation may overestimate

Fig. 4.3. Comparison of merged-beams data for $O^{++} + H(D)$ with other measurements (Ref. 4) and available theory (Ref. 7).

the $3p$ contribution by roughly a factor of two. For collisions with O^{++} , the measurements agree with the general trend predicted by the available theory (Ref. 7), but suggest that rotational coupling between states may not be as important as previously thought.⁷

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DISSOCIATION AND IONIZATION OF CD_4^+ BY ELECTRON IMPACT

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The presence of certain molecular ions near the edges of high-temperature plasma devices has stimulated interest in these ions in the fusion community, adding to the attention received from researchers in plasma processing and flame chem-

istry. The conventional assumption has been that dissociation of molecular ions should be dominated by removal of a single light particle, with more extreme degrees of dissociation becoming increasingly unlikely.³ However, the difficulties involved in performing precise absolute cross section measurements has limited the number of experimental studies on molecular ions. We have measured absolute cross sections for ionization and dissociation of CD_4^+ at collision energies from 4 to 300 eV utilizing the ORNL ECR ion source and crossed electron-ion beams apparatus.⁴

CH_4^+ and CD_4^+ are of particular interest to edge-plasma modelers due to the inevitable presence of these molecular ions in devices using carbon limiters and H (or D) as fuel. An unusual feature of the deuterated form of the ion is that it can be vibrationally excited to a long-lived (metastable) state which is above the dissociation limit, forming what is usually called a "predissociating" ion. We expect that the signature of a predissociating component in the ion beam in this experiment would be the measurement of a non-zero cross section at energies far below the 10 eV threshold for dissociation of the "ground-state" CD_4^+ ions. Indeed, the measured cross sections for each dissociation channel studied are finite at the lowest collision energies obtainable, decrease rapidly with increasing collision energy, and are still non-zero just below 10 eV. The fact that the magnitude of these "below-threshold" cross sections are strongly dependent on ion source conditions indicates that a predissociating component is present in the incident CD_4^+ ion beam.

The cross section for direct ionization of "ground" CD_4^+ (forming CD_4^{2+}) is negligible compared with the competing dissociation channels. As predicted, the resulting CD_4^{2+} is unstable, with a lifetime considerably shorter than the time scale of this experiment. However, the "predissociating" incident ions apparently do ionize since a finite cross section for production of CD_4^{2+} was observed at energies below 10 eV.

The cross sections for dissociation of "ground" CD_4^+ into C^+ , CD^+ , and CD_2^+ were obtained by subtracting the apparent cross section due to the metastable component in the ion beam from the total cross section for production of the desired fragment ion. The resulting cross section for dissociation of "ground" CD_4^+ to C^+ is shown in Fig. 4.4. The peak cross sections for the three dissociation channels measured in this experiment are all within a factor of two (with average value $4.5 \times 10^{-17} \text{ cm}^2$), and are only about a factor of 10 smaller than the predicted cross section for dissociation to CD_3^+ by removal of a single D atom.

Fig. 4.4. Cross section for dissociation of "ground" CD_4^+ to form C^+ .

The "predissociating" state which has been observed in spectroscopic studies of CD_4^+ has not been seen for CH_4^+ . Follow-up measurements will be made to confirm that the cross section measured below 10 eV is real and due to the small predissociating component of the incident CD_4^+ ion beam.

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STUDIES OF ANGULAR DEPENDENCE AND LINE SHAPES FOR AUGER ELECTRON EMISSION IN LOW-ENERGY $\text{He}^{q+} + \text{He}$ COLLISIONS

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In a follow-up experiment to our measurements² of Coulomb focusing in low-energy $\text{He}^+ + \text{He}$ collisions, we studied the energy and angular dependence as well as the lineshapes associated with Auger electron emission resulting from low-energy $\text{He}^{q+} + \text{He}$ collisions. The aim of this study was twofold. The first was to investigate the target/projectile electron emission asymmetry resulting from Coulomb focusing as a function of projectile charge. Results of this investigation are illustrated in Fig. 4.5, which shows electron spectra produced in 10 keV collisions of He^0 , He^+ , and He^{2+} projectiles with He target atoms. As expected, with neutral projectiles (produced by resonant electron capture in an upstream He gas cell) the Auger electron line shapes are no longer broadened by PCI (post-collision interaction), and, within the uncertainty of the measurement, are equal for target- and projectile-based electron emission (i.e., no asymmetry). On the other hand, for He^{2+} projectiles, significantly increased PCI line broadening is observed, as well as increased target/projectile intensity asymmetry, relative to that characterizing the electron spectrum observed for He^+ projectiles.

The second aim of this study was to search for experimental evidence of interference effects that may arise due to the existence of two equivalent and indistinguishable trajectories around the "focusing" ion that an Auger electron may take. In order to increase the rate of data acquisition for non-zero-degree observation angles, a new target gas cell was used for these measurements instead of a gas jet. The new cell had, in addition to the entrance and exit apertures for the ion beam,

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Fig. 4.5. Autoionization electron spectra for 10-keV collisions of He, He⁺, and He²⁺ projectiles with He target gas.

separate openings to permit analysis of Auger electrons emitted at selected non-zero laboratory angles. Figure 4.6 shows typical electron spectra obtained for 5-keV He⁺ + He collisions at four different laboratory observation angles. Pronounced interference structure is observed, particularly in the line shape associated with the Auger decay of the target-based $2s^2\ ^1S$ level. On the basis of a preliminary analysis,³ the dominant mechanism giving rise to the observed interference structure appears to be interference between contributions from different doubly excited states which overlap in energy due to PCI, as, for example, described by Morgenstern et al.⁴ This statement is based on

Fig. 4.6. Electron spectra resulting from 5-keV He⁺ + He collisions, observed at four different laboratory angles.

the fact that, using Morgenstern's treatment, satisfactory fits are obtained to the line shapes observed for electron emission away from the charged collision partner (e.g., at laboratory angles of 0° in the case of projectile-

based transitions, or of 180° for target transitions), as illustrated in Fig. 4.7a. The fits shown in that figure were obtained assuming interference between the $m_l=0$ sublevels of the $2s^2\ ^1S$, $2p^2\ ^1D$, and $2s2p\ ^1P$ initial states, and adjusting the relative amplitudes and phases of the first two states with respect to the third (i.e., four free parameters). While this model predicts that the obtained fitting parameters should equally well describe the line shapes observed for the case of electron emission toward the charged collision partner, it was found that fitting parameters significantly different in amplitude as well as phase were

required to obtain reasonable fits for this case (see Figs. 4.7b and 4.7c). Similar conclusions were derived from analysis of electron spectra obtained at 10 keV collision energies. The fitting parameter adjustment required for the case of electron emission in the direction of the charged collision partner (i.e., under conditions where Coulomb focusing is possible) may be evidence for a modification of the Auger electron phase evolution, or, even more speculatively, for an additional interference mechanism caused by the presence of the He^+ collision partner. Alternatively, the parameter adjustments required may merely reflect the limitations of the model on which the above analysis is based. Work is in progress to obtain a better understanding of the assumptions underlying the model used, and how these assumptions might restrict its range of validity.

Fig. 4.7. Line shape fits to spectra for electron emission away from (a) and toward (b and c) the charged collision partner in 5-keV $\text{He}^+ + \text{He}$ collisions.

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AUGER SPECTROSCOPY OF LOW-ENERGY MULTICHARGED ION-ATOM COLLISIONS

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During the past year, we have continued the analysis of the Auger electron emission resulting from double-electron capture collisions of 60-keV C^{6+} ions colliding with a He target. Unlike our previously studied $\text{O}^{6+} + \text{He}$ system, in which the nonequivalent $2pn\ell$ configurations produced by correlation effects decay by very low energy (<20 eV) Coster-Kronig transitions which are difficult to measure, the nonequivalent configurations produced in the $\text{C}^{6+} + \text{He}$ system decay by KLX Auger transitions occurring around 300 eV, which are relatively straightforward to measure. The other attractive feature of the present system is the fact that

there are no "hidden" (i.e., nonautoionizing) channels for two-electron capture. Consequently, a more quantitative estimate can be made of the importance of correlation effects in this system (e.g., by comparison of the production of nonequivalent vs equivalent doubly excited configurations). In order to infer cross sections for the production of the nonequivalent configurations from the KLX Auger electron intensities, it was found that, based on calculations⁴ of Auger and radiative transition rates, significant corrections had to be made due to Auger yields that were significantly smaller than unity. For example, the calculated average Auger yield for a KLX transition from the $2\ell 7\ell'$ configuration was found to be 0.11, in sharp contrast to the unity yield found for the corresponding Coster-Kronig transition in the $O^{6+} + \text{He}$ system. After this correction was made, very good agreement was found between the O^{6+} and C^{6+} cross sections for the production of nonequivalent configurations.

In addition to the electron spectroscopy studies of double electron capture by ground state projectiles, we have performed Auger spectroscopy measurements of single and double electron capture by He-like metastable ions in a He gas target. The goal of the study was to obtain normalized electron capture cross sections, as well as to determine the metastable fractions of He-like C, N, and O beams extracted from the ECR source. The method used involved the measurement of K-Auger yields in low resolution as a function of He target thickness. In the single collision limit, the K-Auger yield is proportional to the product of the electron capture cross section times the metastable fraction. At equilibrium target thicknesses, where each incident metastable ion has a 100% probability of capturing an electron and subsequently filling the initial K-vacancy by Auger decay, the yield is proportional to the metastable beam fraction. From the yields obtained in these two limits the total (i.e., single plus multiple) electron capture cross section for the He-like metastable ion can be determined. High resolution measurements of the K-Auger electrons were also

performed to permit separation of single- and multiple-electron capture by identifying the corresponding Li-like, Be-like, etc., K-Auger transitions. Figure 4.8 shows the target thickness dependence of the normalized K-Auger yield for the collision systems studied. The target thickness was calibrated using a capacitance manometer, while the electron spectrometer efficiency was determined by normalizing to the known⁵ Auger electron emission cross section for 10-keV $\text{He}^+ + \text{He}$ collisions. The metastable fractions determined from these measurements are consistent with independent measurements of this quantity using ion-surface collisions.⁶ For all three ion species investigated, the total electron capture cross sections determined for the metastable ions were in reasonable agreement with the total ground state electron capture cross sections obtained from the literature. Further work is planned to resolve single vs

Fig. 4.8. Target thickness dependence of the normalized yields of K-Auger electrons associated with electron capture by metastable He-like ions of C, N, and O. The metastable fractions, f_m , and capture cross sections, σ_K , shown in the figure were determined using the asymptotic thick target K-Auger yields and the initial yield slope in the low target thickness limit as described in the text. The solid curves are the calculated yields $Y = f_m[1 - \exp(-\sigma_K(\pi))]$ and do not represent least squares fits to the data.

multiple electron capture processes by analysis of the high resolution K-Auger spectra.

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ELECTRON SPECTROSCOPY OF MULTICHARGED ION-SURFACE INTERACTIONS

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We have continued our collaborative effort to study the interaction of multicharged ions with surfaces. Our previous measurements of a variety of projectile ions incident on Cu and Au single crystals have shown electron Auger emission from both the projectile and target. The projectile Auger electrons result from the decay of inner-shell vacancies either carried into the collision, or produced by vacancy transfer from empty outer projectile levels via close collisions with target atoms. If the incident projectile vacancy survives the neutralization process above the surface, subsequent close collisions with the target atoms may lead to the creation of inner-shell vacancies in the target, which give rise to Auger emission characteristic of the metal. The important timescales of the neutralization of the projectile ion (the rate at which electrons fill the higher levels and the rate of decay of the inner-shell vacancy) are only qualitatively understood.³

In order to quantitatively determine neutralization times above the surface, we monitor the target Auger emission resulting from collisions of the projectile with the target atoms. The variation of the N projectile KLL peak and the Au target NVV (69 eV) and KVV (220 eV) peaks were measured for N^{6+} incident on Au at various angles of incidence (see Fig. 4.9). Assuming neutralization begins at a critical distance⁴ above the surface at which the Coulomb barrier between the projectile and

Fig. 4.9. Electron energy distributions for 60 keV N^{6+} ions incident on Au, for four different observation angles, θ , and corresponding above-surface neutralization times, t .

metal falls below the Fermi level (equal to about 16 a.u. for N^{6+} ions), each angle of incidence, θ , corresponds to a different above-surface neutralization time, t . Since the observed N KLL peak position is relatively insensitive to incident angle, it is inferred that filling of the upper L levels is accomplished quickly compared to the relevant KLL Auger decay. The disappearance of the 69-eV target line at the lowest angles of incidence indicates that the N K vacancy does not survive the neutralization process before interacting with the surface. The area under the 69- and 220-eV Au peak is plotted in Fig. 4.10 as a function of the above-surface neutralization time. The slopes of both curves are nearly the same and lead to an estimate of the K-vacancy lifetime, τ , above the surface, to be on the order of 1.5×10^{-14} s.

It is hoped that the above technique can be applied to a system where the various electron configurations leading to Auger emission may be resolved in the electron emission spectra. Comparison of the observed and calculated decay rate may then lead to a better understanding of

Fig. 4.10. Semi-log plot of the area under the two observed Au lines as a function of above-surface neutralization time. The slopes of the straight line fit to the data lead to estimates for the lifetime of the N K-vacancy above the surface.

the neutralization process, especially the apparent rapid filling of the upper levels.

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MERGED-BEAMS EXPERIMENT FOR ELECTRON-IMPACT EXCITATION OF IONS

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Apart from their fundamental importance, cross sections for electron-impact excitation of multiply charged plasma impurity ions are critical to radiative power loss and diagnostics of magnetic fusion plasmas. All such excitation cross-section measurements to date have been based on the crossed-beams approach and on absolute intensity measurements of the radiation emitted as the excited states decay. The number

of such measurements has been severely limited by low intensities and efficiencies of photon detection. Resonances are predicted to play a major role in the near-threshold region, but the experiments performed to date have had insufficient energy resolution to adequately test theoretical calculations.

A novel experimental approach to this problem has been under development for a number of years at the Joint Institute for Laboratory Astrophysics (JILA) in Boulder, Colorado. This approach involves merging fast beams of electrons and multiply charged ions in a uniform axial magnetic field, and using electron energy-loss spectroscopy to detect electron-impact excitation events. This experiment has been developed specifically for use in conjunction with the ORNL-ECR multicharged ion source. During a six-month assignment of R. A. Phaneuf to JILA during FY-1989, the proof-of-principle of the technique was established, systematic tests were completed, and preliminary measurements of excitation of C⁺ were initiated.⁷

Plans call for transportation of the apparatus to ORNL in mid-November 1989, with subsequent initiation of collaborative measurements of electron-impact excitation of multiply charged ions. In preparation, modifications were made to the main beamline of the ORNL-ECR ion source, and the existing crossed-beams and merged-beams experiments were relocated. Collaborative experiments using this new experimental approach will comprise a significant fraction of our experimental effort in electron-ion collisions during the next several years.

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ELECTRON-IMPACT IONIZATION OF Ta^{4+}

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In the next generation of magnetic fusion experiments, such as the proposed International Tokamak Experimental Reactor (ITER), the power loading at the vacuum vessel walls and divertor plates will exceed the capabilities of low-Z materials such as carbon, which is widely used in current devices. Refractory metals such as W and Ta are being considered. Such high-Z elements will become only partially ionized in the hot plasma, and radiation from these ions will cool the edge region, insulating the vacuum vessel from the hot core plasma. Line radiation from specific charge states will provide a useful diagnostic of the plasma. Accurate modeling will require knowledge of cross sections for electron-impact ionization and recombination of these high-Z elements.

Preliminary measurements have been made of electron-impact ionization cross sections for Ta^{4+} as a function of collision energy. The experiment utilized the ORNL ECR ion source and electron-ion crossed beams apparatus. This was the first use of heavy refractory metal ion beams from this source in an experiment. The measurements in this preliminary study show that the cross section is approximately 50% larger than that predicted by the simple Lotz formula over the energy range from 150 to 900 eV collision energies. There are no indications of a high-lying metastable component in the incident ion beam or of sharp features in the cross section energy dependence. Possible future experiments include a remeasurement of this cross section in greater detail as well as ionization measurements for additional charge states.

ACCELERATOR-BASED ATOMIC PHYSICS

DIELECTRONIC EXCITATION OF IONS IN CRYSTAL CHANNELS

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Channeled ions interact only with loosely bound target electrons. For ion velocities $v_i \gg v_F$, where v_F is a target Fermi electron velocity, the penetrating ion may be viewed as being bombarded by a flux of electrons moving at velocity v_i . Ions traveling through this medium at velocities v_i equivalent to electron velocities required for sharply varying processes, such as dielectronic or direct excitation of an electron bound to the ion, should experience events similar to those in a hot dense plasma, but with a relatively narrow electron energy distribution, i.e., a Fermi distribution as against a Maxwell-Boltzmann distribution at the temperature necessary to carry out these excitation processes.

In vacuum, a doubly excited state would decay either by an Auger process or by radiative stabilization. In dielectronic recombination (DR), the final products are an ion of reduced charge and two photons. However, if the excited state is created in a dense electron medium (i.e., a dense plasma or a crystal channel), secondary collisional processes leading to further excitation and ionization can come into play and may even dominate.

If we take, as an example, a KLL resonant transition in a hydrogenic ion, a summary of most of the reactions which can occur is given below.

Experiments were carried out using the 25-MV tandem accelerator of the Holifield Heavy Ion Research Facility (HHIRF) at ORNL to obtain beams of H-like Si^{15+} (80 – 210 MeV), H-like Ca^{19+} (150 – 330 MeV), and He-like Ti^{20+} (237 – 375 MeV). The Si^{15+} and Ca^{19+} ion beams were passed through the $\langle 110 \rangle$ axis of a 1.2- μm -thick silicon crystal. Measurements were made of (a) the emerging charge-state distributions

using electrostatic deflection and a solid-state position-sensitive detector, and (b) the X-ray spectra using a Si(Li) detector with a 145-eV resolution at 5.9 keV. With this detector, we are easily able to resolve the $h\nu_1$ ($2p^2 \rightarrow 2p1s$) from $h\nu_2$ ($1s2p \rightarrow 1s^2$), but since both $h\nu_1$ and $h\nu_3$ ($2p \rightarrow 1s$) involve decay to an empty K shell, they cannot be resolved. Hence, the experimentally distinguishable end products are $A^{(Z-2)+}$, A^{Z+} , photons having energies $h\nu_1$ and $h\nu_3$ and photons with energy $h\nu_2$ (these are underlined in the above equations).

In Fig. 4.11a, we show for channeled Ca^{19+} the yield of $(h\nu_1 + h\nu_3)$ as a function of ion energy. The features correspond to dielectronic excitation (to KLL, KLM, KLN, etc.) and, at 300 MeV, to direct $1s \rightarrow 2p$ excitation. The energies at which these contributions should appear are indicated by the arrows at the bottom of Fig. 4.11a. The magnitudes are obtained from the above rate equations, by assuming rapid substate mixing $n\ell \rightleftharpoons n\ell'$ and then using the fastest available radiative and Auger rates, ionization cross sections calculated using the

Fig. 4.11. (a) Yield of $h\nu_1(2lnl' + 1snl) + h\nu_3(2l + 1s)$ calcium X rays (see Eq. (1)) and (b) charge fraction of Ca^{20+} ions as a function of Ca^{19+} ion energy incident on a $\langle 110 \rangle$ channel in Si (1.2 μm thick). The smooth curves are results of a computer simulation as described in the text.

Löbzt formula, and excitation cross sections calculated using the Seaton formula. The collisional rates r_i are obtained from $r_i = \sigma_i \rho_e v_i$, where ρ_e is the electron density taken to be $1.9 \times 10^{23} \text{ cm}^{-3}$ for the Si $\langle 110 \rangle$ channel and σ_i is the cross section for the considered process.

The calculated rates are convoluted with a 10-eV Fermi distribution for the electrons in a $\langle 110 \rangle$ Si channel. Resulting rate equations for populations of the ten lowest hydrogen- and helium-like configurations ($1s$ to $3l$ and $1s^2$ to $3l3l'$, respectively) are iteratively solved and summation bins for numbers of X rays emitted are accumulated in 400 steps through the crystal length of 1.2 μm . Charge-state fractions and X-ray yields per ion are calculated, including effects of Auger and X-ray decay of excited ions downstream of the crystal. The resultant

$(h\nu_1 + h\nu_3)$ X-ray yield/ion is plotted as the solid curve in Fig. 4.11a. It should be noted that the only normalization is the addition of backgrounds linear in projectile energy and that the predicted values are absolute in X rays per ion. Using the same rate coefficients, we can calculate, e.g., the yield of Ca^{20+} ions. [Compare Eq. (1) V.b, and plot it together with the experimental data in Fig. 4.11b).]

In the case of Ca^{19+} , the radiative processes dominate; for example, the ratio of rates for Eq. (1) III.a/III.b = 4. In the case of S^{15+} , the radiative rates are slower and the excitation and ionization cross sections are higher, so that the collisional channel comes more into play; i.e., for S^{15+} (III.a/III.b) = 0.8. In Fig. 4.12a, we show, as a function of S^{15+} ion

Fig. 4.12. (a) Yield of $h\nu_1(2lnl' + 1snl) + h\nu_3(2l + 1s)$ sulphur X rays (see Eq. (1)) and (b) charge fraction of S^{16+} ions as a function of S^{15+} ion energy incident on a $\langle 110 \rangle$ channel in Si ($1.2 \mu\text{m}$ thick). The smooth curves are results of a computer simulation as described in the text.

energy, the data for the yields of $(h\nu_1 + h\nu_3)$ and in Fig. 4.12b, the S^{16+} charge fraction. The solid curves are calculated in the same manner as for Ca^{19+} above.

We now turn to a more complex ion, He-like Ti^{20+} . In this case, the stabilized recombined ion Ti^{19+} is susceptible to ionization by further electron impact.

- I. $\text{Ti}^{20+}(1s^2) + e \rightleftharpoons [\text{Ti}^{19+}(1s2l2l')]^{**}$
- II. a) $[\text{Ti}^{19+}(1s2l2l')]^{**} \rightarrow \text{Ti}^{19+}(1s2l) + h\nu_1$
- II. b) $[\text{Ti}^{19+}(1s2l2l')]^{**} + e \rightarrow [\text{Ti}^{20+}(1s2l)]^* + 2e$
- III. a) $[\text{Ti}^{20+}(1s2l)]^* \rightarrow \text{Ti}^{20+}(1s^2) + h\nu_2$
- III. b) $[\text{Ti}^{20+}(1s2l)]^* + e \rightarrow \text{Ti}^{21+}(1s) + 2e$.

Here the radiative rate for II.a exceeds the collisional rate (II.b) by a factor of ~ 8 . However, the stabilized recombined ion (II.a) is susceptible to ionization via $1s2l + e \rightarrow 1s^2 + 3l \rightarrow 1s^2 + 2e$ with a mean free path of $\sim 1.5 \mu\text{m}$. We demonstrated this effect by passing a $\text{Ti}^{20+}(1s^2)$ beam through a $\langle 100 \rangle$ channel in a Si crystal $2.6 \mu\text{m}$ thick. Because of the relatively low yield of surviving Ti^{19+} ions, coincidence measurements were necessary. In Fig. 4.13, we show the data for coincidence of Ti^{19+} ions with Ti K_α and K_β X rays. The solid curves are results from a computer simulation similar to those described above for incident S^{15+} and Ca^{19+} ions. Here, electron binding and transition energies have been reduced to approximate the Li-like doubly-excited states; small linear backgrounds have been added; and the calculations for K_α and K_β have been independently normalized to the data at 300 MeV.

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Fig. 4.13. Titanium K_{α} and K_{β} X-ray yields for He-like (Ti^{20+}) incident ions axially channelled through a 2.6- μ m-thick Si $\langle 100 \rangle$ crystal. X rays were measured in coincidence with Ti^{19+} ions. Solid curves show normalized results of a computer simulation as described in the text.

RADIATIVE ELECTRON CAPTURE BY BARE- AND ONE-ELECTRON IONS

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Radiative recombination is a fundamental process of positive ion neutralization in which a free electron is transferred to the ion with simultaneous emission of an energy- and momentum-stabilizing photon. When the active electron is initially weakly bound, the process is referred to as Radiative Electron Capture (REC). Motivated by our earlier discovery of small (2%) difference between measured and calculated energies for REC X rays emitted by surfur ions channelled in a thin silicon crystal, we have made precise measurements of X rays emitted by fast, bare- and one-electron oxygen, and titanium ions passing through gas or solid targets. Measurements of REC for (100-225 MeV) O^{8+} in H_2 and He gases give centroid energies which match precisely with theory. For (300 MeV) Ti^{20+} , Ti^{21+} , and Ti^{22+} ions channelled

in silicon and nickel crystals, X rays were detected in coincidence with unscattered Ti^{19+} , Ti^{20+} , and Ti^{21+} , respectively. Typical X-ray spectra in Si $\langle 100 \rangle$ are shown in Fig. 4.14. These coincidence spectra permit the most precise measurements made to date for REC energies and profiles. We find, for 300 MeV Ti^{21+} and Ti^{22+} axially channelled in Si $\langle 100 \rangle$ and Si $\langle 110 \rangle$, that the REC centroid energy lies ~ 70 eV lower than predicted, with peak profiles corresponding very well to those calculated for a Fermi target electron momentum distribution with a Fermi energy of 10.6 eV. Initial measurements in Ni $\langle 110 \rangle$ give an even lower peak energy (~ 120 eV lower than calculated).

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Fig. 4.14. X rays from (I) Ti^{20+} , (II) Ti^{21+} , and (III) Ti^{22+} channeled in a 1.2- μ m-thick Si <100> crystal. Low-energy lines at 5–7 keV are Ti K X rays. The lines are due to (a) $1s2p + 1s^2$, (b) $2p + 1s$, (c) $1s3p + 1s^2$, and (d) $3p + 1s$ transitions. REC by bare- and one-electron Ti lie above 10 keV.

DOUBLE EXCITATION OF He BY FAST BARE IONS

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The double excitation of He by fast, bare projectiles has been measured as a function of the charge, Z , of the projectile. The cross sections for producing the doubly excited states have been found to vary between Z^2 and Z^3 , depending on the particular final state. This suggests that the various doubly excited states may be populated by different excitation mechanisms. This process was investigated in order to probe the role that electron-electron interactions play in ion-atom collisions. The importance of these interactions has been clearly demonstrated in transfer ionization,^{7,8} and is suggested in double ionization.^{9,10} Double excitation of He by bare projectiles is conceptually and computationally simpler than these ionization processes where one or two electrons end up in the continuum.¹¹

We have observed autoionization of He atoms following double excitation by electrons, protons, C^{q+} ($q = 4 - 6$), and F^{q+} ($q = 7 - 9$) projectiles at 1.5 MeV/amu. The autoionized electrons, with line energies between 30 and 45 eV, were detected by using a high-resolution electron spectrometer¹² at laboratory observation angles between 9.6° and 60° relative to the beam axis. A spectrum for C^{6+} on He at 10° is shown in Fig. 4.15. As with all the projectiles, the dominant excitations are to the

Fig. 4.15. An electron spectrum for C^{6+} on He at 10° . The data have been fit using the Shore parameterization¹³ of the Fano profile. The lines used in the fit are identified in the figure.

$2p^2(^1D)$ and $2s2p(^1P)$ states. There is no sign of population of triplet states when using bare projectiles (e^- , H^+ , C^{6+} , and F^{9+}), as might be expected. Even for non-bare projectiles (C^{4+} , C^{5+} , F^{7+} , and F^{8+}), the triplet populations are always very small compared with the singlet populations. A strong Fano profile is seen for all states, indicating interference between the double excitation and direct ionization processes. A fit of these profiles to the data is also shown in Fig. 4.15. The results for all projectiles indicate that excitation to the $2p^2(^1D)$ and $2s^2(^1S)$ states increases as $\sim Z^3$ while excitation to the $2s2p(^1P)$ varies as $\sim Z^2$, where Z is the charge of the projectile.

This result can be qualitatively understood by examining the Z dependencies of the proposed double excitation mechanisms. One mechanism involves a close collision between the projectile and one of the He electrons. This electron in turn interacts with the second electron, and both are excited. This mechanism can be pictured as a 'shake-up' transition¹¹ and should vary as Z^2 . The population of the $2s2p$ state is probably due to this mechanism. A second mechanism involves a close collision of the projectile with each target electron, and should vary as Z^4 . Interference of these two mechanisms is possible and can lead to a Z^3 dependence. This interference term is thought to be responsible for the Z^3 dependence of the $2p^2$ and $2s^2$ states.

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PROJECTILE ENERGY LOSS MEASUREMENTS AS AN n -BODY PROBLEM IN FAST ION-ATOM COLLISIONS

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Multiple target ionization by MeV/nucleon projectile ions which may, in addition, capture or lose an electron appears to be describable

within a classical model. For example, the recoil-ion charge state produced has a distribution which is close to binomial and which is in agreement with the expectations of an independent particle model.

The experiments performed probe the validity and limitations of classical approximations in multielectron processes in fast ion-atom collisions. We measured the projectile energy loss of 10-MeV C^{9+} ions colliding with He, Ne, Ar, and Kr. Simultaneously, we recorded the projectile and the recoil charge state as well as the energy of the ionized electrons. The projectile energy loss exceeded, by a factor of 2–5, the sum of the ionization potentials for a given degree of target ionization. The projectile transfers its energy mainly to the ejected target electrons. We observed a decrease of the mean electron energy with increasing target Z . While the energy loss and the projectile scattering angle increased with increasing recoil charge state, the inelasticity for producing a given charge state did not depend on the impact parameter. Despite a binomial recoil charge state distribution, we found that for direct target ionization the electron energy distribution depends on the degree of ionization. For multiple ionization accompanied by projectile capture, no dependence of electron energy on the recoil charge state was observed.

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ELECTRON-ELECTRON INTERACTIONS IN TRANSFER AND EXCITATION STUDIED IN H-LIKE FLUORINE COLLIDING WITH M_2

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We have measured the energy dependence of the projectile Auger emission cross sections for

H-like F colliding with H_2 at energies between 17 and 33 MeV. Electrons emitted at an angle of 9.6° were analyzed by a two-stage, parallel-plate, electron spectrometer and detected by a position-sensitive microchannel-plate detector (MCP), which permitted the entire F KLn Rydberg series to be measured simultaneously. For H-like ions, an Auger electron can be produced only by a Transfer and Excitation (TE) process or by double capture. Since double capture is negligible for an H_2 target, each Auger electron is a signature of a TE process. In the measured spectra, only He-like Auger lines representing a TE process were observed. Lithium-like lines, representing double capture, could not be discerned.

In Fig. 4.16, the Auger emission cross section shows a pronounced structure as a function of the projectile energy. There are two maxima in the cross sections for the KLL transitions,

Fig. 4.16. Auger emission cross sections vs projectile energy.

σ_{KLL} and one maximum for all the other transitions (KLM-KLO) (σ_{KLn}). The first maximum in σ_{KLL} is attributed to Resonant Transfer and Excitation (RTE). All the other maxima occur at slightly higher projectile energies than the energy of the RTE KLn series limit. We propose that a new process, Two-Electron Transfer and Excitation (2eTE), is responsible for the maxima above the RTE series limit. In 2eTE, one target electron is captured by the projectile and a second target electron excites a projectile electron. The sharp energy threshold for K to L excitation is spread out in the 2eTE cross sections by the Compton profile of the target electrons. The predicted position and shape of the threshold is consistent with the measured cross sections. Also, the n -distribution of the measured KLn cross sections is consistent with that expected for 2eTE.

Spectra taken at projectile energies above 27 MeV show surprisingly strong contributions from high n -state KLn Auger electrons near the Rydberg limit. In order to study the production mechanism of these Auger electrons, we repeated the experiment with higher resolution. A relatively strong and narrow line was observed exactly at the KLn Rydberg series limit (828 eV, see Fig. 4.17), whereas no KLn Auger electrons with n between 7 and some value near the Rydberg limit could be discerned. The fact that there seems to be a gap in the n -distribution of the emitted Auger electrons may be taken as an indication that the very high n -state Auger electrons are not produced by the same mechanism as the lower n -state Auger electrons.

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Fig. 4.17. Electron spectra for 21-, 25-, and 31-MeV $F^{8+} \rightarrow H_2$. The energy scale is in the rest frame of the projectile. The labeled Auger groups are: 1 = KLL, 2 = KLM, 3 = KLN, and 4 = KLO.

HIGH-RESOLUTION X-RAY STUDIES OF THE CHEMICAL ENVIRONMENT OF SULFUR IMPLANTED IN SILICON AND QUARTZ

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High-resolution sulfur K_α X-ray satellite spectra have been obtained for 24-MeV Si and 30-MeV Cl ions colliding with silicon and quartz targets containing ion-implanted sulfur at doses of 2.5 to 8.6×10^{16} atoms/cm². The normalized emission spectra exhibit variations in the intensity distributions of the satellite structures as a function of implant dose. The

variations appear to be due to changes in the local valence electron density caused by changes in the local sulfur density. Sulfur X rays were detected from depths ranging from 500 to 200 angstroms below the target surface. This translates into an ability to detect changes in local chemistry of sulfur at concentrations of less than 0.2 atomic percent.

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OBSERVATION OF LANDAU RESONANCES WELL ABOVE THRESHOLD IN A HIGH-RESOLUTION ($\Delta f = 70$ MHz) LASER PHOTODETACHMENT STUDY OF O^-

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Preliminary studies of the photodetachment process, $O^- + h\nu \rightarrow O + e$, performed well above threshold and in the presence of a very weak magnetic field (0.02 – 0.1 Tesla) suggested that the photodetachment yield oscillates at the cyclotron frequency of the free electron (27.933 GHz/Tesla).¹ Heretofore, an oscillating cross section due to Landau resonances has been predicted and observed only at the photodetachment threshold and in strong magnetic fields (1 – 8 Tesla) for other negative ions.²⁻⁵ In the present reporting period, major apparatus improvements have allowed the effect to be studied under a wide variety of experimental conditions and at greatly improved precision and counting statistics. The results indicate that Landau resonances do occur under more general conditions than have been reported previously.

In the experiments, O^- ions formed in a Colutron ion source are accelerated, focused, momentum analyzed and then refocused before injection into a Wien filter. The nearly parallel ion beam (≤ 100 μ rad FWHM at 800 eV) intersects with the laser beam at the center of the Wien filter at the Doppler-free angle. The laser beam, produced by a near-infrared single-frequency laser diode ($\Delta f = 30$ MHz) is linearly polarized in the direction of the magnetic

field. Neutrals are detected downstream on a high-resolution, two-dimensional, position-sensitive detector (TDFSD). The ion beam is deflected into a Faraday cup located between the Wien filter and the TDFSD.

Stark broadening is eliminated by performing the photodetachment inside the $E \times B$ filter. When simultaneous crossed electrostatic (E) and magnetic (B) fields are adjusted to the balance condition $v = E/B$, where v is the projectile speed, the ions traveling in the $E \times B$ direction experience a slightly reduced but pure magnetic field (no Stark splitting due to $v \times B$). The possibility of observing other predicted electrostatic field effects in photodetachment also is eliminated under these conditions.

High-resolution structure in the photodetachment continuum for the O^- ion has been explored at several laser frequencies between 12137.24 and 12756.60 cm^{-1} and at numerous magnetic fields between 0.01 – 0.126 Tesla. The study at the highest field strength where the effect is largest was most conclusive. The photodetachment cross section obtained by scanning the laser in the vicinity of 12147.06 cm^{-1} and at a magnetic field strength of 0.126 Tesla is shown in Fig. 4.18. This laser frequency nominally exceeds the electron affinity by 362.41 cm^{-1} and is well above threshold for all six fine-structure transitions [i.e., $O^-(^2P_{3/2} = 3/2, 1/2) \rightarrow O(^3P_{3/2} = 2, 10)$]. Sharp cross section variations, typically less than 15% of the total cross section, are observed where statistical uncertainty in the neutral particle yield is about 1%. The steep monotonic increase in the field-free cross section that occurs between threshold (11784.65 cm^{-1}) and its peak (well beyond 13,000 cm^{-1}) is imperceptible over the very small range of the laser scan shown. Structure in the cross section could be reproduced when the laser frequency and the magnetic field were stabilized better than 0.1 ppm and 5 ppm, respectively. Magnet power supply data show that the current was extraordinarily stable (2 ppm) when the laser frequency was below the nominal wavelength in Fig. 4.18.

Fig. 4.18. High-Resolution laser scan of the photodetachment cross section for O^- in the vicinity of 12147.06 cm^{-1} for a magnetic field of 0.126 Tesla.

Concentrating on the structure in Fig. 4.18, a complicated pattern consisting of about 12 lines has a repeat frequency equal to v_e , the electron cyclotron frequency (i.e., 3.53 GHz). Within each of these cycles two patterns of adjacent and equally spaced lines are observed (i.e., patterns A and B).

Adjacent lines in each group are separated by $v_e/12$, which matches the Zeeman splitting for either of two fine-structure transitions that originate from the $O^-(^2P_{3/2} = 3/2)$ ground state and lead to $O(^3P_{3/2} = 2, 1) + e$. These two fine-structure transitions are also known to be the most dominant contributors to the total photodetachment cross section in the vicinity of 12147 cm^{-1} , together accounting for about 60% of the field-free cross section.⁶

These observations are consistent with the prediction of photodetachment theories that have explained undulating cross section measurements performed at threshold.²⁻⁵ Essentially, a sharp Landau resonance occurs whenever the laser frequency identically matches a multiple of the quantized neutral plus electron cyclotron orbital energy in the continuum. Asymmetric peaks,

that are predicted to rise sharply from each Zeeman threshold and decline more gradually, can even be seen for some of the resonances in Fig. 4.18. The Landau quantum numbers for $O(^3P_2)$ and $O(^3P_1)$ are approximately 3065 and 1725, respectively. Only the lowest Landau quantum numbers have been observed in previous threshold studies of the effect (i.e., $N \leq 3$).

Theory predicts that the Landau resonance strength scales as $(\sigma_{ff})/(E^{1/2})$, where σ_{ff} is the field-free cross section and E is the ejected electron energy. Zeeman line strengths are also predicted.² For the conditions of the measurement discussed above, the total yield integrated over all Zeeman lines leading to $O(^3P_2)$ should dominate over that leading to $O(^3P_1)$ by about a factor of 2. Structure A in Fig. 4.18 should therefore be due to $O(^3P_2)$. This final state should have seven Zeeman lines of relative strength 0.09:0.03:0.02:0.72:0.02:0.03:0.09, where the strong central line corresponds to doubly degenerate $M_j = \pm 3/2 \rightarrow M_j + M_e = \pm 2 \mp 1/2$ transitions.² The strong central line is missing in structure A. In fact, the relative strengths in structure B appear to be similar to these strengths but the integrated yield in structure B is at least a factor of 2 smaller than the total yield in structure A. Theory predicts that the relative Zeeman line strengths leading to $O(^3P_1)$ are 0.25:0.167:0.083:0.0:0.083:0.167:0.25; and these are in rough agreement with those observed in structure A. We conclude that the theory must either be incorrect in fine-structure scaling so that structure A corresponds to $O(^3P_1)$ or incorrect in the predicted Zeeman line strength if structure A corresponds to $O(^3P_2)$.

Zeeman structure has been resolved once previously at threshold, for the $Se^-(2P_{3/2}) \rightarrow Se(^3P_2)$ fine-structure transition in a field of 6 Tesla and for a different laser polarization (i.e., $\Delta M_j = -1$ transitions).³ In that experiment, a line predicted to have zero intensity (i.e., $M_j = -3/2 \rightarrow M_j + m_e = -2-1/2$) was observed. The present results (i.e., $\Delta M = 0$ transition*) also grossly disagree with theory,

involving $M_{j1} = \pm 2$ if structure A corresponds to $O(^3P_2)$; but here, the predicted strong line is very weak. Further experimental and theoretical work will be needed to resolve these intriguing puzzles.

Experimental and theoretical discrepancies aside, the present results certainly support the view that Landau resonances occur under more general conditions than have been anticipated.²⁻⁵ In fact, previous experimental results obtained at 20 – 100 times lower resolution suggest that Landau resonances are measureable only at threshold.^{2,3}

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ANGULAR DISTRIBUTION OF THE (1s2s2p²)³D $\rightarrow$ (1s2s)²S AUGER TRANSITION FOR 13 MeV O⁵⁺ ON He TARGET

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Previously, high-resolution projectile electron spectra have been obtained^{6,7} at 0° and 10° observation angles, and no information on the magnetic substate population could be obtained. In this paper, new measurements of the angular distribution of Auger electrons emitted from the excited state (1s2s2p²)³D are reported.

The experiment was performed at ORNL using the high-resolution projectile-electron spectrometer⁸ equipped with a movable microchannel plate that can be rotated and translated to take advantage of kinematic refocusing. The Auger electrons emitted from O⁵⁺ were detected at lab observation angles ranging from 5° to 45° in 5° steps (10° – 90° in the projectile frame).

The state of interest $(1s2s2p^2)^3D$ can be formed through two different processes. The predominant one is the resonant transfer and excitation (RTE), where the electron capture from the He target to the 2p subshell of O^{5+} excites one electron from 1s to 2p of O^{5+} . The second process is the NTE, nonresonant transfer and excitation, where the excitation is induced by the target nucleus. Also direct ionization of the target (binary encounter) contributes a broad background which interferes with 3D line at all angles. The cross section for the formation of the $(1s2s2p^2)^3D$ state was normalized to the cross section for decay of $(1s2s^2)^2S$ to ground state $(1s^2)^1S$ (assumed to be isotropic to avoid uncertainties in the solid angle and the beam current integration).

Our data (Fig. 4.19) clearly indicates a forward-peaked angular distribution of the 3D cross section dominated by $m = 0$ magnetic substate below 60° projectile emission angle and no contribution from the $m = \pm 1$ and $m = \pm 2$ magnetic substates. However, above 60° the 3D cross section approaches zero and is not fitted by $|Y_{20}|^2$.

This may be attributed to interference effects between RTE, NTE, and direct transition to the continuum. Thus one would expect a different angular distribution for the Auger decay of the 3D state when the O^{5+} projectile energy is 8 MeV since, in this case, the NTE

contribution is comparable to RTE, whereas in the first case (13 MeV) the RTE dominates.

Experiments planned for the near future involve 8-MeV O^{5+} on He.

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MEASUREMENTS OF THE METASTABLE FRACTION $C^{2+}(^3P)/C^{2+}$ FOLLOWING GAS STRIPPING OF 1.66 – 3.33 MeV C^- IONS

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When the charge of an ion is increased by electron stripping using a gas or foil medium, the ion is often left in an excited configuration. Long-lived excited configurations complicate the analysis of atomic collision experiments due to uncertainty in the atomic state of the incident ions. For example, He-like beams of light ions are usually avoided due to a significant $(1s2s)^3S$ metastable component. Projectile K Auger electron spectra were measured using incident beams of Be-like carbon ions in gas collisions with H_2 and He. These spectra provide conclusive evidence of a strong $(1s^2 2s2p)^3P$ metastable C^{2+} component. Our analysis shows that the metastable fraction is between 65 and 70% when carbon ions are gas-stripped at terminal voltages between 1.66 and 3.33 MV, respectively. The metastable fractions were obtained using $(1s2s^2)^2S \rightarrow (1s^2)^1S$ and $1s(2s2p\ ^3P)2P \rightarrow (1s^2)^1S$ Auger yields.

Projectile Auger spectra were measured for Be-like carbon ion beams at ion energies of 5, 6, 7, 8, 9, and 10 MeV. Typical spectra are

Fig. 4.19. Angular distribution of the ratio $(1s2s2p^2)^3D/(1s2s^2)^2S$ from 13-MeV O^{5+} on He.

($1s^2$) $1S$ transitions for He or Ar targets. This is probably a consequence of multiple excitation or ionization with target electron effects that become more probable for the complicated heavy targets.

Assuming equal K-shell ionization cross sections for $C^{2+}(1s^2 2s^2 \ 1S)$ and $C^{2+}(1s^2 2s 2p \ 3P)$ ions, the metastable fraction can be found from a ratio of Auger yields:

$$\frac{Y(A2) + Y(A3) + Y(A4)}{Y(A1) + Y(A2) + Y(A3) + Y(A4)}$$

This fraction can also be found using similar arguments for $1s$ - $2p$ excitation, but uncertainty in the branching ratio for transitions involving excited Be-like to either $1s^2 2s$ or $1s^2 2p$ final states complicates the analysis.

Since the $(1s 2s 2p)^4P \rightarrow (1s^2)1S$ decay is itself metastable, only a fraction of these decays are observed by the spectrometer. Also, blends of the $(1s 2s^2 2p)^1P + (2s^2 2p)^2P$ and $2s(2s 2p \ 1P)^2P$ lines would require a fitting procedure to extract the $Y(A4)$. Instead, we have used fractional parentage coefficients to obtain $Y(A2) = 4/3 \ Y(A3)$ and $Y(A4) = 1/3 \ Y(A3)$.

The metastable fraction may then be obtained from the ratio:

$$\frac{2.66 \ Y(A3)}{2.66 \ Y(A3) + Y(A1)}$$

The metastable fraction versus terminal stripping energy is shown for He and H_2 targets in Fig. 4.22.

Table 4.1 shows that a simple statistical stripping argument can account for the observed $1s^2 2s 2p \ 3P$ fraction. The three lowest-energy Be-like configurations that may result when C^- is stripped are in the first column. The second column shows terms allowed by Pauli statistics. A metastable fraction of 64.3% is found by summing the multiplicities $(2J + 1)$, where J is the total angular momentum of all triplet terms and dividing by the multiplicity of all terms. This fraction agrees well with the experimental findings.

Fig. 4.22. The experimental ($1s^2 2s 2p \ 3P$) metastable fractions in C^{2+} beams following gas stripping at various collision energies.

Table 4.1. A scheme used to predict the fraction of triplet ions

Configuration	Terms	$M_{TOT} = (2J + 1)$
$2s^2 2s^2$	$1S_0$	1
$1s^2 2s 2p$	$1P_1$	3
	$3P_{2,1,0}$	9
$1s^2 2p^2$	$1S_0$	1
	$1D_2$	5
	$3P_{2,1,0}$	9
		$f_{\text{triplet}} = 18/28 = 64.3\%$

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PHOTODETACHMENT CROSS SECTION MEASUREMENTS

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The technique of energy- and angle-resolved photoelectron spectroscopy has been used to determine, at three photon energies in the visible, the partial cross sections (differential and integral in angle) for photodetaching an electron from a metastable He^- ion. When the He^- ion, which is formed in the spin-aligned $(1s2s2p)^4P$ state, interacts with visible radiation, two competing photodetachment channels to the continuum are open: $h\nu + \text{He}^-(2^4P) \rightarrow \text{He}(2^3S) + e^-$ and $h\nu + \text{He}^-(2^4P) \rightarrow \text{He}(2^3P) + e^-$. In the present work, the partial cross sections, $\sigma(3S)$ and $\sigma(3P)$, for each of these processes have been measured relative to the known cross section, $\sigma(2S)$, for photodetaching an electron from a D^- ion via the process: $h\nu + \text{D}^-(1^1S) \rightarrow \text{D}(1^2S) + e^-$. The cross sections are determined from measurements of the yields and angular distributions of photoelectrons ejected from the ions at the intersection of crossed laser and negative ion beams. Details of this apparatus can be found in previous Physics Division Reports (ORNL-6420 and -6508). Following photodetachment, electrons ejected in the direction of motion of the ion beam (forward-directed electrons) are collected, energy analyzed, and detected using a spherical-sector analyzer and a channel-electron multiplier. The angular distributions of these detached photoelectrons were determined by measuring their yields as a function of the angle between the polarization vector of the linearly-polarized laser beam and the collection direction. This is accomplished in the present apparatus by keeping the collection fixed in the forward direction and rotating the laser polarization vector using a $\lambda/2$ phase retarder consisting of a double Fresnel rhomb.

In the experiment, relative cross sections were obtained by comparing, under the same geometrical conditions, the yield of electrons produced in the photodetachment of beams of He^-

ions and D^- ions. The yield ratio is multiplied by several measured factors that take account of the different frame-transformed solid angles, photon fluxes, ion densities, and asymmetry parameters associated with photodetaching electrons from the two ion beams. All geometric factors, being equal, cancel out. In the present work, it is arranged (by appropriate choice of ion beam energies) that the photoelectron peaks in each spectra are kinematically shifted to the same energy in the laboratory frame. This novel technique is shown in Fig. 4.23. The efficiency factors for collecting and detecting photoelectrons, at the same energy, from the He^- and D^- ions, are then equal and hence cancel. The ion beam velocities, which are needed to determine the ion beam densities and solid-angle transformation factors, are measured to $\sim 0.1\%$ from an in situ analysis of the photoelectron spectra. The technique, which involves either kinematic shifting or doubling of spectral lines, is described in a recent paper by Pegg et al.⁵ Angle-resolved yield measurements were made on each spectral line to determine the asymmetry parameters, β , that characterize the shape of the photoelectron emission pattern. The measurement technique was first tested by photodetaching electrons from beams of D^- and Li^- ions. The predicted $\cos^2\theta(\beta=2)$ distribution was obtained at all photon energies. The spectral dependences of the asymmetry parameters associated with the angular distributions of electrons ejected in the photodetachment of He^- were measured previously.

The partial cross section ratios, $\sigma(3S)/\sigma(2S)$ and $\sigma(3P)/\sigma(2S)$ have been measured at photon energies of 1.781 eV, 1.946 eV, and 2.091 eV. The results are: $\sigma(3S)/\sigma(2S) = 0.60 \pm 0.02$ (1.781 eV), 0.57 ± 0.04 (1.946 eV), and 0.49 ± 0.04 (2.091 eV); $\sigma(3P)/\sigma(2S) = 0.28 \pm 0.02$ (1.781 eV), 0.18 ± 0.02 (1.946 eV), and 0.12 ± 0.01 (2.091 eV). The uncertainties quoted on these values represent two standard deviations of the weighted mean of several data sets, each comprising a number of individual spectra added together. The major source of statistical error

Fig. 4.23. Three spectral peaks kinematically shifted to the same laboratory-frame energy by an appropriate choice of ion beam energies.

in each data set originates in the measurement of the yield ratios ($\sim 4\%$) and the asymmetry parameter ratios ($\sim 3\%$). Uncertainties in other measured quantities are considered to be negli-

gible. Systematic error sources have been investigated and are estimated to be within the quoted 2σ limits. An absolute scale for the relative cross-section measurements can be readily established by assuming theoretical values for the $\sigma(^2S)$ cross section for photodetaching the D^- ion. Several calculations of this quantity have been made. The perturbation-variation results of Stewart⁶ were arbitrarily chosen for the purpose of normalization in this work. Combining the theoretical results (assuming a 3% uncertainty) with the measured cross-section ratios produced the partial and total cross sections shown in Table 4.2. The

Table 4.2. Photodetachment of He^- : Cross sections (Mb) and asymmetry parameters

	Photon Energy (eV)		
	1.781	1.946	2.091
$\sigma(^3S)$	22.9 ± 1.0	20.5 ± 2.5	16.6 ± 1.8
$\beta(^3S)$	1.15 ± 0.02	1.28 ± 0.02	1.19 ± 0.07
$\sigma(^3P)$	10.0 ± 0.6	6.7 ± 0.6	4.1 ± 0.4
$\beta(^3P)$	1.52 ± 0.04	1.59 ± 0.03	1.53 ± 0.05
σ_{total}	32.9 ± 2.4	27.2 ± 3.1	20.7 ± 3.0

measured asymmetry parameters are also tabulated. The partial and total cross sections are also shown in Fig. 4.24, along with the results of the total cross section calculation of Hazi and Reed.⁷ There is good agreement between theory and the sum of the measured partial cross sections. Fig. 4.25 shows the angular differential partial cross sections, $1_C(\theta)$, for a photon energy of 1.781 eV.

The measured cross sections for photodetaching an electron from the He^- ion can be used to indirectly determine, using detailed balance arguments, the cross sections, σ_a , for the far more improbable inverse process of radiative attachment. The derived radiative attachment cross sections (in barns) are: $\sigma_a(^3S) = 166 \pm 7$

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Total Photodetachment Cross Section For
 $\text{He}^- (^4\text{P}) + h\nu \rightarrow \text{He} + e^-$

Fig. 4.24. The open squares and circles represent the partial cross sections for photodetaching He^- via the $\text{He}(^3\text{P})$ and $\text{He}(^3\text{S})$ exit channels, respectively. The solid circles, which are the sum of the measured partial cross sections, are compared with the upper (length form) and lower (velocity form) curves that represent the total cross-section calculation of Ref. 7.

Differential Cross Section for the
 Photodetachment Of He^- $\lambda=896.2$ nm

Fig. 4.25. Angular distribution partial cross sections for photodetaching an electron from He^- at a photon energy of 1.781 eV.

(1.781 eV), 162 ± 12 (1.946 eV), and 120 ± 13 (2.091 eV); $\sigma_{\text{g}}(^3\text{P}) = 74 \pm 5$ (1.781 eV), 45 ± 4 (1.946 eV), and 30 ± 3 (2.091 eV).

The relatively high precision (~5% in favorable cases) of the present cross section ratio measurements reflects our ability to exploit, in a novel way, certain kinematic effects associated with a fast moving source of ions and the simultaneous collection of electrons in the forward direction. These innovative features of the present apparatus were not used in previous photodetachment studies. An absolute scale for the relative measurements was established by the use of accurate theoretical values for the cross sections for the photodetachment of the reference ion, D^- . As a result, we have been able to determine, absolutely, partial cross sections for the photodetachment of He^- to <10%.

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STATE-SELECTIVE ANGULAR-DIFFERENTIAL
 SINGLE-ELECTRON CAPTURE IN
 VERY SLOW Ar^{4+} -Ar COLLISIONS

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Recently there has been a growing interest in the physics of slow collisions between highly charged ions and atoms. This has been motivated by the need to understand the details of the

fundamental process of charge transfer reactions, which take place in many laboratory and astrophysical plasmas.⁶

In slow collisions where the relative velocity of the heavy particle is much smaller than the orbital velocity of the active electrons, the capture of one or several electrons can be treated in a quasimolecular model. In this framework, the collision complex is viewed as a diatomic molecule in which the internuclear separation changes slowly, compared with the motion of the electrons. The potentials show a series of avoided crossings for nearby molecular states of the same spin and symmetry. The transition probability at an avoided crossing of adiabatic states depends on the collision velocity and the magnitude of the energy splitting.

At very low velocities, i.e., where the inelasticity is of the same order of magnitude as the kinetic energy in the center-of-mass system, the locations of the active avoided crossings and the shape of the interpotential curves have a greater influence on nuclear trajectories. Measurements of angular distributions over a wide angular range and at various very-low velocities should permit resolution of features of the interatomic potential and diabatic transition probabilities which are hidden at higher velocities. In addition, investigations of this kind offer the possibility of testing different theoretical treatments of charge exchange.

We have measured, with a new experimental apparatus, state-resolved angular distributions of single-electron capture of Ar^{1+} -Ar collisions at very low energies.

The experimental setup (Fig. 4.26) consists of a differentially pumped recoil-ion source, a Wien filter, an effusive gas jet, a 30° parallel-plate electrostatic analyzer and a two-dimensional position-sensitive detector.

A 30-MeV Cl^{5+} beam from the Oak Ridge National Laboratory EN-12 Tandem Van de Graaff accelerator produces Ar recoil ions, which are extracted to form an intense very-slow ion beam.⁷ In order to make energy analysis after

Fig. 4.26. Experimental setup for the production of very-low-energy beams of highly charged ions and the study of charge-transfer reactions with an atomic beam.

the secondary collision with the gas jet meaningful, it is essential to collimate the heavy-ion pump beam tightly (± 0.4 mm) and keep the extraction field low (< 0.5 V/cm). Outside the differential pump step, and after acceleration, the recoil-ions enter the Wien filter, which separates the charge states of the beam. Following the Wien filter, the beam is retarded to the collision energy. The very-slow beam has a diameter of 1 mm at the target and is collimated to an angular divergence of $\pm 0.5^\circ$. The collision energy of the very-slow ion beam is given by the positions of the heavy-ion pump beam in the extraction field and the gas-jet target. The effusive gas jet is furnished by a concave glass-capillary array, which is focused onto the very-slow ion beam. To resolve structure in the angular distribution after the collision, it is necessary to diminish the thermal velocity spread of the gas jet. The angular divergence of the drifting gas atoms is limited to less than 10° and the jet has a diameter of 1 mm at the intersection point. With the differentially pumped gas jet, a target pressure of 2 mTorr can be provided, while keeping the pressure in the main chamber at 5×10^{-7} Torr. After the intersection of the very-slow ions with the gas-jet target, the charge and energy of the ions are analyzed with a 30° parallel-plate electrostatic spectrometer. Since the analyzer is focusing only in one

dimension, the energy gain of the projectile can be obtained from the position along the direction of dispersion in the focal plane, while the position in the perpendicular direction gives information on the scattering angle. The energy and angular distributions in the focal plane are mapped onto the two-dimensional position-sensitive detector by two short acceleration fields.

The spectrometer is designed to have a relative energy resolution of 3%. Due to the energy spread of the very-slow ion beam, the measured energy resolution is $\sim 4\%$. The angular acceptance of the present setup is fixed by the size of the microchannelplate and the resistive anode to about $\pm 9^\circ$.

In Fig. 4.27, we show experimental results of state-selected angular distributions of Ar^{4+} -Ar collisions at laboratory kinetic energies between 19 and 200 eV.⁸ The energy-gain spectra show that in the present energy range single-electron capture populates the 4p level (dashed line in Fig. 4.27). No capture to the 4s level (dotted line) is observed here. These results agree well with the diminishing contribution of the 4s level with lower collision energies, seen at 2180 and 800 eV.^{9,10} The 4p angular distribution has a single maximum close to 0° for energies larger than ~ 100 eV. At lower energies, a second maximum develops and forward scattering is suppressed. The secondary maximum moves to larger scattering angles as the collision energy is lowered; and below ~ 60 eV, a third maximum appears.

The main structure of the angular-differential cross section is qualitatively reproduced by semiclassical calculations. The differential cross sections are calculated in a multichannel Landau-Zehner formalism. The classical deflection function is determined from potential curves with the coulomb interaction as the main contribution to the exit potential and polarization and penetration for incoming potential.

The peak at small scattering angles at energies below 50 eV is a 'rainbow' resulting from the fact that many impact parameters in the deflection function can give rise to almost the same scattering angle.

Fig. 4.27. Single-electron capture in Ar^{4+} -Ar collision at (a) 200, (b) 120, (c) 88, (d) 68, (e) 53, (f) 40, (g) 33, and (h) 19 eV. The contours are at 30%, 50%, and 80% of the maximum intensity. Asymmetries in (f), (g), and (h) are due to a higher background of the detector.

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RECOIL ION, PROJECTILE ION, AND CUSP ELECTRON
TRIPLE COINCIDENCE MEASUREMENTS
FOR 1 MeV/u BARE- AND ONE-ELECTRON
O AND C PROJECTILES ON Ne

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We have measured in coincidence the projectile ion charge state, the target recoil-ion charge state, and the energy of a free electron (cusp electron) emerging from the same collision with a velocity close to the beam velocity for 1 MeV/u bare- and one-electron oxygen and carbon projectiles colliding with neon targets. We have determined if collisions in which a cusp electron is produced are characterized by different recoil-ion/projectile ion charge state distributions and if cusp electron production significantly influences the inelasticity in collisions involving multiple target ionization.^{3,4}

Fig. 4.28 shows a diagram of the apparatus used in our experiments. The target gas cell, the recoil-ion spectrometer, and the cusp electron spectrometer are located in the experi-

mental chamber which is lined with two layers of mu-metal magnetic shielding. Recoil ions are extracted by a very weak electric field (~ 7 V/cm) into the time-of-flight (TOF) recoil-ion spectrometer. Cusp electrons are deflected and energy analyzed in the parallel-plate spectrometer. The recoil-ion extraction field in the gas cell must be sufficiently small to allow the cusp electrons, which move with the beam velocity, to escape without being noticeably deflected.

The most probable recoil-ion charge state of recoil ions not associated with cusp electrons is one. In Fig. 4.29, we compare the cross sections for the production of a cusp electron, a recoil ion of charge state q_r , and a projectile ion of charge state q_p in a single collision with those for producing a recoil ion of charge state q_r in coincidence with a projectile ion of charge state q_p , without requiring a coincidence with a cusp electron for O^{7+} projectiles. Most cusp electrons accompany a projectile which does not change charge; they are captured from the target. The recoil-ion

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Fig. 4.28. Experimental apparatus.

Fig. 4.29. Cross sections for the production of neon recoil ions by 1-MeV/u O^{7+} projectiles capturing an electron (a), not changing charge (c), losing an electron (e), and cross sections for recoil-ion/cusp electron production for projectiles capturing an electron (b), not changing charge (d), and losing an electron (f). Errors are relative errors.

charge-state distribution shifts towards higher charge states and closely resembles that measured in coincidence with a bound-state capture without any cusp electron coincidence requirement. This points towards a close relationship between bound-state capture and continuum capture. Target electron capture by the projectile in coincidence with cusp electron production shifts the recoil-ion charge-state distribution towards even higher charge states. This process requires at least two target electrons to be involved and therefore happens at smaller impact parameters and leads to higher recoil-ion charge states. Electron loss by the O^{7+} projectile in conjunction with cusp electron production causes the recoil-ion charge-state distribution to shift to lower charge states. Thus cusp electrons produced in coincidence with projectile electron loss are often associated with gentler, larger impact parameter collisions. The probability of producing a cusp electron given the production of a recoil ion increases with increasing recoil-ion charge state for all incident projectile ions that do

not change charge or capture a target electron and decreases with increasing recoil-ion charge state, if it is associated with projectile electron loss. A collision in which a low charge-state recoil ion is produced and the projectile loses an electron has the highest probability of producing a cusp electron. Overall, the probability of cusp electron production given the production of a recoil ion is small; therefore, we conclude that the production of cusp electrons cannot, by itself, account for the large amount of energy transferred to free electrons in collisions where high recoil-ion charge states are produced.^{3,4}

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PRODUCTION OF HIGHLY EXCITED STATES AND LOW-LYING PROJECTILE-CENTERED CONTINUUM STATES IN FAST ION-ATOM AND ION-SOLID COLLISIONS

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Fast heavy ions passing through gaseous targets under single collision conditions often exit the target region with an electron in a high Rydberg state near the ionization limit or accompanied by an electron in a low-lying projectile-centered continuum state. If the projectile ion entering the collision is bare, target electron capture to a projectile bound or continuum state is responsible for the production of the Rydberg or cusp electron, while projectile electron excitation and ionization are competing processes if the projectile carries electrons into the collision.

Electrons in high Rydberg states or low-lying continuum states of the projectile also accompany fast heavy ions after they pass through thin, solid targets. In this case, the free

electrons traveling with a velocity close to the ion velocity are called convoy electrons. A close relationship between the production of electrons in high Rydberg states and electrons in low-lying continuum states of the projectile is often assumed in both ion-atom and ion-solid collisions, since capture and ionization cross sections are expected to vary smoothly across the ionization threshold. In the experiments described here, we investigate this relationship as a function of incident charge state q_i and exit core charge state q_e for collisions between 2-MeV/u C projectiles and an argon gas target and as a function of foil thickness for subequilibrium to equilibrium thickness C foil targets. The experiments are designed to better elucidate the production mechanisms for Rydberg and convoy electrons in ion-foil collisions.

Fig. 4.30 shows the experimental apparatus. Projectile ions pass through the target located in the entrance focus of a large 30° parallel-plate electrostatic electron energy analyzer. The energy spectra of electrons emitted in the forward direction are measured using the 30° analyzer for energy analysis and a channel electron multiplier (CEM) for detection. After the projectile ions pass through a hole in the back of the 30° analyzer, Rydberg electrons are stripped from the projectile ions in the spherical-ionizer, energy analyzed in the 160° spherical sector electrostatic energy analyzer, and detected with a CEM. Further downstream, the projectile ions are electrostatically separated according to exit charge state, and ions of a particular charge state are deflected

Fig. 4.30. Experimental apparatus.

into a multidynode electron multiplier capable of up to 1 MHz count rate.

Fig. 4.31 shows the convoy electron yield and

Fig. 4.31. Convoy electron yield and the Rydberg electron yield in coincidence with exit charge state q_e normalized to the total number of ions as a function of foil thickness for 2 MeV/u C^{q_i+} ($q_i = 4, 5, 6$) ions striking C foils.

the Rydberg electron yield in coincidence with exit charge state q_e normalized to the total number of ions as a function of foil thickness for 2 MeV/u Cq_i^+ ($q_i = 4, 5, 6$) ions striking C foils with thicknesses ranging from 0.5 to 50 $\mu\text{g}/\text{cm}^2$. The similar dependencies on foil thickness of the convoy and Rydberg electron yields suggest a similar production mechanism. The shape of the convoy electron-energy spectra, when compared with the shape of spectra measured with Ar gas targets, suggests that convoy electrons are produced by projectile electron loss. The ratios of the convoy electron production cross sections to the Rydberg electron production cross sections are approximately equal to the corresponding ratio for projectile electron loss and projectile excitation to high Rydberg states measured with Ar gas targets. Normalizing the number of convoys and Rydbergs detected in coincidence with ions of core charge state q_e to the number of ions exiting the collision with core charge state $q_e - 1$ further strengthens our conclusion: convoy electrons are produced by projectile electron loss from low-lying excited states; Rydberg electrons are produced by excitation from low-lying excited states. These low-lying excited states build up as the ion traverses the foil. Our data suggest that electron capture to highly excited Rydberg states and low-lying projectile-centered continuum states does not happen in a foil.

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EN TANDEM OPERATIONS

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During the past year, EN-12 was operated for 3,050 hours in support of the accelerator-based atomic physics program. A program of accelerator and facility upgrades continues. The high-energy vacuum system was replaced in December, resulting in pressures in the 10^{-9} Torr region on the high-energy end of the accelerator. The terminal gas control valve was replaced and the foil changer reinstalled, resulting in better control and more flexibility of the beam charge state. These improvements, coupled with improved optics and alignment, are allowing more useful beam on target for experiments. The charging belt developed a 6 × 8 inch damaged area that was discovered in December. This damaged area was repaired in place, using a procedure developed by the EN-12 staff, allowing continued limited operation until a new belt could be purchased and installed. The new Radiation Monitoring and Protection System was completed and commissioned this year.

5. THEORETICAL PHYSICS

Research areas in the theoretical physics program include topics in nuclear and atomic physics and some topics common to both. The major emphases in nuclear physics are in low and intermediate heavy-ion reactions and in relativistic heavy-ion collisions. The atomic physics program includes studies of a wide variety of charge transfer, capture, and ionization processes. The programs complement experimental physics programs carried out by Physics Division researchers in the Holifield Heavy Ion Research Facility, the EN Tandem Accelerator at Oak Ridge, and at GANIL and CERN.

We continue to emphasize the application of computers in these areas, and to develop the Center for Computationally Intensive Problems in Atomic, Nuclear, and Particle Physics in collaboration with the University of Tennessee, the UT Science Alliance, and Vanderbilt University. Courses have been offered in computational physics at UT in the last year by ORNL theorists. The Center will participate in the acquisition of a parallel processor supercomputer next year with a theoretical total capacity of 10 gigaflops. The theoretical physics program continues to be enhanced by the presence of Professors F. E. Close and J. H. Macek, UT-ORNL Distinguished Scientists in theoretical nuclear and atomic physics, respectively.

LEPTON PAIR PRODUCTION IN RELATIVISTIC HEAVY-ION PHYSICS

ELECTROMAGNETIC PAIR PRODUCTION IN RELATIVISTIC HEAVY-ION COLLISIONS¹

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We survey the production of electron, muon, and tauon pairs in collisions between nuclei at ultrarelativistic energies. Such studies enhance our understanding of the role of the vacuum in field theory and provide essential input for several experimental programs. A variety of models for the nuclear and nucleon form factors have been considered, revealing some degree of sensitivity to assumptions about sub-nuclear structure. We predict that the cross sections, even at high invariant masses and transverse momenta, are large on hadronic scales, and should act as useful probes of nuclear and nucleon form factors.

LATTICE CALCULATION OF MUON-PAIR PRODUCTION WITH CAPTURE IN RELATIVISTIC HEAVY-ION COLLISIONS¹

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We calculate probabilities for muon-pair production with capture of the negative muon into the $1s_{1/2}$ ground state in relativistic heavy-ion collisions. The muon pairs are generated by the time-dependent electromagnetic fields of the heavy ions. Our numerical calculations are carried out on a 3-dimensional lattice with 20 to 30 mesh points in each direction, utilizing the B-spline collocation method. Numerical convergence has been demonstrated using a Lorentz-boosted, screened Coulomb potential. For the system $^{197}\text{Au} + ^{197}\text{Au}$ at collider energies of 0.2, 1.0, and 2.0 GeV/nucleon, we obtain probabilities for dimuon production with capture between 1.0×10^{-3} and 7.0×10^{-2} at grazing impact parameters. This suggests that the electromagnetic lepton-pair production is strongly nonperturbative.

1. Abstract of paper: Nucl. Instrum. & Meth. B40/41, 354 (1989).

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FEYNMAN-MONTE CARLO CALCULATIONS OF ELECTRON CAPTURE AT RELATIVISTIC COLLIDER ENERGIES¹

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Calculations are presented for electron capture associated with pair production in collisions of heavy ions at relativistic energies. We employ the recently introduced technique of evaluating Feynman perturbation integrals exactly by Monte Carlo methods. The results agree well with virtual-photon approximations if they are carefully formulated, but appear to disagree with some published results. The cross sections for symmetric collisions of uranium, gold, iodine, copper, and silicon are presented as a function of the beam energy. These results are discussed within the context of beam storage times of a relativistic heavy-ion collider.

1. Abstract of paper: Phys. Rev. A40, (1989).

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TWO-PHOTON PROCESS AND ANOMALOUS ELECTRON-PAIR PRODUCTION IN $\pi\pi$ COLLISIONS¹

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The two-photon mechanism for lepton-pair production is calculated in a nonconventional way by treating the relative pion-nucleon motion in the classical limit. The results are compared with existing data for anomalous e^+e^- pairs produced in the collision of 16 GeV/c pions with protons. The results for differential cross sections as a function of the invariant pair mass, Feynman x , and transverse momentum are found to be in reasonable agreement with the data. The dominant piece of the cross section arises from the magnetic, spin-flip part of the nucleon current.

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ANOMALOUS ELECTRON-PAIR PRODUCTION IN $\pi\pi$ COLLISIONS¹

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Anomalous e^+e^- pairs with invariant mass $0.2 < M < 0.7$ GeV/c² have been observed in the collision of pions with protons at a momentum $p_\pi = 16$ GeV/c. Conventional hadronic mechanisms have been unable to reproduce the qualitative features of the observed spectra. The two-photon mechanism for pair production is evaluated in a semiclassical limit. The resulting differential cross sections as a function of the invariant mass, Feynman x , and transverse momentum of the pair are in reasonable quantitative agreement with the data. The dominant contribution to the pair amplitude arises from the magnetic spin-flip term of the proton current. These anomalous lepton pairs are thus consistent with an ab initio calculation of the two-photon mechanism.

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THREE-DIMENSIONAL LATTICE SOLUTION FOR THE LEPTON PAIR PRODUCTION AND CAPTURE IN HEAVY-ION COLLISIONS

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Modern supercomputer technology has stimulated the development of new numerical techniques for obtaining highly accurate solutions to quantum field theory.³ These approaches are applicable to problems of strongly interacting systems in atomic, nuclear, and particle physics. For relativistic fermion fields on lattices, we have developed a distinct approach which fixes the doubling of the fermion spectrum and preserves the gauge invariance. In the numerical formulation, the field operators are eliminated and the quantum states are realized on the space-time lattice of collocation points. Both state vectors and operators are given by expansions in terms of basis splines. Equations

of motion are obtained from the variation of the discretized action. This method is particularly suited to solve problems in which the fermion system is coupled to classical fields on a lattice.

For the lepton pair production and capture in the strong field of heavy-ion collisions, the problem is very sensitive to the particular details of the time evolution and has to be solved nonperturbatively by following the unitary time evolution of the fermion wave functions obeying the Dirac equation which is coupled to the classical fields obeying Maxwell equations. The transition rates obtained in such calculations are reliable only if the results are convergent in the refined lattice calculation. Figure 5.1 shows the setup of the lattice calculation for heavy-ion collisions. For the electron system, because of the smallness of its mass scale and the long range of the Coulomb force, such a calculation involves a huge three-dimensional lattice and renders the equidistant lattice computation expensive. The preliminary calculations show that the lattice has to be non-equidistant

and at least $60 \times 60 \times 60$ before reaching a convergent solution.

Our recent progress can be summarized under the following two aspects: (i) to establish an efficient method to obtain static solutions in strong fields on a large non-equidistant lattice, and (ii) to adapt the codes to massively parallel computing architectures and test the possible algorithms on an INTEL hypercube.

For the static solution, it has proved that the Lanczos method is very efficient for linear systems with a large number of dimensions. Since it is a variational method, the speed of its convergence depends on the relative position of its eigenvalue in the spectrum of the linear system. The closer the eigenvalue to the edge of the spectrum, the faster the eigenvector converges. Therefore, it is preferable to use the square of the Dirac Hamiltonian operator

$$H = H_D^2 \quad (1)$$

instead of H_D , since H_D^2 has the ground (bound) state at the bottom of its spectrum. For an equidistant lattice of $30 \times 30 \times 30$ dimension in

Fig. 5.1. The setup of the three-dimensional calculation for the lattice solution in heavy-ion collisions.

a cube of $(-20.0, 20.0)$ (in units of Fermis) for the U^{92} atom, it takes 90 iterations to obtain a solution with an error less than 10^{-4} , where the error is measured by

$$e = \langle H_D^2 \rangle - \langle H_D \rangle^2. \quad (2)$$

The corresponding computer time on the Cray-2 is about 230 seconds. With the increase of N in every dimension, the number of dimensions increases as N^3 , while the number of floating point operations in each iteration goes up like N^6 . Thus, the whole procedure is slowed down enormously. However, the preliminary results show that the solutions from the Lanczos method consistently converge to the lattice solution except for the slowdown of the convergence.

The codes have been adapted to a parallel computing algorithm — the Fox ring algorithm.⁴ The majority of the computer time used in the time evolution of the Fermion wave function is spent on the subroutine for the matrix product of the Dirac Hamiltonian with the wave function. The Fox ring algorithm separates the lattice into planes of $z = \text{const}$, assigns the operations of the matrix product within each plane to a node of the machine, and sends the results to the next node along the ring for further calculations. Since the Hamiltonian in the B-spline collocation method is not sparse, the multiplication is performed only when the transmission is completed around the ring. The test run for a lattice of $32 \times 32 \times 32$ dimensions is being conducted on the INTEL machine, and the results will be compared to those obtained on the Cray-2. If pilot studies prove successful, the production run will be on much larger machines in the near future.

COHERENT PRODUCTION OF $W^\pm$ PAIRS AND HIGGS BOSONS FROM PULSED ELECTROMAGNETIC FIELDS IN ULTRARELATIVISTIC HEAVY-ION COLLISIONS

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The unified electroweak theory is remarkably successful in the description of the observed weak interaction. However, the experimental confirmation is not yet complete. One of the most important ingredients, the Higgs boson, remains unobserved. The search for the Higgs boson is one of the major tasks for future accelerators. With the new tools of high-energy heavy-ion collisions, predictions based on the standard model and their denial or confirmation by experiments may help to clarify the ambiguities in the theory of weak interactions and serve as a guideline to experiments.

Recently, a model² has been proposed to calculate the lepton pair production from the decay of vacuum excitations induced by the colliding nuclei. In this model the electromagnetic fields are approximated by the classical fields which are very strong and sharply pulsed near nuclei colliding at relativistic velocities, and the coherent production processes are still treated as the excitations of quantum fields with the perturbative method. For the lowest-order processes, the production cross section can be obtained in terms of phase space integrals which are integrated out numerically by using the Monte Carlo method. As a direct extension of this model, we may calculate the coherent production of $W^\pm$ pairs and Higgs bosons.

In the standard electroweak model, the electromagnetic and weak interactions are unified in a common $SU(2) \times U(1)$ gauge structure. The interactions between the electromagnetic and charged boson fields arise from the self-interactions of the non-Abelian $SU(2)$ gauge fields as follows

$$\begin{aligned} \mathcal{M}_3 = & -ie[(\partial_\mu A_\nu - \partial_\nu A_\mu)W^{+\mu}W^{+\nu} + (\partial_\mu W_\nu^+ - \partial_\nu W_\mu^+)A^\mu W^{+\nu} \\ & + (\partial_\mu W_\nu^- - \partial_\nu W_\mu^-)W^{+\mu}A^\nu], \end{aligned} \quad (1)$$

and

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$$\mathcal{H}_4 = -e^2 (W_\mu^+ W^{-\mu} A_\nu A^\nu - W_\mu^+ W_\nu^- A^\mu A^\nu). \quad (2)$$

The lowest-order processes are shown in Fig. 5.2. The W -pair production cross section is

$$\sigma = \int d^2b \sum_{p,q} \sum_{\lambda_1, \lambda_2} \left| \langle p^{\lambda_1} q^{\lambda_2} | S | 0 \rangle \right|^2 \quad (3)$$

where the p, q are the momenta of the pairs and λ 's are their polarizations, and b is the impact parameter.

The coherent production of Higgs bosons via two-photon processes is through the fusion of

the produced pairs. Figure 5.3 shows the lowest-order processes of the Higgs production. The intermediate loops can be formed by quarks, leptons, and weak bosons. The contribution of these loops is summarized in an effective Hamiltonian

$$\mathcal{H}_{\text{eff}} = \frac{e^2 g}{8\pi^2 M_W} IF^{\mu\nu} F_{\mu\nu} H, \quad (4)$$

where

$$I = A_q + A_l + A_W$$

ORNL-DWG 88-14326

Fig. 5.2. Lowest-order Feynman diagrams for W -pair production from the electromagnetic field.

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Fig. 5.3. Feynman diagrams for the Higgs production.

and each amplitude A_i is only a function of the squared ratio of the masses, i.e. $\lambda_i = m_i^2/M_H^2$. The Higgs production cross section is

$$\sigma = \int d^2b \sum_k |\langle k | S | 0 \rangle|^2. \quad (5)$$

Since the mass of the Higgs boson is unknown, the calculation involves an assumption regarding its mass. However, the result could set limits on the uncertainty of the Higgs boson mass if it still remains unobserved.

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RELATIVISTIC HEAVY-ION COLLISIONS

FRAGMENTATION OF A FINITE-MASS STRING¹

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In the physics of strong interactions at high energies, the string fragmentation model³⁻⁵ has

been very successful in describing the processes of particle production. Much insight into the dynamics of the particle production process in nucleon-nucleon and e^+e^- collisions has been obtained from these studies. In the Lund version of the string fragmentation model, the quarks are assumed to be massless, and the mass of each produced hadron comes from the invariant mass of a string segment having a quark and an antiquark at its two ends and undergoing a stretching and contracting oscillation (a yo-yo state). The probability for the occurrence of a vertex to break the string into two segments is given as a function of the momentum fraction z_+ (or z_-) and the invariant mass of one of the two segments (which is interpreted as a produced particle). In the Symmetric Lund Model,⁴ it is stipulated that the physical process of forming the resultant observed hadrons after all the vertices have occurred is independent of the ordering in which they occur. A general formula was obtained to give the probability distribution for locating the point of fragmentation when a string breaks into two smaller segments. However, implicit in the derivation of the probability distribution is the assumption that the light-cone momentum of the quark or the antiquark in the fragmenting $q\bar{q}$ system is infinite in magnitude. Such an assumption simplifies the problem greatly, and a closed formula for the probability distribution, $f(z_+, m^2)$, was obtained. The probability distribution, $f(z_+, m^2)$, is subsequently used in Monte Carlo programs iteratively for the fragmentation of a finite-mass string.^{5,6}

We seek a generalization of the Symmetric Lund Model to study the cases where the string undergoing fragmentation is finite in energy. Such a problem is of practical interest in extending the usefulness of the fragmentation model to the fragmentation of a system with a much smaller initial energy for which the assumption of an infinite energy, $\sqrt{s} \rightarrow \infty$, is inadequate. Furthermore, in the fragmentation of a string with a very large invariant mass, the early stage of the fragmentation process involves strings of large masses and the

Symmetric Lund Model gives a very good approximation. However, the late stage of the fragmentation process must go through the fragmentation of a string with a much diminished mass for which the assumption of a very large invariant mass cannot be justified. Therefore, a general formula for the fragmentation of a string with a definite energy will be useful even for the fragmentation of a string with a large initial invariant mass.

We have obtained the probability distribution for the fragmentation of a finite-mass string by studying the fragmentation of a finite section of an infinite string. This fragmentation process can also be obtained from successive fragmentations of an infinite and semi-infinite string for which the fragmentation distribution functions are given by the Symmetric Lund Model. Relating the probability for the two different ways of fragmentation then gives one the probability distribution governing the fragmentation of a finite string. With this generalization, the fragmentation probability distribution depends on the invariant mass of the fragmenting string. We find that the difference between the new distribution function and that of the Symmetric Lund Model is large when the mass of the fragmenting string is small.

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A MULTIPLE-COLLISION MODEL FOR HIGH-ENERGY NUCLEUS-NUCLEUS COLLISIONS¹

Cheuk-Yin Wong Zhong-Dao Lu²

Recently, there is much interest in relativistic heavy-ion collisions which stems from the

possibility of creating matter with very high energy densities. The energy densities may be high enough to exceed the critical energy density required for a phase transition from the ordinary confined hadronic matter to the unconfined quark-gluon plasma. Initial experimental data have been obtained recently with relativistic heavy-ions at CERN and at Brookhaven.

The study of the dynamics of a nucleus-nucleus collision has not yet reached a stage where such a process can be described from the first principle, starting with the theory of QCD. We seek a phenomenological Glauber-type multiple-collision model which brings out the essential features of the physics involved and is flexible enough to allow the extraction of useful information on the nature of nuclear stopping and particle production in nucleus-nucleus collisions. The physics of the collision process can, of course, be described at the quark level. In fact, there are many processes, (such as in the peripheral direct-fragmentation of a single constituent quark that has suffered no collision) which can be described only in terms of constituent quarks. We have initiated a study to describe the collision process in terms of the collisions of strings. This part of the research is in progress. In the meantime, there are many other aspects of the collision processes for which a collective description of the basic units in terms of baryons will suffice. Clearly, the slowing down of the baryon matter and the production of particles in a complicated multiple-collision process will not be sensitive to whether one uses a microscopic or a "collective" description of the collision process, because the basic physics involves the loss of the energy of the baryon matter and the consideration of energy conservation for particle production. Thus, a collection of collisions at the quark-quark level can be described in terms of equivalent collisions at the baryon-baryon level. For this reason, we shall use baryons as the basic unit of collision. This "collective" description has the advantage of simplicity and economy of effort. We

know that multiple-collisions of the incident baryon matter do take place, as evidenced by the loss of the longitudinal momentum of a nucleon when it passes through a nucleus. This momentum loss depends on the thickness of the target nucleus. In each collision, the baryon number is conserved. We shall loosely associate these leading baryon-content-carrying objects as "baryons." It is reasonable to assume that the leading hadrons (leading baryons in this case) are the ones which can undergo multiple collisions. After each collision, a strong field is created between the colliding objects, and the leading baryons are the sources of the strong fields. While the strong field in each collision later stretches out longitudinally and hadronizes into produced particles (such as pions), the leading particles can proceed forward and make other collisions. As they are the sources of the strong field between the colliding baryons after each collision, their longitudinal momentum must be dissipated in each collision. If we follow the sequence of multiple collisions of one such baryon, i.e. collisions it suffers occur sequentially, and the different collisions are separated by a timelike space-time interval. By causality, the momentum of the product baryon after one baryon-baryon collision should be related to the momentum of the baryon before the collision by a causal relation. We shall describe the longitudinal momentum loss of these baryons by a "stopping law" which expresses the degree of inelasticity of the collision in a causal daughter-parent relation. Along with the loss of longitudinal energy of the baryons, particles are later produced. We can take the shape of the rapidity distribution of the produced particles to be governed in a way similar to that in nucleon-nucleon collisions. In this way, the physics of the longitudinal energy loss and particle production can enter into the dynamics of heavy-ion collisions directly and shows up in the spectrum of the particles detected in high-energy heavy-ion reactions. The model gives results which compare well with the recent WA80 experimental

data³ of 160 on various targets at 60 and 200 GeV and reveals a high degree of stopping in these high-energy nuclear collisions.

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NUCLEAR STOPPING POWER IN NUCLEON-NUCLEUS AND NUCLEUS-NUCLEUS COLLISIONS¹

C. Y. Wong

The term "nuclear stopping power" was introduced in the study of high-energy nucleus-nucleus collisions by Busza and Goldhaber² to refer to the degree of stopping that an incident nucleon suffers when it impinges on the nuclear matter of another nucleus. Besides depicting an important aspect of the reaction mechanism, it is related to the question of quark-gluon plasma (QGP) formation. The loss of the incident nuclear matter kinetic energy is accompanied by the production of a large number of particles (mostly pions). Therefore, by the process of high-energy heavy-ion collisions, a large fraction of the longitudinal energy is converted into the energy of the hadronic matter produced in the region near the center of mass of the colliding system. The degree of stopping will reveal whether the energy density attained is high enough to allow for a phase transition, leading to the formation of a quark-gluon plasma.

Qualitatively speaking, the collision of high-energy heavy ions can be divided into two different energy regimes: the "stopping" regime around a few GeV per projectile nucleon in the center-of-mass system (or about 10 GeV per projectile nucleon in the laboratory system) and the "pure quark-gluon-plasma" regime of about 100 GeV per nucleon in the C.M. system. In the stopping regime, the nuclear stopping power

determines whether the colliding baryons are stopped and pile up together in the center-of-mass system to form a quark-gluon plasma with a large baryon density. In the pure quark-gluon-plasma regime, we need to know the nuclear stopping power to determine whether the baryons will still proceed forward after the collision to leave behind a pure quark-gluon plasma with very little baryon content in the center-of-mass system.

We review the study of the nuclear stopping power in nucleon-nucleus and nucleus-nucleus collisions which has proceeded in three different ways. One way is to measure the energy of the proton after it passes through a target nucleus in a $p+A \rightarrow p+X$ reaction. A second type of experiment measures the transmission of the incident energy within a small range of angles around zero degrees, after an inelastic collision. There is a third way to study the stopping power by measuring the transverse energy of the produced particles which is the sum of the energies of the particles within a certain angle of acceptance weighted by the sine of their angles to the beam. The experimental data reveal that the degree of nuclear stopping in the collision of nuclei at an energy of 14.5 to 200 GeV per projectile nucleon is large. This energy regime is still within the "stopping" regime. Because the stopping is very effective, the energy which is deposited in the center-of-mass region is nearly linearly proportional to the energy measured in the center-of-mass system. The higher bombarding energy at 200 GeV per projectile nucleon will lead to an energy density substantially greater than that at 14.5 GeV per projectile nucleon. Thus, a local energy density of the order of 10 GeV/fm³ may be achieved with the bombardment of a Pb beam on a Pb target nucleus at 200 GeV per projectile nucleon. As this energy is much greater than the energy density required for the formation of a quark-gluon plasma, it is a very promising experimental prospect to study high-energy nuclear collisions with very energetic Pb beams.

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ELECTROMAGNETIC DISSOCIATION DUE TO PROTON KNOCKOUT

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The fragmentation of a nucleus by applying a purely electromagnetic field is known as electromagnetic dissociation, and was first reported by Heckman and Lindstrom¹ who used ¹²C and ¹⁶O projectiles on targets ranging from C to Pb. Electromagnetic dissociation was observed in both the single proton and neutron channels. Other groups have also observed this phenomena with various projectiles and targets.²⁻⁸ The energy range of all of these experiments is of the order of 1-15 GeV/A in the fixed target frame. In relativistic beam collider experiments, such as the Relativistic Heavy Ion Collider (RHIC) proposed at Brookhaven which is expected to produce ion beams with center-of-mass energies (E_{CM}) from 10 to 200 GeV/nucleon, electromagnetic dissociation effects are expected to be much greater than has presently been observed.⁹

An interesting phenomenon which will contribute to the cross section of electromagnetic dissociation is that of the direct knockout of protons from the nucleus. One can use the results of our prompt emission calculations, and other calculations on the other physical processes involved such as those of the equivalent photon method, to determine the effects of electromagnetic dissociation on beam storage in relativistic colliders such as RHIC.⁹ The design criterion for RHIC must be such that the beam is not lost before central collision processes can occur. We are presently working on symmetric systems, and are considering the systems ¹⁶O + ¹⁶O and ²⁸Si + ²⁸Si. There is also a scaling of the cross section with $Z_1^{1/3}$ ⁹ which can be used to discuss such systems as ²⁰⁸Pb + ²⁰⁸Pb.

If we consider particle emission from a reaction of the type

$$A + B \rightarrow N + X$$

(1)

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where N denotes a single emitted nucleon and X stands for everything else, then during this short time scale for particle emission, one can approximate A and B to retain their identity while being perturbed by the fields generated by each other. In the present study we perform calculations in the rest frame of one of the nuclei, A say, and that the projectile in that frame, nucleus B say, is a point nucleus of charge Z and mass M . Our goal is to calculate the probability for emission of protons from nucleus A due to the process of proton knockout as induced by the electromagnetic field of the point nucleus B . The Hamiltonian of the system is obtained by the use of minimal substitution of the electromagnetic field $A_i^\mu = (A_i^0, A_i^G) = A^\mu(R-r_i)$ into the kinetic energy operator of the Hartree-Fock Hamiltonian. From this, we obtain the interaction term due to the vector substitution

$$H_{int}^{(1)} = - \left(\frac{e\hbar}{2M_i} \right) \sum_{i=1}^A \left(\frac{1+r_z}{2} \right) \delta(r-r_i) (\vec{v}_i A_i + A_i \vec{v}_i) + \left(\frac{e^2}{2Mc^2} \right) \sum_{i=1}^A \left(\frac{1+r_z}{2} \right) \delta(r-r_i) A_i^2 \quad (2)$$

$$= \sum_{i=1}^A u^{(1)}(R-r_i),$$

and a term due to the scalar substitution

$$H_{int}^{(2)} = \sum_{i=1}^A \left(\frac{1+r_z}{2} \right) \delta(r-r_i) e A_i^0 \quad (3)$$

$$= \sum_{i=1}^A u^{(2)}(R-r_i).$$

All of the calculations are performed using a cylindrically symmetric coordinate system. The projectile of mass M_B and charge $Z_B e$ moves along the z -axis, so that in the Lorentz gauge the potential A^μ has the form

$$A_0 = \frac{\gamma_{lab} Z_B e}{\sqrt{\gamma_{lab}^2 (z - \beta_{lab} ct)^2 + a^2 + b^2 + 2ab \cos \phi}} \quad (4)$$

$$A_z = \beta_{lab} A_0. \quad (5)$$

where the values of γ_{lab} and β_{lab} are the laboratory frame, b is the collision impact parameter, and (ρ, ϕ, z) are the axial coordinates.

A typical curve for the impact parameter dependence of the probability of emission $P(b)$ of a proton from the nucleus is given in Fig. 5.4. Integration on $P(b)db$ yields the proton knockout cross section. For the $^{16}O + ^{16}O$ system, a typical value for the cross section for proton knockout is 0.3 mb at a laboratory energy of 17 GeV/A.

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Fig. 5.4. Impact parameter dependence of the probability of emission $P(b)$ of the emitted proton. The center-of-mass energy is 2 GeV/A. The total integrated probability gives a cross section at this energy of $\sigma = 0.24$ mb.

INTERMEDIATE-ENERGY HEAVY-ION PHYSICS

NUCLEAR MATTER CALCULATIONS OF THE PROPAGATORS OBTAINED FROM NUCLEAR-DELTA-PION INTERACTIONS

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A series of nuclear matter computer codes is being developed in order to solve Dyson's equations in which nucleon-delta-pion interactions are included. Our immediate goal is to determine whether these equations can be solved self-consistently, and moreover whether the results have a sensible physical interpretation. Then, if this work is successful, we hope to be able to extend the studies to finite nuclei and ultimately to heavy-ion collisions. Here we present some preliminary results showing examples of typical Green's functions or parts of Green's functions, which are calculated using our codes.

We begin with the imaginary part of the delta-particle propagator:

$$\text{Im}[G_{\Delta}(\omega, \hat{p})] = \frac{-\frac{1}{2} \Gamma_{\Delta}(\omega, \hat{p})}{(\omega - \epsilon_{\Delta}(\hat{p}))^2 + \frac{1}{4} \Gamma_{\Delta}^2(\omega, \hat{p})}, \quad (1)$$

where ω and $\hat{p}$ are the energy and momentum in nuclear matter and $\epsilon_{\Delta}(\hat{p})$ and $\Gamma_{\Delta}(\omega, \hat{p})$ are the delta mean-field energy and width, respectively. At high energy Γ_{Δ} reduces to the free-space width of 115.0 MeV, while at lower energies, we assume a functional form that is independent of $\hat{p}$ and vanishes at $\omega = m_N + m_{\pi} = 1077$ MeV. For the nucleon propagator, we assume that

$$\text{Im}[G_N(\omega, \hat{p})] = \pi [2\theta(\mu_N - \epsilon_N(\hat{p})) - 1] \delta(\omega - \epsilon_N(\hat{p})) \quad (2)$$

where $\mu_N = 923$ MeV is the chemical potential, $\theta(x)$ is a step function, and $\epsilon_N(\hat{p})$ is the nucleon mean-field energy which in our approximation does not change during the calculation. The real parts of the delta and nucleon propagators are then obtained from dispersion relations.⁴

Next, we calculate the self-energy and width of the pion, using a Feynman diagram whose main contribution is an integral involving a product of the nucleon and delta Green's functions.⁵

Therefore, we calculate the pion propagator from the assumed delta and nucleon propagators, and the main results are shown in Figs. 5.5 and 5.6. The functions plotted are $\text{Im}[\bar{D}(\omega, \hat{p})]$ and $\text{Im}[\bar{D}(\omega, \hat{p})]/|\hat{p}|^2$, respectively, with

$$\bar{D}(\omega, \hat{p}) = a_1 [1 + a_2 U_{N\Delta}(\omega, \hat{p})] |\hat{p}|^2 D(\omega, \hat{p}), \quad (3)$$

where a_1 and a_2 are constants, $U_{N\Delta}(\omega, \hat{p})$ is basically the nucleon-delta integral mentioned above, and $D(\omega, \hat{p})$ is the true pion propagator. We emphasize that $\bar{D}(\omega, \hat{p})$ displays all of the basic properties of the pion propagator, and we focus on $\bar{D}(\omega, \hat{p})$ because it is the function most relevant for the next step of the calculation.

Figures 5.5 and 5.6 show that there are two distinct families of "spikes" occurring in the pion. First, we see from Fig. 5.5 that for $154 \leq \omega \leq 400$ MeV there is a single spike that arises from the singularity in the "bare" pion propagator. For very low energies, this spike cannot be easily plotted since it is a near delta function, while at higher energies, it becomes quite smooth, eventually (above 1700 MeV) merging with the other spike and forming a rather broad shallow minimum. Figure 5.6 shows the emergence of the second family of spikes at a ω value somewhat above 400 MeV. This second family does not occur for the free pion; it is due entirely to the nucleon-delta-pion coupling. Also, the high-energy family contains spikes which are much less severe than those in the low-energy family.

Finally, the nucleon and $\bar{D}$ propagators can be used iteratively to calculate a new self-energy and width for the delta particle. An integral of a product of the nucleon and $\bar{D}$ propagators is the function⁵ $I(\omega, \hat{p})$ plotted in Figs. 5.7 and 5.8. This integral is exceptionally difficult to evaluate, mainly because of the sharp spikes in $\bar{D}$, particularly the near delta-function spikes occurring at very low energies. Then, it can be shown that to a good approximation⁵

$$\Gamma_{\Delta}(\omega, \hat{p}) = -2 \text{Im}[I(\omega, \hat{p})], \quad (4)$$

and the real part of $I(\omega, \hat{p})$ can be used to calculate effectively a new mean-field energy,

Fig. 5.5. $\text{Imag}[\bar{D}(\omega, p)]$ vs $p \equiv |\vec{p}|$ in fm^{-1} , for three ω values (in MeV) showing the low-energy family of spikes. For smaller ω values, the spikes are almost delta functions and cannot be easily plotted.

Fig. 5.6. $\text{Imag}[\bar{D}(\omega, p)]p^{-2}$ vs $p \equiv |\vec{p}|$ in fm^{-1} for a number of ω values (in MeV) showing both families of spikes. We plot $\bar{D}p^2$ rather than $\bar{D}$ in order not to unduly magnify the extrema at large p . The high-energy spike begins somewhat above $\omega = 400$ MeV and its center (in p), which is labeled by its ω value, is to the left of the center of the other minimum (which is the remnant of the low-energy spike).

Fig. 5.7. $\text{Im}[\Sigma(\omega, p)]$ vs ω for a broad range $p \equiv |\vec{p}|$ values, in steps of 1.0 fm^{-1} . This function is proportional to an integral involving the product of the imaginary parts of the nucleon and D propagators.⁵

Fig. 5.8. $\text{Re}[\Sigma(\omega, p)]$ vs ω for a broad range of $p \equiv |\vec{p}|$ values in steps of 1.0 fm^{-1} . Each curve here is calculated from the corresponding curve in Fig. 5.7 by using a dispersion relation.⁶

$\epsilon_A(\hat{p}) + \epsilon_A(\omega, \hat{p})$. Thus, when these results are substituted into Eq. (1), we obtain a new delta propagator which can be used in the next iteration. We find that the old and the new delta propagators differ quite dramatically in both magnitude and shape. Thus, at this stage, it would appear that we are quite far from self-consistency, at least with our present choice of interaction parameters.

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RELATIVISTIC TRANSPORT THEORY OF FLUCTUATING FIELDS FOR HADRONS¹

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The properties of nuclear matter at high density and excitation remain unknown after more than a decade of relativistic heavy-ion experiments in which such matter is created and its decay products are observed. This paradoxical circumstance seems to be due mainly to theoretical rather than experimental inadequacies. Experiments have been able to observe and record hundreds of particles in the final state of a collision of heavy nuclei at center-of-mass excitation energies up to several hundred MeV per nucleon. They have also succeeded in analyzing these observations quantitatively in terms that surely carry information about the properties of the hot dense matter: the degree of stopping, amount of transverse flow, number of pions and kaons per baryon, entropy of baryons measured by cluster probabilities, shapes and flow patterns measured by two-particle interferometry, and recently, dilepton spectra. Simple theoretical models have demonstrated that these observables

are indeed sensitive to interesting properties of baryonic matter: compression energy, heat capacity, viscosity and thermal conductivity (or equivalently scattering cross sections in the matter), potential energies of mesons and baryons in the matter, and rates of production and absorption of mesons and excited baryons. Nevertheless, convincing quantitative interpretations of the observations are still lacking; the interesting theoretical quantities all remain uncertain by at least a factor of two.

The source of the problem seems to be that each of the observed quantities is sensitive to several of the unknown properties of the hot dense matter. Thus, no subset of the measurements can be interpreted validly without simultaneously interpreting the remaining measurements. (A possible exception is the dilepton data, which seem to be sensitive mainly to meson spectra; unfortunately these measurements are as yet very incomplete.) As a result, a theoretical model is faced with very stringent requirements. First, it must be able to address all the important data described above; otherwise it will not be sufficiently constrained by the measurements to permit any unique interpretation. Second, it must contain a plausible account of all the theoretical properties mentioned above; otherwise all its other inferences will be tainted by the residual uncertainty which in every case has been demonstrated to be very large. Finally, it must be quantitatively reliable at a good level of accuracy; otherwise the errors in each of the half-dozen important theoretical or experimental variables will compound to render them all so uncertain as to be uninteresting.

None of the currently available models of relativistic heavy-ion collisions meets these demands. The best models to date are based on the Boltzmann transport equation with Fermi statistics included by blocking factors in the collision term. These models, often known by such labels as BUU, VUU, or Nordheim-Vlasov, have been developed to be able to address all the important data, and are able to give reasonable account of most of the theoretically necessary

physics. Their most conspicuous failure is in their treatment of pions, whose creation, absorption, and propagation in the matter is described as though the pions were classical particles interacting with the matter only by scattering off baryons and by being created or absorbed via the Δ excitation of the nucleon. Actually, most of the pions observed in nuclear collisions have momenta (relative to the baryonic matter) about equal to their rest mass; thus their wave packets must overlap many nucleons simultaneously instead of colliding with only one at a time. (The baryons, by contrast, have substantially larger momenta and thus can be somewhat better localized.) Furthermore, pions have a large, attractive potential energy in the matter due to their p-wave interaction with the nucleons; this interaction is so large that in the impulse (Kisslinger) approximation it roughly cancels their kinetic energy at normal nuclear density. Therefore, any model which neglects the potential energy of the pions in nuclear matter cannot be considered to be even semi-quantitative. The importance of an adequate account of pions in nuclear collisions around 1 GeV per nucleon is apparent; half the NN cross section consists of inelastic collisions in which the pion takes nearly all the available center-of-mass energy.

While clever tricks might make it possible to include the pions' potential energy and even their wave nature within the fundamentally classical transport theory based on extensions of the Boltzmann equation, there is an even more daunting obstacle to a quantitative treatment of their creation and absorption in the matter. When a pion in the hot dense matter collides with a nucleon, their relative kinetic energy typically places the πN system about halfway down the low-energy tail of the Δ resonance. Thus the amplitude for creation and absorption of pions will be sensitive to the width and shape of the Δ . This width, due in free space to the decay of the Δ into πN , must be modified by the presence of the matter in several ways: the potential energies of the π , Δ , and N in the matter, the Pauli blocking of the nucleon in the

final state into which the Δ decays, and the broadening of the Δ by collisions with other particles in the matter, which shares the pion's energy among several nucleons. This latter effect is not only essentially three-body in nature, casting serious doubt on the Boltzmann stosszahlansatz; it is also a fundamentally quantum effect resting on the time-energy uncertainty principle. The extension of the classical Boltzmann equation to include a quantitatively reliable description of the propagation, creation, and absorption of pions in hot, dense nuclear matter seems unpromising. We have elected instead to pursue a more fundamental approach.

In our studies, we derive equations of motion for the relativistic Green's functions describing the quantum propagation of baryons and mesons in excited nuclear systems. We start from a low-energy effective Lagrangian containing nucleons, deltas, pions, and other heavier mesons motivated by the boson-exchange model of nuclear forces, as well as the nuclear phenomenology of quantum hadrodynamics. We show how to obtain a hierarchy of Dyson equations for one-, two-, and three-point Green's functions, and then truncate this hierarchy by parametrizing a four-point residual effective interaction in a manner introduced by Migdal. This nonperturbative truncation leads to a coupled set of equations for functions of two space-time variables (i.e., eight real numbers) well within the capability of the latest computers. Collisions of the mesons and baryons are included by way of self-energy loops; we show how to regulate the ultraviolet divergences of the loops by a unitary, causal cutoff procedure — necessary because our inclusion of derivative-coupled spin-3/2 particles precludes renormalization, but perfectly acceptable in a low-energy effective theory. Practical calculations implementing this theory in nuclear matter are well under way.

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LOW-ENERGY HEAVY-ION COLLISIONS

LOW-ENERGY HEAVY-ION REACTIONS: SOME RECENT DEVELOPMENTS¹

G. R. Satchler

Three topics were selected for review to illustrate the broad range of phenomena in this category: new properties of the optical model at low energies, understanding subbarrier fusion, and some specific multistep reactions. The common thread that runs through modern descriptions of these phenomena is the recognition of the importance of the couplings between many reaction channels.

1. Summary of invited talk to be published in Proceedings of 1989 International Nuclear Physics Conference, São Paulo, Brazil, August, 1989 (World Scientific Publishing Co.).

HEAVY-ION SCATTERING NEAR THE COULOMB BARRIER¹

G. R. Satchler

A review was given of the "threshold anomaly" that appears in the optical model potential deduced from scattering at near-barrier energies, and the use of a dispersion relation to correlate the behaviors of the real and imaginary potentials in a self-consistent way. It was explained how the enhancement of subbarrier fusion reactions was another aspect of this anomaly, and the optical model of fusion was reviewed.

1. Summary of invited talk to be published in Proceedings of XII Workshop on Nuclear Physics, Iguazú Falls, Argentina, August, 1989 (World Scientific Publishing Co.).

COULOMB-NUCLEAR INTERFERENCE IN ELASTIC HEAVY-ION SCATTERING¹

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Elastic heavy-ion angular distributions at small angles, forward of the quarter-point angle, have often been characterized as examples of either a Coulomb rainbow or of Fresnel diffraction. Using the modern high-quality data of Hostachy et al. as an example, we argue that the truth is intermediate between these two extremes, and indeed so far from them as to make both models quite inappropriate descriptions of nuclear reality. We suggest retreating to the more general label of "Coulomb-nuclear interference", which includes both of these (inapplicable) extremes as special cases. A semiclassical analysis of optical model fits is found to offer helpful insight into the nature of this interference.

1. Abstract of paper: Nucl. Phys. A500, 399 (1989).

2. Physics Division, Argonne National Laboratory, Argonne, IL 60439.

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COMMENT ON "SIMULTANEOUS ANALYSES OF ELASTIC SCATTERING AND FUSION CROSS SECTIONS FOR THE $^{32}\text{S} + ^{50,64}\text{Ni}$ SYSTEMS AT ENERGIES NEAR THE COULOMB BARRIER"¹

G. R. Satchler

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An explanation is offered for the large fusion radii obtained in the optical model description of heavy-ion fusion given by Udagawa et al. An extension of the model is suggested, and possible effects on the spin distribution are discussed. It is contended that the large fusion radii cannot be deduced from the elastic scattering alone. The role of Coulomb excitation for these systems is also discussed.

1. Abstract of paper submitted for publication in Physical Review.

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THE OPTICAL MODEL FOR LIGHT HEAVY-ION SYSTEMS AT LOW ENERGIES

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It has been established² in recent years that the scattering of light heavy-ion systems, such as $^{12}\text{C} + ^{12}\text{C}$ and $^{12}\text{C} + ^{16}\text{O}$, at energies $E/A \geq 10$ MeV, can be described by optical potentials with a deep and diffuse real part (similar to those provided by typical folding models³) and a moderately weak imaginary part that allows some sensitivity to the interior region. This was possible because of the observation of refractive effects such as a residual "nuclear rainbow" or farside dominance. Currently these studies are being extended to low energies, where such clear refractive signatures cannot be seen and optical model analyses are very ambiguous. However, it is found⁴ that a smooth extrapolation of the deep potentials from higher energies can reproduce the main features of these data. More guidance is obtained at the lowest energies from the observation of "molecular" resonances (further evidence of a partial transparency) and the use of the cluster model to select potentials which generate wavefunctions with the appropriate (Pauli-allowed) number of radial nodes. It is found that the deep real potentials extrapolated from higher energies, or obtained from a folding model, generally satisfy these requirements, whereas the very shallow potentials that are often used for these systems cannot.

1. Universidad Nacional Autónoma de México, 01000 México DF, México.

2. M. E. Brandan, Phys. Rev. Lett. 60, 784 (1988).

3. M. E. Brandan and G. R. Satchler, Nucl. Phys. A487, 477 (1988).

4. M. E. Brandan et al., to be published.

ELASTIC AND INELASTIC SCATTERING OF ^{16}O BY ^{92}Zr AT ENERGIES NEAR THE COULOMB BARRIER

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Angular distributions for the elastic and inelastic scattering of ^{16}O by ^{92}Zr were measured at 56 MeV bombarding energy, using the

University of São Paulo tandem, as well as excitation functions at 175° from 34 to 54 MeV, in order to study the Coulomb/nuclear interference in the excitation of the 2_1^+ , 2_2^+ , and 3_1^- states of ^{92}Zr . The data are being analyzed using the deformed optical model and coupled channels calculations. The interference pattern in the angular distributions for both the 3_1^- and 2_1^+ excitations, especially the latter, have provided some difficulties. Good fits to these angular distributions can be obtained if a very strong reorientation coupling is introduced (see example in Fig. 5.9), although the interpretation of this coupling remains unclear. We are investigating the possibility that it arises as an effective interaction from couplings to transfer channels. The overall behavior of the measured elastic and 2_1^+ excitation functions is obtained only if the optical potential is allowed to vary with energy in a way similar to the "threshold anomaly" observed for some other systems.

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ELASTIC SCATTERING OF 344.5 MeV ^{12}C IONS ON ^{11}B , ^{12}C , ^{27}Al , ^{58}Ni , ^{90}Zr , AND ^{197}Au NUCLEI¹

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Angular distributions for elastic scattering of ^{12}C ions on ^{11}B , ^{12}C , ^{27}Al , ^{58}Ni , ^{90}Zr , and ^{197}Au nuclei have been measured at the bombarding energy 344.5 MeV. The data were analyzed using two versions of the optical model: (a) a potential with Woods-Saxon form for both the real and imaginary part, (b) a folded potential for the real part based on the density and energy-dependent DDM3Y interaction supplemented by an imaginary potential of Woods-Saxon form. Three different "families" of six-parameter Woods-Saxon optical model potentials have been found. No preference for a weakly absorbing

Fig. 5.9. Excitation of the 2_1^+ state of ^{92}Zr . The dash-dot curve was obtained using a nuclear deformation parameter, $\beta_N = 0.108$, equal to the Coulomb one β_C obtained from the $B(E2)$ value, and no reorientation. The dotted curve shows the effect of increasing β_N to 0.25, while the solid curve shows the result of then adding reorientation coupling that is 3.8 times the strength of the transition coupling.

imaginary potential was observed. For all target nuclei, except of Al and Au, the normalization factor of the folded potential was about unity.

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TRANSFER REACTIONS AND OPTICAL POTENTIAL AMBIGUITIES FOR LIGHT HEAVY-ION SYSTEMS¹

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We investigate the extent to which measurements of transfer reactions between light heavy ions might provide a signature of a partial transparency in their mutual optical potential.

This transparency allows some contribution from impact parameters smaller than the grazing one. The $^{12}\text{C}(^{12}\text{C}, ^{13}\text{C})^{11}\text{C}$ ground-state transition is used as an example. Optical potentials are derived from $^{12}\text{C} + ^{12}\text{C}$ elastic scattering at energies from $E/A = 20$ to 85 MeV and used in DWBA calculations of the transfer. At the lower energies, potentials which provide similar elastic scattering at forward angles also predict very similar peak cross sections for transfer, but the angular distribution away from this main peak depends upon the degree of absorption present. The sensitivity increases as the energy is raised, so that at $E/A = 85$ MeV even the peak cross section becomes very dependent upon the optical potential used.

1. Abstract of paper to be published in Nuclear Physics A.

VELOCITY DEPENDENCE OF PROMPT, HIGH-ENERGY NUCLEON EMISSION¹

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M. R. Strayer

A time-dependent entrance channel formalism, which treats the relative motion of the heavy ions classically, and the internal excitations quantum mechanically, is used to study prompt nucleon emission from deep-inelastic collisions of the $^{58}\text{Ni} + ^{165}\text{Ho}$ system at $E_{\text{lab}} = 930$ MeV. The calculations employ an external, time-dependent, one-body potential. We investigate the correlation between the most probable velocity of the heavy ions when the nucleons are emitted and the exit channel total kinetic energy of the system, and compare with experimental data. We found that the model predicts a source velocity for the ions which is 10% below the measured projectile-like fragment velocity, and 34% above the measured velocity for the prompt emission source.

1. Abstract of paper: Phys. Rev. C 40, 1213 (1989).
2. Guest Assignee from Vanderbilt University, Nashville, TN 37235.
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NUCLEAR STRUCTURE

HIGH-SPIN STRUCTURE OF N=51 ^{96}Rh AND ^{97}Pd : A SHELL-MODEL STUDY¹

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R. Ma² J. B. McGrory

High-spin states of isotonic ^{96}Rh and ^{97}Pd were studied by means of the $^{64}\text{Zn}(^{40}\text{Ca}, \alpha 3p\gamma)^{96}\text{Rh}$ and $^{64}\text{Zn}(^{40}\text{Ca}, \alpha 2p\gamma)^{97}\text{Pd}$ reactions, respectively, with $E_{\text{lab}} = 167$ MeV. This is the first in-beam study of ^{96}Rh while ^{97}Pd has previously been studied in-beam with the $(^3\text{He}, 2n\gamma)$ reaction. Levels up to 5.5 MeV with $J^\pi = 15^+$ in ^{96}Rh were populated, while for ^{97}Pd levels up to 7.5 MeV with $J = 41/2$ were found. No $21/2^+$ level of ^{97}Pd could be found, in contrast to the results for the lighter odd-A isotones. An attempt to measure lifetimes using

a neutron- γ coincidence technique revealed no new isomers in either nuclide with $t_{1/2} > 5$ ns. The discovery of two low-lying transitions of 125 keV in ^{96}Rh presumably requires a slight revision of the value of the atomic mass of that nuclide as well as that of ^{96}Pb . The high-spin structure and the N=51 systematics, particularly the location of the $vg_{7/2}$ strength, are compared with the results of shell-model calculations.

1. Abstract of paper submitted for publication in Physical Review.
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BRANCHING RATIOS IN ^{206}Pb AND THE EFFECTIVE M1 OPERATOR

S. Raman J. B. McGrory

The structure of ^{206}Pb has been studied with great success over the years in terms of the spherical shell model in which a closed ^{208}Pb core is assumed and neutron holes are "occupied" in the six lowest single neutron hole orbits ($2p_{1/2}$, $2p_{3/2}$, $1f_{5/2}$, $1f_{7/2}$, $0h_{9/2}$, $0i_{13/2}$). In recent years, a number of spin assignments of excited states have been rendered "firm," so that there are now 24 excited states below 3.1 MeV with firm spin assignments. The shell model calculations of the excitation energies of states in ^{206}Pb make a very convincing case for the appropriateness of the assumed spherical shell model. We have repeated the structure calculation of ^{206}Pb using a residual interaction based on the Kuo-Herling interaction.¹ The interaction as used here is a one-parameter interaction in that the core polarization diagram was weakened by 25% so that the calculated excitation energy of the first $J = 2^+$ state agreed with experiment. With that interaction, the calculated energy levels for 24 states below $J = 3.1$ MeV excitation are in virtually exact agreement with experiment - i.e., for the 24 levels, the average deviation (absolute value) between theory and experiment is 5 keV, and the r.m.s. deviation is 12 keV. An inspection of the wave functions for these states shows that there is large configuration mixing for the

ground state and the first excited $J=2^+$ state. Most of the rest of the states are rather pure, simple, single configuration two-hole states.

Recently, greatly improved measurements² of branching ratios for the decay of a number of the states in ^{206}Pb below 3.1 MeV excitation have been made. We have calculated the branching ratios for the electromagnetic decay of the states below 3.1-MeV where the transitions are governed by E2 and M1 transitions. For the E2 operators, we assume a state-independent effective charge $e_n = 0.84e$ for all the neutron single-particle transition matrix elements. This value is such that the calculated lifetime of the first $J^\pi = 2^+$ state agrees with experiment. The M1 operator in the shell model for ^{206}Pb is specified by eight single-hole transition matrix elements. Five of these are determined from measurements of three magnetic moments and two M1 transitions in ^{207}Pb . Thus, there are three free parameters. We form the M1 operator by using the experimental values for the matrix elements, and we use the free nucleon magnetic moment operator for the remaining three matrix elements. The calculated branching ratios for low-lying states in ^{206}Pb are summarized in Table 5.1, where the measured values for the ratios are also shown. We show only those cases where the branching ratio is not necessarily 100% to any given lower-lying state, and we give only those relative probabilities that differ significantly from zero. Thus, the total probabilities in this table do not necessarily sum to 100%. In general, the calculations and observations are in remarkable agreement. The most significant discrepancies are for the decay of the second and fifth $J^\pi=2^+$ states. We have made a preliminary attempt to see if any simple modification of the effective M1 operator can reduce these discrepancies. Because of the simple nature of many of the wave functions, the branching ratios in a number of cases should depend sensitively on only one or two of the effective operator matrix elements. We looked for such behavior by repeating the calculations a number of times, where each time one of the effective M1 matrix elements was set to zero. The calculated branching ratios that

Table 5.1. Branching ratios in ^{206}Pb
(all states listed have positive parities)

Initial State J_i	Final State J_f	Relative Probability	
		Calculated	Observed
2_2	0_1	49	22
	2_1	51	74
4_1	2_1	77	69
	3_1	23	31
1_1	0_1	84	98
	2_1	8	2
	0_2	6	<1
2_3	0_1	0	8
	2_1	60	68
	0_2	5	6
	3_1	3	<4
	2_2	31	19
4_2	2_1	11	13
	3_1	79	69
	4_1	10	17
2_4	2_1	74	70
	3_1	15	19
	2_2	10	11
3_2	2_1	32	35
	3_1	53	65
	2_2	8	
	4_1	5	
1_2	2_1	96	>83
	2_2	4	<17
2_5	2_1	25	53
	3_1	1	4
	2_2	14	13
	1_2	54	27
	2_3	4	4
4_3	3_1	97	>86
3_3	2_1	79	80
	2_2	14	20

are in most serious disagreement with the measurements were not found to be sensitive to any of the three bare matrix elements. Thus, in spite of the simplicity of the wave functions, we have, to date, found no simple "fix" to settle these few discrepancies that do exist for the branching ratios.

1. J. B. McGrory and T.T.S. Kuo, Nucl. Phys. A247, 28 (1975).

2. Measurements of the $^{205}\text{Pb}(n,\gamma)$ reaction made at the Los Alamos Omega West Reactor in collaboration with J. W. Starnes and E. T. Journey.

THREE-DIMENSIONAL UNRESTRICTED STATIC
HARTREE-FOCK CALCULATIONS USING
BASIS SPLINES

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D. J. Dean¹ J. Wu²

The mean-field formalism has been a successful approximation to the nuclear many-body problem for reproducing the principal properties of nuclei throughout the periodic table. The details of these calculations suggest that the Pauli principle plays an important role in simultaneously building up a mean field and suppressing the strong N-N interaction terms. The time-dependent mean-field formalism has proved to be a valuable tool for studying a variety of nuclear phenomena, e.g., fusion, fission, deep-inelastic scattering, and nuclear molecular resonances. A comprehensive review of the previous applications can be found in Refs. 3 and 4.

From the numerical standpoint, new techniques have been developed to handle the solution of the Hartree-Fock equations on a space-time lattice. In particular, equations of motion were obtained via the variation of the lattice repre-

sentations of the constants of the motion, such as the total energy.⁵⁻⁸ In this variation, after discretization approach, resulting equations exactly preserve the constants of the motion. Most numerical calculations employed low-order finite-difference discretization techniques with accuracies appropriate for studying the gross features of the reaction. With the advent of computer technology, it has become feasible to carry out more extensive nuclear structure and reaction studies without resorting to the symmetry assumptions employed in the earlier applications. In order to be able to perform such calculations and to obtain a more detailed comparison with data, it is necessary to exploit higher-order interpolation techniques. Discretization of the energy functional on a basis-spline collocation lattice provides a highly accurate alternative to the finite-difference method.

In Table 5.2 we have tabulated the results obtained from the solution of the three-dimensional HF equations together with the solution of the radial Schrödinger equation for the spherical ¹⁶O nucleus, using the BKN force.⁹

Table 5.2. A comparative study of HF results for ¹⁶O. The force used is the Bonche, Koonin, Megele (BKN) form with $t_0 = -497.726 \text{ MeV}\cdot\text{fm}^3$, $t_1 = t_2 = 0.0 \text{ MeV}\cdot\text{fm}^5$, $t_3 = 17270.0 \text{ MeV}\cdot\text{fm}^6$, $t_4 = 0.0 \text{ MeV}\cdot\text{fm}^5$, $x_0 = x_3 = 1.0$, $\alpha = 1.0$, $V_U = V_L = -363.044 \text{ MeV}$, and $a = 0.45979 \text{ fm}$. We also include the direct and exchange parts of the Coulomb interaction and consider separate neutron and proton densities. The HF energy is calculated via Koopman's formula, with corrections.

	Radial N = 500 $\Delta = 0.025 \text{ fm}$	B-Spline, M=3 N = 22 ³ $\Delta = 0.9 \text{ fm}$	B-Spline, M=5 N = 22 ³ $\Delta = 0.9 \text{ fm}$	B-Spline, M=7 N = 22 ³ $\Delta = 0.9 \text{ fm}$
E_{HF} (MeV)	-119.641	-113.849	-119.135	-119.674
K.E. (MeV)	249.734	250.416	249.809	250.070
r_p (fm)	2.6263	2.6491	2.6284	2.6254
r_n (fm)	2.5970	2.6202	2.5993	2.5961
$E_s(n)$ (MeV)	-30.120	-30.181	-30.160	-30.148
$E_p(n)$ (MeV)	-16.949	-16.702	-16.954	-16.975
$E_s(p)$ (MeV)	-26.237	-26.351	-26.282	-26.265
$E_p(p)$ (MeV)	-13.361	-13.167	-13.372	-13.386

Three-dimensional calculations result in a spherical nucleus with a quadrupole moment on the order of 10^{-12} fm². We have used 22 points in x, y, and z directions in interval (-10,+10) fm. Radial calculations had converged to two significant digits. As we see from Table 5.2, an increase in the B-spline order M leads to a significant improvement in all quantities. The error in binding energy for M = 7 is 0.03%. The energies were calculated using the Koopman's formula with corrections for the density-dependent three-body term and the Coulomb exchange. The three-dimensional calculations involve 16 single-particle states each with a spin-up and a spin-down component. Due to the absence of the spin-orbit interaction in the BKN force, the six p-states for neutrons and protons are degenerate in energy. We have also repeated these calculations for the Skyrme M² force using M = 5 with accuracies almost identical to the BKN case. In this case, the numerical computation of the parity and the third component of the total angular momentum are within 1 part in 10⁴ of the exact spherical value. Each HF calculation consumed 15 minutes on a Cray-2 supercomputer. The computer time for heavier systems will be directly proportional to their mass number.

At this time, we have also completed one TDHF calculation for the ¹⁶O + ¹⁶O system at E_{lab} = 64 MeV using the BKN force with b = 0.0 fm (head-on collision). We have used a time step of $\Delta t = 0.4$ fm/c and followed the reaction for 850 time steps. These numbers are commensurate with the few restricted three-dimensional calculations available in the literature.¹⁰⁻¹³ At the end of the calculation, the error in energy was 32 keV out of the total energy of 193 MeV (error of 0.02%). During the collision, the norm was conserved to better than 1 part in 10⁶. We have, for the first time, performed three-dimensional HF and TDHF calculations with no simplifying assumptions. The use of the BSCM method results in an unprecedented accuracy for relatively coarse meshes. The evolution of nuclear HF and TDHF calculations have closely paralleled the advances made in computer tech-

nology. With these new numerical methods and the technology available today, it is possible to perform static HF calculations with accuracies comparable to more phenomenological models. In the near future, we will incorporate constraints into the HF program which will enable us to perform energy surface calculations for heavier systems. Similarly, unrestricted dynamical calculations will help us correctly address the questions about the amount of mean-field dissipation present in heavy-ion collisions. But, perhaps more importantly, the development of such numerical technologies and programs will lead to spin-offs for addressing many other problems in physics.

1. Guest Assignee from Vanderbilt University.
2. Guest Assignee from University of Tennessee.
3. K.T.R. Davies et al., in *Treatise on Heavy-Ion Science*, ed. by D. A. Bromley (Plenum, New York, 1985), Vol. 3, p. 3.
4. J. W. Negele, *Rev. Mod. Phys.* 54, 913 (1982).
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PREDICTIONS OF $B(E2; 0_1^+ \rightarrow 2_1^+)$ VALUES FOR EVEN-EVEN NUCLEI¹

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Adopted values (from a previous compilation) for the energy, E, and the reduced electric quadrupole transition probability, $B(E2)^+$, for the first-excited 2⁺ state of 276 even-even nuclei are tabulated. The adopted $B(E2)^+$ values are employed to test the various systematic, empirical, and theoretical relationships that

have been proposed to exist among these $B(E2)^+$ values on a global, local, or regional basis. On the basis of these systematics, predictions of unmeasured $B(E2)^+$ values for 181 additional nuclei are made in the tabulation.

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1. Abstract of published paper: At. Data Nucl. Data Tables 42, 1 (1989).
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 4. University of Mississippi, University, MS 38677.

TESTING THE PARAMETERS OF THE "UNIVERSAL" WOODS-SAXON POTENTIAL WITH $B(E2; 0_1^+ \rightarrow 2_1^+)$ VALUES AND NUCLEON SEPARATION ENERGIES¹

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J. Dudek³

The idea of "universality" of an average nuclear field introduced earlier has been applied and tested in the calculations of $B(E2; 0_1^+ \rightarrow 2_1^+)$ values and nucleon separation energies for nuclei in the $Z > 52$, $A > 120$ region. Good description is obtained using a single "universal" choice of 12 constants defining the deformed Woods-Saxon nuclear average field.

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$SP_6 \times SU_2$ SYMMETRY OF THE FERMION DYNAMICAL SYMMETRY MODEL¹

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D. H. Feng² M. W. Guidry⁴

The $SP_6 \times SU_2$ symmetry of the fermion dynamical symmetry model (FDSM) was studied. Analytic expressions are given for the wave functions and matrix elements of the pair creation operators $S^\dagger$, $D^\dagger$, and $E2$ transition operator for the hermitage $u = 0, 1, 2$ cases. Various Pauli effects

which differentiate the FDSM SU_3 from $(IBM)SU_3$, as well as the relationship between the wave functions and matrix elements in the FDSM, the interacting boson model, the $SP(6, R)$ models, and the Elliott model are discussed. Extensive discussions of the physical implications of the model are presented.

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THE CORRESPONDENCE BETWEEN THE FERMION DYNAMICAL SYMMETRY MODEL AND THE GEOMETRICAL MODEL OF ROTATING NUCLEI¹

C. L. Wu² D. H. Feng²
M. W. Guidry³ J. Q. Chen²

The correspondence between the fermion dynamical symmetry model (FDSM) and the geometrical model of rotating nuclei is discussed. It is shown, in all aspects that we have studied, including the particle-rotor Hamiltonian, energy spectrum, the Alaga selection rule, β - γ vibrations, the moment of inertia, the stretching effect, the CAP effect, backbending, etc., that the traditional geometrical descriptions can be obtained from the FDSM as a large N limit (large number of particles). Thus, the FDSM provides a microscopic understanding of the geometrical model and a link from the spherical shell model to the geometrical model. The finite N effects are shown to be responsible for the loss of collectivity in $B(E2)$ strength, and band termination at high spin; it is responsible for Coriolis attenuation in the particle-rotor model as well.

As an example of this study, we show in Table 5.3 the one-to-one correspondence between the geometrical model labeling of β - and γ -like vibrational states (columns 1 and 2) and the corresponding group theoretical labeling in the FDSM (columns 3 and 4). The FDSM energies in column 5 are seen to be equal to the geometrical

Table 5.3 β - γ Vibrations & SU_3 representations

$E_{vib}(\beta, \gamma)$	$n_\gamma \quad n_\beta \quad \kappa/2$	$h_3(\lambda, \mu)\kappa$	$[h_1 \ h_2 \ h_3]$	$B_2AC(\lambda, \mu)$
0	0 0 0	$0(n_1-0,0)0$		0
1β	0 1 0 0 0 1	$0(n_1-4,2)0$ $0(n_1-4,2)2$		$1\beta(1-\frac{1}{n_1})$
2β	0 2 0	$0(n_1-8,4)0$		$2\beta(1-\frac{3}{n_1})$
	0 1 1	$0(n_1-8,4)2$		
	0 0 2	$0(n_1-8,4)4$		$2\beta(1-\frac{3}{n_1})$
	2 0 0	$2(n_1-6,0)0$		
3β	0 3 0	$0(n_1-12,6)0$		$3\beta(1-\frac{5}{n_1})$
	0 2 1	$0(n_1-12,6)2$		
	0 1 2	$0(n_1-12,6)4$		
	0 0 3	$0(n_1-12,6)6$		
	2 1 0	$2(n_1-10,2)0$		$3\beta(1-\frac{10}{3n_1})$
	2 0 1	$2(n_1-10,2)2$		

$$n_\gamma = h_3 = (n_1 - \lambda - 2\mu)/3$$

$$\lambda = n_1 - 3n_\gamma - 4n_\beta - 2\kappa$$

$$n_\beta = (\mu - \kappa)/2 \quad (3.18a)$$

$$\mu = 2n_\beta + \kappa \quad (3.18b)$$

model energies in column 1, up to terms of order $1/N$.

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PHYSICS AT THE NUCLEAR-PARTICLE INTERFACE

THE PARTICLE-NUCLEAR INTERFACE¹

F. E. Close²

Once upon a time nuclear physics was the study of nucleons and pions vibrating and oscillating at the center of the atom; particle physics was the study of nucleons and pions interacting and producing resonances. From the latter, people gradually realized that hadrons are built from quarks; the fundamental rules governing their interactions were deduced ("QCD" - quantum chromodynamics) and the similarities

with QED suggested the possibility that all of the natural forces can be described in a grand unified theory. Today, particle physics deals with questions ranging from the origins of matter in the first microseconds of the universe, whose experimental investigation requires the energies of the SSC, down to the quark structure of protons and nuclei that can be studied at relatively low energies.

1. Summary of paper to be published in Proceedings of Summer School of Computational Atomic and Nuclear Physics, Sewanee, TN, June 26 - July 7, 1989.
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PHOTO- AND ELECTROPRODUCTION OF π^0 IN A QUARK MODEL WITH QCD¹

F. E. Close² Zhenping Li³

We review and update the theory on photo- and electroproduction in the nonrelativistic constituent quark model (MRCQM). The electromagnetic interaction Hamiltonian for a three-quark system is discussed, particularly the

nonadditive term and the role of the binding potential which have been neglected in previous calculations. We find that the successes of the NRQM survive these relativistic corrections and make predictions for baryon resonance excitation that can be tested in forthcoming experiments. Finally, we discuss the limits of application of the long wavelength approximation in resonance photo- and electroproduction.

1. Abstract of paper submitted for publication in Physical Review D.

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TESTING QCD WITH MILLI-TeV ELECTRONS¹

F. E. Close²

Analogies have been drawn between QCD where quarks build up hadrons, which in turn build up nuclei, and QED where electrons build up atoms, which in turn build up molecules. There has been a lot of talk about creating a quark theory of the nucleus in QCD by analogy with the way electrons build up molecules in QED. However, this seems to me to be a case of trying to run before you can walk, in that in QED the first step has been achieved, namely understanding atoms in terms of their electronic structure, but understanding molecules in QED is only understood in rather simple cases. In QCD the situation is even worse, in that we haven't even achieved the first step, namely in understanding how hadrons are built from quarks. We all believe that quarks are in the hadrons, and that at high momentum transfer we can apply perturbative QCD (pQCD). But to build the hadrons, we need pQCD and also nonperturbative QCD, which, at present, means building models to simulate the effects of the confinement. Insofar as any successful model of the nucleus will have it looking to a very good approximation as if it is made of nucleons, then I believe that first we have to understand the dynamics of quarks building the individual nucleons. Throughout this talk, I wanted to show how low-energy electron beams may help us deepen that

understanding, and hopefully lead us towards the correct dynamical picture of the nucleon.

1. Summary of talk presented at First European Workshop on Hadronic Physics in the 1990's with Multi-GeV Electrons, Seillac, France, 1988; Nucl. Phys. A 497, 109c (1989).

2. UT-ORNL Distinguished Scientist.

QCD PARTON RECOMBINATION AND APPLICATIONS TO NUCLEAR STRUCTURE FUNCTIONS¹

F. E. Close² J. Qiu³
R. G. Roberts⁴

We investigate a hitherto neglected sector of perturbative QCD which is normally hidden in conventional hadron analyses but has observable consequences in nuclei. There is a modification to structure functions arising from the fusion of quarks, antiquarks, and gluons, and we derive recombination factors, analogues of familiar splitting function, and compute the effects of parton fusion on the nuclear structure functions. This mechanism causes the structure functions to extend beyond $x = 1$; as $x \rightarrow 0$, we have a source of shadowing within the framework of QCD. We find that the loss of momentum when nucleons bind is shared almost equally between $q\bar{q}$ and gluons. We predict that the nuclear modification of the gluon distribution is a significant suppression as $x \rightarrow 0$ and enhancement for $x \approx 0.2$. We point out how hadronic ν production may be used to disentangle this shadowing mechanism from other nuclear effects.

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PROBING THE POLARIZED SEA BY INCLUSIVE LEPTOPRODUCTION OF HADRONS¹

F. E. Close² R. G. Milner³

Predictions are given for the inclusive production of ν and K in polarized lepton production from polarized nucleons. As $E_{\nu,K}^{\text{lab}} \rightarrow 0$, the

hadron-inclusive asymmetry equals that of the total cross section; for $E_{\nu,K}^{\text{lab}} > 0$, new information is obtained. We show that these processes can provide sensitive tests for a polarized sea in a polarized nucleon.

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1. Abstract of paper submitted for publication in Physical Review Letters.
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NUCLEON SPIN STRUCTURE FUNCTIONS¹

F. E. Close²

There has been much recent excitement arising from the claim by the EMC collaboration that none of the proton's spin is carried by quarks. There are many textbooks which assert that the proton's spin is carried by quarks. The history of deep inelastic scattering of polarized leptons from polarized protons is reviewed, culminating in this most recent dramatic claim. It is shown that, for the last decade, data have appeared consistent with predictions of the quark model and the paper highlights what the new and potentially exciting data are. Polarization dependence of inclusive hadron production is discussed and suggestions are made for the future.

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1. Abstract of talk to be published in Proceedings of Topical Conference on Electromagnetic Nuclear Physics with Internal Targets, Stanford, California, January 9-12, 1989.
 2. UT-ORNL Distinguished Scientist.

POLARIZED STRANGE QUARKS IN THE PROTON AND THE VALIDITY OF QUANTUM CHROMODYNAMICS¹

F. E. Close²

Recent claims that the European Muon Collaboration (EMC) data on polarized proton structure functions violate quantum chromodynamics are shown to be unfounded and driven by the use of an incorrect or outdated value of the F/D ratio for hyperon decays. Conclusions from the EMC experiment as to the amount of strange sea polarization are rather sensitive to this value. Contrary to some statements in the literature,

elastic neutrino scattering data are consistent with vanishing strange polarization.

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1. Abstract of paper to be published in Nuclear Physics.
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EXOTIC MESONS¹

F. E. Close²

Significant in proving the validity of the quark model in the late 1960's were the two following phenomena:

(1) Mesons occur in nonets with $|Q| < 1$ and $|\text{strangeness}| < 1$. There were many fruitless searches for "exotic states of the first kind" such as mesons with charge or strangeness 2.

(2) Mesons have spin parity and charge conjugation, J^{PC} , that are consistent with them being made from (nonrelativistic) spin-1/2 quark and antiquark. Thus one cannot form 0^{--} , nor the sequence 0^{+-} , 1^{+-} , 2^{+-} , etc. There were fruitless searches for such "exotics of the second kind".

Then along came the notion of color, which is the source of the force between quarks. This naturally explained nature's preference for $q\bar{q}$ and qqq colorless systems. However, it also appears to predict multiquark states such as $q^2\bar{q}^2$ with charge and strangeness belonging to the category "exotics of the first kind." If the color forces are not color ionic but instead more akin to covalent (analogous to the familiar electromagnetic case), then these states will consist of two color singlet mesons bound in a "molecule." Weinstein and Isgur³ argue that $K\bar{K}$ form 0^{++} bound states just below the KK threshold, consistent with the known $f_0(975)$ and $a_0(980)$. It is possible that exotics of the first kind can be avoided or are so broad that they do not show up.⁴ It is an open question as to whether other such "molecules" exist. The status of exotic mesons is discussed — states that do not fit into the simple $q\bar{q}$ model.

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- Upton, NY 11973, 1988, to be published in *Z. Phys. C*.
 2. UT-ORNL Distinguished Scientist.
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PIONIC CONTRIBUTION TO THE π -A TRANSITION QUADRUPOLE MOMENT¹

S. Kumano²

The pionic contribution to the scalar and longitudinal $p \rightarrow \Delta^+$ transition quadrupole form factor is calculated. It is shown that the πN channel contributes $+0.032 - i 0.066 \text{ fm}^2$ at the photon momentum $q = 471 \text{ MeV}$ ($E2/M1 = +1.4 - i 2.9\%$). Because this value is much larger than the typical constituent quark model prediction, one should be careful in comparing experimental data and theoretical predictions.

1. Abstract of paper to be published in Proceedings of International Symposium on Weak and Electromagnetic Interactions in Nuclei, Montreal, Canada, May 15-19, 1989.

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NUCLEON STRUCTURE IN A FLUX-TUBE QUARK MODEL¹

S. Kumano²

Nucleon structure with pion clouds has been studied in the framework of a flux-tube quark model.³ The meson clouds are produced by breaking flux-tubes in the nucleon by creating a pair of $q\bar{q}$ within a color field. In the flux-tube model,⁴ for example, a meson is treated as the interacting quark-antiquark pair and the color field connecting them. An extension of this model to the meson decay has been investigated, and it gives a reasonable explanation for the strong decay of mesons,⁵⁻⁷ even though there are still problems in the $q\bar{q}$ creation mechanism, namely 3S_1 or 3P_0 $q\bar{q}$ creation models. It is interesting to investigate the decay problem further⁸ and to relate it to the nucleon structure research. Here we investigate πN dynamics in terms of quark degrees of freedom as a first step in a study of baryon structure with meson clouds in the flux-tube quark model.

Both 3S_1 and 3P_0 models are applied to the nucleon structure problem. We also examine the location where the pair creation occurs. In the flux-tube (FT) model, the $q\bar{q}$ pair creation occurs within a narrow flux-tube. On the other hand, the pair is created anywhere in the vicinity of parent quarks in the flux-volume (FV) model. Furthermore, in order to examine how the results depend on the pion radius, numerical results are obtained for $R_\pi = 0.16$ and 0.129 fm . The effects of color magnetic interactions on hadron wave functions are not very significant except for the pion case. The pion r.m.s. radius shrinks to 0.16 fm from 0.129 fm due to color magnetic interaction.⁴ In Ref. 7, we assumed a hard-core final-state interaction between mesons, which could be justified as a quark exchange effect.³ The same kind of feature is expected for the short-range part of the pion-nucleon final-state interaction; in fact, the hard core size, $0.42 \pm 0.11 \text{ fm}$, is used to explain the low-energy S-wave experimental data.¹⁰ In this work, the hard-core final-state interaction between the pion and the nucleon with radius $C_{\pi N}$ is assumed to take into account this feature. The core radius, $C_{\pi N}$, is determined to explain the Δ width or the coupling constant $f_{\pi NN}$. Then the πNN and πNA form factors are calculated.

In this flux-tube model, a baryon is described by three valence quarks connected by color fields and other configurations including sea quarks. These sea quarks (or virtual meson clouds) generate baryon decay widths and shift their masses; therefore, the hadron spectroscopy in constituent quark models should be reinvestigated by including these mass shifts. In this flux-tube model, the Yukawa potential is explained by a piece of the flux-tube breaking off from a nucleon and attaching itself to the other. Our results are summarized as follows:

(1) The hard core size of the final πN interaction adjusted to explain the Δ width or the $f_{\pi NN}$ in the 3S_1 model is consistent with the one ($\sim 0.4 \text{ fm}$) used for explaining the S-wave phase shifts. The core size in the 3P_0 model is smaller than this.

(2) The Δ mass shift is rather large (300-600 MeV), so the color coupling constant, α_c , determined by the N - Δ mass splitting must be re-examined, and the flux-tube quark model spectroscopy should be repeated by including these mass shifts.

(3) The momentum cut-off parameter, α_2 , depends strongly on the final-state interaction, rather than the $q\bar{q}$ creation models.

(4) α_2 in the 3S_1 model is consistent with the conventional value (4-6 fm), however, the one in the 3P_0 model is slightly larger (≈ 7 fm).

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Δ ELECTROMAGNETIC MOMENTS¹

S. Kumano²

Electromagnetic moments of the Δ are important quantities for testing quark models. A naive quark model, for example the SU(6) model, predicts the Δ^{++} moments: $\mu_{\Delta^{++}} = 2\mu_p$ (μ_p = proton dipole moment), $Q_{\Delta^{++}} = 0$, and $\alpha_{\Delta^{++}} = 0$. Because the SU(6) model is a simple spin-flavor algebra, deviations from these values indicate dynamical aspects of the quark model. Especially, there is considerable interest in

quadrupole moments of the Δ and the N - Δ transition.

Pion-nucleon bremsstrahlung has been investigated for twenty years as a possible process to measure the Δ dipole moment,³ yet there is no definite agreement for the dipole moment. We may attribute the difficulties to several points. First, a description of the πN bremsstrahlung process has to be consistent with the πN elastic scattering. Second, the soft-photon approximation, often used to analyze the bremsstrahlung, is valid at low energies ($k < 40$ MeV), but it is not applicable at higher energies ($k = 100$ MeV) where the dipole moment effect is conspicuous. Third, one must be careful about the gauge invariance (or the current conservation). Once a πN rescattering term is introduced to explain the P_{33} phase shifts, one should pay attention to the current conservation associated with an off-shell form factor. At pion energies of approximately 100 MeV, there are several processes which are of the same order of magnitude and cancel each other. Therefore, one should be sure of the validity of one's model and approximations. Fourth, pionic contributions to the Δ electromagnetic moments should be investigated in order to compare with experimental results.

In our research,⁴ the bremsstrahlung process is analyzed in the isobar model. At first, $\pi N \Delta$ coupling constant, form factor, and bare Δ mass are determined by fitting the P_{33} phase shifts. Other background partial waves, S_{31} and P_{31} , are included in analyzing π^+ -proton bremsstrahlung data. Then, pionic contributions to the Δ electromagnetic moments are studied. For example, the physical Δ dipole moment is given by the bare dipole moment plus the pionic contribution: $\mu_{\Delta}(E_{\Delta}) = \mu_{\Delta} + \mu_{\Delta}^{(\pi N)}(E_{\Delta})$, where the bare moment μ_{Δ} is a parameter to fit the cross section. On the other hand, the pionic contribution can be calculated by using the isobar model. In this model, we introduce the pion rescattering term to explain the P_{33} phase shifts. The imaginary part of the self-energy due to this term provides the Δ width and the real part shifts the Δ

mass. In the same way, the rescattering term contributes to the electromagnetic structures. We should note that the contribution is not only energy (E_Δ) dependent, but also complex, and the imaginary part is as large as the real part. We find that the contribution to the Δ dipole moment is about 20% of the SU(6) prediction. However, the contribution to the Δ quadrupole moment is more dramatic, and it is several times larger than a typical constituent quark model prediction. Therefore, an experimental quadrupole moment such as the $N\text{-}\Delta$ transition comes entirely from the pionic contributions. In fact, a naive estimate indicates that the pionic contributions to the $E2/M1$ ratio are about $+1.4\text{--}15.7\%$.⁵

We have compared our calculations with experimental results of the π^+p bremsstrahlung.⁶ The asymmetry is very sensitive to $\mu_{\Delta^{++}}$ in the range $2\text{--}3 \mu_p$, which suggests that the Δ dipole moment could be measured accurately by this polarization asymmetry.

We also investigated the possibility of measuring the Δ quadrupole moment. However, even if we take a large value like $Q_{\Delta^{++}} = \pm 0.5 \text{ fm}^2$, the cross section changes very little. Therefore, the Δ quadrupole moment measurement in the bremsstrahlung process is almost impossible. This is because the photon energies in the bremsstrahlung are in the long wavelength region ($k < 120 \text{ MeV}$, $1/k > 2 \text{ fm}$), and the photon cannot resolve minute structures such as the Δ quadrupole moment. In the $N\text{-}\Delta$ transition case, the energy transfer is $k = m_\Delta - m_N = 300 \text{ MeV}$, and the resolution ($1/k = 0.6 \text{ fm}$) could be good enough to observe it.⁷

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COMPUTATIONAL AND MATHEMATICAL PHYSICS

DAMPED RELAXATION TECHNIQUES TO CALCULATE RELATIVISTIC BOUND STATES¹

C. Bottcher A. S. Umar²
M. R. Strayer F.-G. Reinhard³

A class of damped relaxation methods for finding stationary (bound-state) solutions of relativistic wave equations represented by matrix equations on a discrete space lattice is discussed. Model calculations are presented for the Schrödinger and Dirac equations using a point-Coulomb potential for which analytic solutions can be obtained. A numerical application using a Gaussian potential in one dimension illustrates the general procedure for practical applications. As a realistic example, we study the Dirac equation on a three-dimensional Cartesian lattice using the Coulomb potential of a uniform charge distribution.

1. Abstract of paper: Phys. Rev. A 40, (1989).

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IMPLEMENTATION OF MONTE CARLO TECHNIQUES ON A PARALLEL SUPERCOMPUTER

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A code has been written to evaluate multi-dimensional integrals by Monte Carlo methods on a parallel processing supercomputer. Specifically we used the iPSC/2 Hypercube at ORNL, but the code's methods are fairly general. Monte Carlo integration is well suited to architectures like that of the iPSC/2 (without shared memory), provided one has a reliable efficient technique for generating independent streams of random numbers on the different processors. Such techniques have been made available by the work of Arbanas and Bottcher, implementing

suggestions of Kalos and Percus. We have tested that the integration code works properly by applying it to some rather simple analytically integrable problems in four dimensions. We find appropriate statistical behavior of errors when the partial sums from different processors are combined. Extensions to higher dimensions and more complex integrands are in progress. One projected application is computation of complex integrals describing lepton production due to the strongly pulsed electromagnetic fields that occur in ultrarelativistic collisions of highly charged heavy ions.

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THE BASIS SPLINE COLLOCATION METHOD FOR BOUNDARY VALUE PROBLEMS

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J. Wu² C. Bottcher

The basis spline collocation method⁴ was designed for the relativistic theory of fermions, but can be generalized to other physics problems. In this approach, state vectors are expanded in spline functions and also discretized on a collocation lattice in space. The basis of spline functions and the lattice representation are linked by a metric to describe the transformation properties. For boundary value problems, it is crucial to include the boundary conditions in the construction of the metric for the numerical representation. We propose a general algorithm⁵ to treat boundary value problems in the B-spline collocation method, which provide great flexibility in applications.

It is more convenient to illustrate the algorithm for an example in one dimension. A smooth function, $f(x)$, defined in the interval, (x_1, x_2) , can be expanded in terms of B-spline functions as

$$f(x) = \sum_{i=1}^{N+M-1} B_i^M(x) c^i, \quad (1)$$

where M is the order of the spline functions, N is the number of subintervals in (x_1, x_2) and c^i

denotes the expansion coefficients. When we discretize $f(x)$ on the collocation points x_α , Eq. (1) reads

$$f_\alpha = \sum_{i=1}^{N+M-1} B_{\alpha i} c^i, \quad (2)$$

where $f_\alpha \equiv f(x_\alpha)$, and $B_{\alpha i} \equiv B_i^M(x_\alpha)$. Using matrix notation, we have

$$(f)_N = (B)_{N \times (N+M-1)} (c)_{N+M-1}, \quad (3)$$

where the subscripts indicate the dimensions of the matrices (or vectors). For the transformation back and forth between the c -space and the f -space, we need the matrices B and B^{-1} . Equation (3), as it stands, is not in the right form, since B is not even a square matrix except for periodic boundary conditions. However, for an extensive class of boundary conditions, we may introduce an algorithm to achieve it as follows.

Consider the fixed boundary conditions which can be cast into the following form

$$\sum_{p \geq 0} K_{rp} \frac{d^p}{dx^p} f(x) \Big|_{\text{boundary}} = 0, \quad (4)$$

where r counts the number of such conditions and K is the coefficient array. When the boundary conditions are realized in terms of the B-spline functions, they become

$$\sum_{i=1}^{N+M-1} \left(\sum_{p \geq 0} K_{rp} \left[\frac{d^p}{dx^p} B_i^M(x) \right]_{\text{boundary}} \right) c^i = 0. \quad (5)$$

Equation (5) can be put into the form

$$\sum_{i=1}^{N+M-1} B_{ri} c^i = 0, \quad (6)$$

where

$$B_{ri} \equiv \sum_{p \geq 0} K_{rp} \left[\frac{d^p}{dx^p} B_i^M(x) \right]_{\text{boundary}} = 0. \quad (7)$$

For realistic problems, we may properly choose $M-1$ such conditions to give a square matrix

$$\hat{B} \equiv \begin{pmatrix} B \\ B \end{pmatrix}_{(N+M-1) \times (N+M-1)} \quad (8)$$

and find the inverse $\hat{B}^{-1}$. With $\hat{B}$ and $\hat{B}^{-1}$, we can construct the corresponding matrix form for

any differential operator⁵ with boundary conditions already built in. A library of sub-routines is now available to set up the B-spline collocation representation and apply it to a number of applications, such as the Schrödinger equation, the Poisson equation, and the generalized Helmholtz equation in three dimensions. Figure 5.10 shows an example of the high accuracy achieved for the lattice solution of the radial Helmholtz equation. The solid line gives the lattice solution on the interval (0,20) with 100 mesh points and 5th order B-splines. The dotted line gives the error when compared with the known analytical solution.

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STUDIES ON RANDOM NUMBER GENERATORS

G. Arbanas¹ C. Bottcher

Monte Carlo techniques are used to solve many problems in physics, both theoretical and experimental. Such applications require reliable sources of random numbers. Motivated initially by the inadequacies of the Random Number Generators (RNGs) supplied by computer vendors, we set out to develop some portable generators, together with the software to test their statistical properties rigorously. We also wanted to remedy the lack of generally available generators for vector and parallel computers.

We have been able to construct a family of new, machine-independent, RNGs which pass elaborate tests. In particular, we have written general codes to implement the relatively simple "chi-squared" test and the highly elaborate "spectral" test, which uses sophisticated number theoretic ideas. These are now being used by several groups in the Division.

These ideas have further been combined with a recent proposal by Kalos and Percus to produce

Fig. 5.10. The error of the lattice solution for the radial Helmholtz equation.

algorithms for independent streams of random numbers on the nodes of a parallel computer. Finally, we developed a theory to justify the use of so-called "scramble tables", which have hitherto been used on an empirical basis and showed that they could be used to generate uncorrelated random number streams in a vectorized mode.

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EVALUATION OF A CLASS OF INTEGRALS OCCURRING IN MATHEMATICAL PHYSICS VIA A HIGHER-ORDER GENERALIZATION OF THE PRINCIPAL VALUE¹

K.T.R. Davies R. W. Davies²

The notion of the principal value of an integral is generalized to treat higher-order singularities. The principal value of an integral can be considered the "convergent part" of a divergent integral, an interpretation which is almost trivial for simple poles but more meaningful for higher-order poles. Application of this concept leads to a simple algorithm which may be applied to the evaluation of a class of integrals arising in mathematical physics. Many of these integrals frequently occur in the analytic and numerical evaluation of folding functions arising from the product of single-particle Green's functions.

1. Abstract of paper to be published in Canadian Journal of Physics.

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DISPERSION RELATIONS FOR CAUSAL GREEN'S FUNCTIONS; DERIVATIONS USING THE POINCARÉ-BERTRAND THEOREM AND ITS GENERALIZATIONS

K.T.R. Davies R. W. Davies¹
G. D. White²

In the theory of dispersion relations, one frequently has to deal with multiple integrals involving products of Schwartz distributions (e.g., delta functions or principal-value terms). In evaluating such integrals, one must

be very careful about reversing the order of integration. For example, in a double integral it is permissible to interchange the order of integration for a product involving two delta functions, or for a product containing a delta function and a principal-value singularity. However, due to an important theorem by Poincaré and Bertrand, in certain products involving two principal-value factors the order of integration cannot be freely switched; in particular, the Poincaré-Bertrand (PB) theorem states that

$$\int_{-\infty}^{\infty} dx \frac{P}{(x-u)} \int_{-\infty}^{\infty} dy \frac{P}{(y-x)} f(x,y) \\ = \left[\int_{-\infty}^{\infty} dy \int_{-\infty}^{\infty} dx \frac{P}{(x-u)} \frac{P}{(y-x)} f(x,y) \right] - \pi^2 f(u,u), \quad (1)$$

where P denotes principal value. Note the last term on the right-hand side of Eq. (1) which results from reversing the order of integration.

The most familiar example from many-body theory that involves a double principal value occurs when computing loop corrections (bubble diagrams) to the single-particle propagators. Generally, one can write the loop as a frequency integration of two causal Green's functions (Feynman propagators),

$$L_{AB}(u) = -i \int_{-\infty}^{\infty} du' G_A(u') G_B(u+u'). \quad (2)$$

The Feynman propagators are used because they are directly related to the quantum mechanical observables. Frequently other propagators, such as the retarded Green's function, are used when calculating particular classical quantities (potentials, for example) which are then used in a quantum or relativistic theory. The correct propagator for quantum fields (requiring holes traveling backwards in time) is the Feynman propagator. However, the formalism developed here is quite general and also applies to advanced and retarded Green's functions.

Since "free" propagators are usually proportional to functions of the form

$$f^{(\pm)}(u) = \frac{1}{u^2 - \alpha^2 \pm i\delta} \rightarrow \frac{P}{(u^2 - \alpha^2)} \mp i\pi\delta(u^2 - \alpha^2), \quad (3)$$

it is clear that the PB theorem is relevant for computing first-order loops (i.e. loops containing only free propagators). However, even for such simple loops, one must be very careful about introducing multiple principal-value factors. In particular, the limit indicated in Eq. (3) is not valid if another principal-value term is already present in the integral. In our work, we show how the PB theorem allows one to generalize Eq. (3) to first-order loops containing two free propagators. Fortunately, all of this complication is not really necessary for first-order loops since such integrals can be very simply evaluated by other methods (usually complex contour integration). The most significant application of the PB theorem involves the more general case, where the dressed and/or finite-temperature propagators no longer have the simple form of Eq. (3), but, from the spectral representation, the real and imaginary parts satisfy a causal dispersion relation.

In this case, the PB theorem can be used to show that $L_{AB}(\omega)$ also satisfies a similar dispersion relation. In Ref. 3, this very important causality relation has been implemented in the development, at zero temperature, of a self-consistent nuclear transport theory. In our present work we have concentrated on various generalizations such as the finite temperature dispersion relation, the case of multiple principal-value integrals, and the case of higher-order poles.

Also, there is an intimate connection between the PB theorem and analyticity. Thus, any result obtained using the theorem can usually be derived from standard complex variable theory, for which it is especially useful to introduce the spectral representations of the Green's functions. Nevertheless, many of our most important results are easier to obtain using the PB theorem than complex variable theory. In particular, the statistical properties of finite-temperature loop integrals containing two- and three-particle causal propagators follow, in a straightforward way, from the PB theorem. These relations are not as simply

derived using complex variable theory, mainly because the spectral representation of a causal Green's function has a rather complicated structure. Moreover, as one tries to evaluate even more sophisticated types of many-body diagrams (e.g. loops containing more than three particles), complex variable manipulations become increasingly unwieldy. In contrast, the advanced and retarded Green's functions have much more tractable spectral representations, thereby allowing one to easily simplify expressions involving these propagators. Again, because we are mainly interested in dispersion relations in quantum field theory, our focus is on causal Green's functions; when, integrals containing these functions provide a real "showplace" for the applicability of the PB theorem. Thus, this theorem is seen to be an important tool for formally manipulating complicated many-body diagrams which involve causal propagators.

Finally, we emphasize that while the main thrust of our work pertains to nuclear or particle physics, many of the results should be applicable to other specialties, e.g., condensed matter physics. In particular, our work on finite temperature Green's functions should be of interest in studies involving the general theory of response functions.

1. GTE Laboratories, Inc., Waltham, MA 02254.

2. Consultant from Northwestern State University, Natchitoches, LA 71457.

3. P. J. Siemens, et al., "Relativistic Transport Theory of Fluctuating Fields for Hadrons," this report.

STUDY OF ATTRACTORS OBTAINED FROM A TWO-DIMENSIONAL VAN-DER-POL OSCILLATOR

B. Luce¹ K.T.R. Davies

Consider a particle of unit mass moving in the two-dimensional (NELSON) potential²

$$V(x,y) = (y - \frac{1}{2}x^2)^2 + \frac{1}{20}x^2, \quad (1)$$

and subject to the Rayleigh dissipation function

$$\bar{F}(x,y) = \frac{1}{2} [\alpha + \alpha(x^2 + y^2)] (x^2 + y^2), \quad (2)$$

where α and β are parameters and the dot denotes differentiation with respect to time. The equations of motion are then given by

$$\ddot{x} + \frac{\partial V}{\partial x} + [\alpha + \beta (x^2 + y^2)] \dot{x} = 0 \quad (3a)$$

and

$$\ddot{y} + \frac{\partial V}{\partial y} + [\alpha + \beta (x^2 + y^2)] \dot{y} = 0. \quad (3b)$$

In order to simplify the equations, we take $\alpha = -8$ and $\beta > 0$. With these restrictions we note, for the dissipative term, that outside of the unit circle there is nonlinear damping, tending to force the particle inward, while inside this circle the motion is forced outward. This is basically a two-dimensional Van-der-Pol oscillator whose one-dimensional counterpart is well known to possess "limit cycles."³ A limit cycle is periodic and is the limiting asymptotic trajectory for a given choice of the nonlinear parameters.

After discretizing the equations of motion (3), we have made a study of the types of limit cycles which one obtains for a wide range of the parameter β . Figures 5.11 and 5.12 are examples of such trajectories. These are among the simplest of the limit cycles studied; in general, one finds a rich variety of behavior, including

period multiplying trajectories. Also, we have studied the sensitivity of the results to the time step used in the discretized equations, and we find that spurious behavior can easily occur if the time step is not carefully chosen.

Finally, there is some hint that a "strange attractor" could exist for this system. Such an attractor is not allowed for the simple one-dimensional Van-der-Pol oscillator,^{3,4} but it could conceivably occur for the present system. In particular, we found for some of the limit cycles a certain "compression followed by splitting" behavior which is reminiscent of the "folding and stretching" observed in a true strange attractor.⁴ However, while the existence of a strange attractor remains an exciting possibility for this system, much more work needs to be done in order to verify its existence.

1. Participant in University of Tennessee Science Alliance Summer Research Program from State University of New York College, Fredonia, Fredonia, NY 14063.
2. M. Baranger and K.T.R. Davies, *Ann. Phys. (N.Y.)* 177, 330 (1987).
3. P. Bergé, Y. Pomeau, and C. Vidal, pp. 25-27 in *Order Within Chaos*, John Wiley and Son, New York, 1984.
4. *ibid.*, pp. 111-123.

Fig. 5.11. Limit cycle for the NELSON potential with nonlinear dissipation; $\beta = 1.19$.

Fig. 5.12. Limit cycle for the NELSON potential with nonlinear dissipation; $\delta = 1.455$. Notice the change in complexity compared to the curve in Fig. 5.11.

NUMERICAL EVALUATION OF PRINCIPAL-VALUE INTEGRALS OCCURRING IN THE SOLUTION OF DYSON'S EQUATIONS

K.T.R. Davies R. W. Davies¹
G. D. White²

In intermediate-energy physics studies, it is usually much easier to evaluate the imaginary part of a Green's function than its real part. Also, there are often problems in calculating the real and imaginary parts directly since causality may not automatically be satisfied. We have taken the point of view that the imaginary part of a Green's function is obtained from Dyson's equations, but its real part is calculated numerically from a dispersion relation, thereby guaranteeing exact causality.

At zero temperature, the real part of a causal Green's function, $G(u)$, is related to the imaginary part via a Hilbert transform:

$$\text{Re}[G(u)] = \frac{P}{\pi} \int_{-\infty}^{\infty} du' \frac{\text{Im}[G(u')]}{(u' - u)} \text{Sign}(u' - u) \quad (1)$$

where P denotes principal value, u is the chemical potential, and ω is the energy or frequency variable. If we define

$$F(u) = \text{Re}[G(u)]; \quad f(u) = \text{Im}[G(u)] \text{Sign}(u - u), \quad (2)$$

we can evaluate Eq. (1) by a famous subtraction trick,³ and the discretized version of the resulting integral becomes

$$F_i \equiv F(u_i) = \frac{1}{\pi} \sum_j W_j \left(\frac{f_j - f_i}{u_j - u_i} \right) + \frac{1}{\pi} W_i \left(\frac{df}{du} \right)_{u=u_i} \quad (3)$$

with W_i the quadrature weight corresponding to u_i . The last term in Eq. (3) is obtained by L'Hospital's rule and is not needed if the mesh (u_i) for $F(u)$ is totally distinct from the mesh (u_j) for $f(u)$. We have found that in order to obtain reasonable accuracy for the integral in Eq. (1), it is crucial to use discretizations that give an optimum distribution of mesh points in the regions which contribute most strongly to the integral. We will now summarize how to evaluate these integrals for the delta particle and pion Green's functions. The results also apply to auxiliary functions which comprise only part of the Green's function; e.g., its self energy or its width.

For the delta particle, the $\text{Im}[G(u)]$ is proportional to $\theta(u - u_\Delta)$ where $u_\Delta = u_N = 923 \text{ MeV}$ and θ is a step function. Then it can be shown that

the $\text{Re}[G(u)]$ can most efficiently be evaluated by the transformed equations

$$F(u_\Delta + sy) = \frac{1}{\pi} \int_0^\infty \frac{f(u_\Delta + sy^-)}{(y^- - y)} dy^-; \quad y < 0, \quad (4a)$$

and

$$F(u_\Delta + sy) = \frac{1}{\pi} \int_0^\infty dy^- \frac{[(y^- + y)f(u_\Delta + sy^-) - 2y f(u_\Delta + sy)]}{(y'^2 - y^2)}; \quad y \geq 0, \quad (4b)$$

and we have introduced a "scale factor" s to spread the mesh points in a prescribed fashion. In Eq. (4a), the point $u = u_\Delta + sy$ on the left-hand side is outside the range of integration on the right-hand side, and the principal-value integral reduces to an ordinary integral.

The pion Green's function is even; i.e., $G(u) = G(-u)$, and $u_\pi = 0$. The appropriate transformed dispersion relation for the pion is given by

$$F(uy) = F(-sy) = \frac{1}{\pi} \int_0^\infty dy^- \frac{[(y^- + y)f(sy^-) - 2y f(sy)]}{(y'^2 - y^2)} + \frac{1}{\pi} \int_0^\infty dy^- \frac{f(sy^-)}{(y^- + y)}, \quad (5)$$

and again a scale factor has been introduced.

In Eqs. (4) and (5), it is convenient to make the further transformation³

$$y^- = \tan \left[\frac{\pi}{4} (u+1) \right]; \quad -1 < u < +1, \quad (6)$$

with the resulting integrals evaluated by Gaussian-Legendre quadrature. Also, we have found that $s = 400$ MeV gives an optimum spreading of mesh points for both the delta particle and the pion. Then, with these meshes the real part can be evaluated to at least 4 or 5 significant-figure accuracy, using as few as 54 Gaussian-Legendre points.

A SIMPLE DERIVATION AND GENERALIZATION OF THE FOLDY-WOUTHUYSEN EXPANSION¹

Cheuk-Yin Wong Shun-Jin Wang²

In the presence of an external electromagnetic field represented by the four-potential A_μ , the Foldy-Wouthuysen expansion gives a non-relativistic approximation to the Hamiltonian for a fermion obeying the Dirac equation. This result is widely used and has been discussed in great detail in many textbooks. To obtain this result, the usual Foldy-Wouthuysen transformation can be carried out in a straightforward manner. The steps are, however, rather tedious, as it involves performing three successive transformations of successively greater complexity. On the other hand, it is well known that for a free particle, the Foldy-Wouthuysen expansion can be obtained from the Klein-Gordon equation. For the case of an external electromagnetic field we wish to study, the effective Klein-Gordon equation derived from the Dirac equation is well known. An alternative derivation of the Foldy-Wouthuysen expansion starting from the Klein-Gordon equation can be useful for pedagogical purposes, as a naive expansion using the effective Klein-Gordon equation indeed gives immediately most of the terms of the Foldy-Wouthuysen expansion. However, some of the high-order terms are missing. It will be of interest to understand why this occurs and to show how we can obtain the missing terms of the correct expansion. We have succeeded in giving a simple derivation and a generalization of the Foldy-Wouthuysen expansion which starts from the effective Klein-Gordon equation, and the results maintain the space-time symmetry of the electromagnetic potential. While the results give higher-order corrections involving the square of the timelike component of the electromagnetic potential, the derivation may also be useful for pedagogical purposes.

1. GTE Laboratories, Inc., Waltham, MA 02254.

2. Consultant from Northwestern State University, Natchitoches, LA 71457.

3. M. I. Haftel and F. Tabakin, Nucl. Phys. A 158, 1 (1970).

1. Summary of paper submitted for publication in American Journal of Physics.

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GROUP THEORY APPROACH TO SCATTERING IV. SOLVABLE POTENTIALS ASSOCIATED WITH $SO(2,2)$ ¹

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We use the potential group $SO(2,2)$ to realize a class of solvable potentials, Matansson potentials. The bound-state spectra and scattering matrices can be obtained by purely algebraic techniques.

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1. Abstract of paper: Ann. Phys. (N.Y.) 196, 163 (1989).
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THE POTENTIAL GROUP APPROACH AND HYPERGEOMETRIC DIFFERENTIAL EQUATIONS¹

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We propose a generalized realization of the potential groups $SO(2,1)$ and $SO(2,2)$ to describe the confluent hypergeometric and the hypergeometric equations, respectively. It implies that the classes of Schrödinger equations with solvable potentials whose analytical solutions are related to the confluent hypergeometric and the hypergeometric functions can be realized in terms of the above group structure.

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NUMERICAL METHOD FOR THE TIME EVOLUTION OF THE DIRAC EQUATION¹

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We propose an iterative procedure for the numerical evolution of the Dirac equation. It is a fast and stable version of the coordinate-space predictor-corrector method and can be extended to (3+1) dimensions for the relativistic mean-field calculation of heavy-ion collisions.

A detailed example is worked out for the case of positron production in (1+1) dimensions.

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HOMOENERGETIC OSCILLATING SOLUTIONS OF THE NONLINEAR BOLTZMANN EQUATION¹

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The nonlinear Boltzmann equation in the presence of external forces is considered. Exact inhomogeneous homoenergetic solutions are found by means of a nonisotropic generalization of Nikolskii's transform. In particular, an interesting oscillating behavior is obtained in the presence of an external time-independent force. For small values of the vorticity this oscillation becomes a sharp pulsation.

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GALILEAN INVARIANCE AND THE PERTURBED STATIONARY STATES EQUATIONS¹

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The Galilean invariance of the perturbed stationary states (PSS) equations is examined. It is shown that, contrary to widespread belief, the PSS equations are Galilean invariant and contain no ambiguities with respect to the electron coordinate origin. Misconceptions may have arisen from a mistaken generalization of the original PSS formulation.

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IONIZATION PROCESSES

STRONG-FIELD LASER IONIZATION OF ALKALI ATOMS USING 2D AND 3D TIME-DEPENDENT HARTREE-FOCK THEORY¹

M. S. Pindzola² G. J. Bottrell³
C. Bottcher

The time-dependent Schrödinger equation is solved directly for an alkali atom subject to an arbitrarily strong electromagnetic field. Two methods are compared. A tridiagonal finite difference method is used to solve Schrödinger's equation on a two-dimensional cylindrical coordinate lattice, while a finite element method employing odd-order B splines is used to solve Schrödinger's equation on a three-dimensional Cartesian coordinate lattice. Multiphoton ionization cross sections are extracted from the 2D calculations for hydrogen and lithium and then compared with previous perturbation theory results. Single photon ionization probabilities are compared from the 2D and 3D calculations for hydrogen.

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COUPLING EFFECTS FOR ELECTRON-IMPACT EXCITATION IN THE POTASSIUM ISOELECTRONIC SEQUENCE¹

M. S. Pindzola² D. C. Griffin³
C. Bottcher

Electron-impact excitation cross sections for outer-subshell transitions in Ca^+ , Sc^{2+} , Ti^{3+} , Cr^{5+} , and Fe^{7+} are calculated in the close-coupling and distorted-wave approximations. Coupling effects, beyond the first-order perturbation included in the distorted-wave approximation, are found to decrease rapidly as one moves to higher Z along the potassium isoelectronic sequence. Only for Fe^{7+} , however, are the close-coupling and distorted-wave results in

agreement to 10% or better for all the excitations studied.

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1. Abstract of paper: *Phys. Rev. A* 39, 2385 (1989).
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INDIRECT PROCESSES IN THE ELECTRON IMPACT IONIZATION OF ATOMIC IONS¹

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C. Bottcher

General theoretical methods for the calculation of indirect processes in the electron impact ionization of atomic ions are reviewed. Theory is compared with the results of recent crossed-beams experiments for several atomic ions.

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1. Abstract of paper: pp. 129-145 in *Electronic and Atomic Collisions* (Elsevier Science Publishers, 1988).
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CORRELATION ENHANCEMENT OF THE ELECTRON-IMPACT IONIZATION CROSS SECTION FOR EXCITED STATE He-LIKE IONS¹

M. S. Pindzola² D. C. Griffin³
C. Bottcher

The electron-impact ionization cross section is calculated in the distorted-wave approximation for the He-like ions Ar^{8+} , Ti^{12+} , Fe^{16+} , Zn^{20+} , and Se^{24+} . For ionization from the $2p^6$ ground state, the contributions from inner-shell excitation followed by autoionization are negligible. However, when these ions are initially in the $2p^53s$ excited configuration, contributions arising from the inner-shell excitations $2p^53s \rightarrow 2p^43sn\ell$ and $2p^53s \rightarrow 2s2p^53sn\ell$ are large. The overall branching ratio for autoionization of the $2p^43sn\ell$ and $2s2p^53sn\ell$ levels increases when the atomic structure calculations are extended beyond the single configuration approximation to include configuration interaction.

The resulting correlation enhancement of the excited state ionization cross section is found to increase as a function of Z . For Se^{2+} the correlation enhancement of the total ionization cross section is found to be 42%.

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ELECTRON CORRELATION IN THE CONTINUUM¹

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We consider a class of problems, notably double ionization, which require accurate descriptions of correlation in both the initial and final states. Methods are presented for representing correlated wavefunctions on a basis spline lattice, and for calculating bound-continuum transition probabilities.

1. Abstract of invited talk to be published in Proceedings of XVI International Conference on the Physics of Electronic Collisions, New York, July 26 - August 1, 1989.

TIME-DEPENDENT HARTREE-FOCK STUDIES OF ION-ATOM COLLISIONS

G. J. Bottrell¹ C. Bottcher

We have now completed studies on $p+H$ and $C^{6+} + \text{Ne}$ collisions using our three-dimensional TDHF codes. In the case of $p+H$, calculations have been made at two ion velocities, $v = 1$ and 2 atomic units, and in the case of $C^{6+} + \text{Ne}$ at one velocity $v = 6$. For each velocity and a range of impact parameters, we have extracted excitation and capture probabilities and secondary electron spectra in the target and projectile frames. Typical energy distributions are shown in Fig. 5.13. The $p+H$ runs at $v = 2$ show evidence of "ridge" electrons, trailing behind the projectile at a relative velocity $v_e = v/2$. We expect that a definitive picture will emerge when the angular distributions are plotted. It will be appreciated that the amount of data arising from all possible excitations of the

Fig. 5.13. Secondary electron energy distributions in projectile (P) and target (T) frames for a $p+H$ collision at $v = 1$. The curves refer to three impact parameters: top, $b = 0.5$, middle, $b = 2.5$, lowest, $b = 5.5$.

five active orbitals of $C^{6+} + \text{Ne}$ is rather large. Thus far, the results agree with intuition based on the geometry of the orbitals and the extent to which the electrons' velocities match that of the projectile.

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NEW SUM RULE FOR TOTAL "PARTICLE" PRODUCTION
(EXCITATION + EJECTION + TRANSFER)
IN COINCIDENCE WITH A HOLE
IN A SPECIFIC SHELL

R. L. Becker

A very great part of the work in collision theory goes into the development and use of methods¹ for calculating the transition amplitudes for single electrons. A related, important problem is the formulation of methods for handling collisions in which more electrons than one are active. Except for a small amount of work on the two-electron problem, almost the only available method is the independent particle model, sometimes supplemented by multiplet theory. It neglects correlations arising from residual interactions, but can and should contain the "Pauli correlations"² arising from the Fermi statistics. The resulting independent Fermi particle model³ (IFPM) has the advantages that it employs the single-electron transition amplitudes and that with it one can derive expressions for cross sections of inclusive processes. Almost all collision measurements are inclusive, i.e., they involve a sum over exclusive processes, because the measurement does not uniquely determine the final state. Another advantage of the IFPM is that it possesses a set of sum rules which can be used to rewrite expressions for inclusive processes in different forms and to simplify calculations.

Consider a basis of N spin-orbitals, k , and a system of $F < N$ electrons which initially occupy the set H of F "hole" states, h . The complementary set P contains the remaining $N-F$ initially unoccupied "particle" states, p . The single electron transition amplitude from k to k' is written $a_{k'k}$ and the corresponding element of the transition density matrix is

$$a_{k'k}^{(2)} = \sum_h a_{k'h}^* a_{kh}.$$

Its diagonal elements are the spin-orbital final inclusive occupation probabilities

$$\rho_k^k = a_{kk}^{(2)} = 1 - \rho_k, \quad (1)$$

where ρ_k is the inclusive probability of a final vacancy in state k . In general, we use superscripts for final occupancies and subscripts for final vacancies.

Corresponding to "singles" measurements are inclusive-single (i.s.) expectation values. That for finding a hole anywhere in the atom is

$$Q_H = \sum_h \rho_h$$

and that for finding one of the initially unoccupied states occupied after the collision is

$$Q^P = \sum_p \rho^p.$$

Equation (1) implies the trivial and easily interpreted sum rules

$$Q_H + Q^H = F, \quad Q_p + Q^P = N-F, \quad Q_T + Q^T = N,$$

where the total i.s. vacancy expectation value is $Q_T \equiv Q_H + Q_p$. The unitarity of the single-particle scattering matrix implies the sum rule

$$Q^T = F$$

and its corollaries

$$Q_T = N-F, \quad Q^P = Q_H, \quad \text{and} \quad Q_p = (N-F) - (F-Q^H).$$

The second of these says that the expectation value for i.s. "particle" production, i.e., the sum of direct ionization (I), excitation (E), and electron transfer (ET) equals that for i.s. "hole" production. This is obviously true for exclusively single particle and hole production. The equality for the i.s. processes reflects the fact that the contributions from reactions involving two or more electron transitions are counted in the same way in Q^P and in Q_H .

Now consider particle-hole coincidence measurements. The process can be accomplished with a single-electron transition (SET), with amplitude a_{ph} . Then

$$\text{SET } Q_h^P = \sum_p |a_{ph}|^2 = 1 - \sum_h |a_{hh}|^2 = \rho_h. \quad (2)$$

In the case of very weak interaction between projectile and target, so that the i.s. processes are dominated by the exclusively single component, one can use (2) to infer one of Q_h^I ,

Q_h^E , and Q_h^F from ρ_h and the other two. However, when the first Born approximation is not dominant, in particular when employing multiply charged projectiles, Eq. (2) is not the full value of Q_h^P ; the complete expression for inclusive single-particle, single-hole processes contains double electron transition (DET) terms.

The IFPM expression for ρ_h^P is

$$\rho_h^P = \rho^P \rho_h + \frac{1}{2} \{a_{p,h}^{(2)}\}^2, \quad (3)$$

a sum of direct and exchange terms. The expected value for direct ionization in coincidence with a specific hole therefore involves transition amplitudes to the many pseudo-states in the continuum. In re-expressing* this solely in terms of initially occupied states in order to simplify its calculation, some moderately involved algebraic manipulations were involved. The work is streamlined and additional insight is gained by recognizing that implicitly a new sum rule⁵ was involved. This can be expressed by the nontrivial result

$$\text{exch } Q_h^T = \rho_h^h \rho_h,$$

and hence

$$Q_h^T = F \rho_h. \quad (4)$$

The latter can be combined with straightforward results of using the complementarity relation

$$\rho_h = \rho_{h,k} + \rho_{h,k}^k, \quad k \neq h \quad (5)$$

namely

$$Q_h^P + Q_{p,h} = (N-F)\rho_h, \quad Q_h^H + Q_{H,h} = (F-1)\rho_h$$

where

$$Q_{H,h} \equiv \sum_{h' \neq h} \rho_{h'h},$$

to obtain a useful form of the sum rule,

$$Q_h^P = \rho_h + Q_{H,h}. \quad (6)$$

In addition to the SET term of Eq. (2), we have the DET term, expressed conveniently as $Q_{H,h}$.

The fact that $\rho_{h'h}$, which is contained in ρ_h (see Eq. (5)), appears in addition to ρ_h in Eq. (6) reflects the different countings of the

multiple-electron terms of Eq. (6). We can show that

$$Q_h^P = \sum_{j=1}^F j P_{h,p}^{p^j N-F-j} \quad (7a)$$

whereas

$$\rho_h = \sum_{j=1}^F P_{h,p}^{p^j N-F-j} \quad (7b)$$

in terms of "number-exclusive" particle-production contributions. It has been verified that

$$Q_{H,h} = \sum_{j=2}^F (j-1) P_{h,p}^{p^j N-F-j}, \quad (8)$$

which is consistent with Eqs. (6) and (7a,b).

The crucial aspect of Eq. (7a) is that it corresponds to the measurement: if j electrons make transitions into "particle" states, there are j ways in which the event can be detected by looking at a single electron. Thus, the event carries the weight factor j . But in ρ_h only the vacancy is detected so the event with j electrons in "particle" states is counted only once. On the righthand side of Eq. (8) one detects the hole and one of the j excited electrons; but one electron among the j corresponds to the hole so there are $j-1$ ways of verifying that there was a second hole.

Calculations are being made of the impact parameter-dependent expectation value, Eq. (6), for total particle production in coincidence with a hole in the K or L shell of Ne and Ar. Preliminary results for the case of a K hole in Ne, with He^{2+} and C^{6+} impact, are shown in Fig. 5.14. One sees that over a range of energies the enhancement factor (Total/Set) is >2 for He^{2+} and >5 for C^{6+} , because the inclusive double hole cross section, $\sigma_{H,h}$, is large.

The sum rule (6) is being used to evaluate direct ionization in coincidence with a hole. Additional sum rules are being derived and will be used to simplify the calculation of other coincidence cross sections.

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 4. R. L. Becker, Acta Physica Hungarica 65, Nos. 2-3 (1989), special issue in honor of D. Berényi, in press.
 5. R. L. Becker, Bull. Am. Phys. Soc. 34, 1365 (1989).

Fig. 5.14. Components of the cross section, reduced by Z_p^2 , for inclusive-single "particle" production in coincidence with inclusive-single K-shell hole production in He by He^{2+} and C^{6+} as a function of impact energy per nucleon. The curves are for $\text{SET } \sigma_K^p = \sigma_K$ (short dashed line), $\text{DET } \sigma_K^p = \sigma_{H,K}$ (long dash, short dash), and the total, σ_K^p (full lines). Values for He^{2+} impact are given by circles and for C^{6+} by triangles.

ENHANCEMENTS OF PARTICLE-HOLE COINCIDENCE CROSS SECTIONS OVER SINGLE-ELECTRON-TRANSITION VALUES

R. L. Becker

The best currently available general framework for handling atomic reactions in which more electrons than one are active is the independent

Fermi particle model (IFPM).¹ Because total "singles" measurements have been rather thoroughly investigated, attention has been turning toward cross sections differential in angle or energy, or spin selective, and toward coincidence cross sections. An early "doubles" experiment was that of Macdonald et al.² and Rødbro et al.³ in which electron transfer in coincidence with a hole in the K-shell was measured. Such a particle-hole excitation can be accomplished by a single-electron transition (SET) for which the h+p probability at a given value of the impact parameter is

$$\text{SET } \sigma_h^p = |a_{ph}|^2.$$

The data² for p, He^{2+} , and Li^{3+} on Ar, Ne, and C at energies above about 0.5 or 1.0 MeV/amu were rather closely approximated by values calculated using the SET expression.⁴ The experimentalists considered also the effect of a two-step mechanism, which I call a double-electron-transition (DET) term. Its contribution to the coincidence cross section is approximately $\sigma_K \delta$, where δ is the small-b probability for electron transfer from all but the K-shell. Their estimated values of δ were considerably larger than those which could be accommodated by the data. The IFPM gives the expression^{3,1}

$$\sigma_h^p = \text{dir } \sigma_h^p + \text{exch } \sigma_h^p$$

for the inclusive probability for the coincidence where, with $\sigma^p(\sigma_h)$ being the probability for occupancy of the state p (vacancy of h),

$$\text{dir } \sigma_h^p = \sigma_h \sigma^p$$

leads approximately to $\sigma_h \delta$ and the dominant SET term (referred to as SPM or SP in Refs. 4 and 5) is contained (approximately) in the absolute squared transition-density matrix element

$$\text{exch } \sigma_h^p = |a_{ph}^{(2)}|^2 = \left| \sum_h a_{ph}^* a_{hh} \right|^2,$$

in which the sum is over all initially occupied states. The paradox propounded in Refs. 2 and 3 was resolved by our finding that $\text{exch } \sigma_h^p = \text{SET } \sigma_h^p$

was negative and of magnitude comparable to $\text{dir } \rho_h^D$ over the energy range of the Macdonald experiments. Thus, $\text{DET } \sigma_h^D$ was small in comparison to its direct part. Since then, we have found that $\text{DET } \sigma_h^D$ increases in importance (see Fig. 5.15) at somewhat lower energies (0.1-0.3 MeV/amu on He)⁶ and with increasing projectile charge.⁷ Data at the lower energies and for more highly charged projectiles such as C^{6+} would provide a valuable test of the calculations.

A related, but apparently unmeasured, coincidence process is that for direct ionization in coincidence with a hole in a given shell. Without the measurement of the hole, one has the expectation value for inclusive single (i.s.) direct ionization (I)

$$Q^I = \sum_p \rho^D = \sum_p \sum_h |a_{ph}|^2.$$

Fig. 5.15. The enhancement factor ratio (SET+DET)/SET for inclusive single ionization or electron transfer in coincidence with a hole in the neon K-shell, versus impact energy per nucleon. Full curves are for $\text{He}^{2+} + \text{Ne}$ and dashed curves for C^{6+} .

which contains only SET terms. This suggests that the coincidence value Q_h^I should be the part of Q^I coming from h, namely

$$\text{SET } Q_h^I = \sum_{p \in I} |a_{ph}|^2 = \rho_h - \text{SET } Q_h^E - \text{SET } Q_h^{\bar{E}}$$

where E stands for excitation and $\bar{E}$ for electron transfer. The assumption that $\sigma_h^I + \sigma_h^E + \sigma_h^{\bar{E}}$ equals σ_h is sometimes made by experimentalists and by theorists to infer one of these cross sections from a knowledge of the other three. The assumption is correct only for the case of weak interaction. Otherwise, especially for highly stripped projectiles, there are DET terms which enhance the coincidence cross section.⁷ From a new sum rule implicit in Ref. 7 (with $P = I + E + \bar{E}$, all "particle" states), namely,

$$Q_h^P \equiv Q_h^I + Q_h^E + Q_h^{\bar{E}} = \rho_h + Q_{H,h}, \quad (1)$$

where

$$Q_{H,h} \equiv \sum_{h'(\neq h)} \rho_{h',h}$$

is the expected value for two holes, one of which is h, we see that total "particle" production in coincidence with a hole in h is greater than ρ_h , the inclusive probability of creating one hole, for the reasons given in Ref. 8. Equation (1) has been used to calculate Q_h^I and hence, by integrating over the impact parameter, σ_h^I , solely in terms of bound spin orbitals.

Figure 5.16 gives preliminary results of coupled-channels calculations for the SET and DET contributions to σ_K^I in neon. Below 1.4 MeV/amu $\text{DET} > \text{SET}$ even for He^{2+} impact. The DET term is much greater relative to SET for direct ionization than for electron transfer. This is clear in Fig. 5.15, which gives the enhancement factor (SET+DET)/SET for both processes. For C^{6+} the enhancement factor is greater than ten over the energy range 0.2 to 1.7 MeV/amu. The I-h coincidence is rather similar to multiple L-shell vacancy production in coincidence with a K-shell hole (as seen in K X-ray or Auger satellites) in that the direct-DET term of the IFPM

Fig. 5.16. Contributions to σ_K^I/Z_p^2 , the inclusive cross section scaled by Z_p^2 for single direct ionization in coincidence with a K-shell hole in neon, versus the impact energy per atomic mass unit. Circles and triangles label He^{2+} and C^{6+} , respectively. Short dashed curves give the SET part, long dash-short dash lines are for the DET part, and full lines represent the total.

dominates the exchange term (but for different reasons). The determination of the energy dependence for C^{6+} will be completed, and calculations are planned for K and L holes in argon.

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CAPTURE PROCESSES

ELECTRON CAPTURE AND ENERGY-GAIN SPECTROSCOPY¹

K. Taulbjerg²

The applicability of translation energy spectroscopy as a tool to determine individual reaction cross sections in atomic collisions is analyzed with special emphasis on the electron capture process in highly charged ion collisions. A condition is derived to separate between higher collision energies where translation energy spectroscopy is problem-free and lower energies where strong overlap of individual spectra features prohibits an analysis of the total translation energy spectrum by means of a simple deconvolution procedure.

1. Abstract of paper to be published in Proceedings of Sixteenth International Conference on the Physics of Electronic and Atomic Collisions, New York, NY, July 26 - August 1, 1989.

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COUPLED-CHANNEL CALCULATIONS OF PARTIAL CAPTURE CROSS SECTIONS IN MULTIPLY CHARGED ION COLLISIONS WITH HYDROGEN¹

J. P. Hansen² K. Taulbjerg³

Partial cross sections for electron capture in 1 to 50 keV collisions of Ar^{+6} and Ar^{+8} with atomic hydrogen have been calculated using an atomic expansion including two complete principal shells of final states ($n = 4, 5$ for Ar^{+6} and $n = 5, 6$ for Ar^{+8}). The qualitative structure of the results is in good accord with a reaction window picture. The results for Ar^{+6} ions are in agreement with published experimental data when precaution is made with respect to uncertainties in absolute normalization of the data and with respect to a proper analysis of translation energy spectra at lower impact energies.

The limited experimental data for Ar^{+8} do not agree with the present results.

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COMMENT ON OBSERVATION OF ELECTRON CAPTURE INTO CONTINUUM STATES OF NEUTRAL ATOMS¹

R. O. Barrachina² J. H. Macek³

A model of electron capture to the continuum of neutral projectiles in atom-atom collisions is developed. It is shown that the presence of a virtual state lying very close to the threshold of a metastable state of the projectile can produce a sharp peak in the electron spectrum. Recent experimental observations in He-He and He-Ar collisions are explained on the basis of this theory.

1. Abstract of paper submitted for publication in Physical Review Letters.
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ION-ATOM SCATTERING

THEORY OF EMISSION-ANGLE-DEPENDENT AUGER TRANSITIONS IN ION-ATOM COLLISIONS¹

R. O. Barrachina² J. H. Macek³

By means of a continuum distorted-wave approximation of the postcollision state we derive an analytical equation for the Auger emission amplitude in ion-atom collisions. This theory includes previous models as particular cases. We show further that the presence of the projectile strongly affects the intensity profile, giving rise to a dependence on the emission angle that is missed in previous theories.

In particular, a sharp enhancement in the forward direction is computed.

1. Abstract of paper: J. Phys. B: At. Mol. Opt. Phys. 22, 2151 (1989).
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PERTURBATION THEORY FOR STRONGLY INTERACTING ATOMIC SYSTEMS¹

K. Taulbjerg² R. O. Barrachina³
J. H. Macek⁴

The strong potential Born (SPB) approximation has been formulated to include effects of elastic scattering in initial and final states. We use the standard distorted-wave theory and the eikonal approximation to derive closed-form expressions for scattering wavefunctions. Our results show that lowest-order theories must account for off-energy-shell electron propagation in the strong potential as well as for elastic scattering in initial and final states. Capture from inner shells and radiative electron capture are computed to illustrate the theory.

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STRONG POTENTIAL WAVE FUNCTIONS WITH ELASTIC CHANNEL DISTORTION¹

J. Macek² K. Taulbjerg³

The strong potential Born (SPB) approximation is analyzed in a channel distorted-wave approach. Channel-distorted SPB wave functions are reduced to a conventional form in which the standard off-energy-shell factor g has been replaced by a modified factor γ , which represents

a suitable average of g over the momentum distribution of the distorted-channel function. The modified factor is evaluated in a physically realistic model for the distortion potential, and it is found that γ is well represented by a slowly varying phase factor. The channel-distorted SPB approximation is accordingly identical to the impulse approximation if the phase variation of γ can be ignored. This is generally the case in applications to radiative electron capture and to a good approximation for ordinary capture at not-too-small velocities.

1. Abstract of paper: Phys. Rev. A 39, 6064 (1989).

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OTHER PHYSICS

INTERACTION OF A NEUTRAL COMPOSITE PARTICLE WITH A STRONG COULOMB FIELD¹

Cheuk-Yin Wong

The interaction between a neutral particle and an external electromagnetic field depends on the structure of the particle. A neutral elementary particle without charged constituents will hardly interact with an external electromagnetic field. The large value of the magnetic moment of a neutron, which measures the response of the neutron to an external magnetic field, is a consequence of the composite nature of the neutron. Likewise, the polarization potential of a neutral particle with charged constituents due to an external Coulomb field is well known. An interesting question arises whether there can be additional higher-order interaction terms which are small for weak Coulomb fields but become important in a strong Coulomb field. This question is of interest in view of the possible production of neutral particles in a strong Coulomb field in recent experiments at GSI during the bombardment of very heavy projectiles on very heavy targets near the Coulomb

barrier. We study the single-particle states of an (e^+e^-) composite particle in the strong Coulomb potential V of a superheavy nucleus. We find that the neutral composite particle consisting of a positive and a negative constituent is subject to an effective attractive interaction proportional to the square of the Coulomb potential. Such an attractive interaction may lead to the spontaneous production of a quasi-bound (e^+e^-) composite particle in a strong Coulomb field.

1. Summary of published paper: Prog. Theo. Phys. 81, 23 (1989).

FURTHER PROGRESS WITH A COVARIANT ELECTRODYNAMIC TWO-FERMION EQUATION FROM CONSTRAINT DYNAMICS

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P. van Alstine²

Constraint dynamics leads to two compatible, coupled, two-particle, Dirac equations containing an effective interaction, Φ , which we call the constraint potential. Φ may be regarded as a generalization of the Todorov quasipotential, to which it reduces for sufficiently weak interactions. In previous work³ manipulation of the two sixteen-component Dirac equations led to a single second-order, spin-dependent equation. In the Dirac representation of the gamma matrices, the four four-component pieces of the wave function, $\psi_{\pm\pm}$, where $\pm$ indicates the sign of the unperturbed Dirac energy of each particle, are uncoupled. When applied to the case in which the constraint potential corresponds to electro-dynamical one-photon exchange, this equation led⁴ to a weak overcriticality⁵ in the 3P_0 states, which are those for which the spin-dependent interactions are the most singular. This prompted consideration of the possible condensation of e^+e^- pairs in a 3P_0 state during collisions of very heavy ions.⁶

Recent re-examination of the derivation of the second-order equation, sparked by a comment by H. Sazdjian, has revealed a subtle error. For the 3P_0 states, the difficulty has been

overcome by use of a slightly modified procedure. For the uncoupled 3P_0 states, the second-order equation containing the constraint potential corresponding to one-photon exchange is no longer overcritical. A confirmation of this result has also been obtained in the chiral representation of the Dirac gamma matrices, which had been used earlier to give a closed-form solution of the second-order equation for singlet states.⁷ Our numerical calculations in the Dirac representation show that the constraint potential is not sufficiently strong, even in the 3P_0 states, to exhibit a resonance in the e^+e^- system. The effective interaction, including the centrifugal term, behaves predominantly as $-\alpha^2/r^2$ (where α is the fine structure constant) at short distances, as $l(l+1)/r^2$ at intermediate distances, and as $-\alpha/r$ at large distances.

Present efforts are concentrated on solving the second-order equation for coupled states, beginning with the 3S_1 - 3D_1 states, and in re-writing the equation in Breit-Kemmer form.

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VACUUM OSCILLATIONS AROUND A LARGE-Z "NUCLEUS"¹

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A possible explanation of sharp e^+ peaks in heavy-ion collisions by analyzing QED with a large atomic number external source is investigated. A highly polarized vacuum around a large Z "nucleus", having at least two neutral oscillation modes whose energies are calculated to be 1.8 MeV and 1.5 MeV with an appropriate choice of the nuclear radius, is shown. They decay into a pair of $e^\pm$ through electromagnetic interactions.

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1. Abstract of paper to be published in Proceedings of Gross Properties of Nuclei and Nuclear Excitations International Workshop XVII, Hirschegg, Kleinwalsertal, Austria, January 16-21, 1989.
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6. LASER AND ELECTRO-OPTICS LAB

The plasma diagnostics development program focuses on the development of advanced diagnostic systems for existing and future magnetic fusion experiments, relying primarily on optical and laser technology. The Laser and Electro-Optics Lab (LEOL) encompasses these activities and makes this technology available to other ORNL programs. The current emphasis is on the application of infrared and far-infrared lasers to the diagnostics of the next generation of ignited fusion reactors. Small-angle Thomson scattering of pulsed CO₂-laser radiation is being developed as a diagnostic for energetic alpha particles produced by the D-T fusion reaction. A high-resolution multichannel interferometer system has been developed for the measurement of electron density profiles in the Advanced Toroidal Facility (ATF) in the ORNL Fusion Energy Division. An innovative optics design has been incorporated in the interferometer system to reduce the required number of optical components by an order of magnitude compared to other existing multichannel interferometers on other plasma experiments. An infrared laser interferometer/polarimeter system, operating at 10.6 and 28 μm , has been proposed for the Compact Ignition Tokamak (CIT) and a prototype 28- μm laser has been constructed and tested for this program. Another LEOL activity includes measurements of damage to optical components produced by intense laser irradiation. This work formed part of the ORNL program in support of the Strategic Defense Initiative. Finally, with support from the ORNL Laboratory Director's Discretionary Fund, experiments were performed in response to the report of "cold fusion" in electrolytic cells using palladium cathodes and heavy water. Initial measurements have indicated anomalous energy balance in one of four experiments and investigations are continuing to determine the source of this effect.

SMALL-ANGLE CO₂ LASER THOMSON SCATTERING DIAGNOSTIC FOR D-T FUSION PRODUCT ALPHA PARTICLES

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D. P. Hutchinson H. T. Hunter
K. L. Vander Sluis

The D-T fusion reaction produces alpha particles at 3.5 MeV. For a fusion reactor to maintain ignition, these alpha particles must deposit this energy in the plasma fuel. Because of this critical importance, the dynamics of alpha particle heating is the main physics goal of the next generation of fusion reactors.⁵ To study the behavior of alpha particles in a plasma as they lose energy and produce a distribution characteristic of this energy loss, we have proposed a Thomson scattering diagnostic.⁶ With a scattering source at the CO₂ laser wavelength (10.6 μm), the background from electron scattering requires that small angle ($\sim 1^\circ$) detection be used to monitor the alpha particle distribution.

As a measure of this diagnostic capability in detecting scattered signals at these small scattering angles, a proof-of-principle test is

currently in progress on a nonburning plasma in the Advanced Toroidal Facility (ATF). The goal is to measure a scattered signal (in this case a low-level electron signal) at angles around 1° . Installation of the major hardware components at the ATF facility has been completed and preliminary tests have been conducted using the extremely sensitive heterodyne receivers.

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MULTICHANNEL FAR-INFRARED INTERFEROMETER AND SCATTERING SYSTEM FOR THE ADVANCED TOROIDAL FACILITY

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K. L. Vander Sluis

During the past year, a multichannel far-infrared (FIR) interferometer system has been

fully installed on ATF to measure the line-integrated electron density along 15 vertical chords on the $\phi = 0$ plane of the ATF plasma. The system is a modification of the FIR interferometer system that was used on the ISX-B tokamak.³ However, instead of using separate probing beams, a phase image technique⁴ is used to improve the spatial resolution of the measurement. A schematic diagram of the interferometer system is shown in Fig. 6.1. Briefly, the system employs a pair of cw 214- μm difluoromethane (CH_2F_2) lasers, optically pumped by separate CO_2 lasers. The FIR cavities are tuned such that the two oscillate at frequencies differing by Δf of the order of 2 MHz. As shown in the figure, cylindrical parabolic mirrors are used to create a slablike 2 cm $\times$ 45 cm probing beam. The beam is transmitted through almost the whole cross section of the plasma. After passing through the plasma, the probing beam is dissected at the focal plane of the optics system by an array of 15 off-axis paraboloid reflectors, each of which illuminates a single Schottky-diode detector. Part of the beam from the reference laser is mixed first in a reference detector with a portion of the probing laser beam, which is split off before passing through the beam expansion optics. The

remainder of the reference beam is also expanded and is guided to the signal detectors to mix with the probing beam. The detector signals are filtered, amplified, and fed into a digital phase detection circuit to extract the phase shift between the output of the signal detector and the reference signal, which is proportional to the line-integrated electron density. The outputs of the phase detectors are displayed on oscilloscopes for photographic recording and are digitized for computer storage and processing. A plasma density measurement has been made successfully along one chord of the system. The multichannel system is being tested.

A study has also been carried out to determine the optimum design of a FIR scattering system for the measurements of spatial and temporal electron density fluctuations in ATF plasma. The proposed system may be operated at wavelengths from 447 μm to 119 μm . Lasers operated at these wavelengths have been designed, constructed, and tested. Output power levels from 100 to 500 mW have been achieved. A pair of crystal quartz windows, 38 mm $\times$ 300 mm, located adjacent to the multichannel FIR interferometer windows will allow scattering angles of $\pm 15^\circ$ from the incident beam. A single FIR laser beam will be split to provide both the scattering beam and local oscillator beam in a 3- to 5-channel detector array. The detector is designed to observe scattering from a single point at 3 to 5 different angles or from several points at the same angle. Storage of the scattered signals will be accomplished by a PC-based CAMAC data acquisition system.

Fig. 6.1. Schematic of the 15-channel FIR interferometer system on ATF.

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FEASIBILITY STUDIES OF A TWO-COLOR INTERFEROMETER/POLARIMETER FOR THE COMPACT IGNITION TOKAMAK

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Feasibility studies of a two-color infrared interferometer/polarimeter system for measurements of electron density and plasma current profiles in the Compact Ignition Tokamak (CIT) were continued. During the past year, the proposed 28- μm system was investigated both theoretically and experimentally. A prototype water-vapor laser was successfully designed, constructed, and tested. The maximum output power of 30 mW was achieved at a wavelength of 27.972 μm . A photograph of the laser is shown in Fig. 6.2. The laser is of waveguide type and is operated in the TEM_{00} mode. The total length of the laser tube is 2 m and the inside diameter of the tube is 0.9 cm. A cooling jacket is provided outside the tube for ethylene glycol cooling at 5°C. Two cathodes are located at the center of the tube and the anodes are at either end. The distance between the anode and the cathodes is approximately 74 cm. The laser operates with the ends at ground potential and

only the center section at high voltage. This configuration makes high voltage shielding easier and removes the electrical hazard from the regions where the operator works. The semi-confocal resonator is formed by a flat mirror and a concave mirror with radius of curvature of 3 m. The concave mirror is mounted in a piezo-electric translator. The concave mirror has a 0.75-mm-diam coupling hole at the center. The position of the flat mirror can be adjusted manually by a micrometer. The mirror mounts and the tube supports are connected by invar rods for temperature stability. A KRS-5 window is used to transmit both the 28- μm beam and the He-Ne laser beam for alignment. Water vapor in the water reservoir and gas additive are continuously pumped out through the Pyrex glass tube. The flow rate and the pressure are controlled by needle valves. A typical cavity detuning curve obtained by changing the piezo-electric voltage is shown in Fig. 6.3. The operating conditions are: the water vapor pressure of 1.5 torr, He pressure of 0.5 torr, H_2 pressure of 0.5 torr, and discharge current of 250 mA. Figure 6.4 illustrates the dependence

Fig. 6.2. Photograph of the cw 28 μm water vapor laser.

Fig. 6.3. Output power of the water vapor laser versus the piezoelectric voltage under the operating conditions: the water vapor pressure of 1.5 torr, He pressure of 0.5 torr, H_2 pressure of 0.5 torr, and discharge current of 250 mA.

Fig. 6.4. Output power of the water vapor laser versus the discharge current under the operating conditions: the water vapor pressure of 1.5 torr, He pressure of 0.5 torr, and H_2 pressure of 0.5 torr.

of the output power as the discharge current is varied.

The feasibility of a 28- μm polarimeter using both the electro-optic and photoelastic polarization-modulation techniques was investigated. A cadmium telluride (CdTe) crystal is utilized in the electro-optic polarization modulator. The electro-optic modulation technique has an important advantage over the photoelastic technique in fast time response. A modulation frequency of 1 MHz can be easily achieved. The drawback of electro-optic modulation is the high loss in beam transmission. Even with perfect antireflective coating, the transmission of the 28- μm laser beam through a 3 cm-long CdTe crystal is only 19%. On the other hand, the photoelastic modulation technique offers the advantage of high beam transmission. But the time response is limited by the natural standing wave frequency of the crystal. A rectangular silicon bar is used in the photoelastic modulator. The silicon bar vibrates at its lowest frequency of standing compression waves; thus a time-varying birefringence is obtained. In order to sustain these vibrations in the bar, the bar is bonded to a quartz transducer tuned to the same frequency. The amplitude of the vibrations and therefore the magnitude of the

birefringence is controlled by the signal generator driving the transducer. The transmission of the water-vapor laser beam through a 1-cm-long silicon bar has been measured. A transmission of 45% is observed without any antireflective coating. With perfect coating, transmission of 92% is expected. For a $5 \times 5 \times 1$ -cm silicon bar, the modulation frequency is approximately 42 KHz.

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OPTICS DAMAGE AND IRRADIATION STUDIES (ODIS)

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D. F. Hutchinson

Optics Damage and Irradiation Studies (ODIS) have as their main goal the screening of high quality infrared mirrors, windows, and coatings in support of the Advanced Optical Materials and Components Technology Development Program at Martin Marietta Energy Systems, Inc.

Initiated in 1985, the screening was performed by irradiating window samples with micro-second bursts of fast neutrons from the Health Physics Research Reactor (HPRR) facility at ORNL. Transmission effects at three different laser wavelengths were recorded during and after the irradiations.

Currently, the work effort has shifted to pulsed CO_2 laser damage of both infrared mirrors and windows. For the last two years, ODIS has been measuring the Laser Induced Damage Thresholds (LIDT) of these optics and their coatings to screen samples for improving manufacturing techniques and developing new coatings that have high infrared transmission or reflectance. This work is sponsored by the U. S. Army Strategic Defense Command (USASDC).

To date many types of mirrors, windows, and other optical materials have been successfully tested for their damage threshold. The equipment allows for selecting different CO_2 laser pulse widths and spot sizes from approximately

1 mm² and 30 ns to 10 mm² and 100 ns. Further sample analysis is provided by other groups at ORNL both before and after ODIS damage testing.

All the test samples are carefully cleaned prior to damage testing and all damage tests are conducted in high vacuum. Our capabilities allow for testing all sizes and shapes of test samples from 5 mm² to 8-in.-diam optics. A helium-neon laser illuminates the target site on the test optic and the scattered radiation is collected. Damage of an optic surface, after a pulsed CO₂ laser shot, will be indicated by a change in scattered signal from the helium neon laser. A schematic of the ODIS facility is shown in Fig. 6.5.

Fig. 6.5. Schematic of Optics Damage and Irradiation Studies facility.

Currently, we are capable of damage testing up to ten optics per day with the ability to scan over the surface of a test optic for multiple LIDT measurements. Work is performed under a contract with USASDC.

CALORIMETRY EXPERIMENTS IN THE PHYSICS DIVISION OF ORNL

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Introduction

Immediately following the announcement by Fleischmann and Pons at the University of Utah of the discovery of cold fusion in an electrolysis cell containing a palladium cathode, several experiments were begun to investigate this claim.³ A number of electrolysis cells were constructed using palladium foil cathodes and platinum gauze anodes in an attempt to measure cold-fusion-produced neutrons. A neutron counter was assembled using NE213 scintillator detectors, which employed pulse shape discrimination to reduce the effective gamma-ray background. The background count rate of this detector was approximately 90 events per hour. Another detector located near the primary system was used to monitor any changes in the background level. No neutrons above the background rate were detected during these initial experiments. We then focused our attention on the observation of excess heat which was also reported by the University of Utah group.

Experimental Apparatus

Four calorimetry cells were constructed with an electrolyte volume of 300 cc in a 54-mm-o.d. quartz envelope. Each cell contained a Teflon plug in the top of the container with a number of penetrations for electrical connections, heavy water refilling, and sampling. Two 6.35-mm Teflon rods projected through the top plug to support the palladium cathode rod in the center of the envelope. The Teflon rods were spring loaded to allow for expansion of the palladium electrode during charging with deuterium. The anode was helically wound from platinum wire on the inside of a perforated quartz tube. The anode helix was wound on a mandrel and allowed to spring against the inside of the quartz tube for support. No internal recombiner was used to catalyze the recombination of the gases produced by electrolysis back into heavy

1. Fusion Energy Division, ORNL.

water. The D_2 and O_2 gases were allowed to escape through a vent hole in the top Teflon plug. The quartz cells were placed inside Teflon cylinders that in turn were immersed in a temperature-controlled water bath. A 2.5-mm gap between the quartz and the Teflon cylinder was filled with D_2O and contained a platinum resistance temperature detector (RTD). Another platinum RTD was placed in the water bath adjacent to the Teflon socket. A cell containing a resistance heater, similar in size to the palladium cathode and identical in construction to the actual cells, was placed into each Teflon socket, prior to activation of the cells, for calibration. Varying amounts of electrical power were applied to the resistance heater and the temperature difference across the Teflon was noted for each setting. The calibration data were fitted with a fourth order polynomial for use with the cell calorimetry data. The second order term was very small, and the third and fourth order terms nearly zero. The cells were periodically recalibrated during the course of the experiments and specifically when the bath temperature was altered. A shielded neutron counting chamber was prepared next to the cooling baths to permit neutron counting of the cells during operation without interruption of the electrolysis.

Electrode Preparation

Two of the cells contained 6.35-mm-diam $\times$ 10-cm-long palladium annealed cathodes, one of which was precharged in D_2 gas to a stoichiometry of 0.6, in a 0.2-M $LiOD$ electrolyte. One cell contained a precharged annealed cathode in a 0.1-M $LiOD$ electrolyte solution; and one used a cast 1.27-cm-diam $\times$ 10-cm palladium rod in a 0.2-M electrolyte. Annealing was performed by heating the rods to a temperature of $900^\circ C$ for four hours in vacuum. The cast 1.27-cm-diam rod and the 6.35-mm-diam nonprecharged rod were baked at $200^\circ C$ in vacuum for 24 hours to remove any residual protium before being placed in operation. The experimental parameters for the palladium cathodes are summarized in Table 6.1. The three 6.35-mm-o.d. rods were purchased from

Table 6.1. Experimental parameters

Cell No.	Electrode Configuration	Electrolyte Concentration	Electrode Conditioning
0	6.35 mm diam	0.2 M $LiOD$	Annealed
1	6.35 mm diam	0.2 M $LiOD$	Annealed/ pre-charged/ arsenic added
2	6.35 mm diam	0.1 M $LiOD$	Annealed/ pre-charged
3	12.7 mm diam	0.2 M $LiOD$	Cast

Note:

1. All rods were 100-mm long.
2. The 12.7-mm-diam rod was dropped cast in a chilled copper mold. The rod was x-rayed to identify any possible voids.
3. All rods were heated in vacuum to remove residual protium.
4. Current density = 250 mA/cm^2 .

Johnson-Matthey. The cast rod was fabricated from stocks of palladium obtained at ORNL.

Results

The cells were operated at an initial current density of 50 mA/cm^2 for 48 hours and then at a current density of 250 mA/cm^2 for over 1800 hours. Referring to the cell numbering from Table 6.1, cells #1, #2, and #3 have remained in power balance within an experimental uncertainty of $\pm 1 \text{ W}$ for the duration of the experiments. However, cell #0 exhibited an apparent excess power level of approximately 3 W for a 300-hour period, beginning 180 hours after the start of the experiment. This power level was approximately 10% of the input power. Our calorimetry cells did not use an internal catalyst to promote the recombination of the electrolyzed gases back into heavy water. D_2O was added to the cells every twelve hours to replace the water depleted by electrolysis. By carefully recording the water usage rate, we were able to determine that no recombination was occurring in the cells.

The power balance for our cells was determined from the equation

$$P_{\text{imbalance}} = \text{heat output} + \text{electrolysis} - \text{electrical input}$$

The heat output of the cells was measured by the calibrated platinum RTDs. The electrolysis term was determined by measuring the make-up water for the cells assuming the exhaust gases were 100% humidified. The electrical input was determined by monitoring the voltage and current going to the cells. The electrolysis cells were driven by computer-controlled constant-current sources and the voltages across the electrodes were monitored by a digital-to-analog converter in the control computer. The constant-current power supplies were calibrated prior to the experiment. At an operating current density of 250 mA/cm², the total current to the 6.35-mm-diam rod cathodes was 5.03 amps. At this current, 1.88 grams of D₂O was electrolyzed per hour of operation, resulting in a volumetric water usage rate of 1.702 cc/hour. Using the value of 70.41 kcal/mole for the heat of formation of heavy water, this electrolysis rate results in 7.68 W of power consumption. Assuming that the exhaust gases have a relative humidity of 100%, the total water consumption rate was calculated to be 1.88 cc/h, corresponding to a total electrolysis power level of 7.77 W, including power due to evaporation. The consumption of D₂O was monitored over the entire course of the experiment. The average measured value of 1.87 cc/hour is in excellent agreement with the predicted value of 1.88 cc/hour. Using this result, the heat balance equation becomes

$$P_{\text{imbalance}} = \text{heat} + 7.77 \text{ W} - V_{\text{cell}} \cdot I_{\text{cell}}.$$

In addition to control of the power supplies and constant monitoring of the cell parameters, the control computer was programmed to sweep the cell current once each hour. The duration of each current sweep was 5 seconds. The slope of the I-V curve is the electrolyte resistance.⁴ By multiplying the square of the cell current by this quantity, the total power deposited in the electrolyte may be determined. Cell #0 remained in balance until the 180-hour mark when a positive imbalance of 2 W was observed. Twelve hours after this excess heat event began, the temperature of the water bath was inadvertently changed from an initial value of 18°C to 13°C.

The ohmic power increased at this point due to the increased electrolyte resistance at the lower temperature. The input power also increased with the increased electrolyte resistance because the cells were driven by constant current sources. The calorimeter output also increased with the lower temperature and maintained the 2-W excess. The input and ohmic power levels exhibited a sawtooth behavior because of the changing level of liquid in the cell, due to electrolysis and the periodic refilling twice a day. As the liquid level decreases, the heat transfer area changes and the electrolyte resistance decreases as the molality increases. Although the effect of these changes is not accurately known, for our evaluation, we use only data taken at the peaks of the sawtooth, where we know the calibration is accurate. The imbalance increased slightly until the 370-hour mark, when the temperature of the bath was deliberately raised to 18°C. The excess power nearly disappeared but recovered and increased over the next 120 hours to slightly over 3 W. At approximately 480 hours the cell bath temperature was lowered to 5°C in an attempt to study the effect of temperature changes on the imbalance. The indication of excess power disappeared at this point; and repeated temperature and current cycling failed to restore the effect. We continued the experiment for a total period of 1800 hours with no observed recurrence of the excess heat. The other cells remained in accurate power balance during the entire experimental period. During the period of heat imbalance in cell #0, cells #0 and #1 were switched in their calorimeter sockets to verify that the apparatus was working properly. The power readings for each cell during this period were consistent with the calibrations for both cells. The imbalance in cell #0 remained, irrespective of the calorimeter socket used.

Additional Measurements

Shortly after the power imbalance was observed in cell #0, it was removed from the calorimetry socket and placed in a shielded

neutron counter containing a pair of NE213 scintillator detectors with pulse shape discrimination. The neutron emission level of the cell was determined to be less than 1×10^{-24} neutrons/sec/d-d pair, set by the background level of the counting system. The tritium level of the initial electrolyte fill of D_2O was measured to be 10^6 dpm/cc, and increased to a level of 1.3×10^6 dpm/cc 50 hours after the beginning of the excess power production. The accuracy of the tritium measurement was at best 10%; and, because of this uncertainty, we draw no conclusions from this increase.

Follow-up experiments using improved calorimeters and electrolysis cells are being

planned to establish unequivocally whether or not excess heat is being produced, and, if so, to determine the mechanism(s) responsible for its production.

1. On sabbatical from University of North Carolina, Asheville.

2. Fusion Energy Division, ORNL.

3. M. Fleischmann and S. Pons, J. Electroanal. Chem. 261, 301-8 (1989).

4. J. S. Bullock, IV, G. L. Powell, and D. P. Hutchinson, Electrochemical Factors in Cold Fusion Experiments, TM Y/DZ-490, visuals prepared for Workshop on Cold Fusion Phenomena, Santa Fe, New Mexico, May 23-25, 1989, Martin Marietta Energy Systems, Inc., Oak Ridge Y-12 Plant, May 1989.

7. HIGH ENERGY PHYSICS

H. O. Cohn

A paper was published¹ on particle production by 200-GeV/c hadrons on gold, silver, and magnesium. The data derived from the Fermilab 30-in. bubble-chamber hybrid spectrometer where the bubble chamber was fitted with plates of gold, silver, and magnesium, and was exposed to beams of positively charged pions, kaons, and protons with momenta of 200 GeV/c. The work was done by the hybrid spectrometer collaboration, consisting of fifteen different institutions. It was found that the multiplicities of produced particles and negative particles increase linearly with the number of projectile collisions, with no beam or target dependence. The number of secondary collisions in the nucleus increases significantly less rapidly with the number of projectile collisions than has been reported by a streamer chamber experiment.² The properties of secondary collisions suggest that they arise from rescattering of recoil nucleons rather than intranuclear cascade of produced particles. Dispersions of multiplicity distributions at fixed impact parameter are in better agreement with a model of independent sources than with Koba-Nielson-Olesen scaling.

In a second experiment at Fermilab (E-745), a study of high-energy neutrino interactions in the Tohoku bubble chamber,³ data were obtained with two independent optical systems. Three normal stereo views were recorded, as well as two holographic images. The holographic photography was undertaken to improve the optical resolution, which was limited for the conventional photography due to the extreme 1.4-meter depth of the chamber. For the normal photography, two sets of high resolution lenses, specifically manufactured by the Nikon lens company, were used for each stereo view in order to attain acceptable focus over the full depth with an F-stop of $f/12$. This system achieved

a resolution of about 300 microns. Holography on 70-mm film can potentially improve this resolution by an order of magnitude. Indeed, for the best conditions, a resolution of about 50 microns was achieved. To take advantage of this improved resolution, the holographic photographs were taken 200 μ s after the trigger signal, corresponding to a bubble size of 50 microns for the chamber operation conditions.

All events that were found during the scanning process of the normal film, and that were measured, were searched for on the holographic film. Holograms were taken only when a trigger, supplied by upstream and downstream hodoscope arrays, indicated that an interaction had occurred. Untriggered random events would likely miss the time slot where the hologram would be observable, therefore not every event found through the normal film scan had corresponding hologram. In addition, some holograms were not available for reasons ranging from a malfunction of the laser system to triggers by an interaction not associated with the desired event. Further, the intensity of the laser light varied over the full 1150-liter volume of the chamber and some light masking was necessitated by optical considerations; thus, at times, tracks from an event were visible on the holographic reconstruction while the vertex of the event could not be seen.

Forty-seven rolls of film were analyzed at ORNL and at the University of Tennessee. In the normal optics film, we found 4073 events of which three quarters were triggered by an external counter system. Due to fiducial volume cuts and other rejections, only 1806 events were measured. For the holographic analysis, a further 808 events were not recorded as a hologram because they were untriggered or were missed for other reasons.

The holograms were scanned by illuminating the film with a uniform and parallel argon laser light beam over the full surface of the film image at an incident angle similar to the angle subtended to the film when the hologram was taken. An optical wedge was used to compensate for a similar device used in the original photography. The real image thus formed in space was looked at with television cameras and a suitable arrangement of mirrors and beam splitters. The film was held flat between two glass plates; and the whole assembly could be rotated about vertical and horizontal axes so as to permit adjustments to minimize astigmatic effects.

Of 980 events that were measured and for which we had holograms, 825 events were actually observed. For 749 events, the vertex region was visible on the holographic projection. Since the events had already been seen on the conventional photographs, particular attention was given to elucidating features that require improved resolution. Short-prong identification is of particular importance for the study of the EMC effect⁴ where the grouping of the type of interaction is based on whether or not a short

stub is visible. Our data have been sharpened by the holographic film analysis. Potential candidates for observation of charm events were also identified for further analysis. All events were examined in search of tracks that exhibited a small-angle scattering within 2 cm of the interaction vertex. This search was undertaken in order to look for tau decays. Once a candidate is identified, the fast forward track must be further identified as a muon by the downstream muon identification system. A tau could have been produced only by a tau neutrino interaction. We have identified 20 candidates; however, all failed the criteria for identification of the event as a tau decay. This negative result is not unexpected since the expected number of tau neutrinos in the beam, based on uncertain cross sections, is very low.

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1. D. H. Brick et al., Phys. Rev. D 39, 2484 (1989).
 2. C. DeMarzo et al., Phys. Rev. D 29, 2476 (1984).
 3. T. Kitagaki et al., Nucl. Instrum. Meth. Phys. Res. A281, 81 (1989).
 4. T. Kitagaki et al., Phys. Lett. B 214, 281 (1988).

8. COMPILATIONS AND EVALUATIONS

CONTROLLED FUSION ATOMIC DATA CENTER

I. Alvarez ¹	R. K. Janev ⁴
C. F. Barnett ²	M. I. Kirkpatrick
C. Cisneros ¹	E. W. McDaniel ⁵
H. B. Gilbody ³	F. W. Meyer
D. C. Gregory	T. J. Morgan ⁶
C. C. Havener	R. A. Phaneuf
H. T. Hunter	M. S. Pindzola ⁷
E. W. Thomas ⁶	

The Controlled Fusion Atomic Data Center (CFADC) collects, reviews, evaluates and recommends numerical atomic collision data which is relevant to controlled thermonuclear fusion research. The CFADC operates with an equivalent of 1.5 full-time staff members and a number of expert consultants under contract. Members of the experimental atomic physics for fusion group also contribute a small fraction of their time to literature searches and categorization of relevant publications.

The major activities of the CFADC are the following:

- the maintenance of an on-line computer data base of fusion-related publications on atomic collision processes, and periodic distribution of updates to other data centers.
- the preparation and publication of compilations of recommended atomic collision data.
- the deduction of scaling laws and parametrization of atomic-collision data for ease of application in fusion research.
- the establishment of a computer data base of recommended atomic-collision data, and a data exchange format to facilitate their application in fusion research.
- the review of the existing atomic-collision data base with respect to current applications in fusion research, identification of data needs, and coordination of research to fill those needs.
- the handling of individual requests for specific data or literature searches on specific processes.

The CFADC participates in the Atomic and Molecular Data Center Network established by the

International Atomic Energy Agency (IAEA) in Vienna and has cooperative agreements with a number of other data centers. These include:

- the Atomic and Molecular Processes Information Center at the Joint Institute for Laboratory Astrophysics, Boulder, Colorado.
- the Data Center for Atomic Spectral Lines and Transition Probabilities at the National Institute for Standards and Technology, Gaithersburg, Maryland.
- the IAEA Atomic and Molecular Data Unit in Vienna, Austria.
- the Research Information Center at the Institute of Plasma Physics (IPP), Nagoya University, Japan.
- The Atomic and Nuclear Data Center of the Japan Atomic Energy Research Institute (JAERI), Tokai, Japan.

Updates of our bibliography are sent periodically on computer diskettes to the IAEA and to both Japanese data centers. This forms the basis for the semiannual IAEA International Bulletin on Atomic and Molecular Data for Fusion.

During this reporting period, work has continued on preparation of the "Redbook" series of recommended data, Atomic Data for Fusion. Volume 6 of this series, entitled "Spectroscopic Data for Titanium, Chromium, and Nickel" by W. Wiese and A. Musgrove of NIST was published and distributed as ORNL-6551/V1/V2/V3. Data compilation and evaluation work has recently been completed for another volume, entitled "Collisions of H, H₂, He and Li Atoms and Ions with Atoms and Molecules." Publication and distribution of this volume (ORNL-6086) is planned for late 1989. All tabular and graphical data for this series are computer-generated in publication-ready format. Maxwellian rate coefficients are calculated from the cross-section data, and Chebyshev polynomial fits are given for all the recommended data.

The CFADC also participated in two IAEA-sponsored workshops held in Vienna during the period:

"Specialists' Meeting on Review of the Status of Atomic and Molecular Data for Fusion Edge Plasma Studies"

"Consultants' Meeting of the Atomic and Molecular Data Network"

A major role of the CFADC is to assist with the implementation of a new atomic data interface program, called "ALADDIN", a FORTRAN code designed to facilitate effective exchange of data and the establishment of a computer data base for "users." It can accept a wide range of data formats, including tabular, parametrized, and fitted data, and operates on a wide range of computer systems, including personal computers. Plans call for a diskette containing the data and the ALADDIN program to be distributed with the next volume of the "Redbook" series.

In collaboration with JAERI, work also has continued on the scaling, parametrization, and fitting of heavy-particle ionization data using functional forms based on analytical physical models for the process. Often the available data are limited to a narrow energy range, and such "physical" fitting formulae permit extrapolation of the data outside this range with some measure of confidence. Such extrapolation of data is impossible with polynomial fits.

The death of C. F. Barnett, the founder of the CFADC, in June 1982, is a most significant loss to the data center. "Barney" served as director of the CFADC until his retirement from ORNL in 1985, and subsequently as a consultant until the time of his death. His keen insights and tireless efforts will be sorely missed.

1. Instituto de Fisica, Universidad Nacional Autonoma de Mexico.

2. Consultant, ORNL.

3. Consultant, Queen's University, Belfast, Northern Ireland.

4. Consultant, Institute of Physics, Belgrade, Yugoslavia, and International Atomic Energy Agency, Vienna, Austria.

5. Consultant, Georgia Institute of Technology, Atlanta, Georgia.

6. Consultant, Wesleyan University, Middletown, Connecticut.

7. Consultant, Auburn University, Auburn, Alabama.

NUCLEAR DATA PROJECT

Y. A. Akovali
M. R. Lay

M. J. Martin
M. R. Schmorak

The Nuclear Data Project (NDP) is one of five data evaluation centers comprising the U.S. Nuclear Data Network (USNDN). The Project is responsible for the evaluation of nuclear structure information in the mass region $A > 199$. The NDP maintains a complete computer-indexed library of reports and published articles in experimental nuclear structure physics as well as copies of the Evaluated Nuclear Structure Data and Nuclear Structure Reference files (ENSDF, NSR).

The Editor-in-Chief of the Nuclear Data Sheets is a member of the Nuclear Data Project staff. All mass chains from the 14 centers in the International Nuclear Data Network are edited here, and the Editor-in-Chief has the ultimate responsibility for the quality of the mass chains entered into ENSDF and, thus, for what is published in the Nuclear Data Sheets.

Activities

Data Evaluation. During this report period, NDP staff members prepared revised evaluations for the $A = 225, 229, 233, 236, 249, 251, 253, 255, 257, 259, 261, \text{ and } 263$ mass chains. These evaluations have been published or are in press in the Nuclear Data Sheets.

Mass Chain Editing and Review. NDP staff members edited and/or reviewed 18 mass chains.

Information Services. NDP staff members responded to requests for specific information by researchers outside the evaluation center. Responses took the form of searches of the ENSDF and NSR files and personal consultation. A list of reports and preprints received by the NDP is prepared and distributed monthly to division staff members.

Research. NDP staff members have participated in research with other groups in the division. Discussion of these activities may be found in the research section of this report.

9. ACCELERATOR DESIGN AND DEVELOPMENT

HISTRAP PROTOTYPE HARDWARE STUDIES¹

D. K. Olsen W. H. Atkins
D. T. Dowling J. W. Johnson
R. S. Lord² J. W. McConnell
W. T. Milner S. W. Mosko
B. A. Tatum

HISTRAP, Heavy Ion Storage Ring for Atomic Physics, is a proposed 2.67-Tm synchrotron/cooler/storage ring, optimized for advanced atomic physics research, which will be injected with ions from either the HHIRF 25-MV tandem accelerator or a dedicated ECR source and RFQ linac. Over the last two years, hardware prototypes have been developed for difficult and long lead-time components. A vacuum test stand, the rf cavity, and a prototype dipole magnet have been designed, constructed, and tested.

1. Abstract of paper presented at the Twelfth International Conference on Cyclotrons and their Applications, Berlin, West Germany, May 1989.
2. Consultant.

DESIGN, CONSTRUCTION, AND FIELD MAPPING OF THE HISTRAP PROTOTYPE DIPOLE¹

B. A. Tatum D. T. Dowling
R. S. Lord² S. W. Mosko
D. K. Olsen

The HISTRAP lattice will contain eight 45°, C-design dipole magnets. A prototype of these dipoles has been designed, fabricated, and mapped. The magnet design utilizes curved and angled coil ends to compensate for end effects in the field. Field maps for this dipole were obtained using a Hall-effect probe affixed to a PC-based, horizontal positioning system.

The midplane of the prototype dipole has been mapped over its entire magnetic field range. A given mapping consists of 419 points along each of 21 curved, parallel orbits, each orbit separated by

1 cm. Mapping points are located along an orbit such that the path length between points is constant at 5 mm, yielding a total path length of 209 cm. Positioning accuracy along a single axis is assured to within 0.04 mm for each of the 8799 mapping points.

The dipole field was mapped at 15 excitation levels ranging from 72 to 2406 A, or 0.06 to 1.61 T. Figure 9.1 shows representative low, middle, and high-excitation field profiles. Each plot shows field profiles in the central region of the dipole (triangles) and profiles integrated along the ion path length (squares connected by line). These measurements show a small quadrupole component in both the central and integrated profiles. This quadrupole component was not predicted by either TOSCA or POISSON and it also appears in the field measurements for the IUCF and Heidelberg dipoles. The origin of this field component is not understood. However, it can be compensated, if needed, by making small geometrical changes in the lattice. The measured sextupole and octupole components of the field are small, and are consistent with the magnet code predictions. With decreasing excitation, the quadrupole component decreases and changes sign. This decrease is consistent with a remnant field measurement of 0.0030 T with a ± 0.0002 -T quadrupole component at ± 6 cm.

The integrated curves of each of the 15 mappings were approximated with a least-squares fit for a polynomial of the form

$$\Delta B(x)/B_0 = B''x/B_0 + B'''x^2/2B_0 + B''''x^3/6B_0$$

where x is the equilibrium orbit deviation in meters. Table 9.1 gives the quadrupole, B'/B_0 ; sextupole, $B''/2B_0$; and octupole, $B'''/6B_0$ components of the dipole field.

Knowing these coefficients permits the magnetic elements in the ring to be tuned for proper beam focusing. Correction magnets for the octupole

Fig. 9.1. Measured Field Profiles ($\times 10^{-5}$) vs. distance from the equilibrium orbit (cm).

Table 9.1. Multipole Coefficients of the Dipole Field

Amps	Field Gauss	L-eff m	B'/B_0 m^{-1}	B''/B_0 m^{-2}	$B'''/6B_0$ m^{-3}
72	607	1.2793	0.0186	-0.0304	1.4241
125	863	1.2839	-0.0068	0.0284	1.3788
230	1587	1.2932	-0.0131	-0.0150	1.8267
327	2269	1.2967	-0.0224	-0.0160	1.8956
555	3887	1.2981	-0.0257	-0.0103	2.0764
704	4970	1.2983	-0.0241	-0.0126	1.8866
906	6380	1.2997	-0.0238	-0.0062	1.9210
1130	7959	1.2984	-0.0223	-0.0061	1.9090
1312	9249	1.2987	-0.0209	-0.0052	1.9218
1519	10650	1.2984	-0.0201	-0.0071	1.9689
1729	12181	1.2993	-0.0184	-0.0503	1.9597
1936	13537	1.2982	-0.0180	-0.0202	2.0052
2134	14800	1.2961	-0.0177	-0.0766	2.1009
2343	15827	1.2941	-0.0186	-0.1627	2.1994
2406	16111	1.2942	-0.0186	-0.1821	2.0858

component may not be required. The magnet's effective ion path length, L_{eff} , is also tabulated.

In summary, a prototype dipole has been successfully designed, constructed, and mapped. Measurements showing almost identical integrated and central profiles verified that the curved and angled coil end design did cancel the sextupole component found in typical C-shaped dipoles with straight coil ends. Except for the small quadrupole component, the predicted field profiles very accurately modeled the measured field profiles. This includes the predicted loss of field shape at both high and low excitation. The prototype dipole is adequate and will be used without modification in HISTRAP.

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1. Summary of paper presented at the 1989 U.S. Particle Accelerator Conference, Chicago, Illinois, March 1989.
 2. Consultant.

PROTOTYPE RF CAVITY FOR THE HISTRAP ACCELERATOR¹

S. W. Mosko D. T. Dowling
D. K. Olsen

HISTRAP, a proposed synchrotron/cooler/storage ring, is designed to both accelerate and decelerate very highly charged, very heavy ions for atomic physics research. The HISTRAP rf accelerating system must provide ± 2.5 kV of peak accelerating voltage per turn while tuning through a 13.5:1 frequency range in a fraction of a second. A prototype half-wave, single-gap rf cavity with biased ferrite tuning was built and tested over a continuous tuning range of 200 kHz through 2.7 MHz. Initial test results establish the feasibility of using ferrite tuning at the required rf power levels. The resonant system is located entirely outside the accelerator's 15-cm-ID beam line vacuum enclosure except for a single

rf window which serves as an accelerating gap. Physical separation of the cavity and the beam line permits in situ vacuum baking of the beam line at 300°C.

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1. Abstract of paper presented at the 1989 U.S. Particle Accelerator Conference, Chicago, Illinois, March 1989.

HEAVY ION STORAGE RING FOR ATOMIC PHYSICS VACUUM TEST STAND FOR PRESSURES OF 10^{-12} TORR¹

J. W. Johnson W. H. Atkins
D. T. Dowling J. W. McConnell
W. T. Milner D. K. Olsen

HISTRAP (heavy ion storage ring for atomic physics) is a proposed synchrotron/cooler/storage ring accelerator optimized for advanced atomic physics research. The ring has a circumference of 46.8 m, a bore diameter of ~15 cm, and requires a vacuum of 10^{-12} torr to decelerate highly charged, very heavy ions down to low energies. To be able to test components and procedures to achieve this pressure, a test stand approximately modeling 1/16 of the ring vacuum chamber has been built. The 3.5-m-long test stand has been fabricated from 10-cm-diam components, with 316LM stainless steel flanges. Prior to assembly, these components were vacuum fired at 950°C at a pressure of 10^{-4} torr. The test stand is bakable in situ at 300°C. Pumping is achieved with two 750 l/s titanium sublimator pumps and one 60 l/s ion pump. Pressure is measured with two extractor ion gauges and a 10^{-4} partial pressure residual gas analyzer. The roughing for the test stand consists of cryosorption pumps followed by a cryopump. A pressure of 4×10^{-12} torr has been achieved.

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1. Abstract of paper published in J. Vac. Sci. Technol. A7, 2430 (1989).

10. PUBLICATIONS

List Prepared by Shirley J. Ball

The following list of publications includes primarily those articles by Physics Division staff members and associates which appeared in print from October 1988 through September 1989. Articles pending publication as of September 30, 1989, are listed immediately following this section.

BOOK, JOURNAL, AND PROCEEDINGS ARTICLES

Akovali, Y. A.

"Nuclear Data Sheets for A = 214," Nucl. Data Sheets 55, 665-713 (Dec. 1988)

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11. PAPERS PRESENTED AT SCIENTIFIC AND TECHNICAL MEETINGS

October 1988 Through September 1989

List Prepared by Shirley J. Ball

1988

Fourth International Laser Science Conference (ILS-IV), Atlanta, Georgia, October 2-6, 1988

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"HISTRAP Vacuum Test Stand for Pressures of 10^{-12} Torr"

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Garrett, J. D. (Invited Presentation)

"Experimental Data Confronts Nuclear Structure

Kumano, S., and A. Iwazaki

"Oscillations of the Polarized Vacuum Around a Large Z (≈ 180) Nucleus"

Lee, I. Y. (Invited Presentation)

"Lifetime Measurement of the Correlated Continuum Gamma Rays in ^{170}Hf "

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"Micropolyelectrons as Possible Sources of the Anomalous Positron Peaks in Heavy-Ion Reactions"

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Gross, E. E., D. C. Hensley, J. R. Beene, F. E. Bertrand, M. L. Halbert, G. Vourvopoulos, T. Vancleve, and D. L. Humphrey
"E2 and E4 Matrix Elements for ^{26}Mg from HI Inelastic Scattering," Bull. Am. Phys. Soc. 33, 1572 (Sept. 1988)

Lisantti, J., F. E. Bertrand, D. J. Horen, R. L. Auble, B. L. Burks, E. E. Gross, R. O. Sayer, D. K. McDaniels, K. W. Jones, J. B. McClelland, S. J. Seestrom-Morris, and L. W. Swenson
"Collective Model DWBA Analysis of 500 MeV Proton Scattering from ^{40}Ca ," Bull. Am. Phys. Soc. 33, 1596 (Sept. 1988)

Obenshain, F. E.
"Nuclear Stopping in Heavy-Ion-Induced Reactions at 200 A GeV," Bull. Am. Phys. Soc. 33, 1592 (Sept. 1988)

Plasil, F.
"Transverse Energy and Charged Particle Multiplicity Distributions from ^{32}S -Induced Reactions at 200 A GeV," Bull. Am. Phys. Soc. 33, 1592 (Sept. 1988)

Raman, S. (Invited Presentation)
"Global Understanding of Nuclear Deformation Parameters," Bull. Am. Phys. Soc. 33, 1588 (Sept. 1988)

Satchler, G. R.
"Relation Between Mn/Mp and Hadronic Excitation Strengths," Bull. Am. Phys. Soc. 33, 1581 (Sept. 1988)

Virtanen, A., M. R. Johnson, C. Baktash, I. Y. Lee, F. K. McGowan, M. A. Riley, J. C. Wells, and J. Judek
"Lifetimes of High-Spin States in ^{172}Os ," Bull. Am. Phys. Soc. 33, 1585 (Sept. 1988)

Young, G. R. (Invited Presentation)
"New Detectors for Ultrarelativistic Heavy-Ion Experiments," Bull. Am. Phys. Soc. 33, 1580 (Sept. 1988)

41st Annual Gaseous Electronics Conference, Minneapolis, Minnesota, October 18-21, 1988

Gregory, D. C.
"The Importance of Indirect Processes in Electron-Impact Ionization of Ions," Bull. Am. Phys. Soc. 34, 302 (Feb. 1989)

Symposium of Northeastern Accelerator Personnel, New Haven, Connecticut, October 24-27, 1988

Alton, G. D., and G. D. Mills (Invited Presentation)
"Production of Atomic Negative Ion Beams of the Group IA Elements"

Alton, G. D., Y. Mori, A. Takagi, A. Ueno, and S. Fukumoto (Invited Presentation)
"A High-Intensity Plasma Sputter Heavy Negative Ion Source"

Haynes, D. L.
"SF₆ Dryer Alumina Analysis"

Haynes, D. L., D. O. Hobson, and M. F. Ziegler
"Pelletron Chain Nylon Link Test"

Jones, M. L.
"EN-12 at ORNL"

Juras, R. C., M. F. Ziegler, G. D. Mills, M. J. Meigs, R. L. McPherson, C. M. Jones, D. L. Haynes, and G. D. Alton
"Oak Ridge 25URC Tandem Accelerator - SNEAP Lab Report"

Meigs, M. J., C. M. Jones, D. L. Haynes, R. C. Juras, M. F. Ziegler, J. E. Raatz, and R. D. Rathmeil
"Improved Voltage Performance of the Oak Ridge 25URC Tandem Accelerator"

Thirtieth Annual Meeting of the Division of Plasma Physics, American Physical Society, Hollywood, Florida, October 31-November 4, 1988

Richards, R. K., C. A. Bennett, L. K. Fletcher, H. T. Hunter, and D. P. Hutchinson
"A Test of a Fusion-Product Alpha Particle Diagnostic on a Nonburning Plasma," Bull. Am. Phys. Soc. 33, 1966 (Oct. 1988)

4th International Workshop on Cross Sections for Fusion, College Station, Texas, November 2-4, 1988

Burgdorfer, J. (Invited Presentation)
"The Kicked Rydberg Atom: Regular and Stochastic Motion"

Fall Meeting of the Texas Section, American Physical Society, Lubbock, Texas, November 4-5, 1988

Raman, S. (Invited Presentation)
"Understanding Nuclear Ground State Shapes," Bull. Am. Phys. Soc. 34, 1513 (June 1989)

Tenth Conference on the Application of Accelerators in Research and Industry, Denton, Texas, November 7-9, 1988

Alton, G. D. (Invited Presentation)
"A High-Brightness, Plasma-Sputter Negative Ion Source," Bull. Am. Phys. Soc. 33, 1710 (Sept. 1988)

Alton, G. D. (Invited Presentation)
"The Sputter Generation of Negative Ion Beams: Analytical Modeling," Bull. Am. Phys. Soc. 33, 1716 (Sept. 1988)

Bottcher, C., and M. R. Strayer (Invited Presentation)
"Heavy-Ion Collisions at Ultrarelativistic Energies," Bull. Am. Phys. Soc. 33, 1745 (Sept. 1988)

Breinig, M. (Invited Presentation)
"Recoil Ion, Scattered Ion, Free Electron Triple Coincidence Measurements," Bull. Am. Phys. Soc. 33, 1769 (Sept. 1988)

Burgdorfer, J. (Invited Presentation)
"Production and Scattering of Low-Energy Recoil Ions: An Overview," Bull. Am. Phys. Soc. 33, 1694 (Sept. 1988)

Datz, S., (Invited Presentation)
"Electron Energy Distributions Accompanying Multiply Ionizing Collisions," Bull. Am. Phys. Soc. 33, 1694 (Sept. 1988)

Elston, S. B., J. P. Gibbons, C. E. Gonzalez-Lepera, R. Deserin, M. Breinig, O. Heil, H. P. Hulskotter, H. Rothard, I. A. Sellin, and C. R. Vane
"Production and Transport of Convoy Electrons in Amorphous Carbon Foils," Bull. Am. Phys. Soc. 33, 1778 (Sept. 1988)

Gaither, C. C., III, M. Breinig, J. Freyou, and T. A. Underwood
"Comparison of Target-Thickness Dependence of the Convoy-Electron Yield and Rydberg-Electron Yield Measured in Coincidence with Exit Charge States in Fast-Ion-Solid Collisions," Bull. Am. Phys. Soc. 33, 1778 (Sept. 1988)

- Gibbons, J. P., S. B. Elston, R. Deserio, C. Biedermann, M. Breinig, I. Nemirovsky, and I. A. Sellin
 "Velocity and Target Dependences of ELC Radial Angular Distributions," Bull. Am. Phys. Soc. 33, 1778 (Sept. 1988)
- Giese, J. P. (Invited Presentation)
 "Differential Charge State Fractions of He Following Ionization by Fast H^- Projectiles," Bull. Am. Phys. Soc. 33, 1786 (Sept. 1988)
- Girit, I. D. (Invited Presentation)
 "The UNISOR On-Line Nuclear Orientation Facility," Bull. Am. Phys. Soc. 33, 1740 (Sept. 1988)
- Havener, C. C. (Invited Presentation)
 "Merged-Beams Cross Section Measurements for Slow Collisions of Multicharged Ions with Hydrogen Atoms," Bull. Am. Phys. Soc. 33, 1750 (Sept. 1988)
- Meyer, F. W. (Invited Presentation)
 "Ejected Electron Energy Distributions in Low-Energy Multicharged Ion-Surface Interactions," Bull. Am. Phys. Soc. 33, 1761 (Sept. 1988)
- Pegg, D. J. (Invited Presentation)
 "Energy- and Angle-Resolved Photoelectron Spectroscopy of Negative Ions," Bull. Am. Phys. Soc. 33, 1761 (Sept. 1988)
- Schoene, H. (Invited Presentation)
 "Charge and Angular Correlated Inelasticities in MeV/amu Ion-Atom Collisions," Bull. Am. Phys. Soc. 33, 1744 (Sept. 1988)
- Schulz, M. (Invited Presentation)
 "Separated Resonances in Simultaneous Capture and Excitation of Si^{15+} and $F^{6,8+} + H_2$," Bull. Am. Phys. Soc. 33, 1753 (Sept. 1988)
- Stolterfoht, M. (Invited Presentation)
 "Studies of Correlation Effects and Angular Momenta States in Multicharged Ion-Atom Collisions Involving Double Electron Capture," Bull. Am. Phys. Soc. 33, 1714 (Sept. 1988)
- Swenson, J. K. (Invited Presentation)
 "Observation of Strong Asymmetry in the Emission of Autoionization Electrons at 0° and 180° Following 10 keV $He^+ + He$ Collisions," Bull. Am. Phys. Soc. 33, 1696 (Sept. 1988)
- Toth, K. S. (Invited Presentation)
 "Direct and β -Delayed Particle Decays Near Closed Shells," Bull. Am. Phys. Soc. 33, 1714 (Sept. 1988)
- Wang, J. (Invited Presentation)
 " $\nu/2$ Electron Emission in Ion-Atom Collisions with Short-Ranged Potentials," Bull. Am. Phys. Soc. 33, 1690 (Sept. 1988)
- Meeting of the Southeastern Section of the American Physical Society, Raleigh, North Carolina, November 10-12, 1988
- Beckerman, M. (Invited Presentation)
 "Subbarrier Fusion of Atomic Nuclei," Bull. Am. Phys. Soc. 33, 2205 (Nov. 1988)
- Bennett, C. A., and D. P. Hutchinson
 "Far Field Propagation of the Truncated EH_{11} Dielectric Waveguide Mode," Bull. Am. Phys. Soc. 33, 2209 (Nov. 1988)
- Pegg, D. J. (Invited Presentation)
 "Fast Beam Photoelectron Detachment Spectroscopy," Bull. Am. Phys. Soc. 33, 2192 (Nov. 1988)
- Shafnith, S. M., M. Benhenni, J. K. Swenson, M. Schulz, J. P. Giese, S. Datz, P. F. Dittner, H. F. Krause, H. Schone, and C. R. Vane
 "A Comparison of Projectile Auger Electron Spectra Taken near the RTE Maximum for C^{3+} and O^{5+} on He," Bull. Am. Phys. Soc. 33, 2207 (Nov. 1988)
- Stelson, P. H.
 "Heavy-Ion Fusion Cross Sections in the Subbarrier Region," Bull. Am. Phys. Soc. 33, 2194 (Nov. 1988)

Hadron Structure '88, Piest'any, Czechoslovakia, November 14-18, 1988

Lund, I., R. Albrecht, T. C. Awes, C. Baktash, P. Beckmann, F. Berger, R. Bock, G. Claesson, L. Dragon, R. L. Ferguson, A. Franz, S. Garpman, R. Glasow, H. A. Gustafsson, H. H. Gutbrod, K. H. Kampert, B. W. Kolb, P. Kristiansson, I. Y. Lee, H. Loehner, F. E. Obenshain, A. Oskarsson, I. Otterlund, T. Peitzmann, S. Persson, F. Plasil, A. M. Poskanzer, M. Purschke, H. G. Ritter, R. Santo, H. R. Schmidt, T. Siemiarczuk, S. P. Sorensen, E. Stenlund, and G. R. Young (Invited Presentation)
 "Fluctuations in Multiparticle Production and γ/π^0 Ratios in 200-A-GeV $^{16}\text{O} + \text{Au}$ Collisions"

13th International Conference on Infrared and Millimeter Waves, Honolulu, Hawaii, December 5-9, 1988

Bennett, C. A., R. K. Richards, and D. P. Hutchinson

"Design and Calibration of a Two-Channel Low Noise Heterodyne Receiver at 10.6 μm "

Hutchinson, D. P., C. A. Bennett, J. Lee, L. K. Fletcher, C. H. Ma, and K. L. Vander Sluis

"A High Power CH_3OH Laser System Using Stark Stabilized CO_2 Pump Lasers"

Hutchinson, D. P., C. H. Ma, C. A. Bennett, J. Lee, and K. L. Vander Sluis (Invited Presentation)

"A Multichannel Submillimeter Wave Interferometer System on ATF"

Richards, R. K., C. A. Bennett, L. K. Fletcher, H. T. Hunter, and D. P. Hutchinson

"A CO_2 Laser Thomson Scattering Diagnostic for Fusion Product Alpha Particle Measurement"

Symposium on Nuclear Physics 1988, Bombay, India, December 27-31, 1988

Chaturvedi, L., A. V. Ramayya, J. H. Hamilton, C. Girit, J. Kormicki, X. Zhao, S. Zhu, W.-B. Gao, N. R. Johnson, I. Y. Lee, C. Baktash, F. K. McGowan, M. L. Halbert, M. A. Riley, and M. O. Kortelahti

"In-Beam Gamma Ray Measurements for the High Spin States in ^{68}Ge "

1989

XII Symposium on Nuclear Physics, Oaxtepec, Mexico, January 3-6, 1989

Beene, J. R. (Invited Presentation)

"Studies of Giant Multipole Resonances with Intermediate Energy Heavy Ions"

Topical Conference on Electronuclear Physics with Internal Targets, Stanford, California, January 9-12, 1989

Close, F. E. (Invited Presentation)

"Nucleon Spin Structure Functions"

XVII International Workshop on Gross Properties of Nuclei and Nuclear Excitations, Hirschegg, Austria, January 16-19, 1989

Awes, T. C.

"Extended Emission Sources Observed Via Two-Proton Correlations"

Kumano, S., and A. Iwazaki

"Vacuum Oscillations Around a Large-Z 'Nucleus' "

27th International Winter Meeting on Nuclear Physics, Bormio, Italy, January 23-28, 1989

Plasil, F., Albrecht, R., T. C. Awes, C. Baktash, P. Beckmann, F. Berger, R. Bock, G. Claesson, L. Dragon, R. L. Ferguson, A. Franz, S. Garpman, R. Glasow, H. A. Gustafsson, H. H. Gutbrod, K. H. Kampert, B. W. Kolb, P. Kristiansson, I. Y. Lee, H. Loehner, I. Lund, F. E. Obenshain, A. Oskarsson, I. Otterlund, T. Peitzmann, S. Persson, A. M. Poskanzer, M. Purschke, H. G. Ritter, R. Santo, H. R. Schmidt, T. Siemiarczuk, S. P. Sorensen, E. Stenlund, and G. R. Young (Invited Presentation)

"Transverse Energy and Neutral Pion Spectra Obtained from ^{16}O - and ^{32}S -Induced Reactions at 200 GeV/Nucleon"

Workshop on Internal Magnetic Structure in Tokamaks, Austin, Texas, February 22-24, 1989

Ma, C. H., C. A. Bennett, D. P. Hutchinson, and K. L. Vander Sluis
 "A Two-Wavelength Infrared Interferometer System for CIT"

XXIV Recontres de Moriond, "New Results in Hadronic Energy," Les Arcs, Savoie, France, March 12-18, 1989

Albrecht, R., T. C. Awes, C. Baktash, P. Beckmann, F. Berger, R. Bock, G. Claesson, G. Clewing, L. Dragon, A. Eklund, R. L. Ferguson, A. Franz, S.I.A. Garpman, R. Glasow, H. A. Gustafsson, H. H. Gutbrod, J. Idh, P. Jacobs, K. H. Kampert, B. W. Kolb, P. Kristiansson, I. Y. Lee, H. Loehner, I. Lund, F. E. Obenshain, A. Oskarsson, I. Otterlund, T. Peitzmann, S. Persson, F. Plasil, A. M. Poskanzer, M. Purschke, H. G. Ritter, S. Saini, R. Santo, H. R. Schmidt, T. Siemiarczuk, S. P. Sorensen, K. Steffens, E. Stenlund, D. Stueken, M. L. Tincknell, and G. R. Young
 "Fluctuations in the Density of Charged Particles in 200 A GeV $^{16}\text{O} + (\text{C,Au})$ Collisions"

Awes, T. C., R. Albrecht, C. Baktash, P. Beckmann, F. Berger, R. Bock, G. Claesson, G. Clewing, L. Dragon, A. Eklund, R. L. Ferguson, A. Franz, S. Garpman, R. Glasow, H. A. Gustafsson, H. H. Gutbrod, J. Idh, P. Jacobs, K. H. Kampert, B. W. Kolb, P. Kristiansson, I. Y. Lee, H. Loehner, I. Lund, F. E. Obenshain, A. Oskarsson, I. Otterlund, T. Peitzmann, S. Persson, F. Plasil, A. M. Poskanzer, M. Purschke, H. G. Ritter, S. Saini, R. Santo, H. R. Schmidt, T. Siemiarczuk, S. P. Sorensen, K. Steffens, E. Stenlund, D. Stueken, M. L. Tincknell, and G. R. Young (Invited Presentation)
 "Transverse Energy Scaling and Energy Density Estimates from ^{16}O - and ^{32}S -Induced Reactions"

Workshop on Highly Charged Ions: New Physics and Advanced Techniques, Berkeley, California, March 13-15, 1989

Rhoades-Brown, M. J., C. Bottcher, and M. R. Strayer (Invited Presentation)
 "Electromagnetic Phenomena and Collider Performance at Ultrarelativistic Energies"

1989 Particle Accelerator Conference, Chicago, Illinois, March 20-23, 1989

Aiton, G. D. (Invited Talk)
 "Recent Developments in Negative Heavy Ion Sources," Bull. Am. Phys. Soc. 34, 234 (Feb. 1989)

Dowling, D. T., R. S. Lord, S. W. Mosko, D. K. Olsen, and B. A. Tatum
 "Design, Construction, and Field Mapping of the HISTRAP Prototype Dipole," Bull. Am. Phys. Soc. 34, 199 (Feb. 1989)

Mosko, S. W., D. T. Dowling, and D. K. Olsen
 "Prototype RF Cavity for the HISTRAP Accelerator," Bull. Am. Phys. Soc. 34, 190 (Feb. 1989)

ACS Symposium on Nuclear Dynamics and Nuclear Disassembly, Dallas, Texas, April 10-14, 1989

Plasil, F. (Invited Presentation)
 "Attained Energy Densities and Direct Photon Emission in Nucleus-Nucleus Collisions at 200 GeV/Nucleon"

Sobotka, L. G., D. G. Sarantites, D. W. Stracener, Z. Majka, V. Abenante, T. M. Semkow, D. C. Hensley, J. R. Beene, and M. L. Halbert (Invited Presentation)
 "Decomposition of Incomplete Fusion"

American Chemical Society Symposium on Chemical Applications of Particle Accelerators, Dallas, Texas, April 9-14, 1988

Vane, C. R., S. Raman, T. Walkiewicz, S. Kahane, and T. M. Rosseel
 "Chemical Effects on Target X Rays Produced by Heavy-Ion Impact"

Seventh International Workshop on Stellerators, Oak Ridge, Tennessee, April 10-14, 1989

Ma, C. H., D. P. Hutchinson, Y. Lockley, K. L. Vander Sluis, and C. A. Bennett
 "FIR Interferometer and Scattering Measurements on ATF"

American Physical Society Meeting, Baltimore, Maryland, May 1-4, 1989

Burgdorfer, J. (Invited Presentation)

"The Kicked Hydrogen Atom: Noise-Induced Stochastic Dynamics," Bull. Am. Phys. Soc. 34, 1167 (Apr. 1989)

Dean, D. J., A. S. Umar, and M. R. Strayer

"Velocity Dependence of Prompt, High-Energy Nucleon Emission in Heavy-Ion Reactions," Bull. Am. Phys. Soc. 34, 1222 (Apr. 1989)

Hutchinson, D. P., R. K. Richards, C. A. Bennett, C. C. Havener, C. H. Ma, F. G. Perey, R. R. Spencer, J. K. Dickens, B. D. Rooney, J. Bullock IV, and G. L. Powell

"A Search for Cold Fusion Neutrons at ORELA"

Mantica, P. F., Jr., B. E. Zimmerman, W. B. Walters, M. O. Kortelahti, E. F. Zganjar, W. L. Croft, W. J. Newbolt, W. D. Schmidt-Ott, and H. K. Carter

"Decay of ^{119}I to Levels of ^{119}Te ," Bull. Am. Phys. Soc. 34, 1189 (Apr. 1989)

Mantica, P. F., Jr., B. E. Zimmerman, W. B. Walters, D. Rupnik, E. F. Zganjar, W. L. Croft, Y.-S. Xu, and H. K. Carter

"The Decay of ^{126}Cs ," Bull. Am. Phys. Soc. 34, 1236 (Apr. 1989)

Obenshain, F. E.

"Energy Spectra and Energy Densities Obtained from Sulfur-Induced Reactions at 200 GeV/Nucleon," Bull. Am. Phys. Soc. 34, 1205 (Apr. 1989)

Saini, S.

"Fluctuations in the Multi Charged-Particle Production in Nucleus-Nucleus Collisions at CERN SPS Energies," Bull. Am. Phys. Soc. 34, 1205 (Apr. 1989)

Strayer, M. R. (Invited Presentation)

"Lepton Pair Production from Ultrarelativistic Heavy-Ion Collisions," Bull. Am. Phys. Soc. 34, 1195 (Apr. 1989)

Thoennessen, M., J. R. Beene, F. E. Bertrand, D. J. Horen, R. L. Auble, M. L. Halbert, D. C. Hensley, W. Mittig, Y. Schutz, J. Barrette, N. Alamanos, F. Auger, B. Fernandez, A. Gillibert, B. Haas, J. P. Vivien, and A. M. Mathan

"Search for High Energy Target Excitations with Heavy Ion Inelastic Scattering," Bull. Am. Phys. Soc. 34, 1135 (Apr. 1989)

Tincknell, M. L.

"The Space-Time Configuration of an Expanding Hadronic System at Freeze-Out Time," Bull. Am. Phys. Soc. 34, 1138 (Apr. 1989)

12th International Conference on Cyclotrons and Their Applications, Berlin, West Germany, May 8-13, 1989

Olsen, D. K., W. H. Atkins, D. T. Dowling, J. W. Johnson, R. S. Lord, J. W. McConnell, W. T. Milner, S. W. Mosko, and B. A. Tatum

"HISTRAP Prototype Hardware Studies"

International Symposium on Weak and Electromagnetic Interactions in Nuclei (WEIN-89), Montreal, Quebec, Canada, May 15-19, 1989

Kumano, S.

" $N(e, e'\gamma)$ and the $N\Delta$ Transition Quadrupole Moment"

Kumano, S.

"Pionic Contribution to the $N\Delta$ Transition Quadrupole Moment"

American Physical Society, Annual Meeting of the Division of Atomic, Molecular, and Optical Physics, Windsor, Ontario, Canada, May 17-19, 1989

Becker, R. L.

"New Sum Rule for Excitation Plus Ejection and Transfer in Coincidence with a Hole in a Specific Shell," Bull. Am. Phys. Soc. 34, 1365 (May 1989)

- Benhenni, M., S. M. Shafroth, J. K. Swenson, M. Schulz, J. P. Giese, S. Datz, P. F. Dittner, H. F. Krause, H. Schone, C. R. Vane, L. D. Hendrick, and D. M. Peterson
 "Angular Distribution from 10-90° for (1s2s2p³p)²P and (1s2s2p¹p)²P - g.s. Auger Decay of 13 MeV O⁶⁺ on He," Bull. Am. Phys. Soc. 34, 1397 (May 1989)
- Biedermann, C., H. Cederquist, J. C. Levin, C.-S. O, L. Liljeby, H. Rothard, C. R. Vane, K.-O. Groeneveld, and I. A. Sellin
 "State-Selected Angular Distributions of Single-Electron Capture in Very Slow Ar⁴⁺-Ar Collisions," Bull. Am. Phys. Soc. 34, 1358 (May 1989)
- Biedermann, C., H. Cederquist, J. C. Levin, C.-S. O, R. T. Short, and I. A. Sellin
 "Production of Highly-Charged Recoil-Ion Beams at Very Low Energy," Bull. Am. Phys. Soc. 34, 1364 (May 1989)
- Burgdorfer, J., J. Wang, and J. Muller
 "Forward Electron Production in Antimatter-Solid Collisions," Bull. Am. Phys. Soc. 34, 1396 (May 1989)
- Gibbons, J. P., S. B. Elston, R. DeSerio, C. Biedermann, I. A. Sellin, and A. Kover
 "A Comparison of the Transport of Convoy Versus Free Electrons in Amorphous Carbon," Bull. Am. Phys. Soc. 34, 1364 (May 1989)
- Gregory, D. C., R. A. Phaneuf, M. Sataka, and M. Druetta
 "Electron-Impact Ionization of Ar⁸⁺ Ions," Bull. Am. Phys. Soc. 34, 1404 (May 1989)
- Havener, C. C., M. S. Huq, M. P. Nesnidal, and R. A. Phaneuf
 "Merged-Beams Measurements for Slow Collisions of Multicharged Ions with Hydrogen Atoms," Bull. Am. Phys. Soc. 34, 1365 (May 1989)
- Levin, J. C., C.-S. O, H. Cederquist, C. Biedermann, and I. A. Sellin
 "Role of Vacancy Cascades in Argon Recoil-Ion Charge Distributions Produced by High-Energy Heavy-Ion Impact," Bull. Am. Phys. Soc. 34, 1364 (May 1989)
- Meyer, F. W., J. K. Swenson, C. C. Havener, N. Stolterfoht, and K. Sommer
 "Observation of Coulomb Focusing of Autoionizing Electrons Produced in Low Energy He⁺ + He Collisions," Bull. Am. Phys. Soc. 34, 1367 (May 1989)
- Pegg, D. J., J. S. Thompson, J. Dellwo, G. D. Alton, and R. N. Compton
 "Partial Cross Sections for the Photodetachment of Metastable He⁻," Bull. Am. Phys. Soc. 34, 1411 (May 1989)
- Short, R. T., J. C. Levin, C.-S. O, H. Cederquist, S. B. Elston, J. P. Gibbons, and I. A. Sellin
 "Dependence of Recoil-Ion Energy on Target and Projectile Ionization and Impact Parameter," Bull. Am. Phys. Soc. 34, 1365 (May 1989)
- Thompson, J. S., D. J. Pegg, J. Dellwo, and G. D. Alton
 "Cross Section for the Photodetachment of B⁻," Bull. Am. Phys. Soc. 34, 1411 (May 1989)
- Wahlin, E., C. Timmer, L. Forand, D. Swenson, B. DePaola, R. Phaneuf, D. Belic, K. Rinn, A. Muller, and G. Gunn
 "Measurement of Electron-Impact Excitation of Ions Using Merged Beams: C⁺," Bull. Am. Phys. Soc. 34, 1403 (May 1989)
- International Advanced Courses on the Nuclear Equation of State, Peniscola, Spain, May 21-June 3, 1989
- Bottcher, C., M. R. Strayer, C. Albert, and D. J. Ernst (Invited Presentation)
 "Probing Nuclear Currents with Dilepton Production in Ultrarelativistic Heavy-Ion Collisions"
- Ernst, D. J., C. J. Albert, C. Bottcher, and M. R. Strayer (Invited Presentation)
 "Two-Photon Processes and Anomalous Electron-Pair Production in ω Collisions"
- Oberacker, V. E., A. S. Umar, M. R. Strayer, and C. Bottcher (Invited Presentation)
 "Lattice Calculations of Dilepton Production in Peripheral Relativistic Heavy-Ion Collisions"

Workshop on Cold Fusion Phenomena, Santa Fe, New Mexico, May 23-25, 1989

Hutchinson, D. P., C. A. Bennett, R. K. Richards, J. Bullock IV, and G. L. Powell
 "Calorimetry Cell Design for Cold Fusion Studies"

Hutchinson, D. P., R. K. Richards, C. A. Bennett, C. C. Havener, C. H. Ma, F. G. Perey, R. R. Spencer,
 J. K. Dickens, B. D. Rooney, and G. L. Powell
 "Cold Fusion Neutron Measurements at ORNL"

Tau-Charm Factory Workshop, Stanford, California, May 23-27, 1989

Close, F. E. (Invited Presentation)
 "Exotic Hadrons and Hadron Dynamics at a Tau-Charm Factory"

5th International Conference on Electrostatic Accelerators and Associated Boosters, Strasbourg, France, and Heidelberg, Germany, May 24-30, 1989

Alton, G. D. (Invited Presentation)
 "Recent Advances in High Intensity Heavy Negative Ion Sources Based on the Sputter Principle"

Datz, S. (Invited Presentation)
 "Atomic Physics Using Large Electrostatic Accelerators"

Jones, C. M., D. L. Haynes, R. C. Juras, M. J. Meigs, and N. F. Ziegler
 "Operational Experience with Compressed Geometry Acceleration Tubes in the Oak Ridge 25URC Tandem Accelerator"

9th International Conference on Ion Beam Analysis, Kingston, Ontario, Canada, June 19-23, 1989

Alton, G. D. (Invited Presentation)
 "Fundamental Aspects of Heavy Negative Ion Sources Based on the Sputter Principle"

International Conference on Selected Topics in Nuclear Structure, Dubna, U.S.S.R., June 20-24, 1989

Rizman, S. (Invited Presentation)
 "Understanding Nuclear Quadrupole Deformations"

International Conference on the Spectroscopy of Heavy Nuclei, Crete, Greece, June 25-30, 1989

Beene, J. R., and F. E. Bertrand (Invited Presentation)
 "Excitations and Decay of Giant Multipole Resonances in Intermediate Energy Heavy Ion Reactions"

Few Body XII, 12th International Conference on Few Body Problems in Physics, Vancouver, B.C., Canada, July 2-8, 1989

Kumano, S.
 "Nucleon Structure in a Flux-Tube Quark Model"

Kumano, S.
 "An Estimate for Pionic Contributions to the N-Δ Transition E2/M1 Ratio"

Kumano, S.
 "Δ Electromagnetic Moments"

International Conference on Ion Sources, Berkeley, California, July 10-14, 1989

Alton, G. D.
 "Characteristics of Negative Ion Beams Generated by the Sputter Technique"

Alton, G. D., Y. Mori, A. Takagi, A. Ueno, and S. Fukumoto (Invited Presentation)
 "A High-Intensity Plasma-Sputter Heavy Negative Ion Source"

- Alton, G. D., P. M. Read, and J. T. Maskrey
 "Liquid Metal Ion Sources Suitable for High-Voltage Terminal Applications"
- Meyer, F. W., and J. Hale
 "Ion Source Studies at the ORNL ECR Source Facility"
- XVI International Conference on the Physics of Electronic and Atomic Collisions, New York, New York,
 July 26-August 2, 1989
- Barrachina, R. O., and J. H. Macek
 "Emission-Angle-Dependent Auger Transitions in Ion-Atom Collisions"
- Becker, R. L.
 "Enhancement of the Cross Section for Direct Ionization in Coincidence with a Specific Hole from a New Sum Rule"
- Biedermann, C., H. Cederquist, J. C. Levin, C.-S. O, L. Liljeby, H. Rothard, C. R. Vane, K-O. Groeneveld, and I. A. Sellin
 "State-Selected Angular Distributions of Single-Electron Capture in Very Slow Ar^{4+} -Ar Collisions"
- Bottcher, C. R., and M. R. Strayer (Invited Presentation)
 "Electron Correlation in the Continuum"
- Burgdorfer, J. (Invited Presentation)
 "Collisionally Induced Stochastic Dynamics of Fast Ions in Solids"
- Bottrell, G. J., C. Bottcher, and M. R. Strayer
 "Time-Dependent Hartree-Fock Studies of Ion-Atom Collisions"
- Datz, S. (Invited Presentation)
 "On the Utility and Ubiquity of Atomic Collision Physics"
- Datz, S., C. R. Vane, P. F. Dittner, J. Giese, J. Gomez del Campo, M. L. Jones, H. F. Krause, T. M. Rosseel, M. Schulz, and H. Schone
 "Dielectronic Excitation of Hydrogenic Ions in Crystal Channels"
- Gaither, C. C., III, M. Breinig, T. A. Underwood, and J. Freyou
 "Highly Excited Electrons from Ion-Atom and Ion-Solid Collisions"
- Gibbons, J. P., S. B. Elston, R. D. DeSerio, and I. A. Sellin
 "Comparison of Convoy and Free Electron Transport Properties Through Amorphous Carbon Foils"
- Giese, J. P., M. Schulz, J. K. Swenson, M. Schone, S. L. Varghese, C. R. Vane, M. Benhenni, P. F. Dittner, S. M. Shafroth, and S. Datz
 "Double Excitation of He by Fast Bare Ions"
- Gregory, D. C. and H. Tawara
 "Dissociation and Ionization of CD_4^+ by Electron Impact"
- Havener, C. C., M. S. Huq, M. P. Nesnidal, and R. A. Phaneuf
 "Merged-Beams Cross Section Measurements for Slow Collisions of Multicharged Ions with Hydrogen Atoms"
- Krause, H. F.
 "Observation of Landau Resonances at Magnetic Fields Below 0.07 Tesla in a High-Resolution ($\Delta f = 70$ MHz) Laser Photodetachment Study of O^- "
- Levin, J. C. (Invited Presentation)
 "Synchrotron-Radiation Experiments with Recoil Ions"
- Macek, J., K. Taulbjerg, and R. Barrachina
 "Strong Potential Wavefunctions with Elastic Channel Distortion"
- Meyer, F. W., C. C. Havener, K. J. Snowden, and D. M. Zehner
 "Electron Spectroscopy of Multicharged Ion - Surface Interactions at keV Energies"
- Pegg, D. J. (Invited Presentation)
 "Photodetachment Collisions"

- Schone, H., S. Datz, R. Hippler, P. F. Dittner, J. P. Giese, H. F. Krause, R. Schuch, M. Schulz, J. K. Swenson, and Q. C. Kessel
 "Electron Energy Distributions Accompanying Multiply Ionizing Collisions"
- Schulz, M., J. P. Giese, J. K. Swenson, S. Datz, P. F. Dittner, H. Schone, C. R. Vane, M. Benhenni, and S. M. Shafroth
 "Electron Electron Interactions in Transfer and Excitation Studied in H-Like Fluorine Colliding with H_2^+ "
- Sommer, K., N. Stolterfoht, V. Montemayor, C. C. Havener, J. K. Swenson, R. A. Phaneuf, and F. W. Meyer
 "Correlated Double Capture in the Collision System C^{6+} on He"
- Swenson, J. K., C. C. Havener, K. Sommer, N. Stolterfoht, and F. W. Meyer
 "Observation of Coulomb Focusing in Low Energy $He^+ + He$ Collisions"
- Taulbjerg, K. (Invited Presentation)
 "Electron Capture and Energy Gain Spectroscopy"
- Thompson, J. S., D. J. Pegg, J. Dellwo, R. M. Compton, and G. D. Alton
 "Photodetachment of He^- ($1s2s2p^4P$)"
- Wahlin, E., C. Timmer, L. Forand, D. Swenson, B. DePaola, R. Phaneuf, D. Belic, K. Rinn, A. Muller, and G. Dunn
 "Absolute Cross Sections for Electron Impact Excitation of C^+ Using Electron Energy Loss"
- Underwood, T. A., M. Breinig, C. C. Gaither, III, and J. Frey
 "Excitation of Two Electrons in the Vicinity of the Double Escape Threshold in 0.1 MeV/u Ion-Atom Collisions"
- 13th International Conference on Atomic Collisions in Solids, Aarhus, Denmark, August 7-11, 1989
- Datz, S., C. R. Vane, P. F. Dittner, J. P. Giese, J. Gomez del Campo, N. L. Jones, H. F. Krause, P. D. Miller, M. Schulz, H. Schone, and T. M. Rosseel
 "Dielectronic Recombination in Crystal Channels"
- Workshop on Rainbow Scattering and Catastrophe Theory, Dubrovnik, Yugoslavia, August 14-17, 1989
- Datz, S. (Invited Presentation)
 "Rainbow Scattering in Axial Ion Channeling"
- 1989 Nuclear Physics Conference, Sao Paulo, Brazil, August 20-26, 1989
- Bertrand, F. E., and J. R. Beene (Invited Presentation)
 "Giant Resonances - Progress, New Directions, New Challenges"
- Obenshain, F. E., R. Albrecht, T. C. Awes, C. Baktash, P. Beckmann, F. Berger, R. Bock, G. Claesson, L. Dragon, R. L. Ferguson, A. Franz, S. Garpman, R. Glasow, H. A. Gustafsson, H. H. Gutbrod, K. H. Kampert, B. W. Kolb, P. Kristiansson, I. Y. Lee, H. Loehner, I. Lund, A. Oskarsson, I. Otterlund, T. Peitzmann, S. Persson, F. Plasil, A. M. Poskanzer, M. Purschke, H. G. Ritter, R. Santo, H. R. Schmidt, T. Siemiarz, S. P. Sorensen, E. Stenlund, and G. R. Young
 "Energy Spectra and Energy Densities Obtained from Sulfur-Induced Reactions at 200 A GeV"
- Plasil, F., R. Albrecht, T. C. Awes, C. Baktash, P. Beckmann, F. Berger, R. Bock, G. Claesson, L. Dragon, R. L. Ferguson, A. Franz, S. Garpman, R. Glasow, H. A. Gustafsson, H. H. Gutbrod, K. H. Kampert, B. W. Kolb, P. Kristiansson, I. Y. Lee, H. Loehner, I. Lund, F. E. Obenshain, A. Oskarsson, I. Otterlund, T. Peitzmann, S. Persson, A. M. Poskanzer, M. Purschke, H. G. Ritter, R. Santo, H. R. Schmidt, T. Siemiarz, S. P. Sorensen, E. Stenlund, and G. R. Young
 "Transverse Momentum Distributions of Neutral Pions from $^{16}O + Au$ Collisions at 200 GeV/Nucleon"
- Raman, S., and C. W. Nestor, Jr.
 "Low-Lying Collective E2 Strengths in Even-Even Nuclei"
- Satchler, G. R. (Invited Presentation)
 "Low-Energy Heavy-Ion Reactions: Some Recent Developments"
- Wong, C. Y.
 "Possible Sources of Anomalous Positron Peaks in Heavy-Ion Reactions"

International Workshop on Relativistic Aspects of Nuclear Physics, Rio de Janeiro, Brazil, August 28-30, 1989

Obenshain, F. E., R. Albrecht, T. C. Awes, C. Baktash, P. Beckmann, F. Berger, R. Bock, G. Claesson, L. Dragon, R. L. Ferguson, A. Franz, S. Garpman, R. Glasow, H. A. Gustafsson, H. H. Gutbrod, K. H. Kampert, B. W. Kolb, P. Kristiansson, I. Y. Lee, H. Loehner, I. Lund, F. E. Obenshain, A. Oskarsson, I. Otterlund, T. Peitzmann, S. Persson, F. Plasil, A. M. Poskanzer, M. Purschke, H. G. Ritter, R. Santo, H. R. Schmidt, T. Siemiarczuk, S. P. Sorensen, E. Stenlund, and G. R. Young
 "Transverse Momentum Distributions of Neutral Pions from $^{160} + \text{Au}$ Collisions"

Plasil, F., Albrecht, R., T. C. Awes, C. Baktash, P. Beckmann, F. Berger, R. Bock, G. Claesson, G. Clewing, L. Dragon, A. Eklund, R. L. Ferguson, A. Franz, S. Garpman, R. Glasow, H. A. Gustafsson, H. H. Gutbrod, J. Idh, P. Jacobs, K. H. Kampert, B. W. Kolb, P. Kristiansson, I. Y. Lee, H. Loehner, I. Lund, F. E. Obenshain, A. Oskarsson, I. Otterlund, T. Peitzmann, S. Persson, A. M. Poskanzer, M. Purschke, H. G. Ritter, S. Saini, R. Santo, H. R. Schmidt, T. Siemiarczuk, S. P. Sorensen, K. Steffens, E. Stenlund, D. Stucken, M. L. Tincknell, and G. R. Young (Invited Presentation)
 "Fluctuations in Transverse Energy and Multiplicity, Energy Densities, and Neutral Pion Spectra in Nucleus-Nucleus Collisions at 200 GeV/Nucleon"

XII Workshop on Nuclear Physics, Iguazu Falls, Argentina, August 28-September 1, 1989

Satchler, G. R. (Invited Presentation)
 "Heavy-Ion Scattering Near the Coulomb Barrier: Some Recent Developments"

12th Werner Brandt Workshop on Penetration of Charged Particles in Matter, San Sebastian, Spain, September 4-7, 1989

Burgdorfer, J., J. Wang, and J. Muller (Invited Presentation)
 "Wake-Riding Electrons Emitted by Antiprotons Traversing Solid Targets"

1989 Meeting of the American Chemical Society, Miami Beach, Florida, September 10-15, 1989

Johnson, M. R. (Invited Presentation)
 "Nuclear Collectivity and Complex Alignment Mechanisms in Light W and Os Nuclei"

Mantica, P. F., W. B. Walters, E. F. Zganjar, H. K. Carter, J. Rikowska, and N. J. Stone
 "Particle-Hole Intruder Structures in the Te and Xe Nuclides"

McNeill, J. H., J. Blomqvist, A. A. Chishti, P. J. Daly, W. Gelletly, M.A.C. Hotchkis, M. Piiparinen, B. J. Varley, and P. J. Woods
 "The Study of Exotic $N \sim 82$ Nuclei Using the Daresbury Recoil Mass Separator"

Toth, K. S., J. M. Nitschke, and P. A. Wilmarth (Invited Presentation)
 "Nuclear Spectroscopy in the Rare Earth Region Near the Proton Drip Line"

Yu, C. H., J. Gascon, G. B. Hagemann, and J. D. Garrett
 "High-Spin Spectroscopy of Odd- Z $N = 90$ Isotones and $Z = 71$ Isotopes"

12. GENERAL INFORMATION

PERSONNEL CHANGES

New Staff Members

A. Scientific Staff

- E. C. Halbert (transferred from Engineering Physics and Mathematics Division)
- R. C. Juras (transferred from Instrumentation and Controls Division)

Staff Transfers and Terminations

A. Scientific Staff

- J. A. Martin (retirement)

B. Administrative and Technical Staff

- D. M. Galbraith, User Support and Computer Systems (transferred to Chemical Technology Division)

Temporary Assignments

A. Visiting Scientists

- R. O. Barrachina Tejada, Comision Nacional de Energia Atomica, Bariloche, Argentina
- X-L. Han, Jilin University, Changchun, People's Republic of China
- K. Kimura, Kyoto University, Kyoto, Japan
- J. E. Miraglia, Instituto de Astronomia y Fisica del Espacio, Buenos Aires, Argentina
- K. E. N. Taulbjerg, Aarhus University, Aarhus, Denmark
- M. J. Veskovic, University of Novi Sad, Duvicica, Yugoslavia
- J. Wu, University of Tennessee, Knoxville, Tennessee
- L. Zhou, Institute of Atomic Energy, Beijing, People's Republic of China

B. Postdoctoral Research Associates

- E. Eschenazi, University of Tennessee, Knoxville, Tennessee
- A. Franz, Lawrence Berkeley Laboratory, Berkeley, California
- S. Kumano, University of Illinois, Urbana-Champaign, Illinois
- J. C. Levin, University of Tennessee, Knoxville, Tennessee
- X. T. Liu, University of Tennessee, Knoxville, Tennessee
- J. H. McNeill, University of Manchester, Manchester, United Kingdom
- A. Ray, University of Washington, Seattle, Washington
- S. Saini, University of Pennsylvania, Philadelphia, Pennsylvania
- M. Schulz, Heidelberg University, Heidelberg, West Germany
- J. K. Swenson, University of North Carolina, Chapel Hill, North Carolina
- M. R. Thoennesen, State University of New York, Stony Brook, New York
- U. Thamm, Freiburg University, Freiburg, West Germany
- M. L. Tincknell, Lawrence Berkeley Laboratory, Berkeley, California
- J. D. Weinstein, University of Toronto, Toronto, Ontario, Canada
- J. P. Wieleczko, Commissariat a l'Energie Atomique, Gif-sur-Yvette Cedex, France
- C-H. Yu, University of Copenhagen, Copenhagen, Denmark

C. Graduate Students

U. Bechthold, University of Frankfurt, Frankfurt, West Germany
 C. Biedermann, University of Frankfurt, Frankfurt, West Germany
 H. V. Carmichael, University of Tennessee, Knoxville, Tennessee
 J. Dellwo, University of Tennessee, Knoxville, Tennessee
 L. K. Fletcher, Tennessee Technological University, Cookeville, Tennessee
 J. E. Freyou, University of Tennessee, Knoxville, Tennessee
 C. C. Gaither, University of Tennessee, Knoxville, Tennessee
 W-B. Gao, Vanderbilt University, Nashville, Tennessee
 J. P. Gibbons, University of Tennessee, Knoxville, Tennessee
 R. C. Hunt, University of Tennessee, Knoxville, Tennessee
 Y-r. Jiang, Vanderbilt University, Nashville, Tennessee
 H. Jin, University of Tennessee, Knoxville, Tennessee
 E. F. Jones, Vanderbilt University, Nashville, Tennessee
 R. W. Kincaid, University of Tennessee, Knoxville, Tennessee
 M. Korolija, Ruder Boskovic Institute, Croatia, Yugoslavia
 J. M. Lewis, University of Tennessee, Knoxville, Tennessee
 J. Mueller, University of Frankfurt, Frankfurt, West Germany
 J. D. Richards, University of Tennessee, Knoxville, Tennessee
 H. Schone, University of Frankfurt, Frankfurt, West Germany
 J. Y. Shea, Vanderbilt University, Nashville, Tennessee
 W. Spang, Kernforschungsanlage Julich (KFA), Julich, West Germany
 K. M. Teh, Vanderbilt University, Nashville, Tennessee
 J. S. Thompson, University of Tennessee, Knoxville, Tennessee
 T. A. Underwood, University of Tennessee, Knoxville, Tennessee
 J. Wang, University of Tennessee, Knoxville, Tennessee
 H. Xie, Vanderbilt University, Nashville, Tennessee
 Y-s. Xu, Oregon State University, Corvallis, Oregon

D. Joint Institute for Heavy Ion Research (JHIR) Long-Term Guests

S. G. Aberg, University of Lund, Lund, Sweden
 G. Arbanas, Massachusetts Institute of Technology, Cambridge, Massachusetts
 P. Beckmann, University of Muenster, Muenster, West Germany
 K. H. Bhatt, University of Mississippi, University, Mississippi
 F. E. Donau, Zentralinstitut fur Kernforschung, Dresden, East Germany
 R. M. Dreizler, University of Frankfurt, Frankfurt, West Germany
 A. G. Eklund, University of Lund, Lund, Sweden
 J. M. Espino, Faculty of Physics, Seville, Spain
 W. D. Hamilton, University of Sussex, Brighton, United Kingdom
 Y. Shimizu, Kyushu University, Fukuoka, Japan
 S-J. Wang, Lanzhou University, Lanzhou, People's Republic of China
 C-L. Wu, Jilin University, Changchun, People's Republic of China
 C. P. Yannouleas, Niels Bohr Institute, Copenhagen, Denmark

E. ORAU Faculty Research Participant

C. A. Bennett, Jr., University of North Carolina, Asheville, North Carolina

F. ORAU Postgraduate Research Training Program Participants

G. J. Bottrell, University of Georgia, Athens, Georgia
 J. P. Giese, Kansas State University, Manhattan, Kansas

G. ORAU Graduate Research Participant

D. J. Dean, Vanderbilt University, Nashville, Tennessee

H. ORAU Student Research Participants

G. J. Baker, Southern Methodist University, Dallas, Texas
 J. H. Irby, Western Kentucky University, Bowling Green, Kentucky
 J. S. Miller, Gordon College, Wenham, Massachusetts
 J. R. Olive, Carson-Newman College, Jefferson City, Tennessee

I. Oak Ridge Science and Engineering Research Semester (ORSERS) Participants

L. B. Foutch, Texas A&I University, Kingsville, Texas
 I. C. Frosch, Colorado School of Mines, Golden, Colorado
 R. L. Knight, University of Southern Colorado, Pueblo, Colorado
 M. M. Messick, Gettysburg College, Gettysburg, Pennsylvania
 J. K. Pope, University of North Carolina, Charlotte, North Carolina
 L. Y. Shen, University of Miami, Miami, Florida
 S. M. Sipe, Anderson College, Anderson, Indiana
 R. T. VanHook, Hendrix College, Conway, Arkansas

J. Great Lakes Colleges Association Science Program Participants

S. R. Broshar, Lawrence University, Appleton, Wisconsin
 K. M. Isbister, DePauw University, Greencastle, Indiana
 R. L. Kehoe, Earlham College, Richmond, Indiana
 S. S. McWilliams, Earlham College, Richmond, Indiana
 M. P. Nesnidal, Lawrence University, Appleton, Wisconsin

Summer Assignments

A. Visiting Faculty

J. M. Anthony, U.S. Naval Academy, Annapolis, Maryland
 G. A. Pettitt, Georgia State University, Atlanta, Georgia

B. Graduate Student

P. M. Gore, Vanderbilt University, Nashville, Tennessee

C. Nuclear Energy Research Associate (NERA)

J. K. Pope, University of North Carolina, Charlotte, North Carolina

D. ORAU STRIVE Participant

R. B. Schneck, McArthur High School, Hollywood, Florida

E. ORAU Faculty/Student Team Research Program Participants

W. H. Brantley, Furman University, Greenville, South Carolina
 W. L. Croft, Mississippi State University, Mississippi State, Mississippi
 J. C. Morgan, Mississippi State University, Mississippi State, Mississippi
 G. B. Quinn, Mississippi State University, Mississippi State, Mississippi
 C. D. Roper, Furman University, Greenville, South Carolina
 J. M. Turner, Mississippi State University, Mississippi State, Mississippi
 B. E. Zimmerman, University of Maryland, College Park, Maryland

F. Service Academies Research Associates (SARA) Participant

J. H. Blalock, U.S. Naval Academy, Annapolis, Maryland

G. University of Tennessee/ORNL Science Alliance Undergraduate Program Participants

J. A. Alley, University of Tennessee, Chattanooga, Tennessee
 M. H. Anderson, Hendrix College, Conway, Arkansas
 S. L. Balkum, Rice University, Houston, Texas
 J. M. Bauer, University of Dallas, Irving, Texas
 M. J. Beauchamp, Marquette University, Milwaukee, Wisconsin
 E. D. Boerner, Case Western Reserve University, Cleveland Heights, Ohio
 B. A. Edington, Hendrix College, Conway, Arkansas
 T. H. Fox, Austin Peay State University, Clarksville, Tennessee
 C. L. Johnston, University of Michigan, Ann Arbor, Michigan
 B. Luce, State University of New York, Fredonia, New York
 W. F. Mueller, Appalachian State University, Boone, North Carolina
 J. M. Nash, Southern College of Seventh Day Adventists, Collegedale, Tennessee
 M. L. Vaughn, Centre College, Danville, Kentucky
 J. R. Withrow, Carroll College, Waukesha, Wisconsin
 G. Zhang, University of Tennessee, Knoxville, Tennessee

PHYSICS DIVISION SEMINARS: OCTOBER 1988-SEPTEMBER 1989

Seminars arranged by the Physics Division and announced in the ORNL Technical Calendar are listed below. During the period of this report, Edward E. Gross served as Seminar Chairman.

<u>Date</u>	<u>Speaker</u>	<u>Title</u>
1988		
Oct. 6	Franz Plasil Division Staff Member	"Nucleus-Nucleus Collisions at Relativistic Energies— WA80 Status for the Novice"
Oct. 10	Jurg X. Saladin University of Pittsburgh Pittsburgh, Pennsylvania	"Population of High-Spin States by Quasi-Elastic and Deep Inelastic Collisions"
Oct. 20	Joseph Ford Georgia Institute of Technology Atlanta, Georgia	"A Girl's Guide to Chaos"
Oct. 27	John J. Domingo CEBAF, Newport News, Virginia	"CEBAF Physics and Accelerator Programs"
Oct. 31	Michel Ruenerd ISM, Grenoble, France	"Total Cross Sections, Hadron Geometry, and Interaction Dynamics in High Energy Collisions"
Nov. 3	David Miller Pennsylvania State University, Hazelton, Pennsylvania	"Thermodynamical Properties of Strongly Interacting Particles"
Nov. 10	Uwe Wille Hahn-Meitner Institute, Berlin, Federal Republic of Germany	"Molecular and Quasi-Molecular Collision Systems in Very Strong Magnetic Fields"
Nov. 15	Sadayoshi Fukumoto National Laboratory for High- Energy Physics, Tsukuba, Japan	"Tandem Injector for Medical Proton Synchrotron and Status of the National Laboratory for High-Energy Physics"
Nov. 17	David Schramm Department of Astronomy and Astrophysics, The University of Chicago, Chicago, Illinois	"The Great Supernova of 1987—18 Months Later"
Nov. 28	Peter Mohr National Institute of Standards and Technology, Gaithersburg, Maryland	"Quantum Electrodynamics of High Z Atoms"
Dec. 1	Julian R. Preston Biology Division, ORNL	"Chromosome Alterations, Mutations, and Cancer"
Dec. 12	Kim Maltman York University Toronto, Ontario, Canada	"Nucleon-Nucleon Potential in the Quark Model"
1989		
Jan. 3	Adriaan van der Woude KVI, Groningen The Netherlands	"Neutron Decay of the Giant Resonances—Especially, the Giant Monopole"
Jan. 10	Wolfgang Mittig GANIL, Caen, France	"Masses of Exotic Nuclei"
Jan. 26	Lester D. Mullett, Jr. Analytical Chemistry Division ORNL	"Use of Slow Positrons in Microscopy and Other Applications"

<u>Date</u>	<u>Speaker</u>	<u>Title</u>
1989		
Feb. 7	Ted Barnes University of Toronto Canada	"Monte Carlo Study of 2D Anisotropic Heisenberg Anti-Ferromagnets, or How Good Is Spin Wave Theory?"
Feb. 9	Howard I. Adler Medical and Health Sciences Division, Oak Ridge Associated Universities, Oak Ridge, Tennessee	"Life Without Air"
Feb. 13	Fumihiko Sakata Institute for Nuclear Studies University of Tokyo Tokyo, Japan	"Onset of Quantum Stochastic Motion"
Feb. 22	Walter Greiner University of Frankfurt Federal Republic of Germany	"Shock Waves and the Nuclear Equation of State"
Feb. 23	Mikkel R. Johnson Los Alamos National Laboratory Los Alamos, New Mexico	"Probing for Structure in the Dirac Vacuum of Nuclei"
Mar. 9	Constantine Yannouleas Niels Bohr Institute Copenhagen, Denmark	"Surface Plasma Oscillations in Metal Microclusters: Similarities with Nuclear Giant Resonances"
Mar. 16	Dennis Hamilton University of Sussex Brighton, England	"Mixed Symmetry States in Vibrational Nuclei"
Mar. 23	Tetsuo Matsui Massachusetts Institute of Technology, Cambridge, Massachusetts	"Quark-Gluon Plasma Formation and J/ ψ Suppression in Ultrarelativistic Nucleus-Nucleus Collisions"
Mar. 27	Fred Meyer Division Staff Member	"Recent Experiments at the ORNL ECR Multicharged Ion Facility"
Mar. 30	Dave H. Youngblood Texas A&M University College Station, Texas	"Texas A&M K-500 Cyclotron Facility: Opportunities and Programs"
Apr. 5	David M. Brink University of Oxford Oxford, England	"Heavy-Ion Transfer Reactions"
Apr. 6	Peter Mazur Biology Division, ORNL	"Freezing of Living Cells"
Apr. 13	William D. Walker Duke University Durham, North Carolina	"A Search for Quark Gluon Plasma"
Apr. 18	Jens Jørgen Gaardhøje Niels Bohr Institute Risø, Denmark	"Shapes and Shape Fluctuations in Hot Nuclei Studied Through the Decay of Giant Dipole Resonances"
Apr. 27	Steven E. Lindberg Environmental Sciences Division ORNL	"Atmospheric Deposition to High- and Low-Elevation Forests in North America and Europe"
Apr. 28	Peter Hayes Kings College, London, England	"Proton and Neutron Deformations in Light-Deformed Nuclei"
May 17	Michael Hass University of Rochester Rochester, New York	"Polarization and Alignment for Separated Reaction Products"

<u>Date</u>	<u>Speaker</u>	<u>Title</u>
1989		
May 18	Michael W. Guidry Division Staff Member and University of Tennessee, Knoxville, Tennessee	"Fermi Dynamical Symmetry Model: A Conceptual Introduction"
May 24	Claude Detraz GANIL, Caen, France	"GANIL National Laboratory Research Program and Some Current Issues in French Nuclear Physics"
Jun. 1	Koji Niita University of Giessen Federal Republic of Germany	"Particle Production in Heavy-Ion Collisions from 20 MeV/A to 20 GeV/A"
Jun. 8	Don Hutchinson Division Staff Member	"Status of Cold Fusion Research in the Physics Division"
Jun. 21	Yoshifumi Shimizu Niels Bohr Institute Copenhagen, Denmark	"Effect of Pairing Correlations on Superdeformed Bands"
Jun. 29	Michael W. Guidry Division Staff Member and University of Tennessee, Knoxville, Tennessee	"Lumps, Quivering Lumps, and Berry's Phase: A Simple Introduction to Topological Concepts in Modern Physics"
Jul. 17	Yoshiharu Mori KEK, Tsukuba, Japan	"Japanese Hadron Project"
Jul. 27	Scott Pratt University of Wisconsin Madison, Wisconsin	"Nucleating Nuclear Matter"
Aug. 3	Anders Eklund University of Lund Sweden	"Global and Local Fluctuations in Multiplicity and Transverse Energy for Central Ultrarelativistic Heavy-Ion Interactions"
Aug. 7	Klaus Moelmer Aarhus University Denmark	"Laser Cooling of Ion Beams"
Aug. 24	Knud E. Taulbjerg Aarhus University Denmark	"Translation-Energy Spectroscopy in Highly Charged Ion-Atom Collisions"
Aug. 31	John Briggs University of Bochum Federal Republic of Germany	"Molecular Orbits in Atomic Physics"
Sept. 7	Reiner Dreizler University of Frankfurt Federal Republic of Germany	"Optical Potential Description of Ion-Atom Collisions"
Sept. 11	Hans Weidenmüller University of Heidelberg Federal Republic of Germany	"Chaos in Nuclear Physics"
Sept. 12	John F. Reading Texas A&M University College Station, Texas	"Double Ionization in Proton and Anti-Proton Helium Collisions"
Sept. 14	Werner Scheid University of Giessen Federal Republic of Germany	"Photon and Lepton Production by Bremsstrahlung in Relativistic Heavy-Ion Collisions"
Sept. 26	Michael J. Tannenbaum Brookhaven National Laboratory Upton, Long Island, New York	"E _T Distributions, the Fireball Model, and Other Tidbits from E802"

SCIENTIFIC MEETINGS HELD DURING THIS PERIOD

Workshop on Microscopic Models in Nuclear Structure Physics

Oak Ridge, Tennessee, October 3-6, 1988

M. W. Guidry, J. B. McGrory, M. R. Johnson,
J. H. Hamilton (Vanderbilt),
and D. H. Feng (Drexel), organizers

Town Meeting on High-Energy Heavy Ion Physics

Oak Ridge, Tennessee, April 24-25, 1989

G. R. Young, M. Gyulassy (LBL), and R. L. Robinson, organizers

UNISOR Nuclear Orientation Workshop

Oak Ridge, Tennessee, June 20-23, 1989

K. S. Krane (Oregon State) and H. K. Carter, organizers

Summer School of Computational Atomic and Nuclear Physics

University of the South, Sewanee, Tennessee, June 26-July 7, 1989

C. Bottcher, M. R. Strayer, and J. B. McGrory, organizers

Planning Workshop for GAMMASPHERE

Oak Ridge, Tennessee, September 21-22, 1989

I. Y. Lee, organizer

INFORMATION MEETING

The most recent Physics Division Information Meeting was held on May 8-9, 1989. The members of the Advisory Committee were:

D. Cline, University of Rochester
R. Henry, Auburn University
M. Macfarlane, Indiana University
S. Nagamiya, Columbia University
J. B. Natowitz, Texas A&M University
L. C. Teng, Argonne National Laboratory

PHYSICS DIVISION
OCTOBER 1988

J. B. BALL, DIRECTOR
J. K. THACHER, SEC

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AND PROGRAMS**
E. E. GROSS

**ENGINEERING
COORDINATION**
J. W. JOHNSON*
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W. H. DAVIS
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