LEGIBILITY NOTICE

A major purpose of the Technical Information Center is to provide the broadest dissemination possible of information contained in DOE's Research and Development Reports to business, industry, the academic community, and federal, state and local governments.

Although a small portion of this report is not reproducible, it is being made available to expedite the availability of information on the research discussed herein.

ORNL--6420

DE88 008957

PHYSICS DIVISION

PROGRESS REPORT

for Period Ending September 30, 1987

J. B. Ball Director

F. E. Bertrand	Section Head
S. Datz	Section Head
C. M. Jones	Section Head
J. B. McGrory	Section Head
F. Plasil	Section Head
R. L. Robinson	Section Head

Edited by: A. B. Livingston

Date Published: March 1988

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831
operated by
MARTIN MARIETTA ENERGY SYSTEMS, INC.
for the
U.S. DEPARTMENT OF ENERGY
under Contract No. DE-AC05-84OR21400

MASTER

2P

Reports previously issued in this series are as follows:

ORNL 2718	Period Ending March 10, 1959
ORNL-2910	Period Ending February 10, 1960
ORNL-3085	Period Ending February 10, 1961
ORNL-3268	Period Ending January 31, 1962
ORNL-3425	Period Ending May 21, 1963
ORNL-3582	Period Ending January 31, 1964
ORNL-3778	Period Ending December 13, 1964
ORNL-3924	Period Ending December 31, 1965
ORNL-4082	Period Ending December 31, 1966
ORNL-4230	Period Ending December 31, 1967
ORNL-4395	Period Ending December 31, 1968
ORNL-4513	Period Ending December 31, 1969
ORNL-4659	Period Ending December 31, 1970
ORNL-4743	Period Ending December 31, 1971
ORNL-4844	Period Ending December 31, 1972
ORNL-4937	Period Ending December 31, 1973
ORNL-5025	Period Ending December 31, 1974
ORNL-5137	Period Ending December 31, 1975
ORNL-5306	Period Ending June 30, 1977
ORNL-5498	Period Ending December 31, 1978
ORNL-5787	Period Ending June 30, 1981
ORNL-6004	Period Ending September 30, 1983
ORNL-6120	Period Ending September 30, 1984
ORNL-6233	Period Ending September 30, 1985
ORNL-6326	Period Ending September 30, 1986

CONTENTS

INTRODUCTION	xv
--------------------	----

1. HOLIFIELD HEAVY ION RESEARCH FACILITY

ACCELERATOR OPERATIONS AND DEVELOPMENT

Overview — R. L. Robinson, C. M. Jones, J. A. Martin	1
Accelerator Operations — G. D. Alton, J. A. Biggerstaff, S. L. Birch, M. R. Dinehart, D. T. Dowling, H. D. Hackler, C. L. Haley, D. L. Haynes, D. E. Hoglund, E. D. Hudson, C. A. Irizarry, C. M. Jones, M. L. Jones, R. C. Juras, S. M. Lane, C. T. LeCroy, C. A. Ludemann, C. A. Maples, J. A. Martin, R. L. McPherson, M. J. Meigs, G. D. Mills, S. W. Mosko, S. N. Murray, D. K. Olsen, N. F. Ziegler	2
Tandem Accelerator — G. D. Alton, J. A. Biggerstaff, D. L. Haynes, D. E. Hoglund, C. M. Jones, R. C. Juras, R. L. McPherson, M. J. Meigs, G. D. Mills, N. F. Ziegler	3
ORIC Accelerator — D. T. Dowling, C. A. Giles, E. D. Hudson, S. M. Lane, C. A. Ludemann, J. A. Martin, S. W. Mosko, D. K. Olsen	4
Tests of Compressed Geometry Acceleration Tubes in the Tandem Accelerator — C. M. Jones, J. E. Raatz, D. L. Haynes, R. D. Rathmell, N. F. Ziegler	7
Recent Electronic Improvements to the Oak Ridge 25URC Accelerator — N. F. Ziegler, G. K. Schulze, J. W. Rochelle, W. T. Milner, M. J. Meigs, R. L. McPherson, R. C. Juras	9
Evolution and Development of the Oak Ridge 25URC Tandem Accelerator Control System — R. C. Juras, N. F. Ziegler, M. J. Meigs, R. L. McPherson, D. E. Hoglund, J. A. Biggerstaff	10
Charge-State Distributions of 240 and 300 MeV Neodymium Ions Emerging from Thin Carbon Folios — J. A. Martin	10
Evaluation of Techniques for Sputter Generation of the Hydrides of Ca, Mg, Ti, and Zr — G. D. Alton, J. Allen, G. D. Mills	12
The Emittances of Ion Beams Extracted from High-Intensity Negative Ion Sources — G. D. Alton, J. W. McConnell, R. W. Sayer	14
A Mathematical Model for Determining Work Function Changes by Electropositive Adsorbates — G. D. Alton	15
Secondary Negative Ion Generation Modeling Studies — G. D. Alton, D. H. Olive	19
A Scaled Sigmund Theory Model for Determining Sputter Ratios — G. D. Alton, D. H. Olive	21
The Emittances of Needle-Type, Liquid-Metal Ion Sources — G. D. Alton, P. M. Read	24

FACILITY OPERATIONS AND DEVELOPMENT

HHIRF Experiments — R. L. Robinson	27
Experimental Facilities — R. L. Auble, N. R. Johnson, H. J. Kim, H. K. Carter, R. W. Miles, M. E. Whitley, I. C. Girit, R. L. Robinson, D. L. Haynes, J. L. Blankenship, M. L. Halbert, J. W. Johnson, D. Shapira, C. A. Reed, I. Y. Lee, J. Kormicki, P. L. Pepmiller, C. R. Vane	30

Computer Systems — J. A. Biggerstaff, W. H. Atkins, D. M. Galbraith, J. W. McConnell, J. B. McGrory, W. T. Milner, C. M. Thomas	32
The Joint Institute for Heavy Ion Research — R. L. Robinson, J. H. Hamilton, L. L. Riedinger	33
The Program Advisory Committee — R. L. Robinson	33

2. EXPERIMENTAL NUCLEAR PHYSICS

NUCLEAR STRUCTURE STUDIES VIA ELASTIC AND INELASTIC SCATTERING

Coulomb Excitation of Giant Resonances in ^{208}Pb by $E = 84$ MeV/Nucleon ^{170}O Projectiles — D. J. Horen, J. R. Beene, F. E. Bertrand, R. L. Auble, B. L. Burks, J. Gomez del Campo, M. L. Halbert, R. O. Sayer, J. Barrette, N. Alamanos, F. Auger, B. Fernandez, A. Gillibert, W. Mittig, Y. Schutz, B. Haas, J. P. Vivien	37
Photon Decay of Isovector Giant Resonances in ^{208}Pb — J. R. Beene, F. E. Bertrand, R. L. Auble, B. L. Burks, J. Gomez del Campo, M. L. Halbert, D. J. Horen, R. O. Sayer, J. Barrette, N. Alamanos, F. Auger, B. Fernandez, A. Gillibert, W. Mittig, Y. Schutz, B. Haas, J. P. Vivien	41
Electromagnetic Decay of the Giant Resonance Region in Nuclei — R. L. Varner, J. R. Beene, R. L. Auble, F. E. Bertrand, B. L. Burks, M. L. Halbert, D. C. Hensley, D. J. Horen, R. L. Robinson, R. O. Sayer	43
Calculation of Ground State Gamma Yields in Giant Resonance Decay — J. R. Beene	44
Neutron Decay of Giant Resonances in ^{208}Pb — A. Bracco, J. R. Beene, F. E. Bertrand, M. L. Halbert, D. C. Hensley, R. L. Auble, D. J. Horen, R. L. Robinson, R. O. Sayer	47
Comment on the Characterization of the Giant Quadrupole Resonance in ^{208}Pb as Reported from π^+/π^- Scattering — D. J. Horen, J. R. Beene, F. E. Bertrand	47
First Quantitative Study of $T = 1$, Spin-Dipole Strength in ^{40}Ca — D. J. Horen, J. Lisantti, R. L. Auble, F. E. Bertrand, B. L. Burks, E. E. Gross, R. O. Sayer, D. K. McDaniels, K. W. Jones, J. B. McClelland, S. J. Seestrom-Morris, L. W. Swenson	49
Near Exhaustion of the 0^+_{h} M1 Strength in ^{28}Si — J. Lisantti, D. J. Horen, F. E. Bertrand, B. L. Burks, C. W. Glover, D. K. McDaniels, L. W. Swenson, X. Y. Chen, O. Hausser, K. Hicks	53
Giant Resonance Strength Distributions in ^{28}Si and ^{40}Ca as Determined with Intermediate Energy Protons — J. Lisantti, F. E. Bertrand, D. J. Horen, R. L. Auble, B. L. Burks, E. E. Gross, R. O. Sayer, C. W. Glover, D. K. McDaniels, K. W. Jones, J. B. McClelland, S. J. Seestrom-Morris, L. W. Swenson, X. Y. Chen, O. Hausser, K. Hicks	53
Extraction of Giant Resonance Cross Sections for ^{208}Pb Using a Surface Response Model — L. W. Swenson, X. Y. Chen, J. Lisantti, D. K. McDaniels, I. Bergqvist, F. E. Bertrand, D. J. Horen, E. E. Gross, C. Glover, R. O. Sayer, B. L. Burks, O. Hausser, K. Hicks, M. J. Iqbal	55
Nuclear Response Mechanism and Medium Effects — X. Y. Chen, L. W. Swenson, F. Farzanpay, D. K. McDaniels, Z. Tang, Z. Xu, D. M. Drake, I. Bergqvist, A. Brockstedt, F. E. Bertrand, D. J. Horen, J. Lisantti, K. Hicks, M. Vetterli, M. J. Iqbal	57
Collective Model DWBA Analysis of 500 MeV Proton Scattering from ^{40}Ca — J. Lisantti, 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, L. W. Swenson	58
Validity of Collective Model DWBA Analysis for Intermediate Energy Proton Scattering to Low-Lying States of ^{208}Pb — D. K. McDaniels, J. Lisantti, I. Bergqvist, L. W. Swenson, X. Y. Chen, D. J. Horen, F. E. Bertrand, E. E. Gross, C. Glover, R. Sayer, B. L. Burks, O. Hausser, K. Hicks	60

Use of the Spin Spectrometer to Study Inelastic Scattering of Heavy Ions on ^{208}Pb — D. C. Hensley, E. E. Gross, G. Vourvopoulos	60
Inelastic Scattering of ^{24}Mg from ^{208}Pb — G. S. Vourvopoulos, D. C. Hensley, E. E. Gross	64
Coupled Channels Analysis of ^{24}Mg Scattering from ^{208}Pb at 200 MeV Lab — E. E. Gross, D. C. Hensley, M. L. Halbert, J. R. Beene, F. E. Bertrand, G. Vourvopoulos, D. Humphrey, T. VanCleve	65
Single and Correlated Spin Alignments for Resonances in $^{24}\text{Mg} + ^{24}\text{Mg}$ Inelastic Scattering — A. H. Muosmaa, R. W. Zurmuhle, P. H. Kutt, S. F. Pate, S. Saini, M. L. Halbert, D. C. Hensley	67
Properties of the Neutron Single-Particle States in ^{208}Pb from an Extrapolation of the Optical Potential — C. H. Johnson, D. J. Horen, C. Mahaux	67
Dispersion Relation Predictions of Scattering Functions for Neutrons on ^{86}Kr — R. Carlton, C. H. Johnson, R. R. Winters	69
Evidence for Parity Dependence in the Imaginary Part of the Neutron Optical Potential — R. R. Winters, C. H. Johnson	70
Global Parameterization of the Nucleon-Nucleus Optical Model Potential — R. L. Varner, W. J. Thompson, T. B. Clegg, T. L. McAbee	71
Global Set of B_2 Values for Even-Even Nuclei — S. Raman, C. W. Nestor, Jr., K. H. Bhatt	72
Elastic Scattering of ^{58}Ni on ^{27}Al at Near- and Below-Barrier Energies — J. Gomez del Campo, P. H. Stelson, G. R. Satchler, H. Kim, D. Shapira	73

NUCLEAR STRUCTURE STUDIES VIA CHARGE-EXCHANGE REACTIONS

The $(\bar{p},n)$ Reaction on Carbon Isotopes at $E_p = 160$ MeV — J. Rapaport, D. Wang, J. A. Carr, F. Petrovich, C. C. Foster, C. D. Goodran, C. Gaarde, J. Larsen, C. A. Goulding, T. M. Taddeucci, D. Horen, E. Sugarbaker	74
The (p,n) Reaction as a Probe of Beta Decay Strength — T. M. Taddeucci, C. A. Goulding, T. A. Carey, P. C. Byrd, C. D. Goodman, C. Gaarde, J. Larsen, D. Horen, J. Rapaport, E. Sugarbaker	75
Gamow-Teller Strength Distribution in ^{84}Kr and the Consequences for a ^{81}Br Solar Neutrino Detector — D. Krofcheck, E. Sugarbaker, A. J. Wagner, J. Rapaport, D. Wang, J. N. Bahcall, R. C. Byrd, C. C. Foster, C. D. Goodman, C. Gaarde, D. J. Horen, T. Carey, T. M. Taddeucci	75
The $^{52,54}\text{Cr}(p,n)^{52,54}\text{Mn}$ and $^{57,58}\text{Fe}(p,n)^{57,58}\text{Co}$ Reactions at $E_p = 120$ MeV — D. Wang, J. Rapaport, D. J. Horen, B. A. Brown, C. Gaarde, C. D. Goodman, E. Sugarbaker, T. M. Taddeucci	76

NUCLEAR STRUCTURE STUDIES VIA TRANSFER AND CAPTURE REACTIONS

Single-Nucleon Transfer Reactions Induced by 376-MeV ^{17}O on ^{208}Pb — M. A. G. Fernandes, F. E. Bertrand, R. L. Auble, R. O. Sayer, B. L. Burks, D. J. Horen, E. E. Gross, J. L. Blankenship, D. Shapira, M. Beckerman	76
Quasi-Elastic Interactions Between Heavy Ions at Subbarrier Energies — H. J. Kim, P. H. Stelson, J. Gomez del Campo, D. Shapira, M. Hindi	76
Direct Thermal Neutron Capture — S. Raman, S. Kahane, J. E. Lynn	77
Analysis of Primary Electric Dipole Gamma Rays from Slow-Neutron Capture by Ca Isotopes — S. Kahane, J. E. Lynn, S. Raman	78
Nuclear Structure of ^{208}Pb from $^{207}\text{Pb} + n$ Resonances — R. Kohler, J. A. Wartena, H. Weigmann, L. Lewissen, F. Poortmans, J. P. Theobald, S. Raman	78

Population of High-Spin States in the Actinide Region by Heavy-Ion Transfer Reactions — C. Y. Mu, X. T. Liu, S. P. Sorensen, R. W. Kincaid, M. W. Guidry, D. Cline, W. J. Kernan, E. Vogt, T. Czosnyka, A. E. Kavka, M. A. Stoyer, J. O. Rasmussen, M. L. Halbert	79
Oscillating Two-Neutron Transfer Probabilities at Large Radial Separation in Heavy-Ion Reactions — C. Y. Mu, S. P. Sorensen, M. W. Guidry, W. J. Kernan, T. Czosnyka, B. Kotlinski, X. T. Liu, R. W. Kincaid, D. Cline, E. Vogt, A. E. Kavka	79
Two-Neutron Pairing Enhancement Factors — X. T. Liu, C. Y. Mu, X. L. Han, R. W. Kincaid, S. P. Sorensen, M. W. Guidry, D. Cline, W. J. Kernan, E. Vogt, T. Czosnyka, A. E. Kavka	81
Two-Neutron Transfer in Sn+Sn Collisions — X. L. Han, C. Y. Mu, X. T. Liu, R. W. Kincaid, S. Juutinen, S. P. Sorensen, M. W. Guidry, D. Cline, W. J. Kernan, T. Czosnyka, A. E. Kavka, M. A. Stoyer, J. O. Rasmussen, M. L. Halbert, D. C. Hensley	83

NUCLEAR STRUCTURE STUDIES VIA COMPOUND NUCLEUS REACTIONS

Gamma-Ray Measurements on the High-Spin States of ^{172}Os — J. C. Wells, A. Virtanen, M. R. Johnson, M. Riley, F. K. McGowan, C. Baktash, I. Y. Lee	84
Spin and Excitation Energy Dependence of Continuum Gamma-Ray Correlations — I. Y. Lee, C. Baktash, J. R. Beene, M. L. Halbert, D. C. Hensley, M. R. Johnson, F. K. McGowan, D. G. Sarantites	85
Transition Quadrupole Moments of High-Spin States in ^{170}W — F. K. McGowan, M. R. Johnson, M. N. Rao, I. Y. Lee, C. Baktash, J. C. Wells, M. Kortelahti, V. P. Janzen	87
Shape Changes, Band Terminations and Transition Rates in ^{157}Tm — M. A. Riley, C. Baktash, Y. A. Ellis-Akovali, P. L. Halbert, D. C. Hensley, M. R. Johnson, I. Y. Lee, F. K. McGowan, V. P. Janzen, L. L. Riedinger, L. Chaturvedi	89
Search for Superdeformed Shapes in ^{144}Gd — V. Schutz, C. Baktash, I. Y. Lee, M. L. Halbert, D. C. Hensley, M. R. Johnson, M. Oshino, R. Ribas, J. C. Lisle, L. Adler, K. Honkanen, D. G. Sarantites, A. J. Larabee, J. A. Saladin	90
High-Spin Spectroscopy in $^{179,181}\text{Ir}$ and ^{181}Au — V. P. Janzen, C. R. Bingham, M. P. Carpenter, K. Hart, H. Q. Jin, L. L. Riedinger, L. Zhou, C. Baktash, M. L. Halbert, M. R. Johnson, I. Y. Lee, F. K. McGowan, M. A. Riley	90

NUCLEAR STRUCTURE STUDIES VIA RADIOACTIVE DECAY

Identification of ^{182}Pb in ^{40}Ca Irradiations of ^{147}Sm — K. S. Toth, D. M. Moltz, F. Blonnigen, F. T. Avignone, III	92
Observation of ^{149}Tm Decay to ^{149}Er Levels and β -Delayed Proton Emission — K. S. Toth, J. Gilat, J. M. Nitschke, P. A. Wilmarth, K. Vierinen, F. T. Avignone, III	92
Masses of ^{77}Kr and ^{75}Kr — D. M. Moltz, A. C. Betker, J. P. Sullivan, R. H. Burch, C. A. Gagliardi, R. E. Tribble, K. S. Toth, F. T. Avignone, III	94
The α -Decay Reduced Width of ^{194}Pb and Low-Spin Levels in ^{194}Tl Populated in ^{194}Pb β Decay — Y. A. Ellis-Akovali, K. S. Toth, H. K. Carter, C. R. Bingham, I. C. Girit, M. O. Kortelahti	95

STRONGLY DAMPED HEAVY-ION REACTIONS, FUSION, FISSION

Are Pions Emitted in the Spontaneous Fission of ^{252}Cf ? — J. R. Beene, C. E. Bemis, Jr., M. L. Halbert	96
Studies of Giant Resonances in Hot Nuclei — J. R. Beene, R. L. Varner, R. L. Auble, F. E. Bertrand, B. L. Burks, M. L. Halbert, D. C. Hensley, I. Y. Lee, H. P. Morsch, D. G. Sarantites, R. O. Sayer, W. Spang, D. W. Stracener	97

Reactions with ^{40}Ar and ^{84}Kr Leading to the same Compound Nucleus, ^{200}Po - R. L. Hahn, K. S. Toth, Y. LeBeyec, B. Legarde, M. W. Guidry	98
Nuclear Shapes from Alpha - Gamma-Ray Angular Correlations - Z. Majka, D. G. Sarantites, L. G. Sobotka, K. Honkanen, E. L. Dines, L. A. Adler, Li Ze, M. L. Halbert, J. R. Beene, D. C. Hensley, R. P. Schmitt, G. Nebbia	99
Nuclear Temperature Measurements and Feeding from Particle Unbound States - H. M. Xu, C. J. Fields, W. G. Lynch, M. B. Tsang, C. K. Gelbke, M. R. Maier, D. J. Morrissey, J. Pochodzalla, D. G. Sarantites, L. G. Sobotka, M. L. Halbert, D. C. Hensley, D. Hahn, H. Stocker	99
Charge and Mass Distribution of Projectilelike Fragments in the Reaction $^{58}\text{Ni} + ^{16}\text{O}$ at 15.7 MeV/Nucleon - V. Penumetcha, G. A. Pettitt, T. C. Aves, R. L. Ferguson, F. E. Obenshain, F. Plasil, G. R. Young	99
Neutron Flow Between Nuclei as the Principal Enhancement Mechanism in Heavy-Ion Subbarrier Fusion - P. H. Stelson	100
Emission of Complex Fragments and Nuclear Temperature Measurements in the $^{58}\text{Ni} + ^{58}\text{Ni}$ Fusion Reaction at 11-MeV/Nucleon - J. Gomez del Campo, J. L. Charvet, A. D'Onofrio, R. L. Auble, J. R. Beene, M. L. Halbert, H. Kim	100
Heavy Residue Masses as Possible Indicators of the Impact Parameter in the Reaction $^{20}\text{Ne} + ^{60}\text{Ni}$ at 742 MeV - A. D'Onofrio, B. Delaunay, J. Delaunay, H. Dumont, J. Gomez del Campo, F. Andreozzi, A. Brondi, R. Moro, M. Romano, F. Terrasi, J. F. Bruandet	103
Evidence for Equilibration of Hot Nuclei - A. D'Onofrio, B. Delaunay, J. Delaunay, H. Dumont, J. Gomez del Campo, A. Brondi, R. Moro, M. Romano, F. Terrasi, J. F. Bruandet	103
Crystal Blocking in Heavy Ion Reactions - J. Gomez del Campo	103
The Angular Momentum Dependence of Complex Fragment Emission - L. G. Sobotka, D. G. Sarantites, Ze Li, E. L. Dines, M. L. Halbert, D. C. Hensley, R. P. Schmitt, Z. Majka, G. Nebbia, H. C. Griffin, A. J. Sierk	104
Particle-Bound Excited State Yields Produced in the Reaction of 181-MeV $^{19}\text{F} + ^{159}\text{Tb}$ - L. G. Sobotka, D. G. Sarantites, H. Puchta, F. A. Dilmanian, M. Jaaskelainen, M. L. Halbert, J. H. Barker, J. R. Beene, R. L. Ferguson, D. C. Hensley, G. R. Young	104
Excitation Energy Division in the Quasielastic Region from Reactions of 12 MeV/Nucleon ^{90}Ti with ^{150}Nd - T. M. Semkow, D. G. Sarantites, K. Honkanen, Z. Li, M. Ross, J. R. Beene, M. L. Halbert, D. C. Hensley	104
Angular Momentum Effects in Subbarrier Fusion - M. L. Halbert, J. R. Beene, D. C. Hensley, K. Honkanen, T. M. Semkow, V. Abenante, D. G. Sarantites, Z. Li	105

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

Two-Proton Correlations in ^{32}S -Induced Reactions at 22.3 MeV/Nucleon - T. C. Aves, Z. Chen, R. L. Ferguson, C. K. Gelbke, W. G. Lynch, F. E. Obenshain, F. Plasil, J. Pochodzalla, S. Pratt, H. M. Xu, G. R. Young	105
Energetic Photon Emission ($E_\gamma > 50$ MeV) - M. Alamanos, T. C. Aves, P. Braun-Munzinger, R. L. Ferguson, R. Freifeider, F. E. Obenshain, P. Paul, F. Plasil, K. Smith, J. Stachel, L. Waters, G. R. Young	107
Neutron Emission in Damped Reactions of $^{58}\text{Ni} + ^{16}\text{O}$ at 15.5 MeV/Nucleon - G. A. Pettitt, C. Butler, V. Penumetcha, T. C. Aves, J. R. Beene, R. L. Ferguson, F. E. Obenshain, F. Plasil, S. P. Sorensen, G. R. Young	108
Light-Particle Multiplicity Accompanying Projectile Breakup at 20 MeV/Nucleon - T. C. Aves, R. C. Connolly, S. Gil, D. Leach, S. P. Sorensen, R. Vandenbosch, C. L. Wu	109

NUCLEAR PHYSICS WITH ULTRARELATIVISTIC PROJECTILES

Performance of the Calorimeters for the Relativistic Heavy-Ion Experiment WA80 at CERN – T. C. Awes, C. Baktash, J. L. Blankenship, R. P. Cumby, R. L. Ferguson, A. Franz, S. Garpman, H. A. Gustafsson, J. W. Johnson, P. Kristiansson, I. Y. Lee, F. E. Obenshain, A. Oskarsson, I. Otterlund, S. Persson, F. Plasil, A. M. Poskanzer, H. G. Ritter, S. P. Sorensen, E. Stenlund, G. R. Young	110
First Heavy-Ion Experiments with the WA80 Setup – 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. Lohner, 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, G. R. Young	113
Energy Measurements in Oxygen-Induced Reactions at 60 A GeV and 200 A GeV – R. Albrecht, T. C. Awes, C. Baktash, P. Beckmann, F. Berger, R. Bock, G. Claesson, L. Dragon, R. L. Ferguson, A. Franz, S. Garpman, R. Glasow, H. A. Gustafsson, H. H. Gutbrod, J. W. Johnson, K. H. Kampert, B. W. Kolb, P. Kristiansson, I. Y. Lee, H. Lohner, 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, G. R. Young	115

MISCELLANEOUS TOPICS

Studies of the Channeling Characteristics of 400 MeV/Nucleon Uranium Ions in Single Crystals of Si and Fe – C. E. Bemis, Jr., J. Gomez del Campo, C. A. Ludemann, C. R. Vane, H. Gould, B. Feinberg, M. Claytor	120
Search for Axions from the 1115 keV Transition of ^{65}Cu – F. T. Avignone, III, C. Baktash, W. C. Barker, F. P. Calaprice, R. W. Dunford, W. C. Haxton, D. Kahana, R. T. Kouzes, H. S. Miley, D. M. Moltz	121

INSTRUMENTATION

Development of Advanced Calorimeters – F. E. Obenshain, G. R. Young	122
Computer Network Connections to HEPnet/PHYSnet – C. E. Bemis, Jr.	122
Procurement of ACP Farm – W. T. Milner, G. R. Young	123
Evaluation of 50-mm-Diameter Photomultiplier Tubes for BaF_2 Scintillator Spectroscopy and Timing Applications – J. L. Blankenship	123
Progress on HILL – D. Shapira, H. Kim, J. Mitchell, J. W. McConnell, R. Novotny, K. Teh, M. Hindi	124

3. THE UNISOR PROGRAM

Separator Development – M. L. Simpson, H. K. Carter, D. Abraham, J. Kormicki, I. C. Girit, W. B. Newbolt	127
UNISOR Nuclear Orientation Facility – I. C. Girit, D. Abraham, G. D. Alton, C. R. Bingham, H. K. Carter, J. D. Cole, J. H. Hamilton, B. D. Kern, P. F. Mantica, C. A. Reed, M. L. Simpson, E. F. Zganjar	128
Development of a Laser Ion Source for the Separator – W. M. Fairbank, Jr., S. M. Fischer, G. A. Barrera, J. P. Judish, S. L. Allman, H. K. Carter	129
Energy Levels and Structure of Light Rare-Earth Nuclei, $^{136,138,140}\text{Sm}$, Via Beta Decay – B. D. Kern, G. A. Leander, R. L. Miekodaj, H. K. Carter, M. O. Kortelahti, E. F. Zganjar, R. A. Braga, R. W. Fink, C. P. Perez, P. B. Semmes, W. Nazarewicz	131

Energy Levels of Light Rare-Earth Nuclei, $^{132,134,136}\text{Nd}$, Via Beta Decay - B. D. Kern, G. A. Leander, R. L. Miekodaj, M. O. Kortelahti, R. A. Braga, R. W. Fink, P. B. Semmes, W. Nazarewicz	133
Study of Odd Mass Pr, Nd, and Pm Nuclei in the $A = 135$ Region - M. O. Kortelahti, B. D. Kern, R. W. Fink, R. A. Braga, C. P. Perez, H. K. Carter, J. Kormicki	134
Decay of ^{195}Pb to Levels in ^{195}Tl ; Tests of Particle-Core Coupling - C. R. Bingham, H. V. Carmichael, V. P. Janzen, L. L. Riedinger, W. Schmitz, R. A. Braga, R. W. Fink, J. L. Wood, M. O. Kortelahti, E. F. Zganjar, I. C. Girit, H. K. Carter, P. B. Semmes, R. L. Miekodaj	135
Possible Shape Coexistence in ^{195}Pb - J. C. Griffin, C. R. Bingham, R. W. Fink, J. L. Wood, M. O. Kortelahti, H. V. Carmichael	137
Low-Energy E0 Transitions in Odd-A Nuclei: $180 < A < 200$ - E. F. Zganjar, M. O. Kortelahti, J. L. Wood, C. D. Papanicolopoulos	139
Very Converted Transitions in the Neutron Deficient Au Isotopes - C. D. Papanicolopoulos, M. A. Grimm, J. L. Wood, E. F. Zganjar, M. O. Kortelahti, J. D. Cole, H. K. Carter	141
Location of the Excited Deformed Band in ^{199}Hg - M. O. Kortelahti, E. F. Zganjar, C. R. Bingham, H. K. Carter, H. V. Carmichael, D. Brown, R. W. Fink, J. L. Wood, L. Chaturvedi, J. Kormicki, W. B. Newbolt, E. van Walle, K. S. Toth	143
Systematics of the Low-Lying Excited States of $^{185,187,189}\text{Au}$ - M. O. Kortelahti, E. F. Zganjar, H. K. Carter, C. D. Papanicolopoulos, M. A. Grimm, J. L. Wood	144
Strongly Coupled Bands in the Light Au Isotopes - C. D. Papanicolopoulos, J. L. Wood, M. O. Kortelahti, E. F. Zganjar, H. K. Carter	146
Study of Highly Converted Transitions in ^{195}Pt - J. Schwarzenberg, R. W. Fink, J. L. Wood, E. F. Zganjar, M. O. Kortelahti, E. van Walle	147
Spectroscopic Model Analysis of Data on ^{195}Tl and ^{185}Au - P. B. Semmes	148

4. EXPERIMENTAL ATOMIC PHYSICS

ACCELERATOR-BASED ATOMIC PHYSICS

Inelasticity and Angular Distributions for Charge Correlated Multiple Ionization of Ne and Ar by C Ions - R. Schuch, S. Datz, P. F. Dittner, H. F. Krause, P. D. Miller, H. Schone, R. E. Olson	150
Electron Capture, Ionization, and Transfer Ionization in Rapid (0.1 - 1.0 MeV/Nucleon) Highly Charged Ion Collisions with Helium - S. Datz, R. Hippler, L. H. Andersen, P. F. Dittner, H. Knudsen, H. F. Krause, P. D. Miller, P. L. Pepmiller, T. Rosseel, N. Stolterfoht, C. R. Vane	151
Partial Cross Sections for Capture to Specific n States in Collisions of 0.1 and 0.25 MeV/Nucleon Iq^+ Ions with Molecular Hydrogen - P. D. Miller, R. Hippler, S. Datz, P. F. Dittner, H. F. Krause, P. L. Pepmiller	151
Attempted Measurement of Dielectronic Recombination via a $\Delta n = 1$ Transition - P. F. Dittner, S. Datz, H. F. Krause, P. D. Miller, P. L. Pepmiller, C. M. Fou	153
Resonant Transfer and Excitation Cross Section Measurements of the System $\text{F}^{6+} + \text{H}_2$ - M. Schulz, S. Datz, R. Schuch, P. D. Miller, H. Schone	154
High Resolution Spectroscopy of Heavy-Ion Induced X Rays - C. R. Vane, T. Walkiewicz, T. Rosseel, S. Raman, S. Kahane, S. Stewart	154
A Novel High-Resolution Experimental Approach for Studying Laser Photodetachment in a Magnetic Field - H. F. Krause	156

Negative-Ion Structure Measurements Using Crossed-Beam Photoelectron Detachment Spectroscopy — D. J. Pegg, J. S. Thompson, G. D. Alton, K. M. Compton	157
Coincident Detection of Two Highly Excited/Ionized Electrons in Fast Ion Atom/Solid Collisions — M. Breinig, H.-P. Hülskötter, T. Underwood	159
Doubly Differential Convoy Electron Emission Distributions in High Velocity Ion-Solid Collisions: Target Thickness Dependence — S. B. Elston, C. E. González Lepera, J. P. Gibbons, M. Breinig, R. DeSerio, O. Heil, H.-P. Hülskötter, I. A. Sellin, C. R. Vane	160
Observation of Steep Variation of Recoil-Ion Energy on Scattered Ion Charge State in Coincident Multielectron Projectile and Target Ionization Events — C. S. O, J. C. Levin, R. T. Short, H. Cederquist, S. B. Elston, J. P. Gibbons, I. A. Sellin, Horst Schmidt-Böcking	161
EM Tandem Operation — P. D. Miller, P. L. Pepmiller	162

ATOMIC PHYSICS FOR FUSION PROGRAM

Electron Capture Cross Sections for $O^{5+} + H$ and $N^{5+} + H$ at eV Energies Using Merged Beams — C. C. Havener, M. S. Huq, R. A. Phaneuf	163
Electron-Impact Ionization of Multiply Charged Ni Ions — L. J. Wang, K. Rinn, D. C. Gregory	164
Search for Recombination Resonances in Electron-Impact Ionization of O^{5+} — K. Rinn, D. C. Gregory, L. J. Wang, R. A. Phaneuf, A. Müller	166
High Resolution Auger-Electron Spectroscopy of Low-Energy Double-Electron Capture Collisions of Multiply Charged Ions with Neutral Atoms and Molecules — F. W. Meyer, C. C. Havener, J. K. Swenson, D. C. Griffin, M. S. Huq, R. A. Phaneuf, N. Stolterfoht	167
Studies of Low-Energy Multicharged Ion-Surface Interactions by Ejected-Electron Spectroscopy — F. W. Meyer, C. C. Havener, D. M. Zehner, S. H. Overbury, K. J. Snowden, W. Heiland	168
ECR Ion Source Upgrade: Addition of New User Beam Lines — J. K. Swenson, F. W. Meyer, J. W. Hale	170

5. THEORETICAL PHYSICS

COMPUTATIONAL AND MATHEMATICAL PHYSICS

Relativistic Theory of Fermions and Classical Fields on a Collocation Lattice — C. Bottcher, M. R. Strayer	172
Atomic Time-Dependent Hartree-Fock Calculations in Three Space Dimensions — C. Bottcher, M. R. Strayer	172
Calculation of Continuum Excitation Amplitudes for Time-Dependent External Field Problems — C. Bottcher, M. R. Strayer, A. S. Umar, V. E. Oberacker	173
Periodic Trajectories for a Two-Dimensional Nonintegrable Hamiltonian — M. Baranger, K.T.R. Davies	174
Bifurcations of Periodic Trajectories in Nonintegrable Hamiltonian Systems with Two Degrees of Freedom: Numerical and Analytical Results — M.A.M. de Aguiar, C. P. Malta, M. Baranger, K.T.R. Davies	175
Complex-Plane Methods for Evaluating Integrals with Highly Oscillatory Integrands — K.T.R. Davies	175
Evaluation of a Class of Integrals Occurring in Mathematical Physics via a Higher-Order Generalization of the Principal Value — K.T.R. Davies, R. W. Davies	175

LOW-ENERGY, HEAVY-ION REACTIONS

Isospin and Macroscopic Models for the Excitation of Giant Resonances and Other Collective States — G. R. Satchler	176
Effects of Density Dependence of the Effective Interaction in a Macroscopic Folding Model for the Excitation of Giant Resonances and Other Collective States — M. E. Farid, G. R. Satchler	176
The Threshold Anomaly and the Effective Interaction for Nuclear Nonelastic Scattering — G. R. Satchler	177
An Optical Model Analysis of $^{16}\text{O} + ^{12}\text{C}$ Elastic Scattering at $E/A = 94$ MeV — A. M. Kobos, G. R. Satchler	177
Further Optical Model Studies of ^{16}O Scattering at $E/A = 94$ MeV — A. M. Kobos, M. E. Brandan, G. R. Satchler	178
Folding Model Analysis of $^{12}\text{C}-^{12}\text{C}$ and $^{16}\text{O}-^{12}\text{C}$ Elastic Scattering at Intermediate Energies Using a Density-Dependent Interaction — M. E. Brandan, G. R. Satchler	179
Enhanced Dissipation in New Mean Field Studies of Strongly Damped Collisions — S. J. Lee, A. S. Umar, K.T.R. Davies, M. R. Strayer, P. G. Reinhard	179

NUCLEAR STRUCTURE

Tails of the Rotational Strength Function in the Nuclear Quasicontinuum — G. A. Leander, P. Arve, B. Lauritzen	180
Simulation of Nuclear Quasicontinuum Gamma-Ray Spectra — G. A. Leander	180
Statistical E1 and M1 Gamma Strength Functions from Heavy-Ion, xny Data — G. A. Leander	180
Cranked Shell Model at Finite Temperature — T. Bengtsson, Y. S. Chen, G. A. Leander, J. Y. Zhang	181
Octupole Shapes and Shape Changes at High Spins in Ra and Th Nuclei — W. Nazarewicz, G. A. Leander, J. Dudek	181
Abundance and Systematics of Nuclear Superdeformed States; Relation to the Pseudo-Spin and Pseudo-SU(3) Symmetries — J. Dudek, W. Nazarewicz, Z. Szymanski, G. A. Leander	181
Collective Oblate Band in ^{131}La Due to the Rotational Alignment of $h_{11/2}$ Neutrons — E. S. Paul, C. W. Beusang, D. B. Fossan, R. Ma, W. F. Piel, Jr., W. Xu, L. Hildingsson, G. A. Leander	182
Fermion Dynamical Symmetry for Odd-Mass Nuclei — H. Wu, Z. P. Li, D. H. Feng, C. L. Wu, M. W. Guidry	182
An Algebraic Fermion Description of Band Termination and Loss of Collectivity in Heavy Nuclei — M. W. Guidry, Z. P. Li, C. L. Wu, D. H. Feng, J. N. Ginocchio	183
A Microscopic Formula for Actinide Masses — C. L. Wu, Z. P. Li, X. L. Han, M. W. Guidry, D. H. Feng	185
Calculation of Transition Probabilities for High-Spin States in ^{183}Ir and ^{185}Pt — F. Dönau, Y. S. Chen, P. Semmes, V. P. Janzen, L. L. Riedinger, M. P. Carpenter, G. A. Leander	186
Extension of Self-Consistent TRS Calculations to Te, Xe, and Nd Nuclei — V. P. Janzen, M. P. Carpenter, Y. S. Chen, G. Zhang, L. L. Riedinger, J.-Y. Zhang	188

INTERMEDIATE-ENERGY, HEAVY-ION REACTIONS

Perturbative Production of γ 's and π^0 's in Heavy-Ion Reactions — D. J. Ernst, M. R. Strayer	192
---	-----

Model Calculations for Products of One-Body Nucleon Green's Functions — G. D. White, K.T.R. Davies	193
Integral Methods for Calculations of Green's Functions in Pion-Nucleon Problems I — K.T.R. Davies, M. R. Strayer, G. D. White	193

PHYSICS OF RELATIVISTIC PROJECTILES

Pulsed Electromagnetic Production of Leptons in Ultrarelativistic Ion-Ion Collisions — C. Bottcher, M. R. Strayer	194
Particle Production in a Finite Constant Field — R. C. Wang, C. Y. Wong, C. M. Yo	196
Theoretical Aspects of High-Energy, Heavy-Ion Reactions — C. Y. Wong	197
Nuclear Stopping Power in High-Energy Collisions — C. Y. Wong	197

ATOMIC PHYSICS

Role of Projectile $\bar{K}$ -Electrons in Single and Double K to $\bar{K}$ Transfer: Comparison of Passive K-Electron Models and of the IFPM with Data for $Cl^{17+}, 16+, 15+, 14+ \rightarrow Ti$ — R. L. Becker	197
Calculations of Coincident Ionization Plus Excitation — R. L. Becker	197
Several Manifestations of Pauli Correlations in Energetic Ion-Atom Collisions — R. L. Becker	198
Analysis of Coulomb Explosions of Polyatomic Molecules — C. Bottcher	198
Caustics in the Coulomb Three-Body Problem — C. Bottcher	199
Production of High-Angular Momentum Rydberg and Continuum States by Stochastic Collisions — J. Burgdörfer, C. Bottcher	199
Distorted-Wave Calculations of the Electron-Impact Ionization of Highly Ionized Na-like Ions — D. C. Griffin, M. S. Pindzola, C. Bottcher	200
Electron-Impact Ionization in the Iron Isonuclear Sequence — M. S. Pindzola, D. C. Griffin, C. Bottcher	201
Electron-Ion Collisions in the Average-Configuration Distorted-Wave Approximation — M. S. Pindzola, D. C. Griffin, C. Bottcher	201
Ionization in Collisions between Electrons and Complex Ions — C. Bottcher, D. C. Griffin, M. S. Pindzola	201
Double-Auger Processes in the Electron-Impact Ionization of Lithium-Like Ions — M. S. Pindzola, D. C. Griffin	202
Theoretical Calculations of Indirect Processes in Electron-Impact Ionization of Atomic Ions — M. S. Pindzola, D. C. Griffin, C. Bottcher	202

PHYSICS OF e^+e^- SYSTEMS

Nonperturbative Covariant Treatment of the Triplet e^+e^- System Using Two-Body Dirac Equations from Constraint Dynamics — H. W. Crater, C. Y. Wong, R. L. Becker, P. Van Alstine	202
Variational Theory of Multicomponent Quantum Fluids: An Application to Positron-Electron Plasma at $T = 0$ — L. J. Lantto	203

6. FUSION PLASMA DIAGNOSTICS DEVELOPMENT	
Development of a Diagnostic for Fusion-Product Alpha Particles Based on Pulsed CO ₂ -Laser Thomson Scattering — R. K. Richards, D. P. Hutchinson, H. T. Hunter, K. L. Vander Sluis, C. A. Bennett	204
Multichannel Interferometer System Development for ATF — C. H. Ma, D. P. Hutchinson, W. H. Casson, K. L. Vander Sluis, J. Lee	205
Feasibility Study of an Infrared Interferometer/Polarimeter System for the Compact Ignition Tokamak — C. H. Ma, D. P. Hutchinson, K. L. Vander Sluis	205
7. HIGH ENERGY PHYSICS	
H. O. Cohn	208
8. COMPILATIONS AND EVALUATIONS	
Controlled-Fusion Atomic Data Center — C. F. Barnett, H. B. Gilbody, D. C. Gregory, C. C. Havener, H. T. Hunter, M. S. Huq, R. K. Janev, M. I. Kirkpatrick, E. W. McDaniel, F. W. Meyer, T. J. Morgan, P. A. Phaneuf, M. S. Pindzola, J. K. Swenson, E. W. Thomas	210
Nuclear Data Project — Y. A. Ellis-Akova, M. R. Lay, M. J. Martin, M. R. Schmorak	211
9. ACCELERATOR DESIGN AND DEVELOPMENT	
HISTRAP Accelerator Physics Design Studies — I. Y. Lee, J. A. Martin, J. B. McGrory, D. K. Olsen, G. R. Young	213
HISTRAP Prototype Hardware Studies — W. H. Atkins, D. T. Dowling, P. F. Dittner, J. W. Johnson, R. C. Juras, R. S. Lord, J. A. Martin, J. W. McConneil, S. W. Mosko, D. K. Olsen, P. L. Pepmiller	216
ECR Beam Development for Synchrotron Injection — F. W. Meyer	220
Negative Ion Pulsing Studies for Synchrotron Injection — G. D. Alton	221
10. PUBLICATIONS	223
11. PAPERS PRESENTED AT SCIENTIFIC AND TECHNICAL MEETINGS	245
12. GENERAL INFORMATION	257

INTRODUCTION

This report covers the research and development activities of the Physics Division for the 1987 fiscal year, beginning October 1, 1986, and ending September 30, 1987. The activities of this Division are concentrated in the areas of experimental nuclear physics, experimental atomic physics, and theoretical nuclear and atomic physics.

A major activity within the Division is operation of the Holifield Heavy Ion Research Facility as a national user facility. Highlights for this year, which include a record number of beam hours provided for research, are summarized in Chapter 1.

The experimental nuclear physics program continues to be dominated by research utilizing heavy ions. These activities, while continuing to center largely on the Holifield Facility, have seen growth in the use of facilities that provide intermediate energies (GANIL) and ultrarelativistic beams (CERN). Results of this work are presented in Chapter 2.

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

In addition to the Holifield Facility, the Division also operates two smaller facilities, the EN Tandem and the ECR Ion Source Facility, as "User Resources." The tandem continues a long history of supporting research in accelerator-based atomic physics. During this past year, new beam lines have been added to the ECR ion source to create user opportunities for atomic physics experiments with this unique device. These two facilities and the experimental programs in atomic physics are discussed in Chapter 4.

The efforts in theoretical physics, covering both nuclear and atomic physics, are presented in Chapter 5. Also included here is the theory effort in support of the UNISOR structure program. Much of this work maintains a strong tradition of emphasizing computational aspects of theoretical physics.

In addition to research with multicharged heavy ions from the ECR source, the effort on atomic physics in support of the controlled fusion program includes a plasma diagnostics development program, summarized in Chapter 6, and operation of an atomic physics data center, described in Chapter 8. The nuclear physics program also operates a compilation and evaluation effort; this work, in support of the National Nuclear Data Center, is also described in Chapter 8. A small, continuing effort in elementary particle physics is reported in Chapter 7.

The 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 efforts on optimizing the ring design and on component prototyping are presented in Chapter 9.

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

J. B. Ball
February 1988

1. HOLIFIELD HEAVY ION RESEARCH FACILITY

ACCELERATOR OPERATIONS AND DEVELOPMENT

OVERVIEW

R. L. Robinson C. M. Jones
J. A. Martin

Operation of the Holifield facility continued to improve in FY 1987 with a record high 4591 hours of beam available for research (up 10% from FY 1986) and a record low 361 hours of unscheduled maintenance (68% of the FY 1986 value). The average number of hours of beam available for research in a research week was 125, also a record high.

Eighty-four experimental runs were completed in FY 1987, involving 150 different researchers. Of this group, 36 were graduate students. The institutions represented by the group are summarized in Table 1.1.

Extensive use was made of the negative ion source preparation facility for ion source and off-line beam development. As a result, the facility can respond more rapidly to requests from users for new beams. During the year, seven new ion species were provided for the experimental program, making a total number of 61 different ion species to date.

The newly completed chopper/buncher system, designed to provide pulsed tandem beams at 1- or 4-MHz pulse rate, was used for the first time to provide pulsed beams (^{80}Se and ^{82}Se) for an experiment. The pulse width was 4.5 ns at fwhm. There was no evidence of dark current between the pulses. It is probable that about a factor of two better time resolution could be achieved for light heavy ions.

Phase two of the compressed geometry acceleration tube program was successfully completed;

one-third of the tandem accelerator acceleration tubes have now been replaced with tubes of the improved design. Testing of these tubes indicates an improvement in voltage capability of approximately 14%, a value which is consistent with the increase in effective insulator length which the reconfiguration provides. Based on the tests associated with phases one and two, a design has been chosen for the third and final phase of the program, to be completed in FY 1988. In this final phase, conversion of all acceleration tubes to compressed geometry will be completed.

Assembly of two new major experimental devices, the heavy-ion/light-ion detector system (HILI) and the Nuclear Orientation Facility (NOF), were completed in FY 1987. The HILI is a combination of parallel-plate avalanche counters (PPACs), ion chambers, and a hodoscope of 96 scintillator-scintillator telescopes. This system can detect many (all in some cases) light particles emitted in a single event in coincidence with heavy fragments. The NOF, utilizing a He refrigerator, aligns nuclei that are extracted from a mass separator (the UNISOR facility).

On February 18-20, 1987, the Holifield Facility underwent a review by a committee appointed by DOE. The committee's written report proved to be extremely positive concerning the facility, reflecting the high quality of the facility's scientific programs and the involvement of its users and their institutions in its activities. The HHIRF staff was pleased by this report and remains committed to our established tradition of providing a "user-friendly," forefront facility to meet the needs of the physics community.

Table 1.1. Number of researchers from different institutions who participated in experiments at the MHIRF in the twelve-month period between October 1, 1986 and September 30, 1987

Institutions	Number of Researchers
U.S. UNIVERSITIES	
Alabama A&M University	2
Eastern Kentucky University	1
Edinboro University	1
Georgia State University	3
Georgia Institute of Technology	6
JIHIR	1
Louisiana State University	2
ORAU	2
Oregon State University	1
Stanford University	1
Tennessee Technical University	2
Texas A&M University	2
University of California at Berkeley	1
University of Florida	1
University of Kentucky	1
University of Maryland	4
University of Pennsylvania	5
University of Rochester	5
University of Tennessee	19
University of Virginia	1
Vanderbilt University	11
Washington University	10
Washington & Lee University	1
Western Kentucky University	3
Yale University	2
	<u>88</u>
NATIONAL LABORATORIES	
INEL	2
ORNL	39
	<u>41</u>
NON-U.S. INSTITUTES	
Australian National Univ. (Australia)	1
Bruyeres-Le-Chatel (France)	2
Chalk River Nuclear Lab. (Canada)	1
ETH (Switzerland)	1
Inst. Atomic Energy (China)	1
Inst. Kernphysik, Julich (Germany)	2
Katholieke Univ. (Belgium)	1
Niels Bohr Inst. (Denmark)	3
Physics Inst. (Naples)	1
Ruder Boskovic Inst. (Yugoslavia)	1
Univ. of Frankfurt (Germany)	1
Univ. of Giessen (Germany)	1
Univ. of Jyvaskyla (Finland)	1
Univ. of Melbourne (Australia)	3
	<u>20</u>
OTHER	
Texas Instruments	1
Total	<u>150</u>

ACCELERATOR OPERATIONS

G. D. Alton	R. C. Juras ²
J. A. Biggerstaff	S. N. Lane
S. L. Birch	C. T. LeCroy
M. R. Dinehart	C. A. Ludemann
D. T. Dowling	C. A. Maples
H. D. Hackler	J. A. Martin
C. L. Haley	R. L. McPherson
D. L. Haynes	M. J. Meigs ²
D. E. Hoglund ¹	G. D. Mills
E. D. Hudson	S. W. Mosko
C. A. Irizarry	S. N. Murray
C. M. Jones	D. K. Olsen
N. L. Jones	N. F. Ziegler

Facility operating statistics for the current reporting period, FY 1987, are shown in Tables 1.2 and 1.3. Highlights for this year include a record 4591 hours of beam available for research and a further reduction of total unscheduled maintenance (tandem accelerator + cyclotron) to 361 hours, 68% of the value achieved in FY 1986.

A summary of beams provided for research in FY 1986 is provided in Table 1.4. During this period, 30 ion species, ranging in mass from ^1H to ^{150}Nd , were provided for research. Of these, seven were provided for the first

Table 1.2. Tandem accelerator utilization for the period October 1, 1986 through September 30, 1987

	Hours	Percent
Beam available for research (tandem-alone and coupled operation)	4591	53
Beam available during ORIC tuning (coupled operation)	326	4
Accelerator tuning (includes scheduled startup-shutdown)	715	8
Machine studies (includes conditioning not required for specific experiments)	555	6
Total operating time	6187	71
Unscheduled maintenance	253	3
Scheduled maintenance	1940	22
Scheduled shutdown	380	4

Table 1.3. Cyclotron utilization for the period October 1, 1986, through September 30, 1987

	Hours	Percent
Beam available for research (coupled operation)	1292	15
Accelerator tuning (includes scheduled startup-shutdown and operation during tandem tuning)	379	4
Machine studies	25	0
Unscheduled maintenance	108	1
Scheduled shutdown and maintenance	6956	80

Table 1.4. Beams provided for research for the period October 1, 1986, through September 30, 1987

Ion Species	Maximum Energy (MeV)	Mode*	Provided for first time in this period
¹ H	24	T	
⁷ Li	128	T,C	
¹² C	140	T	
¹⁶ O	402	T,C	
¹⁷ O	376	C	
¹⁹ F	115	T	
²⁵ Mg	73	T	
²⁶ Mg	137	T	
²⁷ Al	144	T	
²⁸ Si	267	T	
³² S	700	T,C	
³⁵ Cl	172	T	
⁴⁰ Ca	210	T	
⁴⁴ Ca	205	T	
⁴⁸ Ca	200	T	x
⁴⁶ Ti	250	T	
⁴⁸ Ti	300	T	
⁵⁰ Ti	230	T	
⁵¹ V	220	T	
⁵⁸ Ni	995	T,C	
⁶³ Cu	162	T	
⁶⁵ Cu	290	T	x
⁷⁶ Ge	305	T	x
⁷⁸ Se	320	T	x
⁸⁰ Se	340	T	x
⁸² Se	315	T	x
⁹⁰ Zr	305	T	
¹¹⁶ Cd	499	C	
¹¹² Sn	570	C	x
¹⁵⁰ Nd	302	T	

*T = Tandem alone; C = Coupled mode.

time. Of the new species, the most notable is ⁴⁸Ca, which was produced using the ellipsoidal geometry ion source described in the previous Physics Division progress report.³

The new chopper-buncher system⁴ was used for both coupled operation and for provision of pulsed tandem beams for the experimental program. Operation of the system in both modes was successful.

1. Co-op student, Virginia Polytechnic Institute and State University, Blacksburg, VA 24061.

2. Instrumentation and Controls Division, ORNL.

3. Phys. Div. Prog. Rep. Sept. 30, 1986, ORNL-6326, p. 8.

4. Ibid., p. 14.

TANDEM ACCELERATOR

G. J. Alton	R. C. Juras ²
J. A. Biggerstaff	R. L. McPherson
D. L. Haynes	M. J. Meigs ²
D. E. Hoglund	G. D. Mills
C. M. Jones	N. F. Ziegler

Voltage Performance

As shown in Fig. 1.1, routine operation of the tandem accelerator at terminal potentials up to 21 MV continued during this period. Due to the work on compressed geometry tube testing, no attempts were made to improve the record voltages reported in the previous Physics Division progress report.³ Only 30 full-column sparks were experienced during the period.

As part of our effort to further improve voltage performance of the accelerator, we completed the second phase of the FY 1986 Accelerator Improvement and Modification (AIM) project which will provide for installation of compressed geometry acceleration tubes. As described later in this section, these tests provided the basis for choosing a final design for phase three of the project and also gave a strong indication that installation of compressed geometry acceleration tubes in the remainder of the accelerator will result in improved voltage performance. Work on the final phase of this project is to begin in late September 1987.

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, 1986, through September 30, 1987.

Improvements and Modifications

Development of the tandem accelerator and its ancillary equipment continued during this period. Highlights of this work are briefly summarized below.

The Negative Ion Source Preparation Facility was used for both beam development and ion source studies. Specifically, this work included off-line development of new beams required for the experimental program (see Table 1.4), a more general study of techniques for producing negative hydride ions of Ca, Mg, Ti, and Zr, initial studies and commissioning of a simplified version of the ellipsoidal geometry ionizer source,⁴ as well as emittance studies for several types of negative ion sources and a needle-type, liquid-metal, positive ion source. After the initial studies and commissioning noted above, the ellipsoidal geometry ionizer source was placed into service in the injector in January 1987.

Control system improvements in this period included integration of beam-line-22 controls into the accelerator control system, improved CRT page formats, and development of a multiple-beam profile monitor display.

In addition to the work described above, a number of existing components of the accelerator

were improved. For the injector, these improvements included a new servo-controlled, precision leak-valve system, an improved freon cooling system, and an upgraded turbomolecular pump. Improvements to the accelerator included development and testing of an improved corona point bracket, development of a telescope/TV camera/remote monitor system to monitor foil stripper operation, and replacement of high-maintenance steerer power supplies.

SF₆ System Operation

Operation of the SF₆ storage and recirculation system in FY 1987, including 7 1/2 transfers to and from storage, was without incident.

1. Co-op student, Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061.
2. Instrumentation and Controls Division, ORNL.
3. Phys. Div. Prog. Rep. Sept. 30, 1986, ORNL-6326, p. 4.
4. Ibid, p. 8.

GRIC ACCELERATOR

D. T. Dowling	C. A. Ludemann
C. A. Giles ¹	J. A. Martin
E. D. Hudson	S. W. Mosko
S. N. Lane	D. K. Olsen

During the period of this report, there were 16 separate beam tunings for 18 experiments with coupled operation of the cyclotron and tandem accelerators. There was no stand-alone operation of the cyclotron with an internal ion source. Beam time for research totaled 1291 hours. Two new beams, 128.3-MeV ⁷Li³⁺ and 570.5-MeV ¹¹²Sn²⁸⁺, were accelerated. A performance summary for beams provided during FY 1987 is given in Table 1.5.

Operating efficiency was improved in FY 1987. Tuning as a percent of total scheduled time decreased from 24% to 21%. Unscheduled maintenance decreased from 8.8% to 5.9%. Beam extraction efficiency continued to average about 70% and the accuracy of delivering the desired energy was typically within $\pm 0.5\%$.

Table 1.5. Coupled operation for research for the period
October 1, 1986, through September 30, 1987

Date	Ion	Desired Energy (MeV)	Measured Energy (MeV)	Error ⁽¹⁾ (%)	Extraction Efficiency (%)	Injected Ion	Injection Energy (MeV)	Tandem Voltage (MV)
10/17/86	$^{58}\text{Ni}^{+21}$	696.0	695.6	- 0.06	82	$^{58}\text{Ni}^{+7}$	142.9	17.83
12/19/86	$^{58}\text{Ni}^{+23}$	912.0	910.6	- 0.15	75	$^{58}\text{Ni}^{+9}$	180.0	17.97
1/22/87	$^{58}\text{Ni}^{+23}$	912.0	910.6	- 0.15	82	$^{58}\text{Ni}^{+9}$	180.0	17.97
2/10/87	^{170}Yb	375.0	375.9	+ 0.24	55	^{170}Yb	71.1	17.70
3/24/87	$^{116}\text{Cd}^{+26}$	500.0	498.6	- 0.28	65	$^{116}\text{Cd}^{+6}$	126.8	18.39 ⁽²⁾
4/9/87	$^{58}\text{Ni}^{+22}$	638.0	630.5	- 1.18	74	$^{58}\text{Ni}^{+8}$	159.1	17.65
2/14/87	$^{32}\text{S}^{+15}$	700.0	700.1	+ 0.01	65	$^{32}\text{S}^{+5}$	108.4	18.02
2/20/87	$^7\text{Li}^{+3}$	127.8	128.3	+ 0.36	81	$^7\text{Li}^{+1}$	20.1	9.90
3/9/87	$^{58}\text{Ni}^{+21}$	696.0	696.4	+ 0.06	63	$^{58}\text{Ni}^{+7}$	143.1	17.85
4/7/87	$^{112}\text{Sn}^{+28}$	570.0	570.5	+ 0.09	80	$^{112}\text{Sn}^{+7}$	143.3	17.87
4/15/87	$^{58}\text{Ni}^{+21}$	596.0	695.8	- 0.03	78	$^{58}\text{Ni}^{+7}$	143.5	17.90
5/4/87	$^{58}\text{Ni}^{+21}$	696.0	696.1	+ 0.01	- (3)	$^{58}\text{Ni}^{+8}$	160.1	17.76
5/26/87	^{160}Gd	400.0	401.1	+ 0.28	78	$^{160}\text{Gd}^{+3}$	71.0	17.68
5/30/87	^{160}Gd	300.0	300.4	+ 0.13	71	$^{160}\text{Gd}^{+3}$	71.2	17.72
6/30/87	$^{58}\text{Ni}^{+24}$	993.0	994.6	+ 0.16	70	$^{58}\text{Ni}^{+9}$	178.0	17.77
7/23/87	^{160}Gd	400.0	401.6	+ 0.40	50	$^{160}\text{Gd}^{+3}$	71.0	17.68
8/17/87	$^{58}\text{Ni}^{+23}$	900.0	908.9	+ 0.99	73	$^{58}\text{Ni}^{+9}$	179.4	17.91
9/16/87	$^{58}\text{Ni}^{+23}$	900.0	904.1	+ 0.44	69	$^{58}\text{Ni}^{+9}$	179.5	17.92

NOTES: (1) Error (%) = 100 (Measured - Desired)/Desired

(2) CdO^- injected into tandem

(3) Beam current required for experiment was too low for reliable measurement

Cyclotron and Beam Line Setup Calculations

Comparisons between the calculated predictions for ORIC setup and the values tuned by the operators have followed the pattern of recent years. The only major discrepancy is between the predicted and calculated currents for the outside coil of the main magnetic beam extraction channel. This discrepancy probably results from a large first-harmonic field component, which is not contained in the magnetic field measurement data base. Presently, the cyclotron operates with only 12 of the 22 trim, harmonic, and valley coils energized.

The update of the SETUP program which predicts the strengths required for ORIC beam-line magnets has been completed. This update gives more accurate predictions which tend to be equal to the average of operator-tuned values of recent years scaled by beam rigidity. The revised program lists magnet configuration,

polarities, power supplies, and shunt resistances. The program is now routinely used for initial setting of current and polarity of the beam line bending magnets and quadrupoles.

Control Computer Development

The ORIC control system has been expanded with the installation of control hardware and software for motorized entrance and exit slits of the 153° energy-analyzing magnet. The entrance slit is now operational; the exit slit will be installed early next year. Printouts of operating parameters are provided to the operators and monitoring software now uses a voice synthesizer to announce problems detected in operation. Work has begun on upgrading the monitoring and control of beam line vacuum systems.

File transfer software has been written that provides error-free communication with the tandem CSC computer. This will make it possible to

set up the ORIC directly, without human intervention, from the parameter values calculated by the modeling codes that run on the CSC. This software also makes it possible to easily import and export programs and data. An example is the graphics display subroutine package, originally written for the VAX, that will now be used on the MODCOMP for displaying operation variables.

Cyclotron and Facility Improvements

RF System. The rf system anode power supply developed a primary power transformer fault in one of the new air-cooled units which replaced the original PCB transformers last year. The fault was attributed to a possible manufacturing flaw, but switching transients associated with the primary power contactor are considered a contributing factor. Consequently, a set of primary line capacitors was added to reduce voltage transients that follow primary contactor opening.

A new frequency synthesizer was added to the rf system. The new unit features electronic tuning which avoids the problem of unreliable switch contacts on low-level rf signals. The switch uncertainty has caused subtle operation interruptions in the past through sudden frequency shifts and signal losses.

Power Supplies. The power supply upgrade program is continuing with new units specified and ordered for the electrostatic deflector and for the main beam extraction magnet. Delivery and installation will be accomplished next year.

New power supplies were installed for steering magnets on the ORIC injection beam line. The new units are "off-the-shelf" commercial units which replace four custom-designed units which have been extremely troublesome.

ORIC Vacuum System. Vacuum system improvements have been implemented in both the accelerator tank and in the experiment beam lines.

Two surplus rotary-vacuum pumps with nominal pumping speed of 300 cfm were obtained from the Naval Research Laboratory to replace two of ORIC's 45-year-old roughing pumps. One of the pumps was installed to also serve as an alternate fore-pump. These newer pumps are able to

operate with gas ballast which enhances water evaporation from the pump oil. One of the old pumps is still available for service as a backup, but it will probably be replaced with a combination rotary-blower system in the future.

Extraction System. A new coaxial magnetic channel was built and installed. This was the first such unit fabricated in more than a decade and the first one assembled in the ORNL shops. Several experiments have already been run which indicate satisfactory performance. The old unit, which had developed water leaks, will be repaired, if possible, and retained for standby service.

Fabrication of a new lower-channel extraction magnet is under way in the ORNL shops with completion expected early next year. Meanwhile, the presently used channel developed water leakage problems in its insulated coolant connectors. The channel uses about 40 of these connectors which consist of nylon tubes, three inches long, with inside diameter of 5/16 inch and outside diameter of 5/8 inch. Recessed double O-rings in each end of the connector provide appropriate seals to metal tubing, which is inserted from each end. The leaks were due primarily to inadequate dimensional control during connector fabrication. New close-tolerance connectors were installed. Additional leaks occurred between some stainless steel tubing and the copper/brass fittings on the channel coil windings. This demonstrated once again that stainless steel tubing cannot be easily brazed to copper or brass fittings; the stainless steel was replaced with brass.

Beam Line Improvements. Efforts to improve beam monitoring capabilities are continuing. Installation of beam profile monitors is under way, beam viewers are being added or upgraded, and remote control capabilities are being expanded. The following items were completed this year:

(1) Remote controls were completed for a new viewer, installed during FY 1986, between switching magnets BSM 5-1 and BSM 5-2.

(2) A beam profile monitor was installed at the entrance to switching magnet SM 19-1, which

is the entrance to the ORIC injection line. Control wiring from the control room will be completed soon. Preparations have begun for installation of four additional beam profile monitors on major ORIC beam lines, including one monitor on the ORIC injection line at the entrance to the ORIC vacuum tank.

(3) Wiring was installed for remote control of the 153-degree, beam-analyzing magnet entrance slit assembly. This control permits adjustment of the slit opening and position concurrent with observation of beam current and energy resolution, thereby allowing the operator to optimize beam transmission versus beam energy resolution. A similar slit assembly for the exit of the 153-degree beam-analyzing magnet will follow.

(4) Beam line vacuum improvements consist mainly of the continuing replacement of old, obsolete, and unreliable diffusion pump stations. One new station has a 330-l/s turbomolecular pump and interlock controls to help eliminate operator error which might cause damage to the turbopump.

1. Martin Marietta Energy Systems, Inc.,
Computing and Telecommunications Division.

TESTS OF COMPRESSED GEOMETRY ACCELERATION TUBES IN THE TANDEM ACCELERATOR¹

C. M. Jones D. L. Haynes
J. E. Raatz² R. D. Rathmell²
N. F. Ziegler

As noted in the two previous progress reports,^{3,4} we are engaged in a program of replacing the original acceleration tubes of the tandem accelerator with tubes of a compressed geometry design. In this design, which utilizes a modified National Electrostatics Corporation (NEC) high-gradient 17-cm-long tube section, the 3-cm-thick heatable aperture assembly provided as part of the original installation is replaced with an aperture assembly of essentially zero length. This change has two beneficial effects. The first is that seven tube sections can be installed in the space previously occupied by six, thus increasing the effective insulator

length per unit column length by a factor of $7/6 = 1.17$. The second is that removal of the high-current feedthroughs, which are an integral part of the heatable aperture assembly, removes a source of vacuum leaks in the 25URC accelerator.

The installation and tests described in this report represent the first two of three phases of the tube replacement program for the tandem accelerator. In the first phase, two tube units,⁵ 26 and 27, were replaced with compressed geometry tubes in June 1986 and tested in the interval July 1986 - October 1986.⁶ In the second phase, units 19-25 were replaced with compressed geometry tubes in November 1986 and tested in the interval November 1986 - March 1987. In the third phase, scheduled for October 1987, the final 18 units will be replaced. This sequential approach was chosen to provide an opportunity to evaluate prototype designs before retrofitting the entire accelerator.

As a result of the compressed geometry tube installation, the number of 17-cm-long tube sections used in the tandem accelerator must be increased by 24. To provide an unambiguous comparison between new and reconditioned tube sections, 28 new tube sections were installed in the second phase of the replacement program in units 19+20 and 24+25. All other 17-cm-long tube sections used in the first and second phases of the replacement program were reconditioned tube sections.

Replacement of the heatable aperture assembly with a simple "zero length" flat aperture reduces the strength of the lens effect associated with the aperture. This reduction in lens strength results in a reduction in trapping efficiency for ions and electrons originating from the aperture and from ionization of residual gas. While it appears that reduced trapping efficiency might lead to impaired tube performance, the importance of this effect in practice is not clear. To investigate this question in a systematic way, we installed and tested compressed geometry tubes of two designs: a "conventional" design, similar to that described by Assmann, et al.,⁷ and a new design,

developed for the present program, which has improved ion and electron trapping.³ This new design was used for units 23-27. The conventional design was used for units 19-22.

The technique used to improve ion and electron trapping for the new design is replacement of the conventional flat aperture with a vee-shaped aperture. Specifically, use of a vee-shaped aperture "tilts" the electric field in the region of the aperture so that it has a larger radial component. This radial component of the electric field imparts higher radial velocities to ions and electrons originating at or near the aperture and thus leads to improved trapping. The cone angle (defined as the angle between the aperture surface and a perpendicular to the axis of symmetry) chosen for the present work was 30°. This cone angle was chosen as a compromise between trapping efficiency and the possibility of a one-to-one correspondence between ion trajectories between adjacent apertures - a condition which we feared might lead to excessive microdischarge conditioning.⁶ With a cone angle of 30°, all ion trajectories with an initial energy less than 500 eV appear to be stopped in two tube sections.

As a background for discussion of the performance of the compressed geometry tubes, it is useful to mention two general observations concerning the conventional design tubes which have been used in the tandem accelerator. The first is that it has been our observation that tube voltage performance improves with operating time - over a scale of at least several years. The second is that in contrast to the original equipment tubes, the reconditioned tubes installed in 1983 (Ref. 9) exhibited intense, gradient dependent, continuous X-ray levels which we believe are due to field emission and which have been observed to decrease with time and sparks. [More than 75% of the acceleration tubes of the 25URC accelerator were replaced in the interval August-October 1983 with reconditioned tubes of conventional NEC design.]

Conditioning of the compressed geometry tubes was characterized by the same phenomena as

has been observed for conventional geometry tubes, namely, sparks (increasing in voltage roughly monotonically), pulsed X-ray and vacuum activity, and intense continuous X-ray levels. A notable characteristic of both types of compressed geometry tubes is that they appear to decondition with respect to pulsed X-ray and vacuum activity only slightly with time.

As indicated above, we have noted that voltage performance appears to improve with operating time. Thus, we believe the most meaningful comparison of maximum stable gradient is for tubes at the same time after installation. In Table 1.6, we show such a comparison for a time after installation of approximately three months. Specifically, we show in this table the maximum stable gradient measured for various combinations of units in the group 19-27 for the compressed geometry tubes and for the conventional geometry tubes installed in 1983. As expected, installation of compressed geometry tubes resulted in improved voltage performance. However, it is important to note that the compressed geometry tubes were conditioned more aggressively than the conventional geometry tubes and that some of the differences noted in Table 1.6 may be due to differences in conditioning emphasis. However, we also believe it is clear that use of compressed geometry tubes in the entire accelerator will result in improved voltage performance after completion of the third phase of this program. We also note that we have no data which determines the ultimate gradient capability of the two compressed geometry aperture designs, nor did we observe any clear difference in ease of conditioning for the two aperture designs.

During the course of the last conditioning exercise in February-March 1987, we measured bremsstrahlung spectra for various combinations of units in the group 19-27. For the spectra to be discussed, these measurements were made for gradients of approximately 1.0 MV/unit and at times when no pulsed X-ray activity was present. A comparison of these spectra may be summarized as follows: (1) No significant difference was observed between spectra for pairs of units with

Table 1.6. Maximum stable gradient in MW/unit measured for conventional geometry tubes in March 1984 and for compressed geometry tubes in October 1986 (units 26+27) and March 1987 (units 19-25). In each case, the observed gradients were measured approximately three months after installation.

Unit(s)	Maximum stable gradient (MW/unit)				
	Conventional Geometry		Compressed Geometry		
	March 1984	October 1986	% Improvement	March 1987	% Improvement
Average for single units	0.96	1.20	25%	1.12	17%
Average for pairs of units	0.95	1.16	22%	1.07	12%
19-22	0.94			1.04	11%
23-27	0.91			1.04	14%
19-27	0.84			0.96	14%

vee-shaped apertures, and pairs of units with straight apertures. (2) No significant difference was observed in spectra measured for different numbers of units (ranging from two to five) with vee-shaped apertures. (3) A small higher-energy "tail" is clearly observable in spectra measured with four units with straight apertures; this component is not observed when only two units with straight apertures are operated together. We believe the presence of this higher-energy component with straight aperture units and its absence with vee-shaped aperture units is evidence of the improved trapping effectiveness of the vee-shaped apertures. Primarily on the basis of this observation, we have chosen the vee aperture design for the tubes to be installed in the third phase of this program.

1. Summary of a paper to be published in Nuclear Instruments and Methods in Physics Research.

2. National Electrostatics Corporation, Middleton, Wisconsin 53562, USA.

3. Phys. Div. Prog. Rep. Sept. 30, 1985, ORNL-6233, p. 18.

4. Phys. Div. Prog. Rep. Sept. 30, 1986, ORNL-6326, p. 11.

5. The configuration of the tandem accelerator is based on 27 61-cm-long live modules or "units" separated by two major and three minor dead sections. Proceeding from bottom to top, the units are grouped in the following way: 1-4, 5-9, 10-13, 14-18, 19-22, 23-27.

6. C. M. Jones, K. A. Erb, D. L. Haynes, J. T. Mitchell, M. F. Ziegler, J. E. Raatz, and R. D. Rathmell, "Initial Tests of Compressed Geometry Acceleration Tubes in the ORNL 25URC Tandem Accelerator," Proc. of 1986 Symposium of Northeastern Accelerator Personnel, Notre Dame, Indiana, November 3-6, 1986, to be published.

7. W. Assmann, G. Korschinek, and H. Mnzer, Nucl. Instrum. and Meth. 220 (1984) 86.

8. B. A. Prichard, Mechanisms of Electrical Discharges in High Vacuum at Voltages up to 400,000 Volts, PhD Thesis, University of Wisconsin, 1972, unpublished.

9. C. M. Jones et al, Nucl. Instr. and Meth. A244 (1985) 7.

RECENT ELECTRONIC IMPROVEMENTS TO THE OAK RIDGE 25URC ACCELERATOR¹

N. F. Ziegler W. T. Milner
G. K. Schulze² M. J. Miegs²
J. W. Rochelle³ R. L. McPherson
R. C. Juras²

A new chopper-buncher system has been installed in the 25URC accelerator injection line. The buncher is similar to the one used previously, but incorporates several significant improvements. The chopper is a new device to

provide beam pulses for time-of-flight experiments. The accelerator charging system has been modified to increase reliability and improve chain monitoring. A display unit for beam profile monitors (BPM) is being developed. The display will allow the operator to observe four BPM traces simultaneously.

1. Abstract of a paper to be published in Nuclear Instruments and Methods in Physics Research.

2. Instrumentation and Controls Division, ORNL.

3. Consultant, University of Tennessee, Knoxville, Tennessee.

EVOLUTION AND DEVELOPMENT OF THE OAK RIDGE 25URC TANDEM ACCELERATOR CONTROL SYSTEM¹

R. C. Juras² R. L. McPherson
M. F. Ziegler D. E. Hoglund³
M. J. Meigs² J. A. Biggerstaff

Since acceptance of the 25URC accelerator in 1982, we have continued to develop and improve both the accelerator control system and associated software. In this paper, we describe these improvements and also discuss how our experience with the present system would influence the architecture and design of future, similar systems.

1. Abstract of a paper to be published in Nuclear Instruments and Methods in Physics Research.

2. Instrumentation and Controls Division, ORNL.

3. Co-op student, Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061.

CHARGE-STATE DISTRIBUTIONS OF 240- AND 300-MeV NEODYMIUM IONS EMERGING FROM THIN CARBON FOILS

J. A. Martin

These measurements were made in preparation for acceleration of $^{150}\text{Nd}^{+35}$ to 795 MeV with coupled operation of the cyclotron and tandem accelerator. A previous acceleration of Nd in 1984 had shown low transmission in the cyclotron, suggesting that the charge-state distribution predicted by the Sayer¹ semiempirical charge-distribution formula, which we use for

charge-state predictions, was not sufficiently accurate.

To assure that equilibrium distributions were determined, measurements were made with foil thicknesses of 20, 40, and 60 $\mu\text{g}/\text{cm}^2$ at 240 MeV and with a 60 $\mu\text{g}/\text{cm}^2$ foil at 300 MeV. The 90° double-focusing analysing magnet at the tandem accelerator was used for charge-state separation. The measured charge-state fractions are given in Table 1.7.

The measured distributions were fitted by the least-squares method with skewed Gaussian distributions of the form used by Sayer; $F_q = F_m e^{-0.5t^2/(1+ct)}$ where $t = (q-q_0)/\sigma$. q_0 is the maximum-intensity charge value, σ is the width parameter, and c the skewness parameter.

Comparison of the fits of these data and the Sayer formula predictions are given in Table 1.8. The data and fitted curves for two sets of measurements are shown in Fig. 1.2. The measured most-probable charge states are significantly lower than the formula predictions and the distribution widths are slightly smaller. Figure 1.3 shows a comparison of the measurements with the formulas of Nikolaev-Dmitriev,² Sayer¹ and Shima et al.³

In 1986, we published charge-state distribution measurements for gold ions in the 100- to

Table 1.7. Charge-state fractions for ^{150}Nd ions.

Ion charge	Charge fractions f_q (%)			
	Ion energy (MeV)/foil thickness ($\mu\text{g}/\text{cm}^2$)			
q	240/20	240/40	240/60	300/60
27	0.6	0.5	0.5	
28	1.5	1.1	1.2	
29	3.7	2.7	3.1	
30	7.8	6.5	7.3	1.0
31	13.7	12.5	13.7	2.6
32	22.4	21.5	21.3	7.7
33	21.7	22.5	21.8	16.1
34	15.3	16.6	16.0	20.4
35	8.4	9.7	9.2	18.7
36	3.6	4.5	4.2	16.8
37	1.3	1.5	1.3	10.1
38		0.3	0.4	4.6
39				2.0

Table 1.8. Comparison of most probable charge, distribution width, and distribution skewness from Sayer formula¹ with these measurements.

Energy (MeV)	Thickness ($\mu\text{g}/\text{cm}^2$)	These Measurements			Sayer Predictions			Charge-state difference Δq_0
		q_0	σ	ϵ	q_0	σ	ϵ	
240	20	32.57	1.91	-0.021	34.1	2.10	0.00	-1.53
240	40	32.82	1.89	-0.034	34.1	2.10	0.00	-1.28
240	60	32.71	1.91	-0.033	34.1	2.10	0.00	-1.39
240	60	34.64	1.91	-0.019	36.3	2.09	-0.01	-1.66

Fig. 1.2. ^{150}Nd charge-state distributions at 240 and 300 MeV for $60\mu\text{g}/\text{cm}^2$ carbon foils. Solid curves are least-squares fits.

352-MeV energy range,⁴ which showed discrepancies from semiempirical formula predictions as large as -4.9 charge states (at 352 MeV). The discrepancies reported here for Nd ions are smaller, but reinforce the conclusion of the previous work that currently used charge-state

Fig. 1.3. Average charge states derived from these measurements compared with Nikolaev-Dmitriev, Sayer and Shima et al. semiempirical formulas.

prediction formulas should be used with caution for ions with $Z > \sim 36$ and energies above 1 MeV/nucleon.

1. R. O. Sayer, Rev. Physique Appl. 12 (1977) 1543.
2. V. S. Nikolaev and I. S. Dmitriev, Phys. Lett. 28A (1968) 277.
3. K. Shima, T. Ishihara and T. Mikumo, Nucl. Instr. and Meth. 200 (1982) 605.
4. J. A. Martin, R. L. Auble, K. A. Erb, C. M. Jones, and D. K. Olsen, Nucl. Instr. and Meth. Phys. Res. A244, (1986) 137.

EVALUATION OF TECHNIQUES FOR SPUTTER GENERATION OF THE HYDRIDES OF Ca, Mg, Ti, AND Zr

G. D. Alton J. Allen¹
G. D. Mills

During this reporting period, efforts were made to develop reliable negative ion beams containing chemically active, low electron affinity elements with intensities adequate for tandem accelerator applications. Two methods were evaluated for the formation of molecular negative ion beams of the hydrides of Ca, Mg, Ti, and Zr in a cesium sputter negative ion source: (1) generation by cesium ion sputtering of elemental samples during in situ hydrogenation with H_2 or NH_3 , and (2) generation by direct sputtering of samples preloaded with H_2 .

It is known from previous experience that many elements from the IIA, IIIA, IVA, VA, VIA, VIIA, IIB, and IIIB Groups can be formed as molecular hydride negative beams with intensities which are, in many cases, only marginally adequate for tandem acceleration use. To date, two techniques have been used for their formation: (1) H_2 and (2) NH_3 in situ hydrogenation. However, systematic investigations of these hydrogenation processes have not been made.

Another technique which offers considerable appeal for producing molecular hydride negative ion beams is the use of hydrogen-saturated solid samples in which the molecular hydride negative ion is directly sputtered from the solid sample. This procedure, in principle, does not require additional gas feed.

The cylindrical geometry ionizer negative ion source,^{2,3} was used in conjunction with the Negative Ion Source Preparation Facility throughout the studies to be described.

Most metals are inert to molecular hydrogen under normal pressures and temperatures. However, when heated in the presence of hydrogen, the rate of hydrogen adsorption in Ti, Zr, Mg, and Ca generally increases.⁴ The crucial step in achieving a high hydrogen content seems to be the initial removal of any surface film, commonly oxides, which will impede the adsorption process. To remove surface films, the pellet

containing the material to be hydrogenated was first cleaned with a wire brush in an argon-filled glove box at atmospheric pressure. The clean pellet was then placed inside a tube furnace equipped with a quartz tube which had a continuous supply of hydrogen flowing through it. The tube furnace was heated to a particular adsorption temperature which was determined from the phase diagrams for Mg-H, Ca-H, Zr-H, and Ti-H⁵; an adsorption temperature at 380°C was used for elemental Ca, Ti, and Zr pellets, while that used for Mg was 420°C. During the adsorption process, it was not necessary to precisely control the temperature because of the time/temperature relationship required for adsorption of the maximum amount of hydrogen. Complete hydrogenation is not desirable because of the possibility of sample disintegration. However, surface discoloration usually occurs before this happens; therefore, a change in sample color was used to indicate the termination time for the hydrogenation process. Ca, Ti, and Zr samples were hydrogenated for 2, 2.5, and 2.5 hours, respectively, while Mg was hydrogenated for 25 minutes. During hydrogenation, the quartz tube was maintained at a hydrogen pressure of 1 atmosphere for all four elements.

For the unhydrogenated samples, two studies were made: Negative ion yield vs probe voltage and negative ion yield vs pressure; both studies were made at several oven temperatures. For the pre-hydrogenated probes, negative ion yield vs probe voltage studies were also made at several oven temperatures. The negative ion yields from Ti and Zr were found to be principally in the form of the monohydrides. Figure 1.4 shows negative ion yield vs H_2 and NH_3 pressure at a constant probe voltage of 2 kV for an elemental Ti sample. It is clear from this figure that H_2 is favored for hydride negative ion production. Indeed, H_2 was much easier to control and the monohydride negative ion beams exhibited greater stability than those produced with NH_3 as a hydrogenating agent. It is interesting to note that the optimum pressure was virtually the same for Ti + NH_3 and Ti + H_2 . Results very

Fig. 1.4. Relative TiH^- vs H_2 and NH_3 ambient pressure.

Fig. 1.5. Relative TiH^- yield vs sputter probe voltage.

similar to these were also found for Zr samples. Experiments such as these were repeated for elemental Ca and Mg samples. For these Group IIA

elements, NH_3 was found to be a superior hydrogenating agent to H_2 .

Figure 1.5 displays the negative ion yield vs probe voltage for pre-hydrogenated and in situ hydrogenated Ti samples. Optimum hydrogen pressures were maintained for the in situ hydrogenated Ti samples. Similar data for Zr were accumulated. At low probe voltages (< 1.5 kV), the negative ion yields from all methods of negative ion generation are seen to be approximately the same, while at higher probe voltages the advantage of hydrogenated samples with respect to beam intensity is clear. It should be noted that the elemental Ti and Zr, with NH_3 and H_2 hydrogenation agents, exhibit greater stability than the pre-hydrogenated Ti and Zr samples. This may be due to nonuniform hydrogenation throughout the volume of the Ti and Zr pellets leading to changing yields as the sputtering depth in the pellet increases. However, it should also be noted that the yield from the pre-hydrogenated Zr pellet was observed to steadily increase up to the limit of the probe voltage power supply. Thus, the maximum yield could not be determined. A maximum negative ion current of $5.8 \mu\text{A}$ was recorded at 2.75 kV.

Experiments were also performed with elemental Ca and Mg samples and samples preloaded with H_2 . The results of these measurements suggest that significant increases in MgH^- and CaH^- ion beam intensities can be realized by bleeding additional NH_3 over pre-hydrogenated samples of these materials. However, the negative ion yields were found to be unpredictable from sample to sample. Further development of this technique is required before use in routine production of these negative ion species.

1. Undergraduate student participant in the ORNL-GLCA/ACM Science Semester Program from Ripon College, Ripon, Wisconsin.
2. G. D. Alton, Nucl. Instrum. and Meth. A244, 133 (1986).
3. G. D. Alton, G. D. Mills, IEEE Trans. Nucl. Sci. NS-32, No. 5, 1822 (1985).
4. V. I. Mikheeva, Hydrides of the Transition Metals, eds. T. V. Yananaeva and D. W. Triforov (Publishing House of the Academy of Sciences USSR, Moscow, 1960) pp. 1-21.

5. J. Allen, "Evaluation of Technique for Cesium Sputter Negative Ion Generation of the Hydrides of Ca, Mg, Ti, and Zr." Unpublished report of work performed while participating in the ORNL-GLCA/ACM Science Semester Program.

THE EMITTANCES OF ION BEAMS EXTRACTED FROM HIGH-INTENSITY NEGATIVE ION SOURCES

G. D. Alton J. W. McConnell
R. W. Sayer¹

Emittance Comparisons

The emittances of high-intensity ion beams extracted from cesium sputter negative ion sources equipped with cylindrical^{2,3} and ellipsoidal solid tungsten⁴ and spiral-wound tantalum⁵ (General Ionex Corporation Model 860) cesium surface ionizers were measured for several ion species,⁶⁻⁸ including $^{12}\text{C}^-$, $^{28}\text{Si}^-$, $^{58}\text{Ni}^-$, and $^{197}\text{Au}^-$. The present investigations were made by use of the Negative Ion Source Preparation Facility.⁹ The negative ion sources utilized in the present studies have been described in detail in the literature,²⁻⁴ and further descriptions will not be given here. The sources differ only in the details of construction, geometries of the positive and negative ion generation regions, and the material type and geometries of the ionizers. These sources all utilize identical principles for both positive and negative ion formation. Table 1.9 lists the

spatial positions of the samples in relation to the ion extraction aperture, aperture sizes, and estimated emittances based on simple geometrical arguments for each of these sources. As we shall see, the estimated emittances shown in Table 1.9 agree reasonably well with those measured for the 80% contour levels from the sources.

If we ignore the presence of intensity or mass dependent effects and perform a weighted average of all emittance contour data taken during these measurements regardless of intensity and ion species, we obtain the average emittance versus average percentage of negative-ion-beam intensity data shown in Fig. 1.6. The emittance for a given contour of a beam extracted from the Model 860 source is observed to be considerably higher than that for the same contour associated with beams extracted from the ellipsoidal or cylindrical ionizer geometry negative ion sources. For example, the emittances for the 80% contour level of the Model 860 source are factors of 1.8 and 1.7 higher, respectively, than those for the same contour from sources equipped with ellipsoidal and cylindrical geometry cesium ionizers. These average data are representative and typical of all values derived from measurements associated with a particular ion species and ion beam intensity. Without exception, the ellipsoidal

Table 1.9. Estimated emittances of negative ion sources equipped with ellipsoidal and cylindrical geometry cesium ionizers and the Model 860 negative ion source

Source	Sample Distance to Aperture	Ion Exit Aperture Diameter	Assumed Sample Wear Pattern Diameter	Ion Emission Half Angle	Estimated Emittance
	l(mm)	ϕ (mm)	s(mm)	α (mrad)	ϵ (π -mm mrad (MeV) ^{1/2})
Ellipsoidal Geometry Ionizer ⁴	29.7	4.76	1.25	101	9.06
Cylindrical Geometry Ionizer ^{2,3}	23.0	4.76	1.0	124	8.72
Model 860 ⁵	14.3	6.36	1.0	257	17.8

and cylindrical geometry sources exhibit emittances nominally lower than those of the Model 860 source by the values shown in Fig. 1.6.

Fig. 1.6. Weighted average normalized emittance ϵ versus percentage average negative ion beam intensity for beams extracted from sources equipped with ellipsoidal and cylindrical geometry cesium ionizers and the Model 860 negative ion source.

Species-Dependent Effect

The emittances of negative ion beams should vary from element to element based on expected differences in the energy distribution of sputter-ejected negative ions. Such differences could lead to growth in the transverse phase spaces (emittances) of the negative ion beams through chromatic aberration induced by lenses and dispersive devices prior to the emittance measurements. The possibility of a species-dependent effect was suggested by the results of previous measurements in which the emittances of Si^- in beams were found to be lower by 15% to 20% than those of heavy ions such as Ni^- or Au^- .⁶ As a consequence of these findings, a careful study was initiated with the objective of searching for a species-dependent effect in the emittances of heavy negative ion beams. The ellipsoidal geometry source was selected for use because of the focusing characteristics of the source geometry for the cesium ion beams. During the course of the measurements, the

source operational parameters (cesium oven temperature, ionizer temperature, sputter probe voltage, and ion extraction voltage) were kept constant for all samples. As a consequence, the ion current for each of the elements varied somewhat. Thus, one would expect a possible slight dependence of the emittance on ion beam intensity. This effect, if present, was ignored during the studies.

The results of careful measurements of the emittances versus percentage of negative ion beam for beams of $^{28}\text{Si}^-$, $^{58}\text{Ni}^-$, and $^{197}\text{Au}^-$ are shown in Fig. 1.7. Each data point represents an average of ten or more measurements. These data clearly indicate the existence of a species-dependent effect as previously predicted. Although suggested from earlier emittance measurements,⁶ the effect is clearly delineated in the present investigations and is ostensibly attributable to differences in the intrinsic energy distributions of secondary negative ions which, in turn, leads to differences in the emittances of the ion beams.

1. Participant in the ORAU Undergraduate Research Trainee Program from the University of North Carolina, Chapel Hill, North Carolina.
2. G. D. Alton, Nucl. Instr. and Meth. A244 (1986) 133.
3. G. D. Alton and G. D. Mills, IEEE Trans. Nucl. Sci. NS-32 (5)(1985) 1822.
4. G. D. Alton, Phys. Div. Prog. Rep., Sept. 30, 1986, ORNL 6326, p. 8.
5. R. Middleton, Nucl. Instr. and Meth. 214 (1982) 139.
6. G. D. Alton, J. W. McConnell, S. Tajima, and G. J. Nelson, Nucl. Instrum. and Meth. In Phys. Res. B24/25 (1987) 826.
7. G. D. Alton, Proceedings of the Eleventh Symposium on Ion Sources and Ion Assisted Technology, Tokyo, Japan (1987) 157.
8. G. D. Alton and J. W. McConnell, to be published in Nuclear Instruments and Methods in Physics Research.
9. G. D. Alton, J. W. McConnell, Phys. Div. Prog. Rep., Sept. 30, 1986, ORNL 6326, p. 6.

A MATHEMATICAL MODEL FOR DETERMINING WORK FUNCTION CHANGES BY ELECTROPOSITIVE ADSORBATES¹

G. D. Alton

A semi-empirical mathematical model has been developed which predicts, with good accuracy, the value of the work function at its minimum

Fig. 1.7. Normalized emittance ϵ versus percentage negative ion beam for beams of $^{28}\text{Si}^-$, $^{58}\text{Ni}^-$, and $^{197}\text{Au}^-$. The differences in the emittances of these ion beams are ostensibly attributable to differences in the intrinsic energy distributions of the respective species.

and the variation of the work function with adsorbate coverage θ for members of the Group IA and Group IIA elements. The relationships are couched in terms of known physical parameters, such as the intrinsic work function of the metal surface, ϕ_0 , and the first ionization potential, I_A , and electron affinity, E_A , of the particular adsorbate. The expression for the maximum change in work function, $\Delta\phi_m$, is

$$\Delta\phi_m = -1.24\left[\phi_0 - \frac{1}{2}(I_A + E_A)\right] \quad (1)$$

Experimental and calculated values for changes in work function due to Group IA and Group IIA atomic adsorption are compared in Table 1.10. Note the close agreement between the calculated and measured maximum changes for

all cases. To date, no significant disagreements have been found. The expression is valid for single crystalline, as well as polycrystalline materials. This expression can also be used to determine the first ionization potential, I_A , the electron affinity, E_A , or the sum of $E_A + I_A$ for an adsorbate from experimental work function versus coverage data for which either or both of the quantities are unknown. For example, neither the first ionization potential nor the electron affinity is known for thorium. The sum of $I_A + E_A$, extracted from the thorium on tungsten adsorption data of Becker,² is found to be 6.74 V.

The ease with which most observed work function changes with adsorbate coverage could be

Table 1.10. Comparison of experimentally determined work function change $\Delta\phi_m$ with values $\Delta\phi_{cal}$ calculated by use of Eq. (1).

System	Intrinsic work function	$\Delta\phi_m$	$\Delta\phi_{cal}$	Ref.
Ba/W	4.60	-2.54	-2.54	[2]
Th/W	4.60	-1.53	-1.53 ^{a)}	[2]
Cs/W	4.52	-2.90	-2.89	[3]
Cs/W	4.52	-2.83	-2.89	[4]
Cs/Pt	5.29	-3.76	-3.84	[5]
Cs/C	4.39	-2.72	-2.73	[5]
Cs/Ni	4.84	-3.35	-3.35	[5]
Cs/Cu	4.47	-2.89	-2.88	[5]
Cs/Ag	4.28	-2.54	-2.65	[5]
Cs/Mo	4.27	-2.65	-2.59	[6]
Cs/Ni	4.95	-3.54	-3.45	[7]
Cs/W(100)	4.51	-2.89	-3.06	[8]
Cs/Ta(110)	4.94	-3.42	-3.44	[8]
K/Ta(112)	4.93	-3.12	-3.11	[9]
K/Ta(100)	4.52	-2.95	-2.60	[9]
K/Ta(111)	3.73	-1.52	-1.63	[9]
K/Ta(011)	4.76	-2.89	-2.90	[9]
K/Mo(100)	4.27	-2.29	-2.39	[9]
K/Mo(112)	4.40	-2.58	-2.50	[9]
K/Mo(011)	4.89	-2.99	-3.06	[9]
K/Mo(111)	4.10	-2.06	-2.08	[9]
K/W(112,121)	4.93	-2.98	-3.11	[10]
K/W(111)	4.40	-2.60	-2.46	[10]
K/W(001)	4.80	-3.01	-2.95	[10]
Na/Ni(100)	5.36	-3.12	-3.12	[11]
Na/Ni(111)	5.38	-3.03	-3.14	[11]
Na/Ta(110)	4.94	-2.68	-2.68	[8]

a) Self-consistent value.

represented by least squares fits of a third-degree polynomial in θ prompted attempts to derive still another expression of the form

$$\phi(\theta) = \sum_{n=0}^3 a_n \theta^n \text{ V.} \quad (2)$$

This equation is of limited utility since the generated coefficients are data set specific. Attempts were made to develop an equation by determining the coefficients for a closed form, third-degree polynomial in terms of known physical parameters.

The coefficients a_1 , a_2 , and a_3 in Eq. (2) were determined from the following conditions:

- (1) $\left. \frac{d\phi}{d\theta} \right|_{\theta_m} = 0$, i.e., the work function reaches a minimum at $\theta = \theta_m$.
- (2) The maximum work function change $\Delta\phi_m$ occurs at $\theta = \theta_m$.
- (3) $\left. \frac{d\phi}{d\theta} \right|_{\theta_{max}} = 0$, i.e., the work function

reaches a constant value ϕ_1 at the point at which the fractional coverage $\theta = 1$.

The derived coefficients thus have values

$$a_1 = 6 \Delta\phi_m / \theta_m (3 - \theta_m), \quad (3)$$

$$a_2 = -3 \Delta\phi_m (\theta_m + 1) / (3 - \theta_m) \theta_m^2, \quad (4)$$

$$a_3 = 2 \Delta\phi_m / \theta_m^2 (3 - \theta_m). \quad (5)$$

Equation (2) then takes the form

$$\phi(\theta) = \phi_0 + A \frac{6 \Delta\phi_m}{\theta_m (3 - \theta_m)} \theta - B \frac{3 \Delta\phi_m (\theta_m (\theta_m + 1))}{(3 - \theta_m) \theta_m^2} \theta^2 + C \frac{2 \Delta\phi_m}{(3 - \theta_m) \theta_m^2} \theta^3 \text{ V,} \quad (6)$$

where the coefficients A , B , and C are to be determined by linear least squares fits of Eq. (6) to experimental data. The average values for the coefficients $\langle A \rangle$, $\langle B \rangle$, and $\langle C \rangle$ are found to be sufficiently close to unity (see Ref. 1)

so that the final equation which expresses the functional dependence of ϕ on θ can be written

$$\phi(\theta) = \phi_0 + \frac{6 \Delta\phi_m}{(3-\theta_m)\theta_m} \theta - \frac{3 \Delta\phi_m (\theta_m + 1)}{(3-\theta_m)\theta_m^2} \theta^2 + \frac{2 \Delta\phi_m}{(3-\theta_m)\theta_m^2} \theta^3 \text{ V.} \quad (7)$$

The value of the change in work function $\Delta\phi_1$ at $\theta = 1$ is given by

$$\Delta\phi_1 = \frac{3\theta_m - 1}{3 - \theta_m} \frac{\Delta\phi_m}{\theta_m^2}. \quad (8)$$

The merits of the present model can be readily seen by comparison with the Gyftopoulos and Levine¹² and Topping¹³ semi-empirical models and experimental data as shown in Figs. 1.8 and 1.9. Similar results have been obtained for many other sets of experimental data over the complete range of adsorbate coverage θ . The ability of this model to accurately predict the results of complicated experiments makes it a useful, practical model for estimating the probabilities for secondary negative-ion formation during the sputtering of electro-positive adsorbate-covered surfaces using the

Fig. 1.8. Comparison of the present, Topping (Ref. 13), and Gyftopoulos and Levine (Ref. 12) work function lowering models with the work function versus relative coverage θ experimental data of Becker (Ref. 2) for Th on W.

Fig. 1.9. Comparison of the present, Topping (Ref. 13), and Gyftopoulos and Levine (Ref. 12) work function lowering models with the work function versus relative coverage θ experimental data of Fehrs and Stickney (Ref. 8) for Cs on Ta (110).

Nørskov and Lundqvist,¹⁴ tunneling,¹⁵ or other work-function-dependent models, or for modeling other work-function-dependent processes.

1. Summary of paper published in Surface Science 175 (1986) 226.
2. A. Becker, Phys. Rev. 28 (1926) 341.
3. J. J. Broeder, L. L. van Reijck, W.M.H. Satchler, and G.C.A. Schuit, Z. Elektrochem. 60 (1956) 838.
4. R. Suhrmann, Z. Elektrochem. 60 (1956) 804.
5. Taken from ORNL radial geometry negative ion source data (Ref. [16]).
6. M. L. Yu, Phys. Rev. Lett. 40 (1978) 574.
7. L. W. Swanson and R. W. Strayer, J. Chem. Phys. 48 (1968) 2421.
8. D. L. Fehrs and R. E. Stickney, Surface Science 8 (1967) 267; 24 (1971) 309.
9. M. Blaszczyzyn, Surface Science 59 (1976) 533.
10. R. Blaszczyzyn, M. Blaszczyzyn, and R. Melewska, Surface Science 51 (1975) 396.
11. R. L. Gerlach and T. N. Rhodin, Surface Science 19 (1970) 403.
12. E. P. Gyftopoulos and J. D. Levine, J. Appl. Phys. 33 (1962) 67.
13. J. Topping, Proc. Roy. Soc. (London) A114 (1927) 67.
14. J. K. Nørskov and B. I. Lundqvist, Phys. Rev. B 19 (1979) 5661.
15. L. I. Schiff, Quantum Mechanics, (McGraw-Hill, New York, 1963), 3rd Edition.
16. G. D. Alton and G. C. Blazey, Nucl. Instrum. and Meth. 166 (1979) 105.

SECONDARY NEGATIVE ION GENERATION MODELING STUDIES

G. D. Alton D. H. Olive¹

In recent years, the sputter process, in combination with the work-function-lowering aspects of Group IA elements, has been utilized as a versatile and relatively efficient means of producing negative ions. In such sources, cesium is usually utilized because of the ease of vaporization, high sputtering coefficient, and greater work-function-lowering capabilities. The mechanisms involved in the formation and escape of secondary ions during sputtering are not well understood. Several theoretical arguments have been proposed to explain the phenomenon, but none have been clearly verified by experiment. The emission of secondary ions from clean metal surfaces has been reviewed by Blaise and Nourtier,² while Williams³ has reviewed the topic for ion emission from more complex surfaces. Wittmaack⁴ has also discussed the subject.

The key in all of the theoretical models which have been proposed is the velocity dependence of the secondary-ion emission probability.^{5,6}

Blandin, Nourtier, and Hone⁵ have treated the problem quantum-mechanically by the use of a time-dependent perturbation theory as the atom moves across the surface boundary. Nørskov and Lundqvist⁶ have expanded this treatment and arrive at the following expressions for the positive- and negative-ion emission probabilities $P^+(v)$ and $P^-(v)$:

$$P^+(v) = \frac{2}{\pi} e^{-\pi C_1(I-\phi)/h\gamma v} e^{-\pi C_2/h\gamma v}, \quad (1)$$

$$P^-(v) = \frac{2}{\pi} e^{-C_1\pi(\phi-E_A)/h\gamma v} e^{-\pi C_2/h\gamma v}. \quad (2)$$

C_1 and C_2 are constants, ϕ is the work function of the surface, I is the first ionization potential of the ejected atom, E_A is the electron affinity of the ejected atom, γ is a characteristic distance beyond which no further electron exchange between the atom and the substrate takes place, and v is the perpendicular component of the particle velocity. The velocity dependence is clearly strong. As v decreases to

the extent that the ion energy is of the order of the image potential, the ion emission goes to zero; as v becomes large, the ion emission probability should approach a value of $2/\pi$. The logarithm of $P(v)$ should also be a linear function of $1/v$, with the slope given by the constants C_1 , C_2 , γ , and the value of $I-\phi$ or $\phi-E_A$.

Yu⁷ established a direct correlation between the value of the work function during cesium adsorption and the yield of Mo^- produced by Ne^+ sputtering of the Mo surface. The secondary negative-ion emission probability was found to increase rapidly with decreasing surface work function and reached a maximum when the work function reached its minimum value. Thus, the work function ϕ in Eq. (2) is strongly dependent on the relative coverage σ of adsorbate on the surface. Equation (2) can be cast into a simpler energy-dependent form given by

$$P^-(E, \theta) = \frac{2}{\pi} e^{-\beta(\phi(\sigma)-E_A + V_i)/\hat{v}_1} \quad (3)$$

where V_i is the image potential induced in the surface by the escaping ion with perpendicular velocity $\hat{v}_1$, and β is a constant. This equation, in fact, is differential in that one must integrate the expression over the sputter particle energy distribution $2\pi f(E, \theta) \sin \theta dE$ and the sputter particle angular distribution to determine the total probability for negative ion formation. However, for the purpose of comparison with the data of Yu, we use Eq. (3) and assume that all particles are ejected perpendicular to the surface. A nonlinear least squares fit of Eq. (3) to the data of Ref. 6 is shown in Fig. 1.10.

In this figure, the surface work function lowering models of Alton,⁸ Gyftopoulos and Levine,⁹ and Topping,¹⁰ which are all based on the work function changes induced in metal surfaces by electropositive adsorbates, are used in Eq. (3) for purposes of evaluation. The model of Alton is slightly superior to the model of Topping,¹⁰ while the model of Gyftopoulos and Levine⁹ is found to be completely inappropriate.

Although basic surface ionization theory is, in the strictest sense, only applicable to systems in thermodynamic equilibrium and the sputtering process does not meet this criterion, the

Fig. 1.10. Comparison of the Nørskov and Lundqvist⁶ model for secondary negative ion generation with the experimental data of Yu.⁷ The work-function-lowering models of Alton, Gyftopoulos and Levine and Topping are used to approximate the work function ϕ at a given relative coverage value θ .

results of the previous studies¹¹ using the modified University of Aarhus source, make what appears to be direct quantitative correlation with experiment using a modified surface ionization theory.

In this model, the probability of a particle leaving a surface as a negative ion is given by a modified form of the Langmuir-Saha relation

$$P_I = \frac{\frac{\omega^-}{\omega_0} \left(\frac{1-r^-}{1-r_0^-} \right) \exp(\beta(E_A - \phi)) / \bar{E}}{1 + \frac{\omega^-}{\omega_0} \left(\frac{1-r^-}{1-r_0^-} \right) \exp(\beta(E_A - \phi)) / \bar{E}} \quad (4)$$

where r^- , r_0^- are surface reflection coefficients for the negative, neutral particles, respectively, ϕ is the work function of the surface at relative coverage θ , E_A is the atomic electron

affinity of the target material at infinity, $\bar{E}$ is the average energy of ejection perpendicular to the surface, β is the fitting constant, ω^- , ω_0 are statistical weighting factors which are related to the total electronic spin of the respective species given by

$$\omega = 2 \sum_j s_j + 1.$$

Equation (4) was compared again with the data of Ref. 7 with the same work-function-lowering models as used in the Nørskov and Lundqvist model for secondary negative-ion generation (Eq. 3). The results of these comparisons are seen in Fig. 1.11. The modified surface ionization model is seen to fit to the experimental data as well as that of the Nørskov and Lundqvist model. Again, we note that the Alton model for work

Fig. 1.11. Comparison of the modified surface ionization model for secondary negative ion generation with the experimental data of Yu.⁷ The work function lowering models of Alton, Gyftopoulos and Levine and Topping are used to approximate the work function ϕ at a given relative coverage value θ .

function lowering is superior to the other models mentioned previously.

A SCALED SIGMUND THEORY MODEL FOR DETERMINING SPUTTER RATIOS

G. D. Alton D. H. Olive¹

1. Graduate student, Vanderbilt University, Nashville, Tennessee.

2. G. Blaise and A. Mourtier, Surface Science 90 (1979) 495.

3. P. Williams, Surface Science 90 (1979) 588.

4. K. Wittmaack, in *Inelastic Ion-Surface Collisions*, edited by N. Tolk, J. C. Tully, W. Heiland, and C. W. White (Academic, New York, 1977).

5. A. Blandin, A. Mourtier, and D. W. Hone, J. Phys. (Paris) 37 (1976) 369.

6. J. K. Mørskov and B. I. Lundqvist, Phys. Rev. B19 (1979) 5661.

7. M. L. Yu, Phys. Rev. Lett. 47 (1981) 1325.

8. G. D. Alton, Surface Science 175 (1986) 226.

9. E. P. Gyftopoulos and J. D. Levine, J. Appl. Phys. 33 (1962) 67.

10. J. Topping, Proc. Roy. Soc. (London) A114 (1927) 67.

11. G. D. Alton and C. Blazey, Nucl. Instrum. Meth. 166 (1979) 105.

The Sigmund theoretical model² is the most widely accepted and used model for estimating the number of atoms ejected per ion from a surface as a result of energetic particle bombardment. The theoretical model is based on solution of the Boltzmann transport equation and the use of linear cascade theory to simulate a sequence of elastic collisions set in motion beneath the surface of a solid or liquid by an energetic projectile as it slows down in the homogeneously distributed matrix. This cascade process may lead to particle ejection from the surface; this ejection process is referred to as sputtering. By solving this equation, Sigmund was able to derive analytical formulas for the sputter ratio, $S(\text{atoms/ion})$,

$$S(E, \theta) = \frac{A_1 3\lambda \alpha E}{\pi^2 4U_0(\cos\theta)^F} \quad (\text{for } E < 1000 \text{ eV}) \quad (1)$$

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

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.

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

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

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

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

a_0 is the radius of the first Bohr orbit,

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

$$\text{with } \epsilon = \frac{M_2 E (M_1 + M_2)}{Z_1 Z_2 e^2 / a_{12}} \text{ and } A_1, A_2 \text{ are scaling}$$

parameters which we determine from experimental data. (The original theory does not include such scaling factors.)

While the theory predicts shapes of sputter coefficients versus projectile energy in good agreement with experimental data, calculated values are generally in poor agreement, often varying by factors of 5 or more. As well, experimentally observed sputter coefficients are found to vary periodically with projectile atomic number;³ no such periodicity is predicted by the Sigmund theory. Such deviations are, in part, attributable to approximations and deletions made during the derivation and the assumption of a homogeneously distributed target; in reality, most targets are polycrystalline.

Sputter ratio data, as indicated above, exhibit periodic structure as a function of projectile atomic number Z_1 . This phenomenon is readily apparent in the data of Almen and

Bruce.³ These data offer a relatively large self-consistent set taken at a single energy (45 keV) for targets of Ta, Cu, and Ag; therefore, we chose these data as the basis for determining scaling parameters for adjusting the Sigmund theory into closer agreement with experiment. Because of the periodicity of the sputter ratio versus projectile atomic number for a particular target, a smooth centroid line can be drawn through a given data set. The experimentally measured sputter ratios for a particular projectile/target combination can individually be expressed as

$$S(Z_1, Z_2) = S_0 + \Delta S \quad (3)$$

where S_0 is the component of the sputter ratio up to the centroid line; ΔS is measured from the centroid line to the actual experimentally determined sputter ratio value. Therefore, ΔS may have positive or negative values relative to the centroid line. We utilize a weighted average of the three Almen and Bruce data sets to determine ΔS values for projectile/target combinations where no sputter data or incomplete sputter data exists. Thus,

$$\Delta S(Z_1, Z_2) = \pm \left(\frac{\Delta S(Z_1, Z_2)}{S_0} \right)_{Ex} S_0. \quad (4)$$

An interesting relationship between S_0/Z_1 and the unscaled Sigmund theory S_{Th} was discovered which permits independent determination of S_0 for many targets. Specifically, we find a linear relationship between S_0/Z_1 and unscaled S_{Th} for a given projectile. All targets which have sputter ratios equal to or greater than that of the particular projectile/target combination at 45 keV are found to fall on this line. Thus, S_0 can easily be determined for unknown targets. This information in combination with the weighted average ΔS values computed from Eq. (4) can be used to estimate sputter ratios for any projectile interacting at 45 keV with the particular target. From the linear relationship between S_0 and S_{Th} and the use of Eqs. (3) and (4), the following expression is obtained

$$S(Z_1, Z_2) = \left(1 + \left(\frac{\Delta S}{S_0} \right)_{Ex} \right) \left[(S_{Th} - S^-) + \left(\frac{S_0 - S_0^-}{S_{Th} - S^-} \right) + Z_1 S_0^- \right] \quad (5)$$

where S_0^- and S^- are constants common to all target/projectile combinations.

Scaling factors for the Sigmund theory are determined by use of either Eq. (5) or experimental data from the relation

$$A_{1,2} = S(Z_1, Z_2) / S_{Th} \quad (6)$$

where A_1 is used for the low-energy regime ($E < 1000$ eV) and A_2 is used for the high-energy regime ($E > 1000$ eV).

A versatile and practical computer code has been written for use in estimating sputter ratios as a function of projectile atomic number Z_1 , target atomic number Z_2 , projectile energy

E , and angle of incidence θ with respect to the surface normal for most projectile/target combinations. The code is written in an interactive user input format with versions available for both the DEC/VAX and IBM-PC computer systems. The program can be executed in either one of two modes: sputter ratio as a function of projectile atomic number Z_1 for a particular target or sputter ratio as a function of projectile energy for a given projectile/target combination. In both modes, the user is prompted for Z_1 , Z_2 , θ , and the energy E of the projectile. The masses of the projectile and target are assumed to be the principal isotopes and are tabulated within the program. Hard copy output is either in text or graphical format.

Figure 1.12 compares computed and experimental results for a variety of projectiles on a copper target at 45 keV. The discrete point

Fig. 1.12. Comparisons of calculated sputter ratios based on the Sigmund Theory with the experimental data of Almen and Bruce (Ref. 2) as a function of projectile atomic number. --- scaled Sigmund Theory; — unscaled Sigmund Theory; □ experimental data.

experimental data are taken from the measurements of Almen and Bruce,³ the dashed line is computed from the present model; the monotonic solid curve is computed from unscaled Sigmund theory. Projectile energy-dependent calculations based on the scaled Sigmund theory are shown in Fig. 1.13 for a Xe projectile at normal incidence on a Ta target.

1. Graduate student from Vanderbilt University, Nashville, Tennessee.
2. P. Sigmund, Phys. Rev. 184 (1969) 383.
3. O. Almen and G. Bruce, Nucl. Instrum. and Meth. 11 (1961) 257; 279.

THE EMITTANCES OF NEEDLE-TYPE, LIQUID-METAL ION SOURCES

G. D. Alton P. M. Read¹

The number of applications for ultrahigh brightness ion beams continues to grow. A

potential route to increased brightness beams is through the use of field ionization^{2,3} or liquid-metal ion sources (LMIS).^{4,5} The central cores of beams extracted from these sources have reported brightnesses of 10^5 times those from conventional gaseous discharge sources.^{5,6} The LMIS has the advantage of higher ion beam current and avoids the gas loading and scattering problems associated with the field ionization source.

Knowledge of the distribution of the transverse emittance with percentage beam intensity can provide valuable information for accessing the merits of the source for a variety of focused-beam and other applications. From such measurements, the effective size of the emission region of the source can be estimated since the ion beam angular distributions have been rather carefully documented previously.^{7,8} The ability

Fig. 1.13. Sputter ratios versus projectile energy for xenon at normal incidence on a Ta target. — scaled Sigmund Theory; --- unscaled Sigmund Theory.

to make such determinations with accuracy, however, presupposes that the beam transport system does not significantly increase the emittance of the beam during transport to the measuring device.

During this reporting period, we made first measurements of the emittances and brightnesses of momentum-analyzed $^{69}\text{Ga}^+$ ion beams extracted from needle-type, liquid-metal ion sources. Both conical and planar geometry extraction/post acceleration systems were evaluated. The emittance measuring apparatus, described in detail previously,^{9,10} located at the Negative Ion Source Preparation Facility, was used during these investigations.

The LMIS utilized in the present measurements consists of a tungsten needle with a tip radius of about 10 μm wetted with gallium and supported in a reservoir tube. Ions are extracted from the tip of the Taylor cone¹¹ which is formed by applying between 5 to 6 kV positive voltage relative to the extraction electrode. The ion current can be adjusted from a few μA to several tens of μA by increasing the extraction voltage. After extraction, the ions are accelerated further by 20 to 25 kV and passed through a molybdenum aperture plate which serves to limit the angular divergence. A 50-mm-diameter grid-ded einzel lens is located downstream of the aperture. (This lens has considerably lower spherical aberration coefficients than conventional three-cylinder open bore lenses.¹²)

In these studies, we chose to contrast the emittance of beams extracted from the conical system with those extracted from the planar geometry system. The planar geometry system is expected to have lower aberration coefficients due to the substantial reduction in field curvature over that of the single-aperture conical geometry system. For the planar geometry system, we utilized a flat grid as the high-energy postacceleration electrode. Ions in this source geometry are postaccelerated in an essentially uniform field in contrast to the very strongly

curved fields associated with the postacceleration stage of the conical geometry source.

Evidence of the presence of space charge and perhaps other intensity-dependent sources of energy spread are seen in the normalized emittance versus percentage transmitted ion beam data shown in Fig. 1.14 for the conical geometry ion source. Normalized emittance, ϵ_n , is defined as

$$\epsilon_n = \sqrt{\epsilon_{nx}\epsilon_{ny}} \quad (1)$$

where $\epsilon_{nx} = \overline{xx'}/E$; $\epsilon_{ny} = \overline{yy'}/E$ and x and y are position coordinates, x' and y' are angular coordinates, and E is the energy of the ion beam. All data displayed in this report are computed in terms of Eq. (1). The beam half angle was limited to $\alpha = 7^\circ$ for these measurements. Each data set represents an average of three to five measurements under the same source operating conditions. Dotted lines have been provided to facilitate interpolation of emittance values for intermediate beam percentages. The relative normalized emittances ϵ_n are found to increase roughly as $\epsilon_n \propto I^{1/2}$.

For this source, the x-direction contours are found to be larger by factors of 1.6 to 4 over the analogous y-direction contours at total extracted ion currents between 10 and 60 μA . This factor is even greater at higher extracted beam intensities. These differences are most likely attributable to the change in intrinsic energy spread with beam intensity and the consequent dispersion of the beam in the x-direction by the 90° momentum analysis system.

Emittance versus percentage momentum-analyzed $^{69}\text{Ga}^+$ ion beam current data from the planar geometry source are shown in Fig. 1.15. The relative normalized emittance ϵ_n for this source geometry is found to increase very roughly with transmitted ion beam current I according to $\epsilon_n \propto I^{1/3}$. The x-direction contours are larger by factors of 1.6 to 2.0 over the analogous y contours at total currents between 10 and 60 μA . This effect is clearly less than that observed

Fig. 1.14. Normalized emittance, ϵ_n , versus percentage $^{69}\text{Ga}^+$ ion beam intensity for various beam intensities. Source: conical geometry, limiting angle: $\alpha = 7^\circ$.

from similar measurements involving the conical geometry source, even though the beam-limiting half angle was considerably larger ($\alpha = 11.4^\circ$) for the planar geometry than that used for similar studies with the conical geometry source ($\alpha = 7^\circ$).

Table 1.11 lists average ratios, R , of the 80% emittance contours for the conical geometry to those for the planar geometry source for various transmitted ion currents, I . Thus, we see from Table 1.11 that the ratio R increases approximately linearly with transmitted ion beam intensity I . The results of the present emittance measurements point out the importance of the extraction/postacceleration system design for transporting substantial fractions of the total ion beam intensities from LM-type ion sources. The planar geometry source is clearly superior as anticipated.

Analysis of the various contributions to the observed emittances indicates that dispersion in the magnet is a principal contributor to the growth of the emittance in the x-direction. Obviously, elimination of magnetic analysis could substantially reduce phase space growth due to these effects.

The results of these studies point out the difficulty of transporting highly divergent beams such as those extracted from the LMIS. Serious aberrations to the ion beam can be limited only by aperturing to low angular divergences (e.g., $\alpha < 3^\circ$ from the source). Clearly, aberrations induced by the postacceleration, gridded lens, and momentum analysis obfuscate the true intrinsic emittance of the LMIS.

Fig. 1.15. Normalized emittance, ϵ_n , versus percentage $^{69}\text{Ga}^+$ ion beam intensity for various ion beam intensities. Source: planar geometry, limiting angle: $\alpha = 11.4^\circ$.

Table 1.11. Ratio R of the 80% emittance contours from the conical geometry source to those from the planar geometry source

$I (\mu\text{A})$	R
1	1.22
2	1.32
3	1.43
4	1.54

2. R. Levi-Setti, Nucl. Instrum. and Meth. 168 (1980) 139.

3. S. Sato, T. Kato, and N. Igata, Proceedings of the Eleventh Symposium on Ion Sources and Ion Assisted Technology (1987) 91.

4. R. Clappitt and D. K. Jeffries, Nucl. Instrum. and Meth. 149 (1978) 734.

5. R. L. Seliger, J. W. Ward, and R. L. Kubena, Appl. Phys. Lett. 34 (1979) 310.

6. G. L. Allan, J. Zhu, and G. J. F. Legge, Proc. Fourth Australian Conf. on Nucl. Tech. (1985) 49.

7. P. Marriott, "Angular and Mass Resolved Energy Distribution Measurements with a Gallium Liquid-Metal Ion Source," AERE-R-12674, Harwell Laboratory, Oxfordshire, U.K.

8. L. W. Swanson, G. A. Schwind, A. E. Bell, and J. C. Brady, J. Vac. Sci. Technol. 16 (1979) 1864.

9. G. D. Alton, J. W. McConnell, S. Tajima, and G. J. Nelson, Nucl. Instrum. and Meth. in Phys. Res. B24/25 (1987) 826.

10. G. D. Alton, Proceedings of the Eleventh Symposium on Ion Sources and Ion Assisted Technology, Tokyo, Japan (1987) 157.

11. G. I. Taylor, Proc. Royal Soc. A280 (1964) 383.

12. G. Liebmann, Proc. Phys. Soc. 62 (1949) 15.

FACILITY OPERATIONS AND DEVELOPMENT

HHIRF EXPERIMENTS

R. L. Robinson

Table 1.12 lists the experiments that were performed at the Holifield facility during

Table 1.12. Experiments completed at the MHIRF during October 1, 1986 - September 30, 1987

Title	Spokesman	Run Number	Target Station	Beam		Research Hours
				Type	E (MeV)	
TANDEN						
Subbarrier Fusion Cross Sections for Beams of ^7Li and ^{54}Ni on Medium-Mass Targets	Stelson (ORNL)	H132	Split-Pole Magnet	^{58}Ni	160,170,210	43
Investigation of Band Crossings and Shape Changes in ^{174}Os	Johnson (ORNL)	H136	Spin Spectrometer	^{32}S	162	35
Angular Momentum Distributions in Near-Barrier Fusion	Beene (ORNL)	H138	Spin Spectrometer	^{76}Ge ^{26}Mg	260-305 100-121	86
Isotope Shifts and Hyperfine Structures of Light Lead Isotopes	Griffin (Georgia Tech)	H147	UNISOR	^{16}O	125	44
Study of the γ Decay of Giant Resonances Built on the Excited States as a Probe of Nuclear Deformation at Very High Spins and Temperature	Baktash (ORNL)	H152	Spin Spectrometer	$^{80,82}\text{Se}$ ^{14}N	250-315 24	262
Levels in ^{180}Hg	Cole (INEL)	H156	γ -Ray Spectrometer	^{40}Ca	200,210	48
High Order Electric Multipoles in Convoy Electron Angular Distributions	Elston (U Tennessee)	H164	Atomic Physics	^{16}O	41,82,115	76
Spins and Saddle Point Shapes from Excitation Functions of Large Fragment Emission	Sobotka (Washington U)	H166	Spin Spectrometer	^{65}Cu	240-290	88
Gamma Ray Spectroscopy of High Spin States in the Mass A = 70 Region	Hamilton (Vanderbilt U)	H168	Spin Spectrometer	^{25}Mg	63,68	97
Search for Shape Coexistence in ^{194}Hg	Zganjar (Louisiana SU)	H169	UNISOR	^{16}O	150	85
Search for Band Termination in ^{157}Tm	Johnson (ORNL)	H172	Spin Spectrometer	^{54}Ar	220	116
Binary-Reaction Channel Study at and below the Coulomb Barrier	Kim (ORNL)	H176	Split-Pole Magnet	^{90}Zr	270-305	143
Deformation in the Light Rare Earths Around Sm	Fink (Georgia Tech)	H178	UNISOR	^{46}Ti ^{58}Ni	250 310	76
Band Crossing Frequencies for N = 104 Nuclei	Riedinger (U Tennessee)	H180	Spin Spectrometer	^{27}Al	131-196	97
α Decays of ^{180}Pb and ^{182}Pb ; Influence of the Z = 82 Gap on α Reduced Widths and Search for ^{224}U	Toth (ORNL)	H181	Velocity Filter	^{40}Ca ^{18}F	210 106,115	122
Electromagnetic Decay of the Giant Quadrupole Resonance in ^{208}Bi	Varner (ORNL)	H184	Spin Spectrometer	^4He	24	17
Study of Inelastic Scattering of ^{28}Si and ^{32}S on ^{208}Pb in the Spin Spectrometer	Hensley (ORNL)	H186	Spin Spectrometer	^{32}S ^{28}Si	272 267	72
On-line Nuclear Orientation of ^{180}Hg in Fe	Girit (Vanderbilt U/ JHIR)	H187	UNISOR	^{12}C	110	91
Measurement of Correlated Spin Alignment for Resonances in Inelastic $^{16}\text{O} + ^{16}\text{O}$ Scattering	Zurmuhle (U Pennsylvania)	H189	Spin Spectrometer	^{16}O	93-84	105
Study of Highly-Converted Transitions in ^{18}Pr	Wood (Georgia Tech)	H191	UNISOR	^{12}C	140	89
Study of Giant Resonances in Hot Rotating Nuclei Utilizing Heavy-Ion Induced Particle- γ Coincidence Measurements	Morsch (Inst Kernphysik, Jülich)	H193	Spin Spectrometer	^4He	24	17
High-Spin States in ^{179}Ir : Blocking and Identification of Band Crossings in ^{179}Os and ^{181}Pt	Janzen (U Tennessee)	H194	Spin Spectrometer	^{27}Al	118,134,136	118
$^{28}\text{Si} + ^{12}\text{C}$ Particle- γ Coincidence Experiment	Ray (Texas A&M)	H195	Spin Spectrometer	^{12}C ^{28}Si	34-135 145,160	151

Table 1.12. Experiments completed at the HHIRF during October 1, 1986 - September 30, 1987 (Cont'd)

Title	Spokesman	Run Number	Target Station	Beam		Research Hours
				Type	E(MeV)	
^{190}Hg and ^{192}Hg α Reduced Widths; Influence of the Neutron Number on the $Z = 82$ Gap	Ellis-Akovell (ORNL)	H198	UNISOR	^{12}C	90,115	61
Study of Deformation of Light Rare Earth Nuclei	Kern (U Kentucky)	H200	UNISOR	^{46}Ti	240	94
Spin and Temperature Dependence of Nuclear Deformation using Alpha-Gamma Angular Correlations	Nicollis (Washington U)	H201	Spin Spectrometer	^{50}Ti ^{40}Ca ^{78}Se ^{80}Se	221,230 190,205 320 325	189
Investigation of Superdeformed Bands by a New Selective Technique	Herskind (Niels Bohr Inst)	H207	Spin Spectrometer	^{11}B ^{48}Ca ^{80}Se	87 200 320-40	175
Investigation of Band Crossings and Shape Changes in ^{174}Os	Johnson (ORNL)	H208	γ -Ray Spectrometer	^{32}S	162	196
Study of Low-Energy Level Structure of ^{193}Pb and ^{197}Tl	Bingham (U Tennessee)	H209	UNISOR	^{16}O	155,165	97
Development of UNISOR Ion Sources	Carter (ORAU)	D016	UNISOR	^{12}C ^{16}O ^{46}Ti	130 150 230	76
Heavy-Ion Induced X-Ray Spectroscopy	Yane (ORNL)	D038	Atomic Physics γ -Ray Spectrometer Beam Line 22	^{35}Cl ^{63}Cu ^{28}Si	70 130 84	28 11 108
Test of BRS Detector System	Burks (ORNL)	D042	Broad-Range Magnet	^{16}O	172	20
Test of Detectors of 4% Plastic Ball	Serantites (Washington U)	D043	1.6-m Chamber Atomic Physics	^{26}Mg ^{12}C ^{28}Si ^{58}Ni	137 80-120 140-200 300	9 19
Development of Charged Particle Detectors for MILL	Shapiro (ORNL)	D047	Atomic Physics	^{12}C ^{28}Si ^{58}Ni	80-120 140-200 300	30
Test of Bunched-Chopped Beam	Bektash (ORNL)	D048	Spin Spectrometer	$^{80,82}\text{Se}$	255,285	34
Test of Merged Electron Beam System	Dittner (ORNL)	D050	Atomic Physics	^{32}S	112,149	18
Search for ^{224}U , ^{226}U	Toth (ORNL)	D053	Velocity Filter	^{19}F	102	43
Test of Photomultiplier Tube Bases	Obenshain (ORNL)	D055	Time-of-Flight	^{58}Ni	300	14
Test of Nuclear Orientation Facility	Carter (ORAU)	D057	UNISOR	^{12}C	140	26
Charge State Distribution of ^{150}Nd	Martin (ORNL)	D058	Beam Line 17	^{150}Nd	240,300	11
Test of Phoswich Detectors	Higley (U Maryland)	D061	1.6-m Chamber	^{58}Ni	180	23
COUPLED						
Neutron Emission in Damped Reactions of ^{58}Ni with ^{58}Ni and ^{163}Ho at 15 MeV/u	Petitt (Georgia SU)	H114	Time-of-Flight	^{58}Ni	912	50
Neutron-Particle Correlations for the $^{32}\text{S} + ^{197}\text{Au}$ Reaction	Aves (ORNL)	H146	Time-of-Flight	^{32}S ^{7}Li	700 128	130
Study of Reaction Mechanisms in the Emission of Heavy Fragments for 11 MeV/A $^{58}\text{Ni} + ^{58}\text{Ni}$	Gomez del Campo (ORNL)	H150	Spin Spectrometer	^{58}Ni	636	97
Measurement of Gyromagnetic Ratios of Individual States in First Back-Band of ^{181}Yb	Bolotin (U Melbourne)	H170	Beam Line C-7	^{116}Cd	496	119
Neutron Transfer Between Superfluid Nuclei	Wu (U Tennessee)	H173	Spin Spectrometer	^{112}Sn	510	168

Table 1.12. Experiments completed at the HHIRF during October 1, 1986 - September 30, 1987 (Cont'd)

Title	Spokesman	Run Number	Target Station	Beam		Research Hours
				Type	E(MeV)	
A Search for Giant Pairing Resonances in the Lead Region	Horen (ORNL)	H175	Broad-Range Magnet	^{16}O	400	147
Energy and Angular Momentum Division in Deep Inelastic Collisions Studied via Light Particle Emission from the Reaction $900\text{ MeV } ^{58}\text{Ni} + ^{12}\text{C}$	Tah (ORNL/JINR)	H183	HILI	^{58}Ni	909	83
Electromagnetic Decay of the Giant Quadrupole Resonance in ^{208}Pb	Verner (ORNL)	H184	Spin Spectrometer	^{17}O	375	168
Study of Giant Resonances in Hot Rotating Nuclei Utilizing Heavy-Ion Induced Particle- γ Coincidence Measurements	Morsch (Inst. Kernphysik, Jülich)	H193	Spin Spectrometer	^{16}O	300,406	152
4 π γ and n Measurements in Coincidence with Heavy Fragments for Reactions Induced by 17 MeV/u ^{58}Ni Projectiles	Charvet (Bruyères-le-Châtel)	H205	Spin Spectrometer	^{58}Ni	996	38
Test of BRS Detector System	Auble (ORNL)	D042	Broad-Range Magnet	^{58}Ni	696	21
Test of HILI Detectors	Shapira (ORNL)	D047	HILI	^{58}Ni	696,912	118
						4591

FY 1987. Those with a run number beginning with H were recommended by the Program Advisory Committee. Those with numbers beginning with a D indicate discretionary runs.

The distribution of the FY 1987 research hours by experimental target stations is given in Table 1.13. The Spin Spectrometer continues, as in past years, to be the most heavily used device. The HILI was first used for research this year (experiment H183).

EXPERIMENTAL FACILITIES

R. L. Auble	J. L. Blankenship ³
N. R. Johnson	M. L. Halbert
H. J. Kim	J. W. Johnson
H. K. Carter ¹	D. Shapira
R. W. Miles	C. A. Reed
M. E. Whitley	I. Y. Lee
I. C. Girit ²	J. Kormicki ⁴
R. L. Robinson	P. L. Pepmiller
D. L. Haynes	C. R. Vane

Major projects are described in more detail elsewhere in this report. The following is intended to give a brief overview of changes in and additions to the experimental apparatus.

Applications Beam Line

Beam line 22 (applications beam line) was completed in early 1987 and has since been in routine use for the study of heavy-ion induced X rays with the high resolution Von Hamos spectrometer. The beam line includes a 3° off-set magnet and upstream foil box to allow beam dispersion for single-event upset measurements.

Atomic Physics and Applications Annex

A new 204-m² experimental area, located on the southwest corner of the HHIRF, was completed in December 1986. The area is presently being used to house an ultrahigh vacuum ($<10^{-10}$ torr) test stand. A beam line (beam line 41), which will provide access to tandem beams, is being designed. Future plans call for installation of a switching magnet and ECR source to provide beams for injection into a proposed 2.7-Tm synchrotron/storage ring (HISTRAP).

Spin Spectrometer

The NaI-detector upgrade program is progressing smoothly, following some delay in

Table 1.13. Use of experiment target stations for the period October 1, 1986 through September 30, 1987

Target Station	Research Hours (No. of Runs)		
	Tandem	Coupled	Total
γ -ray spectrometer (tandem)	255(3)	na	255(3)
γ -ray spectrometer (coupled)	na	119(1)	119(1)
Velocity filter	165(4)	na	165(4)
Atomic physics (tandem)	171(7)	na	171(7)
Split-pole magnet	186(3)	na	186(3)
Broad-range magnet	20(1)	168(2)	188(3)
Time-of-flight facility	14(1)	180(2)	194(3)
1.6-m scattering chamber	32(3)	0	32(3)
UNISOR	699(19)	0	699(19)
Spin Spectrometer	1,639(22)	623(5)	2,262(27)
HILI	na	201(6)	201(6)
Beam line 17	11(1)	na	11(1)
Beam line 22	108(4)	na	108(4)
Total	3,300(68)	1,291(16)	4,591(84)

na = not accessible to beam

receiving the first replacement units. Eleven new or rebuilt NaI crystals and 35 new photomultiplier tubes have been received, and additional crystals are arriving on a regular basis. The present plan is to replace approximately 35 units, starting with those exhibiting the poorest performance. In addition, all phototube bases have been modified to eliminate an overheating problem.

The Dwarf Ball, described in the last progress report (ORNL-6326), is being modified to use CsI plus thin plastic scintillators in place of the original fast/slow plastic phoswich. This will provide better particle identification and lower cutoff energies.

A new scattering chamber, which replaces the downstream hemisphere of the original chamber, was fabricated for use in a joint ORNL-Julich experiment and is available to all users. It provides space for installing large auxiliary detectors, but requires removal of the forward ring of NaI detectors from the Spin Spectrometer.

1.6-m Scattering Chamber

A new target ladder and drive mechanism have been installed to correct problems with reproducibility and sticking experienced with the original mechanism. A continuous drive and readout are used in place of the original linear Geneva drive. A new control system with remote target changing capabilities and improved angle readouts for the detector mounting rings is presently under development.

HILI Detector

The HILI has been successfully tested with all components in place with the exception of the second 96-element scintillator array. The existing scintillators use fast/slow plastic and have a low energy cutoff of about 8 MeV for protons. Alternate materials, in particular CsI/thin plastic, are being considered for the second array in order to reduce the cutoff to about 1 MeV.

Nuclear Orientation Facility

Installation of the helium-dilution refrigerator and connecting beam line has been completed. In tests of the beam transport system, over 90% of the beam from the isotope separator was deposited at the cold finger position. Problems with the design of the refrigerator heat shields and an adverse effect of the refrigerator's magnetic field on the germanium detectors have thus far prevented a successful on-line experiment. Both problems are being addressed by the vendors.

Barium Fluoride Detectors

Tests are being made on crystals and photomultiplier tubes from various vendors to evaluate components to be used in a large BaF₂

array. This array, which is expected to include approximately 60 elements, will enhance our capabilities for detecting high-energy gamma rays and discriminating against neutrons. Detector design and writing of specifications are nearly complete and purchase orders for prototype crystals and photomultiplier tubes have been placed.

UNISOR Ion Source Development

A new ion source, designated FEBIAD-B2, has been installed on the isotope separator. This source, which is based on a GSI design, has now been used in several experiments and has demonstrated higher reliability, greater longevity and better yields than previous sources.

Compton-Suppression System

A new detector support stand has been designed which will permit up to 20 Compton-suppressed Ge-detectors to be mounted in close geometry. This stand should reduce the number of configuration changes on the spin spectrometer and will minimize the source-detector distance, which is crucial for triple- or higher-order coincidence measurements.

1. UNISOR, Oak Ridge Associated Universities.

2. Joint Institute for Heavy Ion Research, Oak Ridge, TN and Physics Department, Vanderbilt University, Nashville, TN.

3. Instrumentation and Controls Division, ORNL.

4. Physics Department, Vanderbilt University, Nashville, TN.

COMPUTER SYSTEMS

J. A. Biggerstaff	J. W. McConnell
W. H. Atkins ¹	J. B. McGrory
D. M. Galbraith	W. T. Milner
	C. N. Thomas ²

Data Acquisition/Reduction Computer System

The two of our three CONCURRENT data acquisition computers that are multiprocessors (two processors per system) are now nearly identical; we have added two 650-MByte disk drives to the second CPU to achieve this symmetry. New data

acquisition interfaces to the computers have been implemented. These interfaces are required to eliminate a memory-addressing limitation of the old CAMAC interfaces--our new CAMAC interfaces do not have this limitation but are not really suitable for handling the main event-by-event datastream. The new "BMF" (Buffer Memory FIFO) comprises a 64-kByte FIFO buffer connected to a Selector Channel of the CONCURRENT CPU, a byte-wide data path with parity and cyclic-redundancy checking from the data acquisition station, and a Transmitter/FIFO with a further 8-kByte FIFO in the front-end station. The large buffering capacity of these systems provides essentially complete freedom from computer latency problems. The improved transmission error checking guards against circuit failure. Of particular interest to users is the capability, provided by the Transmitter/FIFO, of placing event data in the datastream in the most convenient sequence and subsequently, if something such as an energy-sum shows that the event is not interesting, "scrubbing" the event from the datastream.

Data acquisition software supporting the BMF has been implemented. Data manipulation, display and analysis programs have been upgraded to support symbols and loops in their command syntax. A complete revision of the Computer Handbook, including documentation of VAX software has been issued. Nearly all CONCURRENT software and its VAX counterparts have been revised to achieve uniformity in command syntax and function. The 3rd edition of VAXPAK (a collection of our acquisition/reduction software and utilities suitable for use on VAXen) has been released.

The VAX 11/785, FPS-164 Array Processor System

An additional RA81 450-MByte disk was added to the VAX. The 900-lpm line printer was replaced with a more rugged 1250-lpm printer. A laser printer was installed. A light-duty line printer was furnished for Bldg. 6008 (JIHR). Terminal ports were provided for all division secretaries. The backplane of the Array Processor was replaced in order to improve

reliability and decrease down-time. The array processor's memory was increased to about 2.4 million words.

Local Area Networks

The fiber-optic link between ORELA and CTD¹ facilities in building 4500 has been installed, giving us full DECNET connectivity to the CTD network. An extension of this Ethernet Local Area Network (LAN) is in progress. An Ethernet cable has been run throughout Bldg. 6000 providing any possible work area with reasonable access to the LAN. Approximately 40 terminals throughout HHIRF and the VAX and CONCURRENT computers will be attached to the LAN. Any of these terminals can access any of the host computer systems without re-cabling or hardware switching. A growing number of Microvax systems in the division may be easily connected to the network for full DECNET functionality with other Physics Division and Laboratory VAXen. The attachment of the CONCURRENT systems and the VAX system on the LAN will allow a more convenient file transfer mechanism to be implemented.

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

THE JOINT INSTITUTE FOR HEAVY ION RESEARCH

R. L. Robinson J. H. Hamilton
L. L. Riedinger

The Joint Institute for Heavy Ion Research (JIHIR), in fulfilling its role of enhancing the research activities of the Holifield Facility, supported 54 guests during FY 1987. These guests are listed in Table 1.14; their average length of appointment was four months.

In October 1986, the Joint Institute sponsored a workshop on Heavy Ion Physics and Instrumentation for a 15-Tm Booster and Storage Ring. There was special emphasis on physics that would be possible only with a storage/cooler ring. The meeting was in the true sense a "workshop." On the second day of the three-day meeting, all attendees participated in one

of four study groups. Rapporteurs summarized the discussions of these working groups on the third day. The program for the workshop is shown in Fig. 1.16.

During September 1987 the Joint Institute assisted in sponsorship of a "theory" month which culminated with a two-day workshop. Speakers at the workshop were:

<u>Name</u>	<u>Institute</u>
S. Ayik	Tennessee Tech. Univ.
A. B. Balantekin	Univ. Wisconsin
A. F. Barfield	Univ. of Arizona
J. Dudek	Univ. of Strasbourg
M. Dworzecka	George Mason Univ.
D. H. Feng	Drexel Univ.
J. J. Griffin	Univ. of Maryland
M. W. Guidry	Univ. of Tennessee
J. I. Kapusta	Univ. of Minnesota
C. M. Ko	Texas A&M
S. Kohler	Univ. of Arizona
K. F. Liu	Univ. of Kentucky
B. Muller	Univ. of Frankfurt
J. W. Negele	MIT
V. E. Oberacker	Vanderbilt Univ.
S. E. Pratt	Univ. of Tennessee
J. Randrup	LBL
M. J. Rhoades-Brown	SUNY, Stony Brook
A. S. Umar	Vanderbilt Univ.
M. Vallieres	Drexel Univ.
Cheuk-Yin Wong	ORNL
Cheng-Li Wu	Drexel Univ.

An important component of the Joint Institute is its dormitory facilities which are available to Holifield users. During FY 1987 there were 212 visitors who were housed for an average of 6 days each.

THE PROGRAM ADVISORY COMMITTEE

R. L. Robinson

The Holifield Program Advisory Committee met twice in FY 1987 (PAC-8 and PAC-9). Information on these meetings is listed in Table 1.15. Because of the reliable performance of the accelerator systems, it has been possible to schedule PACs every six months since 1984. However, the number of hours that PAC-9 was asked to recommend (about 1700) was down from the more typical value of 2000 hours, because of the extended downtime required to install the new tandem acceleration tubes.

Table 1.14 Guest scientists at the Joint Institute
for Heavy Ion Research during the period of
October 1986 - September 1987

<u>Name</u>	<u>Institute</u>	<u>Length of Appointment</u>
P. Arve	Daresbury Laboratory (England)	2 weeks
M. Beckerman	ORNL/JIHIR	4 months
A. Bracco	Univ. of Milano (Italy)	2 months
R. Broglia	Univ. of Milano (Italy)	2 months
J. Charvet	Centre d' Etudes de Bruyeres- Le-Chatel (France)	1 year
Y. Chen	Inst. of Atomic Energy (China)	6 months
R. Donangelo	Inst. de Fisica da UFRJ (Brazil)	3 weeks
F. Donau	Zentralinstitut fur Kernforschung (East Germany)	1 month
J. Dudek	Univ. of Strasbourg (France)	4 months
D. Ernst	Texas A&M Univ.	1 month
J. Forster	Chalk River Nuclear Laboratories (Canada)	5 weeks
J. Garrett	Niels Bohr Inst. (Denmark)	2 weeks
C. Girit	Vanderbilt Univ./JIHIR	1 year
J. Griffin	Univ. of Maryland	3 months
K. Groeneveld	Johann Wolfgang Goethe-Universitat (West Germany)	1 week
X. Han	Jilin Univ. (China)	1 year
B. Herskind	Niels Bohr Inst. (Denmark)	2 months
M. Hindi	Tennessee Tech Univ.	2 months
M. Irvine	Manchester University (England)	1 month
S. Kahane	Nuclear Research Center (Israel)	1 year
J. Kapusta	Univ. of Minnesota	1 week
M. Korolija	Ruder Boskovic Inst. (Yugoslavia)	4 months
S. Landowne	Argonne National Laboratory	2 weeks
L. Lantto	Univ. of Oulu (Finland)	1 year
R. Lemmer	Univ. of Witwatersand (South Africa)	1 month
J. Lisantti	ORNL/JIHIR	1 year
C. Maguire	Vanderbilt Univ.	1 month
C. Mahaux	Univ. of Liege (Belgium)	1 month
C. Magnago	Centre d' Etudes de Bruyeres- Le-Chatel (France)	6 months
J. Maruhn	Univ. of Frankfurt (West Germany)	1 month
J. Mitchell	Yale Univ.	3 months
B. Mottelson	Niels Bohr Inst. (Denmark)	4 days
B. Müller	Univ. of Frankfurt (West Germany)	2 weeks
J. Negele	Massachusetts Inst. of Tech.	1 week
A. Mourreddine	Centre de Recherche Nucleaire (Strasbourg, France)	2 months
J. Parikh	Physical Research Laboratory (India)	3 months
J. Pochodzalla	Michigan State Univ.	1 week
P. Quentin	Univ. of Bordeaux (France)	1 month
J. Randrup	Lawrence Berkeley Laboratory	3 days
J. Rasmussen	Lawrence Berkeley Laboratory	2 weeks
P. Reinhard	Univ. Erlangen (West Germany)	3 weeks
M. Rhodes-Brown	State Univ. of New York	2 weeks
M. Riley	JIHIR/ORNL/Univ. of Tennessee	1 year
S. Saini	ORNL/JIHIR	1 year
M. Schultz	Univ. of Heidelberg (West Germany)	3 months
Y. Schutz	GANIL (France)	6 weeks
D. Sousa	Eastern Kentucky Univ.	2 months
K. Teh	JIHIR/ORNL	1 year
A. Virtanen	Univ. of Jyvaskyla (Finland)	1 year
T. Walkiewicz	Edinboro University	10 months
R. Wang	Lanzhou Univ. (China)	3 weeks
J. Wells	Tennessee Technological Univ.	2 months
C. L. Wu	Jilin Univ. (China)	6 months
J. Zhang	Lanzhou Inst. (China)	1 year

WORKSHOP ON HEAVY ION PHYSICS AND INSTRUMENTATION FOR A 15-Tm BOOSTER AND STORAGE RING

(October 2-4, 1986)

PROGRAM

THURSDAY, OCTOBER 2

8:30 a.m. - Welcoming Remarks, John Hood,
Georgia Tech

Plenary Sessions

Session IA, 8:40 a.m. - Nuclei Far From Stability:
Reactions, Decay, Structure, and Astrophysical
Aspects, Chairman, Ed Eganjer

Amand Faessler, University of Tübingen

Ernst Roeckl, GSI Darmstadt

Session IB, 10:30 a.m. - Quantum Electrodynam-
ic Questions, Chairman, Baha Balantekin

Peter Mohr, National Science Foundation

Jonathan Sapirstein, University of Notre Dame

Session IIA, 1:00 p.m. - Giant Resonances and
Photonuclear Reactions, Chairman, Mike Guidry

Alan Nathan, University of Illinois

John Rasmussen, Lawrence Berkeley Laboratory

Session IIB, 2:40 p.m. - High-Energy Gamma-Ray
Production; Equilibrium-of-State Studies
(Experimental Problems), Chairman, Alice NisenzonJean-Alain Pinston, Centre de Etudes
Nucleaires de Grenoble

Glenn Young, Oak Ridge National Laboratory

Phil Siemens, University of Tennessee/
Oak Ridge National Laboratory

Rainer Morotny, GSI Darmstadt

FRIDAY, OCTOBER 3

Four concurrent sessions on the topics introduced
on Thursday (Session topics and Chairmen same as
on Thursday)

Morning Workshop Sessions

9:00 a.m. - 10:30 a.m.

10:50 a.m. - 12:15 p.m.

Afternoon Workshop Sessions

1:15 p.m. - 2:45 p.m.

3:05 p.m. - 4:15 p.m.

Rapporteurs:

Session IA: Lee Riedinger, University of
TennesseeSession IB: Baha Balantekin, University
of WisconsinSession IIA: Jim Beene, Oak Ridge National
Laboratory

Session IIB: Kevin Wolf, Texas A&M University

WHIRF Users Group Meeting - 4:30 p.m. - 5:20 p.m.

SATURDAY, OCTOBER 4

Rapporteurs' Reports on Workshop Sessions (Session
Topics and Chairmen same as on Thursday)

Session IA, 9:00 a.m., Lee Riedinger

Session IB, 9:50 a.m., Baha Balantekin

Session IIB, 11:50 a.m., Kevin Wolf

Session IIA, 11:00 a.m., Jim Beene

12:40 p.m., End of Workshop

Fig. 1.16.

Table 1.15. Information on PAC-8, PAC-9, and PAC-10

	Meeting Date	Hours Requested	Hours Recommended	Rec/Req.	Yet to be Run (hrs)
PAC-8	Oct. 86	2784	1984	71%	928
PAC-9	May 87	2800	1712	61%	1000
PAC-10	Oct. 87	2320	est. 1900	est. 82%	--

Members of one or both of the PACs that met in FY 1987 are:

John M. Alexander	SUNY at Stony Brook
Harold C. Britt	Lawrence Livermore Laboratory
Alan L. Goodkan	Tulane University
Harvey A. Gould	Lawrence Berkeley Laboratory
Teng Lek Khoo	Argonne National Laboratory
Joe B. McGrory	Oak Ridge National Laboratory
Phil J. Siemens	University of Tennessee
Paul H. Stelson	Oak Ridge National Laboratory

M. W. Guidry and A. C. Mignerey, in their capacity as chairpersons of the Executive Committee of the HHIRF Users Group, were present, respectively, at PAC-8 and PAC-9 meetings.

Proposals for consideration by PAC-10 were due September 22, 1987. Statistics on this PAC, which is scheduled to meet in late October, are included in Table 1.15. The shutdown in the fall of 1987 for completion of installation of new accelerator tubes should have only a small effect on the number of research hours that can be recommended.

2. EXPERIMENTAL NUCLEAR PHYSICS

Our main research program in heavy-ion physics continues to be based on the beams and experimental equipment at the Holifield Heavy Ion Research Facility (HHIRF), but increasing use is being made of facilities elsewhere. In particular, important programs have been established at CERN, using ultrarelativistic heavy-ion beams, and at GANIL, using medium energy heavy-ion beams. In addition, important results continue to appear from experiments using accelerator facilities at IUCF, LAMPF, TRIUMF, and LBL, as well as at the ORELA facility at ORNL. The main in-house program continues to be dominated by the Spin Spectrometer, the first of the 4 π gamma-ray detectors for nuclear structure physics. The Spin Spectrometer has undergone a significant upgrade. Up to 19 of the NaI units can be replaced by germanium Compton suppressed detectors. Innovative uses continue to be made with this remarkable instrument. Of particular note in this regard is the program on giant resonance measurements and the use of the device to measure inelastic scattering and transfer reactions.

NUCLEAR STRUCTURE STUDIES VIA ELASTIC AND INELASTIC SCATTERING

COULOMB EXCITATION OF GIANT RESONANCES IN ^{208}Pb BY $E = 84$ MeV/NUCLEON 170 PROJECTILES

D. J. Horen	J. Barrette ³
J. R. Beene	N. Alamanos ³
F. E. Bertrand	F. Auger ³
R. L. Auble	B. Fernandez ³
B. L. Burks ¹	A. Gillibert ³
J. Gomez del Campo	W. Mittig ⁴
M. L. Halbert	Y. Schutz ⁴
R. O. Sayer ²	B. Haas ⁵
J. P. Vivien ⁵	

During an experiment to study the photon decay of giant resonances being performed at GANIL (see accompanying report on Photon Decay of Isovector Giant Resonances in ^{208}Pb), we have obtained inelastic scattering data from the $^{208}\text{Pb}(^{170},^{170'})^{208}\text{Pb}$ reaction at an incident energy of 1428 MeV. These data show an important qualitative difference with all previous results obtained with heavy-ion projectiles. An example of this is shown in Fig. 2.1 where a spectrum obtained for inelastic scattering of 84 MeV/nucleon 170 ions by ^{208}Pb is compared with a similar spectrum reported⁶ using 22-MeV/nucleon 170 ions. The higher energy spectrum is dominated by Coulomb excitation of the isovector giant dipole resonance (IVGDR) and the ISGQR.

Fig. 2.1. Comparison of spectra obtained by inelastic scattering of 84- and 22-MeV/nucleon 170 ions by ^{208}Pb .

These new results demonstrate that inelastic scattering of high-energy (>100 MeV/nucleon) heavy-ion beams can be an important tool in the study of both isovector and isoscalar giant resonances.

The 84-MeV/nucleon 170 beam was provided by the GANIL accelerator. The scattered 170 ions were detected and identified in the energy-loss

magnetic spectrometer SPEG in which the momentum and scattering angle were obtained by reconstruction of the trajectories in the focal plane of the spectrometer. The overall energy resolution was ~ 800 keV with the use of a 5.1-mg/cm^2 -thick ^{208}Pb target. In the measurements of the inelastic spectra, a movable absorber was inserted near the focal plane to prevent elastically scattered particles from entering the detector system. Elastic data were taken in a separate run. The angular acceptance of the spectrometer covered simultaneously $1.5^\circ < \theta_{\text{c.m.}} < 5.0^\circ$. The vertical acceptance was 13 mrad for the elastic scattering measurements and 45 mrad for the inelastic data. The in-plane angular resolution is better than 0.2° ; however, at the more forward angles the effective angular resolution is determined by the vertical acceptance of the spectrometer. The angular accuracy is estimated to be 0.05° . The absolute normalization of the cross sections was obtained from the target thickness and the integrated beam current measured in a Faraday cup. The error on the normalization is estimated to be $\pm 10\%$.

Inelastic spectra obtained at three different scattering angles are shown in Fig. 2.2. The first peak just above zero excitation energy is due to the tail of the elastically scattered ions which are not stopped by the absorber. Peaks are seen which correspond to the excitation of the $2.62\text{-MeV } 3^-$, $4.09\text{-MeV } 2^+$, and $5.51\text{-MeV } 1^-$ states in ^{208}Pb . A strong giant resonance structure is observed at higher excitation energy which, at all angles, presents an excellent peak-to-continuum ratio. In the middle spectrum, obtained at the angle where the cross section of this structure is maximum, the ratio is 6 to 1! In the top and bottom spectra, a peak is clearly observed near 10.6 MeV , which is consistent with the excitation energy of the ISGQR. These two spectra are very reminiscent of those obtained with lower energy heavy-ions or with lighter probes. The giant resonance structure in the middle spectrum has a very different shape: it is broader and it peaks near 12 MeV .

Fig. 2.2. Inelastic scattering spectra at $\theta_{\text{lab}} = 1.86^\circ$, 2.56° , and 3.98° from the $^{208}\text{Pb}(^{17}\text{O}, ^{17}\text{O})$ reaction at 1428 MeV . The solid curves show a decomposition of the spectra into resonance peaks and an underlying continuum.

The resonance structure between 7 and 25 MeV has been decomposed into 6 peaks, corresponding to observed structure or to known giant resonances. Gaussian peaks at 10.6 MeV ($\Gamma = 2.2\text{ MeV}$) and 13.9 MeV ($\Gamma = 2.9\text{ MeV}$) are assumed to describe the ISGQR and ISGMR respectively. Narrow gaussian peaks at 7.5 MeV ($\Gamma = 1.0\text{ MeV}$) and 9.1 MeV ($\Gamma = 1.0\text{ MeV}$) have also been included in the fit, and can be associated with $L = 2$ strength observed in high resolution measurements.⁷ A broad peak at 19.5 MeV was

also included to describe the observed excess yield at high excitation energy.

Special attention is required in specifying the shape of the peak describing the IVGDR. The IVGDR strength function of ^{208}Pb is well known from photonuclear reactions and, above 9 MeV, can be well parametrized by a Lorentz curve centered at 13.5 MeV with a width of 4.0 MeV.^{8,9} However, the cross section for Coulomb excitation of a dipole state decreases exponentially as a function of the excitation energy of that state. Thus, to properly generate the shape of the IVGDR peak in the inelastic spectra, the strength function must be folded with this exponential excitation probability. In the present analysis, such a modified Lorentz function was assumed to describe the IVGDR. The energy dependence of the excitation probability was obtained from calculations using optical model parameters determined from our elastic scattering data (see below). Since the energy dependence varies with angle, so does the shape of the IVGDR, as shown in Fig. 2.2. The exponential dependence results in an enhancement of the low energy portion of the IVGDR and shifts the position of its maximum from 13.5 MeV to 12.7 MeV.

Typical fits to the data are shown in Fig. 2.2. Overall, the shape of the spectra are well described. At $\theta_{\text{lab}} = 2.56^\circ$, the giant resonance structure is largely dominated by the peak corresponding to the IVGDR.

Experimental angular distributions for the elastic scattering and the inelastic scattering for the 3^- and 2^+ collective states in ^{208}Pb are shown in Fig. 2.3. Using the code ECIS,¹⁰ an optical potential has been obtained from a fit to the elastic scattering data with relativistic kinematics and assuming real and imaginary Woods-Saxon potentials of equal geometry. The calculated angular distribution obtained with the parameters so determined ($V = 50$ MeV, $W = 57.9$ MeV, $r_v = r_w = 1.067$ fm, $a_v = a_w = 9.677$ fm and $r_c = 1.2$ fm) is shown as the solid curve on Fig. 2.3.

The inelastic angular distributions were calculated in the coupled-channel formalism using standard collective form factors generated

Fig. 2.3. Experimental elastic and inelastic angular distributions for the 2.61 3^- and 4.09 2^+ states in ^{208}Pb . The curves are results of optical model and coupled-channel calculations.

by the optical potential.¹¹ The calculated distribution shown in Fig. 2.3 for the 2.61-MeV, 3^- , state was obtained with a deformation length $\delta = \delta_c R_c = \delta_n R_n = 0.74$ fm, which corresponds to a $B(E3)_{\uparrow} = 0.52$ e $2b^3$. This value is in fair agreement with the adopted¹² $B(E3)_{\uparrow} = 0.611$ e $2b^3$. The shape of the angular distribution is reasonably reproduced. The 2^+ angular distribution was calculated with a deformation length $\delta = 0.405$ fm, which corresponds to the experimental $B(E2)_{\uparrow}$ value¹³ ($B(E2)_{\uparrow} = 0.318$ e $2b^2$). The good description of the inelastic angular

distributions shows that macroscopic form factors adequately describe the excitation of collective states.

The measured experimental angular distributions for the IVGDR and the ISGQR are presented in Fig. 2.4. Special note should be made of the dramatically large values of the differential cross sections; of the order of a few b/sr. The two angular distributions also have distinctly different shapes; that for the ISGQR being broader and flatter than that for the IVGDR.

Pure Coulomb excitation was assumed in the calculation of the IVGDR excitation.

Contribution to the IVGDR excitation from nuclear interaction could originate from the difference between the radial distribution of protons and neutrons.¹⁴ The strength of this excitation is expected to be negligible in comparison with Coulomb excitation. The calculated angular distribution (full line in Fig. 2.4) was obtained by integration of the IVGDR strength function between 7 MeV and 18.9 MeV and corresponds to 110% of EWSR depletion. In the same energy range, the photoneuclear reaction yields ~103% of the sum rule limit.^{8,9} The measured angular distribution is well reproduced.

The angular distribution of the ISGQR is described by a $L = 2$ calculation with a deformation length $\delta = 0.49$ fm corresponding to 60% EWSR. This value is in good agreement with the EWSR depletion obtained in recent works using lighter probes.^{7,15,16} Also shown in the figure are calculations assuming pure Coulomb and pure nuclear excitation. The two components have angular distributions which dominate in different angular domains. However, the Coulomb component, which has a distribution nearly identical with that calculated for the isovector IVGDR, is the larger near the maximum of the cross section.

In summary, the present work has shown that 84-MeV/nucleon ^{17}O ions excite the giant resonance region in ^{208}Pb with large cross sections and extraordinarily large peak-to-continuum ratios. To reproduce the spectra it is necessary to fold the IVGDR strength function with the energy-dependent Coulomb excitation probability. This effect results in a sizable shift of the IVGDR response function toward lower excitation energy than that observed in photoneuclear reactions. The large cross-section and peak-to-background ratios resulting from the strong Coulomb excitation of giant resonances by medium-energy heavy ions opens new possibilities for the study of both isoscalar and isovector giant resonances. In particular, such reactions would allow the study of rare decay modes of giant resonances. This would provide a powerful new tool with which to study the microscopic

Fig. 2.4. Experimental and calculated angular distributions for the isovector giant dipole resonance (upper part) and the isoscalar giant quadrupole resonance (lower part) in ^{208}Pb . For the GQR, the calculated Coulomb and nuclear contributions to the cross section are also shown (dashed lines).

structure of giant resonances and would complement similar experiments performed with photon or electron beams.

1. Engineering Physics and Mathematics Division, ORNL.
2. Computing and Telecommunications Division, ORNL.
3. Centre d'Etudes Nucleaires de Saclay, 91191 Gif-sur-Yvette Cedex, France.
4. Grand Accelérateur National d'Ions Lourds, 14021 Caen Cedex, France.
5. Centre de Recherches Nucleaires, 67037 Strasbourg Cedex, France.
6. T. P. Sjoreen et al., Phys. Rev. C 29, 1370 (1984).
7. F. E. Bertrand et al., Phys. Rev. C 34, 45 (1986).
8. A. Veyssiere et al., Nucl. Phys. A159, 561 (1970).
9. B. L. Berman and S. C. Fultz, Rev. Mod. Phys. 47, 713 (1975) and B. L. Berman, Atom. Data and Nucl. Data Tab. 15, 319 (1975).
10. J. Raynal, Phys. Rev. C 23, 2571 (1981).
11. G. R. Satchler, Direct Nuclear Reactions, (Oxford University Press, 1983).
12. J. B. Martin, Nuclear Data Sheets 47, 797 (1986).
13. J. Heisenberg et al., Phys. Rev. C 25, 2292 (1982).
14. G. R. Satchler, Nucl. Phys. A195, 1 (1972); Particles and Nuclei 5, 105 (1973); to be published.
15. H. P. Morsch et al., Phys. Rev. C 28, 1947 (1983).
16. D. K. McDaniels et al., Phys. Rev. C 33, 1943 (1986).

PHOTON DECAY OF ISOVECTOR GIANT RESONANCES IN ^{208}Pb

J. R. Beene	J. Barrette ³
F. E. Bertrand	N. Alamanos ³
R. L. Auble	F. Auger ³
B. L. Burks ¹	B. Fernandez ³
J. Gomez del Campo	A. Gillibert ³
M. L. Halbert	W. Mittag ⁴
D. J. Horen	Y. Schutz ⁴
R. O. Sayer ²	B. Haas ⁵
J. P. Vivien ⁵	

Hadron inelastic scattering has played a major role in the accumulation of information on the properties of isoscalar electric giant resonances over the past decade, but has made almost no contribution to our understanding of isovector giant resonances. This is because the relative weakness of the isovector part of the nucleon-nucleus interaction leads to small excitation cross sections for isovector states. This condition no longer holds for heavy-ion

scattering at bombarding energies sufficiently high that Coulomb excitation, which is blind to isospin, can play a major role in the excitation of high-lying states.

We recently began a series of experiments at the GANIL facility designed to study the isovector giant quadrupole resonance (IVGQR) in ^{208}Pb using the $^{208}\text{Pb}(^{17}\text{O}, ^{17}\text{O}')$ reaction. The IVGQR is predicted to be centered near 22 MeV. Since we depend on Coulomb excitation to excite this high-lying state, a high bombarding energy is needed. The 84-MeV/nucleon ^{17}O beam provided by GANIL should excite the IVGQR with a peak differential cross section several hundred times larger than the 22-MeV/nucleon ^{17}O beam available at HHIRF. Our intention was to attempt to isolate the IVGQR by making use of a predicted^{6,7} distinctive gamma-decay mode. In contrast to isoscalar 2^+ states, the gamma decay of the IVGQR is predicted to be dominated by decay to the 2.61-MeV 3^- state.

A brief initial run was carried out in the summer of 1986. Inelastic singles results from this run are discussed in an accompanying article.⁸ A striking feature of the data is the very large cross section (several barns/sr) in the giant resonance region. The inelastic scattering was studied in coincidence with gamma rays detected in four bundles of seven BaF_2 detectors (individually hexagonal in cross section, 8.7-cm face-to-face and 14-cm long), located at angles θ, ϕ ($95^\circ, 0^\circ$), ($70^\circ, 180^\circ$), ($134^\circ, 180^\circ$), ($90^\circ, 270^\circ$). Figure 2.5 shows the spectrum of inelastically scattered ^{17}O ions detected in coincidence with single gamma decays to the ground state. The analysis described in Ref. 8, combined with simple considerations of relative multipole gamma widths, suggests that the spectrum in Fig. 2.5 above 9 MeV should be dominated by gammas from the isovector giant dipole resonance (IVGDR). In Figs. 2.6 and 2.7, $^{17}\text{O}-\gamma_0$ angular correlations are shown compared with calculations made assuming pure Coulomb excitation of the IVGDR, with the properties of the GDR taken from photonuclear data.¹⁰ The nuclear interaction could, in principle play a role in excitation of the IVGDR since both

Fig. 2.5. Ground state gamma coincidence cross section from the $^{208}\text{Pb}(170, 170'\gamma_0)$ reaction at 84 MeV/nucleon.

Fig. 2.6. $170\text{-}\gamma_0$ angular correlation, for fixed γ angle and variable 170 angle, for the excitation energy range 9.5-25 MeV. The line is a calculation considering only Coulomb excitation of the the IVGDR.

target and projectile have $N \neq Z$.¹¹ Calculations following the methods of Ref. 11 indicate that such nuclear effects should be negligible; the close agreement between theory and experiments demonstrate that this is correct. The correspondence between the absolute cross section of Fig. 2.7 and the calculation involves an overall normalization factor that corresponds to the ground-state, gamma-branching ratio of the IVGDR averaged from 9.5 to 25 MeV. The value 0.017 ± 0.002 , which

Fig. 2.7. $170\text{-}\gamma_0$ angular correlation, for fixed 170 angle and variable γ angle, for the excitation energy range 9.5-25 MeV. The lines are a calculation considering only Coulomb excitation of the the IVGDR. The half of the reaction plane corresponding to $\phi = 180^\circ$ is displayed with $\theta + 180^\circ$.

results from a fit to the data is almost identical to the result (.016) obtained by applying (with no free parameters) the methods described in Ref. 9. The resulting calculation is compared as a function of energy with data in Fig. 2.8. Taken together, these results show that

Fig 2.8. Energy distribution of ground state gamma coincidence cross section, compared with a parameter free calculation using the methods of Ref. 4. The short dashed line is the contribution of decays from compound states, while the dash-dot line is the contribution of the doorway state decay. The solid line is the total.

the ground-state, gamma coincidence data is quantitatively accounted for by the Coulomb excited IVGDR with resonance parameters fixed at values determined in photonuclear data.

Figure 2.9 shows the relative yield of gamma-gamma coincidences as a function of excitation

Fig. 2.9. Distribution in E of relative gamma-gamma coincidence cross section, subject to conditions on the gammas described in the text.

energy (E^*), where $E_{\gamma 1} + E_{\gamma 2} = E^*$ and $E_{\gamma 1} = 2.6$ MeV. The peak in the relative yield near the expected IVGDR energy is tantalizing, in spite of poor statistics. We expect to obtain an order of magnitude more data in our next run.

We believe these initial results demonstrate the potential of intermediate-energy, heavy-ion scattering experiments for investigation of isovector resonance states, and for detailed systematic study of IVGDR gamma decay.

8. D. J. Horen et al., "Coulomb Excitation of Giant Resonances in ^{208}Pb by $E = 84$ MeV/Nucleon ^{17}O Projectiles," this report.

9. J. R. Beene, "Calculation of Ground State Gamma Yields in Giant Resonance Decay," this report.

10. B. L. Berman and S. C. Fultz, Rev. Mod. Phys. 47, 713 (1975).

11. G. R. Satchler, Direct Nuclear Reactions, (Oxford University Press, Oxford, 1983).

ELECTROMAGNETIC DECAY OF THE GIANT RESONANCE REGION IN NUCLEI

R. L. Varner	M. L. Halbert
J. R. Beene	D. C. Hensley
R. L. Auble	D. J. Horen
F. E. Bertrand	R. L. Robinson
B. L. Burks ¹	R. O. Sayer ²

We have an ongoing program of measurement of the properties of the electromagnetic decay from nuclei excited into their giant resonance region by the inelastic scattering of approximately 25-MeV/nucleon ^{17}O ions. Nuclei studied so far are ^{208}Pb (Ref. 3), ^{90}Zr (Ref. 4), and ^{209}Bi ; this report is about the work with Zr and Bi.

From the data we calculate the absolute cross section for the gamma decay of the target nucleus when excited into the giant resonance region. Our interest in the ^{90}Zr and ^{209}Bi systems arose because of the unusual properties of the gamma decay in ^{208}Pb , in which the cross section is much larger than can be accounted for by the decay of the giant resonance. We believe that this discrepancy can be understood in terms of the multistep theory of nuclear reactions. We should consider photon decay not only from the initial (doorway) stage, i.e. the coherent giant resonance state, but also from subsequent stages, including the fully damped compound nuclear states into which the resonance strength is eventually mixed. In the case of ^{208}Pb , the unusually small neutron decay widths of the compound states, resulting from the low density of final states in ^{207}Pb leads to unusually large compound contributions to the photon decay.⁵

The systems of ^{90}Zr and ^{209}Bi were selected to provide contrast with ^{208}Pb in nuclear structure and in the density of final states for neutron decay. In particular, ^{209}Bi was chosen because the direct decay properties of the giant

1. Engineering Physics and Mathematics Division, ORNL.

2. Computing and Telecommunications Division, ORNL.

3. Centre d'Etudes Nucleaires de Saclay, 91191 Gif-sur-Yvette Cedex, France.

4. Grand Accelérateur National d'Ions Lourds, 14021 Caen Cedex, France.

5. Centre de Recherches Nucleaires, 67037 Strasbourg Cedex, France.

6. P. F. Bortignon, R. A. Broglia, and G. F. Bertsch, Phys Lett. 148B, 20 (1984).

7. J. Speth, Phys. Rev. C 31, 2310 (1985).

resonances in Bi should be similar to those of ^{208}Pb , but the density of final states available in ^{208}Bi for neutron decay of the excited nucleus is much higher than in the case of ^{208}Pb , thus testing our Hauser-Feshbach model for the gamma decay yield. The ^{90}Zr nucleus provides a very different system in which to study the model — the neutron separation threshold is much closer to the GQR in energy and the width of the giant resonances is much larger than in the ^{208}Pb system.

In the case of the ^{90}Zr measurement, we have extracted the absolute cross section for gamma decay from the giant resonance region to the ground state, which is shown in Fig. 2.10. As can be seen, the cross section is quite small, and the uncertainties significant. For comparison with the data, we have made calculations using the program ONESTEP,³ which are shown as the curves in Fig. 2.10. These calculations were made for isovector dipole (IVGDR) and isoscalar quadrupole (ISGQR) giant resonance excitations, assuming the full sum rule strength for the excitation of the IVGDR and the measured strength for the ISGQR. The IVGDR calculations were made assuming only Coulomb excitation. The contributions include both direct decays from the resonances and decays from the compound nucleus. The calculation reproduces the data

Fig. 2.10. Cross section for gamma decay of the giant resonance region in ^{90}Zr . The curves are from calculations with ONESTEP.

quite well, and seems to confirm the application of the Hauser-Feshbach model in the ^{90}Zr system.

We will continue to refine the ONESTEP calculation, particularly to improve the agreement with the data near the neutron separation energy. We will also precede with the analysis of the lower energy decays, particularly in the region of the low-energy octupole resonance.

In the case of the ^{208}Bi measurement, the data are in the early stages of analysis. This experiment was performed using basically the same setup as in the ^{208}Pb experiment, with 2-mg/cm² targets and a 375-MeV ^{17}O beam. We applied the same algorithms to these data as were applied in the ^{90}Zr case to increase the density of good events in the data stream, chiefly the elimination of events in which the total gamma energy was below the excitation energy by more than the neutron separation energy. Better hardware in the Spin Spectrometer interface permitted much more accurate and stable application of these algorithms. As a further check, and to enhance our previous data, we measured the same data with a ^{208}Pb target for several shifts at the end of the ^{208}Bi beam time.

The excitation spectra have been calibrated and the calibration of the NaI detectors of the Spin Spectrometer is proceeding.

1. Engineering Physics and Mathematics Division, ORNL.

2. Computing and Telecommunications Division, ORNL.

3. J. R. Beene et al., submitted to Physical Review Letters and this report.

4. R. L. Varner et al., Phys. Div. Prog. Rep. for Period Ending Sept. 30, 1986, ORNL-6326, p. 26.

5. H. Feshbach, A. Kerman, and S. Koonin, Annals of Physics 125, 429 (1980).

CALCULATION OF GROUND STATE GAMMA YIELDS IN GIANT RESONANCE DECAY

J. R. Beene

The giant electric multipole resonances (GR) are simple collective states which are strongly excited by the inelastic scattering of hadronic probes. The coherent GR is not an eigenstate

of the complete nuclear Hamiltonian, rather its strength is mixed (damped) into the dense spectrum of complicated nuclear states of the same spin and parity which exist in the same energy region. The collective GR state can be considered as a doorway state through which the reaction proceeds. A quantitative treatment of the decay of such a GR should consider emission directly from the doorway, as well as from the fully damped compound states and states of intermediate complexity. The multistep theory of nuclear reactions^{1,2} was developed to treat such a situation.

We are interested in calculating the details of the ground-state photon decay of the giant resonance region of a heavy nucleus following inelastic excitation. For that part of the reaction which proceeds through some particular GR state, the ground state (γ_0) photon yield can be expressed schematically in the form¹

$$\sigma_{x,x',\gamma_0}(E) = \sigma_{x,x'}(E) \left(\sum_{i=1}^r \frac{\Gamma_{\gamma_0,i}}{\Gamma_i} \left[\prod_{j=1}^{i-1} \frac{\Gamma_j^\dagger}{\Gamma_j} \right] \right) \quad (1)$$

In this expression the first term represents photon emission directly from the doorway state, while each successive term corresponds to the contribution of successively more complex (e.g., 2p-2h, 3p-3h, etc.) states until finally the r th stage represents the fully damped compound system. The $\Gamma_{\gamma_0,i}$ represent the ground state gamma width for the i th stage ($i = 1$ is the doorway), $\Gamma_i^\dagger$, Γ_i , and Γ_i are the spreading width, escape width and total width ($\Gamma_i = \Gamma_i^\dagger + \Gamma_i$) of the i th stage ($\Gamma_{\gamma_0,i}$ is generally a small piece of $\Gamma_i^\dagger$). The quantity $\sigma_{x,x'}(E)$ represents the distribution (in excitation energy) of the cross section for exciting the GR state.

In general, the full calculation described by Eq. (1) cannot be carried out without a great deal of theoretical input, since the various $\Gamma_i^\dagger$ and Γ_i are not known. For the particular case of ground-state photon decay of heavy systems, the contribution of the doorway and compound terms are easily calculated, using the resonance strength for the doorway term and

results based on Hauser-Feshbach theory for the compound term. For this reason we compare the results of a simple two-step (doorway + compound) calculation to experimental data. In this case, Eq. (1) reduces to

$$\sigma_{x,x',\gamma_0}(E) = \sigma_{x,x'}(E) \left(\frac{\Gamma_{\gamma_0}}{\Gamma} + \left[\frac{\Gamma^\dagger}{\Gamma} \right] B_{CN}(E) \right) \quad (2)$$

where the subscript 1 referring to the first (doorway) stage has been dropped, and the branching ratio for the compound stage is represented by $B_{CN}(E)$. Γ_{γ_0} can be related in a straightforward way^{3,4} to the fraction of the energy-weighted sum rule (EWSR) depleted by the GR, and Γ is taken to be the experimentally observed width of the GR strength distribution. For a heavy nucleus it has generally been found, both experimentally and theoretically, that $\Gamma^\dagger > 0.9 \Gamma$; thus only an ~10% uncertainty is introduced by setting the quantity in square brackets in Eq. (2) to unity.

Some care is required in treating the compound nucleus term. The average ground state photon and total widths $\langle \Gamma_{\gamma_0,CN} \rangle$ and $\langle \Gamma_{CN} \rangle$ of compound states can be calculated by applying standard statistical model techniques. However, in general,

$$B_{CN}(E) \approx \frac{\langle \Gamma_{\gamma_0,CN} \rangle}{\langle \Gamma_{CN} \rangle} \quad (3)$$

It is necessary to take into account effects due to the distribution of partial widths^{5,6,7} (this is particularly true in the present case since $\langle \Gamma_{\gamma_0,CN} \rangle \ll \langle \Gamma_{CN} \rangle$). Fortunately, if individual partial widths are assumed to be distributed according to Porter-Thomas distributions, the relationship between $B_{CN}(E)$ and the mean widths calculated from Hauser-Feshbach theory is well defined and easily calculated.

In general, heavy-ion inelastic scattering leads to significant excitation of strength corresponding to several multiplicities in the "giant resonance region." Fortunately, the rapid decrease in $\sigma_{x,x'}(E)$ for increasing multiplicity and the absence of a ground state gamma

branch for $L = 0$ means that the isovector giant dipole resonance (IVGDR) will dominate the ground state gamma decays if it is significantly excited. The only other multipolarity which needs to be considered is E2. The application of the theory outlined above is illustrated in Fig. 2.11, which shows the coincidence cross section following inelastic 170 scattering from

Fig 2.11. Coincidence cross section for the $^{208}\text{Pb}(^{170},^{170}')$ reaction at 22 MeV/nucleon, integrated over gamma angle. The lines in (a) and (b) correspond to calculations using Eq. (2), as described in the text. The inset (c) shows experimental 170 angular correlations in the 9-11 MeV (solid points) and 12.5-15 MeV (open points) intervals. The correlation in both intervals agree with expectations based on the calculated E1 and E2 spectra. The short dash and dash-dot curves correspond to pure E1 and pure E2 respectively. The heavy solid line corresponds to the mixture of E1 and E2 radiation predicted for the 9-11 MeV interval by the calculations in (a) and (b).

^{208}Pb at 22 MeV/nucleon ($\theta(^{170}) = 13^\circ$).⁸ In this case, the excitation cross section for the isoscalar giant quadrupole resonance (ISGQR) is almost 40 mb/sr, while the giant dipole cross section is less than 3 mb/sr. Figure 2.11a shows the data compared with a calculation in which only the IVGDR is considered, with the resonance properties taken from photonuclear results.⁹ Clearly, the IVGDR accounts for a significant fraction of the yield. The difference between the experimental and theoretical yields is compared with a calculation for the ISGQR (using parameters from proton scattering¹⁰) in Fig. 2.11b. In both the GDR and QDR calculations, the contributions of the first term in Eq. (2) is shown as a short-dashed line, while the contribution of the second term is shown as a dash-dot line, and the total γ_0 yield as a heavy solid line. Similar calculations for other cases are shown in accompanying articles.^{10,11}

Clearly the calculations reproduce the absolute cross sections very well. Other experiments have been carried out to test the predictions concerning the relative contribution of compound and doorway terms more fully, but have not yet been fully analyzed.

1. H. Feshbach, A. Kerman, and S. Koonin, *Ann. Phys.* 125, 429 (1980).
2. M. Hussien and K. McVoy, *Phys. Rev. Lett.* 43, 1645 (1969).
3. J. R. Beene et al., p. 503 in *Nuclear Structure 1985*, edited by R. Broglia, G. Hagemann, and B. Herskind (North-Holland, 1985) and J. R. Beene et al., *Phys. Lett.* 164b, 19 (1985).
4. H. Dias et al., *Phys. Lett.* 173b, 335 (1986).
5. P. A. Moldaur, *Phys. Rev. C* 11, 426 (1974).
6. J. E. Lynn, *Theory of Neutron Resonance Cross Sections* (Oxford University Press, Oxford, 1968).
7. P. Axel et al., *Phys. Rev. C* 2, 68 (1970).
8. J. R. Beene et al., submitted for publication.
9. R. L. Bormann and S. C. Fultz, *Rev. Mod. Phys.* 47, 713 (1975).
10. R. L. Varner et al., "Electromagnetic Decay of the Giant Resonance Region in Nuclei," this report.
11. J. R. Beene et al., "Gamma Decay of Isovector Giant Resonances in ^{208}Pb ," this report.

NEUTRON DECAY OF GIANT RESONANCES IN ^{208}Pb ¹

A. Bracco ²	D. C. Hensley
J. R. Beene	R. L. Auble
F. E. Bertrand	D. J. Horen
M. L. Halbert	R. L. Robinson
	R. O. Sayer ³

The neutron decay of the giant multipole resonance region from 9 to 15 MeV of excitation energy in ^{208}Pb has been studied. Neutron branching ratios for the decay to the ground state or to the low-lying excited states of ^{207}Pb were measured as a function of the excitation energy of ^{208}Pb and compared with Hauser-Feshbach calculations. While the neutron branching ratios from the isoscalar quadrupole resonance are reproduced by the calculations, the ratios from the isoscalar monopole resonance show an excess large with respect to the statistical predictions.

-
1. Abstract of paper submitted to Physics Letters.
 2. Università Degli Studi di Milano, Milano, Italy.
 3. Computing and Telecommunications Division, ORNL.

COMMENT ON THE CHARACTERIZATION OF THE GIANT QUADRUPOLE RESONANCE IN ^{208}Pb AS REPORTED FROM π^+/π^- SCATTERING

D. J. Horen J. R. Beene
F. E. Bertrand

The conclusions that can be derived from experiments which excite the giant quadrupole resonance (GQR) can be, to some degree, dependent upon the assumptions made pertaining to its detailed structure. In this comment we wish to note that the recently reported¹ ratio of neutron to proton matrix elements for the GQR in ^{208}Pb , deduced from a comparison of π^+/π^- inelastic scattering, is inconsistent with results from other experiments when the latter are analyzed using the same assumptions for the GQR. Measurements of $T_\pi = 162$ MeV pion inelastic scattering on ^{208}Pb resulted in a value of the cross section ratio $\sigma(\pi^-)/\sigma(\pi^+) = 2.72 \pm 0.49$ for the 10.6 MeV GQR. These results have been interpreted as implying a matrix element

ratio $M_n/M_p = 3.8$ and reduced transition probabilities $B(E2)_+ = 1010 \pm 60 \text{ e}^2\text{fm}^4$ for the protons, and $B(M2)_+ = (1.45 \pm .36) \times 10^4 \text{ fm}^4$ for the neutrons.

This large difference in neutron and proton matrix elements would imply that the 10.6-MeV GQR in ^{208}Pb is not a predominantly "isoscalar" resonance (i.e., an in-phase oscillation of neutrons and protons with approximately equal amplitudes), as has been assumed heretofore, but rather that its excitation exhausts only $48 \pm 7\%$ of the isoscalar energy-weighted sum rule (ISEWSR), together with $16 \pm 8\%$ of the isovector (IVEWSR).

In contrast to these results, a considerable body of hadron scattering data have been interpreted successfully in terms of a model of the GQR oscillation² in which it is assumed that the neutron and proton deformations are equal, implying $M_n/M_p = N/Z = 1.5$. While such a state is not strictly "isoscalar" unless $N = Z$, in ^{208}Pb it would contain an isovector component of only about $[(N-Z)/A]^2 = 4\%$. A recent high-resolution proton experiment,³ analyzed in this way, yielded a strength of 70% of the ISEWSR for the 10.6-MeV GQR. This agrees within uncertainties with a large body of alpha and proton scattering data and would imply a $B(E2)_+ = 5000 \text{ e}^2\text{fm}^4$, which is about five times larger than that deduced from the pion data. Recent electron scattering results^{4,5,6} are in good agreement with those from hadron scattering.

In contrast with the situation for light ions, inelastic scattering of heavy ions is particularly sensitive to the proton excitations because of the large contribution of Coulomb excitation to the cross section. Furthermore, the Coulomb excitation increases rapidly relative to the hadronic excitation with increasing bombarding energy. Figures 2.12 and 2.13 show data for inelastic scattering on ^{208}Pb of 400-MeV ^{16}O ions⁷ and 1428-MeV ^{17}O ions,⁸ respectively. The solid lines are from DWBA calculations using optical potentials deduced from fits to differential elastic scattering data^{7,8} and the deformed optical potential model with the deformation length βR chosen to

Fig. 2.12. Data for excitation of the 10.6-MeV GQR in ^{208}Pb by 400-MeV ^{16}O ions (Ref. 7). The calculations shown as solid and dashed lines are described in the text. The optical potential of Ref. 7 was used in the calculations, which were carried out with the code Ptolemy.

Fig. 2.13. Data for the excitation of the 10.6-MeV GQR in ^{208}Pb by 1428-MeV ^{17}O . The experiment in which these data were acquired will be described in a forthcoming paper.⁸ The calculations represented by the solid and dashed lines are described in the text. The optical potential used in the calculations was obtained from a fit to elastic scattering.

correspond to 70% of the ISEWSR.³ The dashed lines are calculations obtained with a nuclear deformation length corresponding to 48% ISEWSR

and $B(E2)_{\pi} = 1010 \text{ e}^2\text{fm}^4$ as reported¹ from the pion scattering. The higher energy data (Fig. 2.13) with their larger relative contribution of Coulomb excitation, exceed the cross sections calculated using the pion results by a factor of almost 4. In contrast, both data sets are in good agreement with the calculations which use a model which assumes equal proton and neutron deformations.

Two other recent results which come from photon decay experiments^{9,10} also contradict the description of the 10.6-MeV GQR as presented in Ref. 1. These data concern the strength of the ground state E2 gamma decay of the 10.6-MeV resonance, as well as the decay branch to the 2.61 MeV 3^- state.

The strength of the ground-state E2 photon decay from the GQR yields a reaction-independent $B(E2)_{\pi}$ of 5000-7000 e^2fm^4 , which also agrees with the homogeneous model, but which is much larger than the 1010 e^2fm^4 reported¹ from the pion work.

The E1 photon decay of the GQR to the 2.618-MeV 3^- state should also be sensitive to isovector mixing in the resonance. A study of the photon decay of the GQR following excitation by 381-MeV ^{17}O ions, shows that this decay branch is quite small, ($4 \pm 4\%$ of the ground state branch). Two recent calculations^{11,12} have predicted just such a small cascade to ground-state branching ratio for a predominantly isoscalar GQR. A major reason for the strong suppression of this branch in both calculations is the almost complete cancellation of matrix elements arising from neutron and proton components of the GQR. This cancellation is thus exquisitely sensitive to the relative amplitudes of the neutron and proton components of the GQR. An increase in the ratio of the neutron-to-proton composition in the GQR as required by the pion results would destroy this balance, and lead to a significant increase in the cascade to ground-state branching ratio thus destroying the good agreement with the observed value.

We conclude that all of the experimental results discussed here are incompatible with a

large excess of neutron strength and a consequently large isovector component in the observed GQR.

FIRST QUANTITATIVE STUDY OF $T = 1$, SPIN-DIPOLE STRENGTH IN ^{40}Ca

D. J. Horen	R. O. Sayer ³
J. Lisantti ¹	D. K. McDaniels ⁴
R. L. Auble	K. W. Jones ⁵
F. E. Bertrand	J. B. McClelland ⁵
B. L. Burks ²	S. J. Seestrom-Morris ⁵
E. E. Gross	L. W. Swenson ⁶

Information on spin-dipole resonances in stable nuclei is rather sparse, even though their existence has been the subject of numerous theoretical works.⁷ Of particular interest are the questions of the excitation energy and strength of J^π components of the isovector spin-dipole resonance, as well as whether the $J^\pi = 1^-$ component is mixed with the IVGDR.

Since the isovector excitations are mitigated by the isospin operator $\hat{\tau}$, the isospin-spin-dipole operator, $[\hat{Y} \times \hat{\sigma} \hat{\tau}]$, acting on a ground state with isospin T_0 and $T_z = T_0$, can lead to final states with $T = T_0 + \frac{1}{2}$ and $T_z = T_0$, $T_0 \pm 1$. Final states with $T_z = T_0$ lie in the target nucleus and are accessible via inelastic scattering reactions. Those with $T_z = T_0 \pm 1$ lie in neighboring isobars and can be excited by charge-exchange reactions.

The first evidence for the isovector giant spin-dipole resonance was provided by studies of the $^{90}\text{Zr}(p,n)^{90}\text{Nb}$ reaction⁸ with intermediate energy protons, where a $T = T_0 - 1$ resonance was observed whose angular distribution could be characterized by $L = 1$. A similar resonance was observed in the $^{208}\text{Pb}(p,n)^{208}\text{Bi}$ reaction, and by comparison of the cross sections observed at $E_p = 120$ and 160 MeV, the $L = 1$ peak was identified as a spin-dipole resonance.⁹ The energy systematics of the $T_0 - 1$ component of the spin-dipole resonance observed in the (p,n) reaction has since been established.^{10,11}

Measurements of the $^{40}\text{Ca}(p,p')$ were performed at the Los Alamos Meson Physics Facility (LAMPF) with 500-MeV protons and the high resolution spectrometer (HRS). The target was a self-supported foil of ^{40}Ca with a thickness of 49.88 mg/cm². Inelastic spectra were measured at 4,

1. S. J. Seestrom-Morris, C. L. Morris, J. M. Moss, T. A. Carey, D. Drake, J. C. Dousse, L. C. Bland, and G. S. Adams, *Phys. Rev. C* **33**, 1847 (1986).

2. G. R. Satchler, *Direct Nuclear Reactions* (Oxford University Press, Oxford, 1983). A. Bohr and B. R. Mottelson, *Nuclear Structure*, Vol. 2 (Benjamin, New York, 1975).

3. F. E. Bertrand, E. E. Gross, D. J. Horen, R. O. Sayer, T. P. Sjoreen, D. K. McDaniels, J. Lisantti, J. R. Tinsley, L. W. Swenson, J. B. McClelland, T. A. Carey, K. Jones, and S. J. Seestrom-Morris, *Phys. Rev. C* **34**, 45 (1986).

4. G. O. Boine, L. J. Koester, Jr., L. S. Cardman, R. W. Doerfler, B. L. Miller, C. N. Papanicolas, H. Rotnaas, and S. E. Williamson, in *Proceedings of the International Conference on Nuclear Physics, Florence, 1983*, Vol. I, C13. Bologna: Tipografia Compositio, 1983.

5. L. S. Cardman, "Nuclear Structure Investigations Using the $(e,e'x)$ Reaction," in *Proceedings of the International School of Intermediate Energy Physics*, R. Bergere, S. Costa, and C. Shaerf (eds.), p. 163 (World Scientific, Singapore, 1986).

6. G. Kilgus, G. Kühner, S. Müller, A. Richter, and W. Knupfer, *Zeitschrift für Physik* **A326**, 41 (1987).

7. T. P. Sjoreen, F. E. Bertrand, R. L. Auble, E. E. Gross, D. J. Horen, D. Shapira, and D. B. Wright, *Phys. Rev. C* **29**, 1370 (1984).

8. Preliminary analysis of data obtained at GANIL in an experiment performed by an ORNL, Saclay, GANIL, and Strasbourg collaboration (1987).

9. J. R. Beene, F. E. Bertrand, M. L. Halbert, R. L. Auble, D. C. Hensley, D. J. Horen, R. L. Robinson, R. O. Sayer, and T. P. Sjoreen, p. 503, *Nuclear Structure 1985* (Proceedings of the Niels Bohr Centennial Conference, Copenhagen, May 20-24, 1985), edited by R. Broglia, G. Hagemann, and B. Herskind (North-Holland, 1985).

10. J. R. Beene, F. E. Bertrand, M. L. Halbert, R. L. Auble, D. C. Hensley, D. J. Horen, R. L. Robinson, R. O. Sayer, and T. P. Sjoreen, submitted to *Physical Review Letters*.

11. P. F. Bortignon, R. A. Broglia, and G. F. Bertsch, *Phys. Lett.* **148B**, 20 (1984).

12. J. Speth, D. Cha, V. Klemt, and J. Wambach, *Phys. Rev. C* **31**, 2310 (1985).

7, 10, 12, 14, 17, and 20 degrees. During the off-line analysis the angles were divided into two bins separated by one degree. Our absolute inelastic cross sections agreed within 10% with those reported in Ref. 12.

The level density is quite high in the excitation energy range 10-30 MeV in ^{40}Ca , and there are states with a variety of multipolarities. Even so, use can be made of the variation in strength of the various components of the nucleon-nucleon interaction with momentum transfer to identify excitations of a particular character. At the incident proton energies employed here, the specific signatures that can be used to identify isovector spin dipole transitions in a $T = 0$ target are: (1) the differential cross sections should be peaked near 5° (the maximum for an $L = 1$ transfer), and (2) the distribution of strength should be similar to that observed for the analogue states in the (p,n) reaction with $\frac{d\sigma}{d\Omega}_{pp'} = \frac{1}{2} \frac{d\sigma}{d\Omega}_{pn}$ at the same momentum transfer. The IVGDR ($L = 1, S = 0$) can be distinguished because it is predominantly Coulomb-excited and its cross section falls rapidly with angle. Magnetic dipole states ($L = 0, S = 1$) also have cross sections that decrease rapidly with angle. Transitions which involve isoscalar nonspin $L = 2$ transfer have differential cross sections which peak near 7.5° , while those for $L > 3$ peak at even larger angles.

After subtracting a continuum background, the data were grouped in 0.5-0.8 MeV energy bins. The differential cross sections for each energy bin were plotted to identify the predominant L -transfers. It was found that at the smallest angle measured, the spectra between 10 and 30 MeV were mainly dominated by $L = 0$ and $L = 1$ transfers. From a detailed examination of the spectra, including comparisons of peak cross sections at the two smallest angles, it was easy to identify previously assigned 1^+ states in ^{40}Ca , as well as peaks with $L > 2$. Structures which exhibit nearly the same cross section at the two smallest angles were identified as containing isovector spin-dipole strength.

In Fig. 2.14, spectra for ^{40}Ca taken at 3.5° and 4.5° are shown for the excitation energy range 7-25 MeV. The 2^- state at 8.42 MeV is clearly evident and has about the same cross section at these two angles. Our measured cross section for this state is $\frac{d\sigma}{d\Omega}_{pp'}(3.5^\circ) = 1.0 \pm .2 \text{ mb/sr}$. From normalizing a DWIA calculation for this level to the data using the Love-Franey¹³ effective N-N interaction, the particle-hole excitation transition densities¹⁴ and the code¹⁵ DW81, we deduce $B(M2^+) = 343 \mu_N^2 \text{fm}^2$, which is in good agreement with the value¹⁶ $281 \mu_N^2 \text{fm}^2$ obtained at 334 MeV. We have used DWIA calculations to "scale" the $^{40}\text{Ca}(p,n)^{40}\text{Sc}$ cross

Fig. 2.14. Differential cross sections at 3.5° and 4.5° for excitation of states in ^{40}Ca by inelastic scattering of 500-MeV protons. The plotted spectra were obtained by subtracting a continuum background from the raw data.

section¹⁷ for this level measured at 159.3 MeV to an equivalent value at 500 MeV. Using the latter in conjunction with the relation $\frac{d\sigma}{d\Omega}_{pp'} = \frac{1}{2} \frac{d\sigma}{d\Omega}_{pn}$ at the same momentum transfer for analogous transitions, we deduce $\frac{d\sigma}{d\Omega}_{pp'}(3.5^\circ) = 1.1 \text{ mb/sr}$, which agrees well with our measured value.

The same scaling procedure was used to overlay a histogram of the 5° (p,n) data¹¹ also taken at 159.3 MeV on our 3.5° (p,p') spectrum which is associated with $L = 1$ transfers. These are shown in Fig. 2.15. The (p,p') histogram was generated by fitting the differential cross sections for each energy bin in the angular region beyond 6° with $L > 2$ shapes determined from macroscopic DWBA calculations, and then subtracting the calculated cross sections from the data at 3.5° . Below about 18.5 MeV, the agreement between the structure and cross sections for the (p,p') and (p,n) measurements is quite good. From a recent measurement¹⁸ of the $^{40}\text{Ca}(\tilde{p},\tilde{p}')^{40}\text{Ca}$ at $E_p = 319 \text{ MeV}$, evidence has been found for spin-dipole strength in the

vicinity of 18 MeV that supports our assignment and procedures.

Also shown in Fig. 2.15 is a histogram of the IVGDR cross section. This was calculated by binning the photonuclear cross section¹⁹ and deducing an effective $B(E1+)$ which is proportional to $(1/E)\sigma_T(E)$ for each bin. The (p,p') cross section was then calculated using these $B(E1+)$ and the code ECIS79 with only the Coulomb interaction. In the excitation range 18.5–21.5 MeV, our (p,p') cross-section data have values between those calculated for the IVGDR and the spin dipole deduced from the (p,n) measurements. Since the strength of the isovector spin-orbit component of the N-N interaction is extremely weak¹³ at the momentum transfer considered here, we would expect the amplitudes for excitation of the nonspin ($S = 0$) – and spin ($S = 1$) – dipole transitions to add incoherently. Thus, the observed dipole cross section in (p,p') should be at least larger than the nonspin-dipole cross section as calculated using the photonuclear results and Coulomb excitation. As seen in Fig. 2.15, this condition is satisfied. We believe the discrepancy above 18 MeV can be attributed to the following: (1) Removal of some dipole strength in the cross section decomposition process. The separation of dipole from quadrupole strength is complicated because some of the angular distributions for the spin-dipole (e.g., states with $J^\pi = 2^-$) have a large overlap with those for $L = 2$ transfers. (2) Uncertainties involved in the subtraction of the underlying backgrounds in both the (p,p') and (p,n) spectra. (3) The possibility of some nonspin-dipole strength in the 159.3-MeV (p,n) spectrum which could affect the manner in which we deduce the 500-MeV (p,p') cross section. The experimental uncertainties associated with (1) and (2) are most dominant, and within these the (p,p') cross section could be consistent with an incoherent sum of nonspin (as determined from the photonuclear measurements) – and spin (as determined from the (p,n) measurements) – dipole cross sections.

Microscopic DWIA calculations were performed using p-h transition densities based on a

Fig. 2.15. Distribution of dipole strength in ^{40}Ca . The light solid histogram shows the dipole cross section deduced from 500-MeV inelastic proton scattering. The hatch solid histogram represents the (p,p') cross section calculated using the photonuclear cross section and excitation by the Coulomb interaction. The heavy solid histogram represents the (p,p') spin dipole cross section deduced from the (p,n) measurements.

1d2s1f2p model space (see Table 2.1). No configuration mixing was included in the ground state. The observed $L = 1$ cross section in the interval 13–18 MeV can be ascribed to spin-dipole strength and has $\sigma_{\text{exp}}(3.5^\circ) = 5.1$ mb/sr, which can be compared to a calculated spin-dipole value of 7.8 mb/sr. This gives an observed/calculated ratio of 65% in this energy interval. As we have already noted above, our measured cross section in the 18.5–21.5 MeV region appears to be lower than would be expected if the spin- and nonspin-dipole components were to add incoherently. Therefore, we are unable to discuss quantitative results for spin-dipole strength above 18 MeV. Reference to the spin transfer work¹⁸ would suggest that our assumed continuum background might have been too high in this region. It is possible that more accurate (p,p') spin transfer measurements could aid an investigation of the spin-dipole strength above 18 MeV, as well as possibly provide information pertaining to the J^π distribution as suggested from a study²⁰ of the $^{40}\text{Ca}(\vec{p},\vec{n})^{40}\text{Sc}$ reaction.

1. Partial support from Joint Institute for Heavy Ion Research, ORNL.

2. Engineering Physics and Mathematics Division, ORNL.

3. Computing and Telecommunications Division, ORNL.

4. University of Oregon, Eugene, OR 97403.

5. Los Alamos National Laboratory, Los Alamos, NM 87545.

6. Oregon State University, Corvallis, OR 97331.

7. M. Harvey and F. C. Khanna, Nucl. Phys. A221, 77 (1974); A. Bohr and B. R. Mottelson, Nuclear Structure (Benjamin, New York, 1975), Vol. II; N. Auerbach and A. Klein, Phys. Rev. C 30, 1032 (1984); B. Castel and L. Zamick, Phys. Rpts. 148, 217 (1987); and references contained therein.

8. D. E. Bainum et al., Phys. Rev. Lett. 44, 1751 (1980).

9. D. J. Horen et al., Phys. Lett. 95B, 27 (1980).

10. D. J. Horen et al., Phys. Lett. 99B, 383 (1981).

11. C. Gaarde et al., Nucl. Phys. A369, 258 (1981).

12. K. K. Seth et al., Phys. Lett. 158B, 23 (1985).

13. W. G. Love and M. A. Franey, Phys. Rev. C 24, 1073 (1981); M. A. Franey and W. G. Love, Phys. Rev. C 31, 488 (1985).

14. B. A. Brown, private communication.

15. Program DWBA70, R. Schaeffer and J. Raynal (unpublished); extended version DW81 by J. R. Comfort (unpublished).

16. D. J. Horen et al., Phys. Rev. C 31, 2049 (1985).

17. T. N. Taddeucci et al., Phys. Rev. C 28, 2511 (1983).

18. C. Glashauser et al., Phys. Rev. Lett. 58, 2404 (1987).

Table 2.1. Microscopic DWIA cross sections at $E_p = 500$ MeV and $\theta_{\text{cm}} = 3.5^\circ$ for shell model spin-dipole states in ^{40}Ca .

$T = 1, J^\pi = 0^-$		$T = 1, J^\pi = 1^-$		$T = 1, J^\pi = 2^-$	
$E_x(\text{MeV})$	$\frac{d\sigma}{d\Omega}(3.5^\circ)(\text{mb/sr})$	$E_x(\text{MeV})$	$\frac{d\sigma}{d\Omega}(3.5^\circ)(\text{mb/sr})$	$E_x(\text{MeV})$	$\frac{d\sigma}{d\Omega}(3.5^\circ)(\text{mb/sr})$
9.97	0.86	9.7	0.353	8.44	4.13
14.73	0.27	12.1	0.315	9.60	0.22
24.19	1.89	13.37	0.151	11.69	0.029
		14.69	0.021	12.85	1.12
		15.95	1.65	14.72	0.34
		18.23	0.632	16.21	3.38
		20.14	2.069	17.16	0.277
		24.16	4.106	17.56	1.71
				19.45	1.85
				22.46	1.53

19. J. Ahrens et al., Nucl. Phys. A251, 479 (1975).
 20. J. W. Watson et al., Phys. Lett. 181B, 47 (1986).

NEAR EXHAUSTION OF $0h_{9/2}$ ISOVECTOR M1 STRENGTH IN ^{28}Si

J. Lisantti ¹	D. K. McDaniels ³
D. J. Horen	L. W. Swenson ⁴
F. E. Bertrand	X. Y. Chen ⁴
B. L. Burks ²	O. Hausser ⁵
C. W. Glover ²	K. Hicks ⁶

Excitation of a state (probably a doublet) at 18.0 MeV in ^{28}Si (see Fig. 2.16) is observed in small angle spectra obtained by inelastic scattering of 250-MeV protons. Its relative cross section behaves similar to that found for previously identified^{7,8} 1^+ states in ^{28}Si , i.e., it decreases with increasing scattering angle. This state is not seen in the photo-nuclear reaction, and, hence, the possibility of a $J^\pi = 1^-$ assignment can be excluded. We assign this state as $J^\pi = 1^+$. It contains an M1 strength of about 15% that of the strong 11.45-MeV 1^+ state. This means that the 18.0-MeV state accounts for about 3.5% of the total $0h_{9/2}$ M1 strength in ^{28}Si . Combining our results with data from previous works,^{8,9} we find that approximately 86% of the M1 strength predicted⁴ in a $2s_{1/2} 1d_{5/2} 1d_{3/2}$ model space has been observed in ^{28}Si . Since we have also

Fig. 2.16. Spectra obtained at 6 and 10 degrees for the $^{28}\text{Si}(p,p')^{28}\text{Si}$ reaction at $E_p = 250$ MeV.

found indications for a weak 1^+ level near 16.3 MeV, it is possible that additional weak M1 states not yet detected are probably present in the data. Calculations¹⁰ show that all of the $0h_{9/2}$ M1 strength lies below an excitation energy of 21 MeV. A higher resolution experiment with better statistics seems indicated in order to determine the presence of additional M1 strength in ^{28}Si and to test whether there is a need to extend the model space used in the calculations or to include effects of non-nucleonic degrees of freedom.

1. Partial support from Joint Institute for Heavy Ion Research, ORNL.
2. Engineering Physics and Mathematics Division, ORNL.
3. University of Oregon, Eugene, OR 97403.
4. Oregon State University, Corvallis, OR 97330.
5. Simon Fraser University, Burnaby, B.C., Canada V6T 2A3.
6. TRIUMF, Vancouver, B.C., Canada.
7. R. Schneider et al, Nucl. Phys. A323, 13 (1979).
8. N. Anantaraman et al., Phys. Rev. Lett. 52, 1409 (1984).
9. O. Hausser et al., preprint (Sept. 1987).
10. B. A. Brown, private communication.

GIANT RESONANCE STRENGTH DISTRIBUTIONS IN ^{28}Si AND ^{40}Ca AS DETERMINED WITH INTERMEDIATE ENERGY PROTONS

J. Lisantti ¹	D. K. McDaniels ⁴
F. E. Bertrand	K. W. Jones ⁵
D. J. Horen	J. B. McClelland ⁵
R. L. Auble	S. J. Seestrom-Morris ⁵
B. L. Burks ²	L. W. Swenson ⁶
E. E. Gross	X. Y. Chen ⁶
R. O. Sayer ³	O. Hausser ⁷
C. W. Glover ²	K. Hicks ⁸

Giant resonance studies with intermediate energy protons have mainly concentrated on nuclei with $A > 40$. In such nuclei the excitation energy region near $63 A^{-1/3}$ MeV is generally dominated by a single large structure, containing the isoscalar ($\Delta T = 0$) giant quadrupole resonance (ISGQR), the isoscalar giant hexadecapole resonance (ISGHR), and the isovector ($\Delta T = 1$) giant dipole resonance (IVGDR) which is nearly degenerate in energy with the isoscalar giant monopole resonance (ISGMR).

In lighter nuclei the giant resonance region is found to be highly fragmented. Consequently, identifying the various GR's in lighter nuclei is much more difficult. This has resulted in substantial disagreement among various studies.

With this in mind we have utilized 250- and 500-MeV protons to study giant resonances in ^{28}Si and ^{40}Ca . Angular distributions for the various giant resonances found with intermediate energy protons are unique for each different angular momentum transfer. This allows for an unambiguous identification of the multipolarities excited in the resonance region.

Figure 2.17 shows spectra of the giant resonance region in ^{28}Si taken, at TRIUMF, with 250-MeV protons in which the underlying continuum has been subtracted. As can be seen from Fig. 2.17 the resonance region is highly fragmented and changes with angle, indicating the excitation of a variety of multipolarities. The regions shown correspond to different areas of integration. From fits to the angular distribution for each bin we find an energy-weighted sum rule (EWSR) exhaustion of 26% for

Fig. 2.17. Giant resonance region of ^{28}Si excited with 250-MeV protons. The continuum has been subtracted from the data.

the ISGQR, and 5% for the ISGHR. From photo-nuclear studies, the IVGDR was fixed at a 70% EWSR exhaustion. These sum rule results can be compared to the microscopic particle hole model of Schmid⁹ who calculates sum rule exhaustions of 30.1% (ISGQR), 9.6% (ISGHR), and 68.4% (IVGDR).

We have also studied the giant resonance region of ^{40}Ca excited with 500-MeV protons at LAMPF. Spectra taken at 4.5, 7.5, 11.5, and 14.5 degrees are shown in Fig. 2.18. In ^{40}Ca there are not the isolated structures as seen in ^{28}Si , therefore the resonance region of 13.2 to 22 MeV was binned into 0.5- to 0.8-MeV regions. Except at the smallest angles of 3.5 and 4.5 degrees, the angular distributions for these energy bins could be fit with the $L = 2$ ISGQR and the $L = 4$ ISGHR. The EWSR depletions found for the region of 13.2 to 22 MeV was 70% (ISGQR) and 15% (ISGHR). For angles of 7.5, 9.5, 10.5, 11.5, and 12.5 degrees, a resonance at 31 MeV of excitation energy with a width of 10 MeV was found. This is the previously observed isoscalar giant octupole resonance (ISGOR).¹⁰ Reference 10 found a sum rule depletion of $20 \pm 9\%$; we find $30 \pm 6\%$ EWSR for the ISGOR.

The excitation of giant resonances in ^{40}Ca has been studied by many theoretical groups. Table 2.2 shows our experimentally found EWSR values along with results from various theoretical calculations. The results of Bortignon and

Fig. 2.18. Giant resonance region of ^{40}Ca excited with 500-MeV protons. The continuum has been subtracted from the data.

Table 2.2. Experimental and theoretical EWSR values for giant resonances in ^{40}Ca

Experiment	Ref. 11	Ref. 12	Ref. 13
ISGQR	$70 \pm 14\%$	80%	83%
ISGHR	$15 \pm 3\%$	16%	40.6% (0-33 MeV)
ISGOR	$30 \pm 6\%$	30%	35.5%
IVGDR	$70\%^a$	80%	58%

^aFixed from photonuclear work.

Broglia (ref. 11) agree very well, and in fact their calculated distribution of ISGQR strength agrees quite well with the data.

At the smaller scattering angles for both nuclei, isovector spin-flip strength has been observed and this is the subject of another report.

EXTRACTION OF GIANT RESONANCE CROSS SECTIONS FOR ^{208}Pb USING A SURFACE RESPONSE MODEL

L. W. Swenson ¹	E. E. Gross
X. Y. Chen ¹	C. Glover ⁵
J. Lisantti ²	R. O. Sayer ⁶
D. K. McDaniels ³	B. L. Burks ⁵
I. Bergqvist ⁴	D. Hausser ⁷
F. E. Bertrand	K. Hicks ⁸
D. J. Horen	M. J. Iqbal ⁸

One of the major uncertainties in the extraction of giant resonance parameters through inelastic scattering is an understanding of the continuum upon which the resonances are located. Current progress in determining the parameters of these resonances is closely coupled with progress in modeling the nuclear continuum. The empirical procedure often used in the past consists of representing the continuum shape with straight lines or smooth polynomial curves incorporating a criterion of "reasonableness." Different choices of background can, however, lead to quite different resonance parameters especially the EWSR fraction. Clearly there is a need for a consistent description of the continuum based on some assumption about the underlying reaction mechanism.

As a starting point in formulating a model for the continuum, quasielastic scattering may be assumed to be the dominant contributing process. The observed kinematics and analyzing power of the continuum support this view. From (α, p') measurements⁹ at 200 MeV on ^{60}Ni , ^{90}Zr ,

1. Partial support from Joint Institute for Heavy Ion Research, ORNL.

2. Engineering Physics and Mathematics Division, ORNL.

3. Engineering Physics and Mathematics Division, ORNL.

4. University of Oregon, Eugene, OR 97403.

5. LAMPF, Los Alamos, NM 87545.

6. Oregon State University, Corvallis, OR 97331.

7. Simon Fraser University, Burnaby, B.C., Canada V5A 1S6.

8. TRIUMF, Vancouver, B.C., Canada V6T 2A3.

9. K. W. Schmid, Phys. Rev. C 24, 1283 (1981).

10. T. A. Carey et al., Phys. Rev. Lett. 45, 239 (1980).

11. P. F. Bortignon and R. A. Broglia, Nucl. Phys. A317, 405 (1981).

12. K. F. Liu and G. E. Brown, Nucl. Phys. A265, 385 (1976).

13. H. Sagawa and B. A. Brown, Nucl. Phys. A430, 84 (1984).

and ^{208}Pb , the broad structure underlying the giant resonances is observed to move in excitation energy in accordance with nucleon-nucleon scattering kinematics, modified to include a small energy shift. For scattering angles less than 20° , the analyzing power for the continuum at the quasifree peak location was observed to be somewhat less than the free NN values, but increases rapidly to the free NN values for measurements made at 334 MeV and 800 MeV. Thus, observations of both kinematics and analyzing power support the view that the continuum is dominated by quasifree scattering, at least for moderate excitation energies and momentum transfer.

Significant progress has been made recently in the theoretical description of the nuclear continuum by Bertsch, Scholten, Esbensen, and Smith.¹⁰ The calculations are based on the surface response of semi-infinite nuclear matter, the free NN elastic scattering amplitude and Glauber theory. In the surface response model the double differential cross section for inelastic proton-nucleus scattering is given in factorized form by the relation

$$\frac{d^2\sigma}{d\Omega d\omega} = N_{\text{eff}} \sum_{T,S} \left(\frac{dq_{NN}}{d\Omega} \right)_{T,S} S(q,\omega) \quad (1)$$

where N_{eff} is the effective number of target nucleons as determined by Glauber theory for single scattering. The free differential nucleon-nucleon cross section is represented by $\left(\frac{dq_{NN}}{d\Omega} \right)_{T,S}$. The function $S(q,\omega)$ is the surface response function which is obtained from the Green's function for particle-hole excitations in semi-infinite nuclear matter.

We have applied this model to our 400-MeV $^{208}\text{Pb}(p,p')$ data taken at TRIUMF. The continuum predictions from the surface response model and the extracted resonance peaks are shown compared with the data in Fig. 2.19. For the ISGQR, an EWSR depletion of $60 \pm 12\%$ is found--in excellent agreement with the use of an empirically determined background for 200-, 334-, and 400-MeV $^{208}\text{Pb}(p,p')$ scattering. The ISGHR strength of $12 \pm 3\%$ of the EWSR is also in good agreement with the empirical results.

Fig. 2.19. Spectra of the 400-MeV $^{208}\text{Pb}(p,p')$ reaction. The various giant resonances are labeled on the curve. The continuum shape comes from surface response calculations.

Shown in Fig. 2.19 for the 10° spectra is a peak which has an angular distribution which is best fit by an $L = 5$ angular momentum transfer. This resonance exhausts $10 \pm 3\%$ of the EWSR for a $3\hbar\omega$ $L = 5$ resonance.

The surface response model approach to analyzing the continuum leads to the same EWSR fractions for the prominent giant resonances as previously used empirical results, thus giving us confidence in applying this model to describe the continuum for at least $E_p = 400$ MeV. Currently, we are applying this model to ^{208}Pb

data taken at other incident proton energies in the range of 200 to 400 MeV.

1. Oregon State University, Corvallis, OR 97330.
2. Partial support from Joint Institute for Heavy Ion Research, ORNL.
3. University of Oregon, Eugene, OR 97403.
4. Deceased.
5. Engineering Physics and Mathematics Division, ORNL.
6. Fusion Energy Division, ORNL.
7. Simon Fraser University, Burnaby, B.C., Canada V5A 1S6.
8. TRIUMF, Vancouver, B.C., Canada V6T 2A3.
9. J. Lisantti et al., Phys. Lett. 147B, 23 (1984).
10. H. Esbensen and G. F. Bertsch, Ann. Phys. 157, 225 (1984). H. Esbensen and G. F. Bertsch, Phys. Rev. C 34, 1419 (1986). G. F. Bertsch and O. Scholten, Phys. Rev. C 25, 804 (1982). H. Esbensen and G. F. Bertsch, Phys. Rev. C 32, 553 (1985). R. D. Smith, Bull. Am. Phys. Soc. 31, 1229 (1986).

NUCLEAR RESPONSE MECHANISM AND MEDIUM EFFECTS

X. Y. Chen ¹	I. Bergqvist ⁴
L. W. Swenson ¹	A. Brockstedt ⁵
F. Farzanpay ¹	F. E. Bertrand
D. K. McDaniels ²	D. J. Horen
Z. Tang ²	J. Lisantti ⁶
Z. Xu ²	K. Hicks ⁷
D. M. Drake ³	M. Vetterli ⁷
	M. J. Iqbal ⁷

There has been recent success in describing spin observables in both elastic and inelastic intermediate-energy proton-nucleus scattering using the relativistic impulse approximation (RIA). This was first seen in the superior description of the analyzing power ($A_y(\theta)$) and spin rotation parameter (Q) in elastic proton- ^{40}Ca elastic scattering at 500 MeV. This initial theoretical model was later extended to also cover the excitation of bound states. It was found that in most cases the RIA described the data better than conventional nonrelativistic impulse approximations (NRIA) models, especially the spin observables. With the success of the RIA in calculating elastic scattering and the complexity of nuclear structure input into the calculation of the bound states the next logical step was to extend the RIA calculations to study quasielastic scattering in the continuum. Recently⁸ Horowitz and Iqbal have developed a code to do just that.

Quasifree scattering in the nucleus is quite similar to free NN scattering except that it occurs in the nuclear medium. In the RIA model for quasifree scattering the nuclear media causes an enhancement to the lower components of the nucleon wavefunction. This is caused by the large scalar potential in the nucleus. One of the interesting results of all the RIA models is that the nuclear potential has two large and opposite potentials (~ 500 MeV), these being the attractive scalar (s) and repulsive vector (v) potentials. This potential produces an effective mass of M^* for the nucleon in the nucleus. Horowitz and Iqbal have calculated for quasifree scattering what differences would occur in the spin observables for M^* having values ranging from $0.8M$ to the free value of M for different nuclei. One of the most striking features was that the analyzing power of the quasifree peak as a function of angle was strongly dependent on the value of M^* . Therefore, this presented a test of the model in a fairly straightforward manner.

With this in mind, an experiment was done at TRIUMF to measure the analyzing power for 290-MeV-proton ^{208}Pb quasifree scattering as a function of angle. The experimental results along with various model calculations are shown in Fig. 2.20. The solid squares come from the surface response model of Bertsch-Scholten-Esbensen.⁹ This model has no medium effects, i.e., $M = M^*$. This is to be compared to the $M^* = M$ calculation for the RIA, shown by the dash-dot curve. At angles above 10 degrees the data are clearly lower than these two calculations. The value of M^* calculated for each nucleus at each energy is related to the average nuclear density $\langle\rho\rangle$ by the relation $M^* = (1.0 - .44 \langle\rho\rangle)$. The nuclear density is found by fits to elastic proton-nucleus data. From this method a value of $M^* = 0.83M$ is found for our experiment situation. The RIA result for this value of M^* is shown on Fig. 2.20. Our data is slightly lower and favors a value of $M^* = 0.77M$.

All of the above calculations were done assuming single-step scattering. For our largest angle data there is the possibility of

Fig. 2.20. Analyzing power data at the peak of the quasifree scattering distribution. The solid squares represent calculations from the surface response model. The dash-dot curve comes from the relativistic model with no medium effect applied to the nucleon in the nucleus, i.e., $M^* = M$. The dash curve comes from the relativistic model where the value of $M^* = .83M$ comes from fits to the nuclear density.

multiple scattering and this would tend to lower the analyzing power. During the summer of 1987 we repeated this experiment at 500 MeV, where multiple scattering is not as important. These data are being analyzed.

COLLECTIVE MODEL DWBA ANALYSIS OF 500 MeV PROTON SCATTERING FROM ^{40}Ca

J. Lisantti ¹	R. O. Sayer ³
F. E. Bertrand	D. K. McDaniels ⁴
D. J. Horen	K. W. Jones ⁵
R. L. Auble	J. B. McClelland ⁵
B. L. Burks ²	S. J. Seestrom-Morris ⁵
E. E. Gross	L. W. Swenson ⁶

There has been recent interest in the application and validity of the use of the macroscopic collective model DWBA formalism to describe intermediate energy proton excitation of low-lying collective states along with the giant resonances.⁷⁻⁹ This was brought about because of some earlier theoretical work¹⁰ that showed that the radial shape of the hadronic transition operator was dependent on the incident proton energy. What was found was that the value of δ_H (hadronic deformation length) changed with incident proton energy with values ranging from 1.024 fm at 40 MeV to 0.474 fm at 156 MeV for the 3^- , 2.614-MeV state in ^{208}Pb . The hadronic deformation length can be related to the reduced transition probability $B(EL)_{\uparrow}$. The reduced transition probability is related to the structure of the nucleus and should not change when probed with different incident proton energies. This was then interpreted by Ref. 10 to mean that the collective model formalism is no longer valid at higher (>100 MeV) proton energies.

However, recent work⁷⁻⁹ has shown that this is not the case and, in fact, Refs. 7-9 have shown that the vibrational collective model describes very well the intermediate energy experimental data for low-lying bound states and the giant resonances. It was found that for ^{208}Pb the deformation lengths were constant with varying incident proton energies. Since this model works so well, the hadronic deformation lengths extracted with it, along with electromagnetic results have been used in order to calculate the ratio of the neutron to proton multipole matrix elements.^{11,12}

We have further extended this study to cover the excitation of bound states in ^{40}Ca excited

1. Oregon State University, Corvallis, OR 97330.
2. University of Oregon, Eugene, OR 97403.
3. Los Alamos National Laboratory, Los Alamos, NM 87545.
4. Deceased.
5. Lund University, Lund S-223 62, Sweden.
6. Partial support from Joint Institute for Heavy Ion Research, ORNL.
7. TRIUMF, Vancouver, B.C., Canada V6T 2A3.
8. C. J. Horowitz and M. J. Iqbal, Phys. Rev. C 33, 2059 (1986).
9. G. F. Bertsch and O. Scholten, Phys. Rev. C 25, 804 (1982). H. Esbensen and G. F. Bertsch, Ann. Phys. 157, 255 (1984). H. Esbensen and G. F. Bertsch, Phys. Rev. C 34, 1419 (1986).

with protons over the energy range of 25 to 800 MeV. Table 2.3 has listed deformation lengths for a variety of states in ^{40}Ca as found with different energy protons. Again, it is seen that the deformation lengths are constant with energy. The last row of Table 2.3 is the value of the electromagnetic deformation length. This value along with the hadronic value can be used to calculate the ratio of the neutron-to-proton multipole matrix elements (M_n/M_p) using the following relationship:

$$\frac{M_n}{M_p} = \left(\frac{N}{Z} \right) \frac{\delta_n}{\delta_p} = \left(\frac{N}{Z} \right) \left[\frac{\delta_H}{\delta_p} + \frac{Z}{\left(\frac{b_n^p}{b_p^p} \right) N} \left(\frac{\delta_H}{\delta_p} - 1 \right) \right].$$

The multipole matrix elements that we find are listed in the second row of Table 2.4 along with results from other studies. These results all show that these states are isoscalar in nature.

A further result from this work is that states which do not have surface peaked, gaussian shaped, charge transition densities cannot be described by the use of the collective model DWBA.

1. Partial support from Joint Institute for Heavy Ion Research, ORNL.
2. Engineering Physics and Mathematics Division, ORNL.
3. Computing and Telecommunications Division, ORNL.
4. University of Oregon, Eugene, OR 97403.
5. LAMPF, Los Alamos, NM 87545.

Table 2.3. Hadronic deformation lengths for states in ^{40}Ca excited by (p,p') (units are in fermis)

E_p	3^-	2^+	5^-	2^+	2^+	6^+	3^-
(MeV)	3.736	3.904	4.49	5.63	8.75	8.85	9.38
25 ^a	1.40 ± .03	.42 ± .01	.91 ± .02	--	.17 ± .01	--	--
30 ^a	1.38 ± .03	.43 ± .01	.86 ± .02	--	.15 ± .01	--	--
35 ^a	1.35 ± .03	.42 ± .01	.83 ± .02	--	.15 ± .01	--	.16 ± .01
40 ^a	1.32 ± .03	.43 ± .01	.80 ± .02	--	.14 ± .01	--	--
334 ^b	--	.43 ± .02	--	.13 ± .01	.12 ± .01	--	--
362 ^c	1.22	.42	.69	--	--	--	--
500 ^d	1.31 ± .07	.50 ± .03	.69 ± .03	.14 ± .01	.13 ± .01	.25 ± .01	.20 ± .01
500 ^e	1.41 ± .04	.49 ± .01	.86 ± .03	--	--	--	--
800 ^f	1.39 ± .08	.52 ± .03	.76 ± .05	.15 ± .01	--	.28 ± .02	--
δ_H^g	1.35	.45	.80	.14	.14	.27	.18
σ^h	.06	.04	.08	.01	.02	.02	.03
δ_p	1.40 ± .05 ⁱ	.48 ± .05 ⁱ	.74 ± .05 ⁱ	.13 ± .03 ^j	.13 ± .01 ^j	--	--

^aC. R. Gruhn et al., Phys. Rev. C 6, 915 (1972).

^bD. J. Horen et al., Phys. Rev. C 30, 709 (1984).

^cD. Frekers et al., Phys. Rev. C 35, 2236 (1987), no uncertainty given.

^dPresent work.

^eK. K. Seth et al., Phys. Lett. 158B, 23 (1985).

^fG. S. Adams et al., Phys. Rev. C 21, 2485 (1980).

^gAverage values.

^hStandard deviation.

ⁱM. M. Gazzally et al., Phys. Rev. C 25, 408 (1982).

^jR. Moreh et al., Phys. Rev. C 25, 1824 (1982).

Table 2.4. Ratio of neutron-to-proton multipole matrix elements M_n/M_p

State	Present	800 MeV(p,p') ^a	500 MeV(p,p') ^b
3 ⁻ 3.736 MeV	.93 ± .07	.99 ± .08	.90
2 ⁺ 3.904 MeV	.88 ± .17	1.2 ± .2	.98
5 ⁻ 4.49 MeV	1.16 ± .20	1.06 ± .15	--
2 ⁺ 5.63 MeV	1.15 ± .35	--	--
2 ⁺ 8.75 MeV	1.15 ± .25	--	--

^aM. M. Gazzaly et al., Phys. Rev. C 25, 408 (1982).^bM. L. Barlett, G. W. Hoffmann, and L. Ray, Phys. Rev. C 35, 2185 (1987), no uncertainty given.

6. Oregon State University, Corvallis, OR 97331.

7. D. K. McDaniels et al., Phys. Lett. 162B, 277 (1985).

8. D. J. Horen et al., Phys. Rev. C 30, 709 (1984).

9. K. W. Jones et al., Phys. Rev. C 33, 17 (1986).

10. F. Osterfeld et al., Nucl. Phys. A318, 45 (1979).

11. D. K. McDaniels et al., Nucl. Phys. A467, 557 (1987).

12. A. M. Bernstein, V. R. Brown, and V. A. Madsen, Comments Nucl. Part. Phys. II, 203 (1983).

VALIDITY OF COLLECTIVE MODEL DWBA ANALYSIS FOR INTERMEDIATE ENERGY PROTON SCATTERING TO LOW-LYING STATES OF ²⁰⁸Pb¹

D. K. McDaniels² F. E. Bertrand
J. Lisantti² E. E. Gross
I. Bergqvist² C. Glover⁴
L. W. Swenson³ R. Sayer⁵
X. Y. Chen³ B. L. Burks⁴
D. J. Horen O. Hausser⁵
K. Hicks⁵

New measurements of inelastic proton scattering to low-lying collective states of ²⁰⁸Pb at 200 and 400 MeV are reported. Deformation lengths ($\delta_H = \delta R$) extracted from angular distributions for the 3⁻ (2.614), 5₁⁻ (3.198 MeV), 5₂⁻ (3.709 MeV), 2⁺ (4.086 MeV), and 4⁺ (4.324 MeV) states are in good accord with values extracted at other incident proton energies. The fact that the deformation lengths for these levels are independent of incident proton energy within experimental uncertainty provides further support of the validity of the collective DWBA

for medium energy proton scattering to strongly excited states. Advantage is taken of this to extract more precise values for the ratio of neutron to proton multipole matrix elements for both the low-lying states and the giant quadrupole resonance at 10.6 MeV.

1. Abstract of published paper: Nucl. Phys. A467, 557 (1987).

2. University of Oregon, Eugene, OR 97403.

3. Oregon State University, Corvallis, OR 97330.

4. Engineering Physics and Mathematics Division, ORNL.

5. Computing and Telecommunications Division, ORNL.

USE OF THE SPIN SPECTROMETER TO STUDY INELASTIC SCATTERING OF HEAVY IONS ON ²⁰⁸Pb

D. C. Hensley E. E. Gross
G. Vourvopoulos¹

Studying the inelastic scattering of heavy ions on ²⁰⁸Pb is an excellent but difficult way to probe the properties of the lower lying states of many nuclei. Since the Spin Spectrometer is an excellent device for measuring individual γ rays whenever very few γ rays are involved, a technique has been developed to exploit the few- γ -ray signature of inelastic scattering reactions by using the Spin Spectrometer. ^{24,26}Mg, ²⁸Si, ³²S, and ⁵⁸Ni have now been studied using this technique.

The average number of detectors which are involved in the response of the Spin

Spectrometer to a single γ ray varies from 1.1 at 0.5 MeV to 1.45 at 2.7 MeV. We introduce a term "cluster" for a quantity which is generated by finding the detector with the largest pulse height and adding in the response of its nearest neighbors. Additional clusters are generated after the detectors associated with previous clusters are removed from the list of detectors. In the best of worlds, there would be a one-to-one correlation between γ rays and clusters. Since the Spin Spectrometer has a finite number of NaI detectors, there will be times when a cluster is associated with more than one γ ray or when detection of a γ ray leads to more than one cluster.

Table 2.5 lists the sum and 1-cluster response of the ball to a single γ ray. These data were obtained by placing a Compton-suppressed Ge detector far outside the ball to select one of the two γ rays emitted by various two- γ -ray sources. The table lists the response of the Spin Spectrometer to the other γ ray relative to the number of triggers from the Ge detector. The Sum-Total response in the second column gives the percent chance that the γ ray was seen at all. About 5% of the loss is attributed to the missing detectors and the gaps between detectors. Most of the loss for the 136- and 264-keV γ rays arises from the threshold setting

for the discriminators which was set near 100 keV. The remaining loss is due largely to γ rays which penetrate 7 inches of NaI without interacting.

The column labeled "Gauss" refers to the result obtained when the γ -ray spectrum is fitted with a Gaussian shaped peak. The "20%" column results from setting a gate that is 20% of the total energy, centered on the full energy peak. The small difference between the Sum and 1-Cluster results above 136 keV arises from scattering out of the primary cluster into another section of the ball.

When the Spin Spectrometer is used to study γ rays emitted in the scattering of heavy ions on ^{208}Pb , a Doppler shift correction must be made to the measured energies. Figure 2.21 shows the spectra obtained from 1-cluster γ -ray data where the scattered ion was 8.33 MeV/nucleon ^{24}Mg . In the upper spectrum, the data have been shifted assuming the γ ray was emitted by the slow, recoiling target nucleus ("target focusing"), and in the lower spectrum the data have been shifted assuming the γ ray was emitted by the fast, scattered heavy ion ("projectile focusing").

The sharp peaks in the upper spectrum arise from Pb γ rays; the peaks at low channels correspond to the first two excited states of

Table 2.5. Response of the Spin Spectrometer to a single γ ray

Energy (keV)	Total	Sum Gauss (%)	20%	Total	1-Cluster Gauss (%)	20%
136	75.8	63.9	25.1	53.2	44.2	25.0
264	80.2	56.8	39.0	75.7	55.3	38.9
570	90.5	63.7	62.2	85.1	57.3	60.5
898	87.7	57.4	60.4	82.8	55.8	58.3
1173	90.4	57.8	62.5	85.1	55.4	59.9
1332	89.7	53.0	60.4	84.2	50.6	57.6
1369	88.3	56.6	59.6	83.0	54.0	57.0
1836	88.4	50.6	57.3	82.2	47.6	54.0
2754	85.0	46.8	54.3	77.0	42.3	49.3

Fig. 2.21. 1-cluster γ -ray spectra from 203-MeV ^{24}Mg on ^{208}Pb . The upper spectrum has been Doppler shift corrected to give a target focus (see text). Sharp peaks at channels 57 and 90 are associated with the first two excited states of ^{207}Pb . Peaks at channels 261 and 409 are associated with two excited states in ^{208}Pb . In the projectile-focused lower spectrum, the sharp peak at channel 137 is associated with ^{24}Mg 2^+ at 1.37 MeV.

^{207}Pb (0.57 and 0.90 MeV), and the peaks at the higher channels correspond to two states in ^{208}Pb (2.61 and 4.09 MeV). The large sharp peak in the lower spectrum corresponds to the first excited state of ^{24}Mg at 1.37 MeV. Initial

identification of the emitting nucleus, whether light or heavy, can often be made simply by comparing these two spectra.

Because two strongly excited states of ^{208}Pb (2.61 and 4.09 MeV) emit γ rays with energies close to those of γ rays emitted by several of the states of interest of the projectile nucleus, a method for separating the resulting complex peaks has been developed. Whenever two γ rays have a center-of-mass energy too close to be resolved by the NaI detectors, it is often possible, because of the variation of the Doppler shifts with angle, to choose detectors where the lab energies of the two γ rays differ by enough to be resolved. This is possible only when one of the two γ rays is emitted by the projectile and the other by the recoiling target nucleus. The energy resolution of the Spin Spectrometer is of the order of 6% for the γ rays being studied, and since the Doppler shift is up to 13% for the ^{24}Mg and 1% for the ^{208}Pb , even γ rays with the same center-of-mass energy will be adequately separated in some detectors of the Spin Spectrometer.

The 1-cluster γ -ray spectra shown in Fig. 2.22 were obtained by requiring that the other cluster of a 2-cluster event fall within a 20% window appropriate for the ^{24}Mg 2^+ state at 1.37 MeV. This gating technique should emphasize the $4^+ \rightarrow 2^+$ (2.75 MeV) transition in ^{24}Mg . In the upper, target-focused spectrum, the peaks at 261 and 409 channels correspond to the ^{208}Pb excited states at 2.61 and 4.09 MeV, respectively. These states are reached in the mutual excitation of the two nuclei. In the lower, projectile-focused spectrum, a single peak at 2.75 MeV is evident. It is clear from the low energy tail on the peak at channel 275 that both the ^{208}Pb 2.61-MeV γ ray and the ^{24}Mg 2.75-MeV γ ray share the spectrum near channel 270.

Figure 2.23 shows spectra similar to those of Fig. 2.22 but for which a Doppler shift of at least 150 keV was additionally required. Approximately 30 percent of the data in Fig. 2.22 satisfy this additional requirement. The lower spectrum has been projectile-focused and the upper spectrum has been target-focused.

ORNL-DWG 87-17102

Fig. 2.22. 1-cluster γ -ray spectra projected from 2-cluster events where the other cluster fell within an energy gate set on the 1.37-MeV, 2^+ state of ^{24}Mg . The projectile-focused lower spectrum clearly shows the 2.75-MeV transition from the ^{24}Mg $4^+ \rightarrow 2^+$ states. The low energy tail on the peak arises from the defocused contribution of the 2.61-MeV 3^- state of ^{208}Pb , which can be seen focused in the target-focused upper spectrum. The γ ray from the 4.09-MeV 2^+ state of ^{208}Pb is also evident in the upper spectrum.

Note that in each spectrum the appropriate peak is focused and the overall separation of the peaks is preserved between the two spectra. The yield for the 2.75-MeV peak can now be obtained

ORNL-DWG 87-17103

Fig. 2.23. 1-cluster spectra obtained from the data shown in Fig. 2.22 by requiring a Doppler shift correction of at least 150 keV. The low energy tail on the 2.75 MeV peak in the particle-focused lower spectrum is now clearly resolved. Approximately 30 percent of the data of Fig. 2.22 satisfy this additional requirement.

with little contamination from the ^{208}Pb 2.61-MeV peak.

All of the Spin Spectrometer experiments studying the inelastic scattering of heavy ions on ^{208}Pb have utilized 3- and 5-cm-long position-sensitive Si detectors. These detectors allow the charged particle angular distribution to be

studied simultaneously from 19° to over 50° in the lab. This is a span which includes the near Rutherford scattering region and extends beyond the grazing angle. Since the Si detectors are position sensitive, full angular distributions can be derived readily from the data.

Because the physical geometry of the Spin Spectrometer scattering chamber is somewhat ill defined, a parallel experiment is performed in the 1.6-m chamber with a position-sensitive Si detector fronted by an angle-defining set of slits. The 1.6-m-chamber data serve to measure the elastic scattering into the essentially pure Rutherford region and are then combined with the Spin Spectrometer measurements to provide very precise angular distributions for the elastic scattering and for the first 2^+ state of the projectile. The overall uncertainty in the elastic angular distribution is on the order of 1% and is less than 5% for the first excited state angular distribution. The uncertainty in the various excited state angular distributions depends largely on the counting statistics or on the complexity of the filtering requirements used to obtain the respective yields. The quality of the extracted distributions can be seen in the figures shown in a following paper presenting the ^{24}Mg results.²

Although this technique for studying heavy-ion inelastic scattering is somewhat complex, it should be noted that the results on the states above the first 2^+ are unique. No other heavy-ion technique has been truly able to resolve these higher excited states, and the quality of the elastic and first 2^+ distributions is excellent. The technique also provides information on the mutual excitation of the target as well as on the γ -ray angular correlation for the first 2^+ state. The papers^{2,3} in this report dealing with the theoretical analysis of the results of Spin Spectrometer measurements of ^{24}Mg and ^{26}Mg scattering on ^{208}Pb ^{2,3} highlight the good sensitivity to reaction and nuclear properties this technique provides.

2. E. E. Gross et al., "Coupled Channels Analysis of ^{24}Mg Scattering from ^{208}Pb at 200 MeV Lab," this report.

3. G. S. Yourvopoulos, "Inelastic Scattering of ^{24}Mg from ^{208}Pb ," this report.

INELASTIC SCATTERING OF ^{26}Mg FROM ^{208}Pb

G. S. Yourvopoulos¹ D. C. Hensley
E. E. Gross

Following the encouraging results from the $^{24}\text{Mg} + ^{208}\text{Pb}$ experiment,² the method of determining deformation parameters from heavy-ion inelastic scattering was applied to ^{26}Mg . The quadrupole deformation for ^{26}Mg is known,³ but little is known about any higher deformations. The experiment was performed at the MHRF using a four-particle NA beam of 200-MeV ^{26}Mg incident on a $400\text{-}\mu\text{g}/\text{cm}^2$ ^{208}Pb target. Particle- γ coincident data were taken. The γ rays were detected with 70 NaI detectors of the Spin Spectrometer. Two position-sensitive detectors in the scattering chamber of the Spin Spectrometer, spanning an angular range from $\theta_L = 19^\circ$ to 51° , were used for the detection of the charged particles. Details of the experimental technique are described in a previous paper.⁴

From the data reduced thus far, we have obtained angular distributions for the ground state of ^{26}Mg , the first 2^+ state at 1.81 MeV, the second 2^+ state at 2.94 MeV, and the 4^+ state at 4.32 MeV. Our preliminary analysis with the coupled-channel code ECIS, using a symmetric rotational model, indicates that the best fit to the elastic scattering, (Fig. 2.24) is obtained with the optical parameters $V = 20.4$ MeV, $r_0 = 1.37$ fm, $a = 0.68$ fm, $W = 14$ MeV, $r'_0 = 1.4$ fm, $a' = 0.49$ fm. Fitting of the forward part of the 1.81-MeV 2^+ angular distribution (Fig. 2.24) presently indicates a value for $B(E2) = 0.0281 e^2 b^2$, to be compared with the adopted value² of $0.0305 e^2 b^2$. Very preliminary analysis of the 2_2^+ state at 2.94 MeV suggests that the values for the $\langle 2_2^+ | M(E2) | 0^+ \rangle$ and $\langle 2_2^+ | M(E2) | 2_1^+ \rangle$ matrix elements will be significantly different from those predicted by the shell model.

1. Western Kentucky University, Bowling Green, KY 42101.

Fig. 2.24. Angular distributions for 200-MeV ^{26}Mg on ^{208}Pb . Distribution (a) is the ratio to Rutherford for the elastic scattering and distribution (b) is for the ^{26}Mg 2^+ state at 1.81 MeV. The solid line in both cases is the current prediction using the coupled-channel code ECIS.

The analysis of the distribution for the 4^+ state has just begun, and the range of values for B_4 has not yet been determined.

1. Western Kentucky University, Bowling Green, KY 42101.
2. E. E. Gross et al., "Coupled Channels Analysis of ^{26}Mg Scattering from ^{208}Pb at 200 MeV Lab," this report.
3. Atomic data and Nuclear Data Tables 36, 1 (1987).
4. D. C. Hensley et al., "Use of the Spin Spectrometer to Study Inelastic Scattering of Heavy Ions on ^{208}Pb ," this report.

COUPLED CHANNELS ANALYSIS OF ^{26}Mg SCATTERING FROM ^{208}Pb AT 200 MeV LAB

E. E. Gross	F. E. Bertrand
D. C. Hensley	G. Yourvopoulos ¹
M. L. Halbert	D. Humphrey ¹
J. R. Beene	T. VanCleve ¹

The technique described in the previous report made it possible to obtain the elastic and inelastic scattering cross section data shown in Fig. 2.25. The data set is unique because of the extensive ^{26}Mg 4_1^+ and 2_2^+ cross

sections and because all the data are tied together and normalized to Rutherford scattering at forward angles.

All four states shown in Fig. 2.25 were coupled in a symmetric rotor model calculation using previously reported² matrix elements and an optical potential for 132-MeV ^{22}Ne scattering³ from ^{208}Pb to start the analysis. The optical potential is determined mainly by fitting the elastic scattering provided that the excited states included in the calculation are adequately accounted for by transition matrix elements. Nuclear transition matrix elements were related to Coulomb matrix elements through the Hendrie procedure.⁴ The optical potential found in the present case is: $V = 41.1$ MeV, $r_0 = 1.156$ fm, $a_0 = 0.9$ fm, $W = 20.3$ MeV, $r' = 1.244$ fm, $a' = 0.59$ fm, and $r_c = 1.2$ fm.

The preliminary fit to the ^{26}Mg $2_1^+(1.37$ MeV) state, shown in Fig. 2.25b, determines two quantities: $B(E2; 0_1^+ \rightarrow 2_1^+) = (416.4 \pm 1.5)e^2\text{fm}^4$, from fitting data for $\theta_{\text{cm}} < 35^\circ$, and $Q_2 = (-21.1 \pm 0.7)e^2\text{fm}^2$ from fitting data for

Fig. 2.25. (a) Ratio of elastic scattering to Rutherford scattering. (b) Cross section for exciting the first 2^+ state of ^{24}Mg . (c) Cross section for exciting the first 4^+ state of ^{24}Mg . (d) Cross section for exciting the second 2^+ state of ^{24}Mg . The solid curves are coupled channels fits to the data.

$\theta_{\text{cm}} > 45^\circ$. The errors are χ^2 standard deviations and include systematic as well as statistical errors. These values agree well with those reported by Fewell et al.⁵ but our values have considerably smaller uncertainties. The slight deficiency in fitting the 2_1^+ state near the grazing angle remains a puzzle. The effects of the addition of a spin-orbit potential or of the effect of mutual excitation of the 3^- (2.61 MeV) state in ^{208}Pb were investigated and found to not improve this deficiency. The portion of the 2_1^+ data near the grazing angle does not influence the above two quantities to any appreciable extent.

The preliminary fit to the ^{24}Mg 4_1^+ (4.12 MeV) state shown in Fig. 2.25c adequately represents the shape and magnitude of the data. The observed magnitude for this state is very sensitive to the magnitude and sign of the β_4^C deformation. The fit shown in Fig. 2.25c is for $\beta_2^C = 0.483$ and $\beta_4^C = +0.03 \pm 0.01$ giving a hexadecapole moment of $M(E4) = 118 \pm 6 \text{ e}^2\text{fm}^4$. These values differ from those reported⁶ previously and may pose problems for nuclear structure models.⁷ Also shown in the figure is the effect on the 4^+ state of including the 6^+ member of the rotational band. The effect on the 2^+ state is negligible.

The second 2^+ state cross section is shown in Fig. 2.25d. Within the framework of the symmetric rotor model, the $0^+ \rightarrow 2_2^+$ and $2_1^+ \rightarrow 2_2^+$ transition matrix elements are uniquely determined by fitting the shape and magnitude of these data. For the fit shown, the extracted matrix elements are:

$$\langle 2_2^+ || M(E2) || 0^+ \rangle = +6.1 \text{ e fm}^2;$$

$$\langle 2_2^+ || M(E2) || 2_1^+ \rangle = +5.1 \text{ e fm}^2$$

where the sign adheres to the convention that $\langle 2_1^+ || M(E2) || 0^+ \rangle$ is taken as negative. These are in reasonable agreement with previous values.²

1. Western Kentucky University, Bowling Green, KY 42101.
2. M. P. Fewell, Thesis, Australian National University, October 1978, unpublished.
3. E. E. Gross et al., Phys. Rev. C 29, 459 (1984).
4. D. L. Hendrie, Phys. Rev. Lett. 31, 478 (1973).
5. M. P. Fewell et al., Nucl. Phys. A319, 214 (1979).
6. G. Haouat et al., Phys. Rev. C 30, 1795 (1984).
7. G. Leander and S. E. Larsson, Nucl. Phys. A239, 93 (1975).

SINGLE AND CORRELATED SPIN ALIGNMENTS FOR RESONANCES IN $^{24}\text{Mg} + ^{24}\text{Mg}$ INELASTIC SCATTERING¹

A. H. Wuosmaa² S. F. Pate²
 R. W. Zurmuhle² S. Saini²
 P. H. Kutt² M. L. Halbert
 D. C. Hensley

We have measured the single and correlated magnetic-substate population parameters for the 2^+ and 2^+-2^+ excitations in $^{24}\text{Mg} + ^{24}\text{Mg}$ in the region of two strong resonances seen in inelastic scattering. We interpret our data in terms of an isolated resonance decaying through one preferred λ value in both the 2^+ and 2^+-2^+ channels. Our data suggest a spin assignment of $J^\pi = 36^+$ for the resonance at $E_{c.m.} = 45.70$ MeV, and a value of $\lambda = 34$ for the grazing angular momentum for both the single and mutual inelastic-scattering channels.

1. Abstract of published paper: Phys. Rev. Lett. 13, 1312 (1987).
2. University of Pennsylvania, Philadelphia, PA 19104.

PROPERTIES OF THE NEUTRON SINGLE-PARTICLE STATES IN ^{208}Pb FROM AN EXTRAPOLATION OF THE OPTICAL POTENTIAL

C. H. Johnson D. J. Horen
 C. Mahaux¹

In the preceding Progress Report² we included the dispersion relation³ constraint for deducing an empirical mean field to describe the observed scattering of 1- to 150-MeV neutrons from ^{208}Pb . The real part of the field is the sum of a Hartree-Fock type component plus a dispersive term:

$$V(r;E) = V_H(r;E) + \Delta V(r;E), \quad (1)$$

where $\Delta V(r;E)$ is predicted by the dispersion relation from the empirical imaginary potential. The Hartree-Fock term is a smooth function of energy. In contrast, the energy dependence of $\Delta V(r;E)$ is complicated, particularly near the Fermi energy E_F , which is in the bound region between the energies of the last occupied and first unoccupied orbits. This dispersive term is antisymmetric about E_F ; it is attractive just above E_F but repulsive below E_F . Thus, it has significant influence on the predicted properties of the bound states.

In the previous report² we extrapolated $V(r;E)$ to negative energies and found that the predicted bound state energies agree well with the empirical energies for the valence orbits, which correspond to six particle-states above E_F and five hole-states below E_F . From the bound state wave functions we have now deduced the rms radii, the occupation numbers N_{nj} , and the absolute spectroscopic factors S_{nj} (Ref. 4). These are presented in Table 2.6. For these calculations we recognize that $V_H(r;E)$ is the local equivalent of a nonlocal potential; therefore, we use normalized wave functions with corrections for the "Perey damping factor".⁵

Interest in the occupation numbers has been renewed by the recent measurement⁶ for the $3s_{1/2}$ proton shell in ^{208}Pb . Only small differences should be expected between the occupation probabilities of proton and neutron single-particle states.⁴ Hence, it is of interest that the predicted neutron value, $N(n)_{3p_{1/2}} = 0.86$ from

Table 2.6 Spectroscopic factors, occupation numbers and rms radii of valence neutron particle and hole states in ^{208}Pb

$n\ell j$	$S_{n\ell j}$	$N_{n\ell j}$	$R_{n\ell j}^{\text{rms}}(\text{fm})$
$3d_{3/2}$	0.90	0.07	8.02
$2g_{7/2}$	0.86	0.10	7.15
$4s_{1/2}$	0.91	0.06	8.47
$3d_{5/2}$	0.88	0.08	7.62
$1j_{15/2}$	0.82	0.13	6.73
$1i_{11/2}$	0.32	0.12	6.53
$2g_{9/2}$	0.81	0.12	6.70
$3p_{1/2}$	0.80	0.86	6.36
$2f_{5/2}$	0.81	0.87	6.18
$3p_{3/2}$	0.81	0.87	6.23
$1i_{13/2}$	0.81	0.87	6.36
$2f_{7/2}$	0.85	0.90	5.97
$1h_{9/2}$	0.85	0.90	5.93

Table 2.6 is close to the experimental proton value, $N(p)_{3s1/2} = (0.82 \pm 0.09)$ from Ref. 6.

Also of considerable interest are the wave functions at large radii for the occupied orbits, because one can compare to the neutron densities determined experimentally from sub-Coulomb pickup reactions.⁷⁻⁹ The dots in Fig. 2.26 show the experimental total densities for the occupied valence orbits. From our model wave functions we calculate the neutron density for each orbit,

$$\bar{\rho}_{n\ell j}(r) = (2j+1)/4\pi |\bar{u}_{n\ell j}(r)/r|^2, \quad (2)$$

where $\bar{u}/r$ denotes the radial wave function corrected for Perey damping. For comparison to the data we note that the experimental measurement actually represents the product of the density times the spectroscopic factor. Therefore, we calculate the sum of this product for the occupied valence orbits;

$$(\bar{S}\bar{\rho})_{\text{tot}}(r) = \sum S_{n\ell j} \bar{\rho}_{n\ell j}(r). \quad (3)$$

Fig. 2.26 Total neutron densities for the occupied valence orbits. The data represent experimental values and the solid curve is predicted from the present model. The dashed curve is predicted when the dispersive term is omitted.

The resulting prediction is shown by the solid curve in Fig. 2.26. The agreement with the data is seen to be quite remarkable, especially when one recognizes that it is based almost entirely on analysis of scattering at positive energies with no further adjustment of parameters. The dashed curve results if the dispersive term is omitted.

1. Consultant from University of Liège, Liège, Belgium.
2. Phys. Div. Prog. Rept. Sept. 30, 1986, ORNL-C326, p. 38.
3. C. Mahaux and H. Ngô, Nucl. Phys. A378, 205 (1982).
4. C. Mahaux and H. Ngô, Nucl. Phys. A431, 486 (1984).
5. F. G. Perey and R. Buck, Nucl. Phys. 32, 353 (1962).
6. C. N. M. Quint, et al., Phys. Rev. Lett. 58, 1098 (1987).
7. H. J. Körner and J. P. Schiffer, Phys. Rev. Letters 27, 1457 (1971).
8. J. P. Schiffer and H. J. Körner, Phys. Rev. C 8, 841 (1973).
9. M. A. Franey, J. S. Lilley and W. R. Phillips, Nucl. Phys. A234, 193 (1979).

DISPERSION RELATION PREDICTIONS OF SCATTERING FUNCTIONS FOR NEUTRONS ON ^{86}Kr

R. Carlton¹ C. H. Johnson
R. R. Winters²

The neutron total cross section resonance structures that are measured by the time-of-flight method at ORELA can be described by the R-matrix formalism. For the simplest case of a spin-zero target nucleus, the phase shift for a given partial wave reads

$$\delta(E) = e^{2i\phi(E)} \frac{1 + iP(E)R(E)}{1 - iP(E)R(E)}, \quad (1)$$

where P and ϕ are the penetrability and the hard-sphere phase shift and where the R -function is a sum over all levels for the partial wave

$$R(E) = R^{\text{ext}}(E) + \sum_{\lambda} \gamma_{\lambda}^2 / (E_{\lambda} - E). \quad (2)$$

In Eq. (2), γ_{λ}^2 and E_{λ} are the reduced neutron width and energy for the λ th observed level, and R^{ext} is the contribution for all levels outside the experimental domain.

In the preceding Progress Report³ we presented a detailed R-Matrix analysis for the individual partial waves in order to make comparisons to optical model predictions. Figures 1 and 2 present the pertinent^{4,5} average experimental quantities. In Fig. 2.27 the "staircase" plots represent the cumulative sums of reduced widths for the lowest four partial waves,

namely, $s_{1/2}$, $p_{1/2}$, $p_{3/2}$, $d_{3/2}$ and $d_{5/2}$. (The sharp rise at 525 keV in Fig. 2.27c represents a doorway state which is of interest but is not to be discussed here in relation to the optical model.) In Fig. 2.28 the solid curves represent the functions R^{ext} and the vertical bars show the estimated uncertainties.

The optical model analyses of these average experimental quantities could proceed along the traditional "phenomenological" path in which one selects model parameters to be treated as free parameters to obtain the best fit to the averages. Our approach, however, is to predict the averages without free parameters by use of a model that was developed⁶ on the basis of the dispersion relation⁷ for describing the observed⁸ scattering of 4- to 10-MeV neutrons on a

Fig. 2.27. Cumulative Neutron Strength for (a) s-wave, (b) $p_{1/2}$ and $p_{3/2}$ and (c) d-wave neutrons. The curves represent predictions from the optical model of Ref. 6, as described in the text.

neighboring nucleus, namely ^{86}Kr . The dispersion relation predicts the detailed intricate energy dependence of the real part of the potential. In particular, it allows one to extrapolate the real potential to the negative energies of the bound states. Clearly, it should also allow one to extrapolate from the 4- to 10-MeV region to the intermediate resonance region, which is the subject of this report. At the same time, the imaginary part of the potential can be reasonably extrapolated, since it must reduce to near

Fig. 2.28. The solid curves are the external R-functions derived from R-matrix analysis of $n + {}^{86}\text{Kr}$. The dashed curves represent predictions from the optical model of Ref. 6, as described in the text.

zero at negative energies to account for the small fragmentation of the bound states.

The solid curves in Fig. 2.27 and the dashed curves in Fig. 2.28 give the average quantities predicted from this extrapolation. They are seen to give very good descriptions of the experimental quantities. In making the predictions, we assumed that the central depths for the real parts of the ${}^{96}\text{Kr}$ and ${}^{89}\text{Y}$ potentials differed by an isospin component of $15 (N-Z)/A$. We also assumed the geometric parameters of the surface imaginary potential to be $r_D = 1.27$ fm and $a_D = 0.38$ fm, and the volume imaginary term to increase linearly from zero at $E = 7$ MeV to its maximum at $E = 54$ MeV; these latter assumptions were required for the use of the volume integrals given by the model.⁶

1. Middle Tennessee State University, Murfreesboro, TN.

2. Denison University, Granville, OH.
3. Phys. Div. Prog. Rept. Sept. 30, 1986, ORNL-6326, pp. 41-43.
4. C. H. Johnson and R. R. Winters, Phys. Rev. C 27, 416 (1983).
5. C. H. Johnson, C. Mahaux, and R. R. Winters, Phys. Rev. C 32, 359 (1985).
6. C. Mahaux and R. Sartor, Phys. Rev. C, in press.
7. C. Mahaux and H. Ngo, Nucl. Phys. A378, 205 (1982).
8. R. D. Lawson, P. T. Guenther, and A. B. Smith, Phys. Rev. C 34, 1599 (1986).

EVIDENCE FOR PARITY DEPENDENCE IN THE IMAGINARY PART OF THE NEUTRON OPTICAL POTENTIAL

R. R. Winters¹ C. H. Johnson

Lawson et al.² reported that their spherical optical model potential (OMP) analysis of ${}^{89}\text{Y}$ neutron scattering cross section measurements from 4 to 10 MeV required an energy-dependent imaginary surface potential with radius and diffuseness given by the equations,

$$r_w(E) = 1.5336 - 0.0255 E, \quad (1)$$

and

$$a_w(E) = 0.0166 + 0.0284 E \quad (2)$$

where E is expressed in MeV and r_w and a_w in fermi. We find that, in regard to compound nucleus effects, this energy dependence reduces the importance of $20 < N < 50$ neutrons shell model orbits (3s, 2d, 1g_{7/2}), and places relatively large emphasis on $50 < N < 82$ orbits (3p and 2f). Figure 2.29 shows the radial wave functions, $u_{lj}(r) = rR_{lj}(r)$, calculated at neutron energy of 5 MeV using the real part of the OMP chosen by Lawson et al.² We see that the wave functions of the 3s, 2d, and 1g orbits have nodes in the vicinity of the surface, i.e., near $r = 6$ fm; however, the wave functions for the 2p and 1f orbits have large values (nearly antinodes). Moreover, as shown in Fig. 2.30, the nodes of the 3s, 2d, and 1g wave functions all shift approximately at the same rate toward the origin as the neutron energy is increased.

The neutron transmission factor, $T_{lj}(E)$, is proportional to an overlap integral of the square of the radial wave function and the imaginary part of the OMP,

$$T_{lj}(E) \sim \int W(r; E) |u_{lj}(r)|^2 dr. \quad (3)$$

Fig. 2.29. The radial wave function $u(r)$ for angular momentum quantum numbers $l < 6$ calculated for neutron energy $E = 5$ MeV. Note that the positions of the nodes of the wave functions for the 3s, 2d, and 1g shell model orbits all fall near the radius chosen by Lawson et al.¹ for their real OMP. However, the wave functions for the 2p and 1f orbits have nearly maximal values at this radius.

Fig. 2.30. The positions of the nodes of $u(r)$ as a function of neutron energy. The dashed curve represents the quality $R_w(E) = r_w(E)A^{1/3}$, where r_w is from Eq. (1).

Hence the compound elastic scattering contribution for a given partial wave can be small if the imaginary surface potential $W(r;E)$ is narrow and centered near a node in $u_{lj}(r)$, as in the case in the analysis of Lawson et al.² Thus Eq. (1) can be interpreted as describing the general behavior of the nodes of the 3s, 2d, and 1g_{7/2} wave functions. The phenomenological energy dependence for $W(r;E)$ can therefore be

replaced with a constant shape for the surface imaginary well but with a parity dependence for the surface potential well depth. Figure 2.31 shows angular distributions calculated at $E = 5$ MeV for these alternative parametrizations of the OMP. The solid curve is calculated using the OMP shape reported by Lawson et al.² The dashed curve is calculated using the OMP shape defined by Eqs. (1) and (2) for 10-MeV neutrons ($r_w = 1.28$ fm and $a_w = 0.45$ fm) but with the imaginary well depth for p- and f-waves different from that for the even parity partial waves. The imaginary well depths are 8.93 MeV for the odd parity partial waves and 5.10 MeV for even parity.

1. Denison University, Granville, OH.
2. R. D. Lawson, P. T. Guenther, and A. B. Smith, Phys. Rev. 34, 1599 (1986).

Fig. 2.31. Shape elastic angular distributions for alternate models for neutron scattering from ⁸⁹Y. The solid curve is calculated from the empirical model of Lawson et al.¹ The dashed curve represents a fit to the solid curve using the parity dependent OMP described in the report.

GLOBAL PARAMETERIZATION OF THE NUCLEON-NUCLEUS OPTICAL MODEL POTENTIAL

R. L. Varner T. B. Clegg¹
W. J. Thompson¹ T. L. McAbbee²

We have been engaged in a global parameterization of the nucleon-nucleus optical model potential, which has been described briefly in

the literature.³ In preparing a longer report on this work, we are trying to refine our determination of uncertainties in the model parameters. We have previously used uncertainties estimated by the MINUIT⁴ optimization package, incorporated into our optical model program MINOPT,⁵ for the uncertainties in our parameters. Unfortunately, these uncertainty estimates suffer from several problems.

The uncertainties in model parameters normally used by physicists are standard deviations, which are the square root of the diagonal elements of the covariance matrix. The calculation of the covariance assumes that the fitting function is normally distributed, that is, quadratic in the region of the best-fit, with only linear correlations between parameters. This is not necessarily true for the optical model, in which there are strong nonlinear correlations among the parameters.

Unfortunately, even if uncertainties are derived without directly using the covariance, we must still attach a meaning, that is, a probability associated with the interval of the uncertainty. For known distributions, parametric statistics tells us the probability; e.g., for a normal distribution there is a 68% chance that the true value of a parameter is within 1-standard deviation of the estimate. We do not necessarily know the distribution for the optical model parameters. These are general problems for parametric statistics, as well as problems with the algorithms embodied in MINUIT.⁶

Our proposed solution to this problem is to use nonparametric statistical techniques to analyze the uncertainties.⁷ Nonparametric statistics makes no assumptions about the distribution of the statistical data. Rather, the data are sampled repeatedly, and the statistics of interest are calculated for each sample, not unlike repeating the measurements many times. In the case of optical model parameters, it means estimating the parameters for a number of randomly chosen subsets of the original dataset, then computing the mean and width of the resulting distribution of parameter

values. A by-product of this procedure is that nonlinear correlations between parameters may be measured, at least qualitatively. This avoids both our difficulties associated with the parametric estimates of uncertainty, it does not rely on any assumption about the behavior of the fitting function, and it provides its own normalization for probability.

We have made preliminary trials of these procedures with encouraging results. We will implement the necessary procedures and proceed to make a nonparametric analysis of the optical model parameters. In order to perform the large number of optimizations required, we are modifying our optical model program to incorporate semi-analytic calculation of the optical model derivatives, which are required by the search algorithm.⁸ This has been shown previously to reduce the work of optical model searches by about a factor of 6, making the nonparametric analysis practical.

1. University of North Carolina at Chapel Hill, NC 27514.
2. Lawrence Livermore National Laboratory, Livermore, CA 94550.
3. R. L. Varner et al., Phys. Lett. B185, 6 (1987).
4. F. James and M. Roos, Comp. Phys. Comm. 10, 343 (1975).
5. R. L. Varner, Ph.D. Dissertation, University of North Carolina, Chapel Hill, NC (1986).
6. F. James, "Interpretation of the Errors on Parameters as Given by MINUIT," Supplement to CERN D-506, 1978 (unpublished).
7. B. Efron, SIAM 21, 460 (1983).
8. D. H. Gloeckner, M. H. Macfarlane, and S. C. Pieper, Comp. Phys. Comm. 11, 299 (1976).

GLOBAL SET OF B_2 VALUES FOR EVEN-EVEN NUCLEI¹

S. Raman C. W. Nestor, Jr.²
K. H. Bhatt³

We have completed a compilation of experimental results for the $B(E2)^\dagger$ between the 0^+ ground state and the first 2^+ state in even-even nuclei. The adopted $B(E2)^\dagger$ values (and hence the deformation parameters β_2) have been employed to test empirical relationships proposed by several authors. In general, we find that predictions of $B(E2)^\dagger$ values for nuclei off

the stability line can be made to an accuracy of $\pm 25\%$. It can be shown that, for nuclei away from closed shells, the SU_3 limit of IBA implies that the $B(E2)^+$ values are proportional to $(A_p N_p + A_n N_n)^2$, where A_p and A_n are constants and $N_p(N_n)$ refers to the number of valence protons (neutrons). This proportionality is consistent with the observed behavior of $B(E2)^+$ vs $N_p N_n$. For deformed nuclei, the $B(E2)^+$ values calculated in a schematic microscopic SU_3 model successfully reproduce the empirical variation of the $B(E2)^+$ values with mass number.

1. Abstract of an invited talk at the Workshop on Collective Properties of Mid-Mass Nuclei, Florida State University, Tallahassee, Florida (March 19-20, 1987).

2. Computing and Telecommunications Division.

3. Western Kentucky University, Bowling Green, KY.

ELASTIC SCATTERING OF ^{58}Ni ON ^{27}Al AT NEAR- AND BELOW-BARRIER ENERGIES

J. Gomez del Campo G. R. Satchler
P. H. Stelson H. Kim
 D. Shapira

Recent elastic scattering experiments have shown a rapid, localized variation of the nuclear optical potential as the Coulomb barrier is approached. This effect is usually referred to as the threshold anomaly.¹ The systems $^{16}\text{O} + ^{208}\text{Pb}$ (Ref. 2) and $^{16}\text{O} + \text{Ni}$ (Ref. 3) have been studied in some detail. Data for heavier systems are scarce, although evidence has been presented⁴ for the anomaly in $^{32}\text{S} + ^{40}\text{Ca}$ scattering.

We have chosen to study the elastic scattering of $^{58}\text{Ni} + ^{27}\text{Al}$ using the reverse kinematic method (i.e., heavy beam on light target) in order to be able to measure the elastic scattering at the most backward c.m. angles (most forward in the laboratory system). Beams of ^{58}Ni were extracted from the HHIRF 25 MV tandem accelerator and used to bombard a 150 ug/cm^2 ^{27}Al target. Measurements were carried out at three bombarding energies of 160 MeV, 170 MeV, and 210 MeV in the laboratory angular range of

7° to 33° . The elastic ^{58}Ni , as well as the recoiling ^{27}Al , nuclei was momentum-analyzed by an Enge split-pole magnet equipped with a heavy-ion proportional detector system that can measure their trajectory, energy loss, and total energy. With this system the kinetic energy, mass, and charge of the reaction products were uniquely determined. The overall energy resolution for the ^{27}Al nuclei was $\pm 0.5 \text{ MeV}$, due mostly to energy loss and straggling of the heavy ions through the target and entrance foil of the detector.

Figure 2.32 shows the angular distributions of the ratio of elastic scattering to the Rutherford cross sections, measured for the three bombarding energies. Each angular distribution is labeled by its corresponding center of mass energy. The solid curves are the results of optical model fits to the data using a Woods-Saxon potential with fixed geometry ($r_0 = r_0' = 1.0654$ and $a_0 = a_0' = 0.65$) and an energy-dependent real and imaginary potential well depths. This potential shape was chosen because it had been found previously to give an excellent fit to elastic scattering data⁵ for

Fig. 2.32. Ratio to Rutherford of the measured differential cross sections compared to optical model fits described in the text.

$^{28}\text{Si} + ^{58}\text{Ni}$ at $E_{\text{cm}} = 74$ MeV. Also a folding model analysis using the M3Y interaction was performed producing angular distributions identical to the ones shown on Fig. 2.32. Figure 2.32 shows the resulting real and imaginary strengths V , W of the optical potential which yielded minimum χ^2 in an automatic search. Figure 2.33 shows the corresponding real and imaginary normalization factors (N) for the folding potential. From Fig. 2.33 it is evident that there are rapid variations of both real and imaginary potential strengths, by about a factor of 2 in 16 MeV, as the barrier is approached (about 52 MeV). The present results

show a behavior qualitatively similar to those of Refs. 2-4.

However, closer examination showed that the potential obtained at 160 MeV is very poorly determined. A side-range of (V, W) values can be found to give equivalent fits to these data, even though they predict significantly different cross sections at other angles.

It was also found that the difference between the real strengths obtained at 170 and 210 MeV (the remaining evidence for an anomaly in the real potential) could be eliminated by reducing the diffuseness of the imaginary potential to $a' = 0.3$ fm. While such a sharp surface is surprising, the χ^2 from such fits were reduced by factors of two. The corresponding theoretical cross sections then differed significantly from those shown in Fig. 2.32 at the smaller angles ($\sim 50-60^\circ$ at 210 MeV, $\sim 80-110^\circ$ at 170 MeV). More complete measurements will be needed to resolve these ambiguities.

Fig. 2.33 Strengths of the real (solid points) and imaginary (open points) parts of the optical potentials used for Fig. 2.32 Top: Woods-Saxon shape with $r_0 = r_0' = 1.0654$, $a = a' = 0.65$; Bottom: folded potential (open and solid points) obtained from the M3Y interaction the lines are to guide the eye.

1. C. Mahaux, H. Ngo and G. R. Satchler Nucl. Phys. A449, 354 (1986).
2. J. S. Lilley et al. Phys. Lett. 151B, 181 (1985).
3. B. R. Fulton et al. Phys. Lett. 162B, 55 (1985).
4. A. Baeza et al. Nucl. Phys. A419, 42 (1984).
5. Y. Sugiyama et al. Phys. Lett. 176B, 302 (1986).

NUCLEAR STRUCTURE STUDIES VIA CHARGE-EXCHANGE REACTIONS

$(\bar{p}, n)$ REACTION ON CARBON ISOTOPES AT $E_p = 160$ MeV¹

J. Rapaport ²	C. Gaarde ⁵
D. Wang ²	J. Larsen ⁵
J. A. Carr ³	C. A. Goulding ⁶
F. Petrovich ³	T. N. Taddeucci ⁶
C. C. Foster ⁴	D. Horen
C. D. Goodman ⁴	E. Sugarbaker ⁷

Differential cross sections and analyzing powers for the $(\bar{p}, n)$ reaction on carbon isotopes have been measured for angles up to $\theta_{\text{lab}} = 50^\circ$ using 160-MeV protons. The angular distributions for the stronger transitions are compared

with the results of distorted-wave impulse approximation calculations which utilize transition densities from existing shell model calculations. The total observed Gamow-Teller strength is also compared with the shell model predictions. In addition, the shapes of these angular distributions are discussed, emphasizing decomposition into longitudinal, transverse, and nonnormal-parity-transfer components. Some comparisons of the present (p,n) data with corresponding (p,p') data and with other relevant (p,n) data are also made.

-
1. Abstract of published paper: Phys. Rev. C 36, 500 (1987).
 2. Ohio University, Athens, OH 45701.
 3. Florida State University, Tallahassee, FL 32306.
 4. Indiana University, Bloomington, IN 47405.
 5. Niels Bohr Institute, Copenhagen, Denmark.
 6. Los Alamos National Laboratory, Los Alamos, NM 87545.
 7. Ohio State University, Columbus, OH 43215.

THE (p,n) REACTION AS A PROBE OF BETA DECAY STRENGTH¹

T. N. Taddeucci ²	C. Gaarde ⁴
C. A. Goulding ²	J. Larsen ⁴
T. A. Carey ²	D. Horen
R. C. Byrd ³	J. Rapaport ⁵
C. D. Goodman ³	E. Sugarbaker ⁶

The evidence for a useful proportionality relationship between 0° (p,n) cross sections and the corresponding Gamow-Teller and Fermi beta decay transition strengths is examined in detail. A simple parametrization for small momentum transfer $L = 0$ transitions is developed and used in the analysis of (p,n) data in the bombarding energy range 120-200 MeV. The parametrization describes the (p,n) differential cross section in terms of momentum transfer, energy loss, mass number, and bombarding energy and provides a straightforward way of extrapolating to zero momentum transfer. It is found that a single proportionality constant can serve to relate all Gamow-Teller transitions origi-

nating from the same target nucleus. The target dependence of this proportionality constant, however, is found to be unpredictable at the 20%-50% level, even within isotopic chains. Such large variations cannot be easily explained in the context of the standard single-step, direct-reaction, distorted-waves, impulse approximation model.

-
1. Abstract of published paper: Nucl. Phys. A469, 125 (1987).
 2. Los Alamos National Laboratory, Los Alamos, NM 87545.
 3. Indiana University, Bloomington, IN 47405.
 4. Niels Bohr Institute, Copenhagen, Denmark.
 5. Ohio University, Athens, OH 45701.
 6. Ohio State University, Columbus, OH 43214.

GAMOW-TELLER STRENGTH DISTRIBUTION IN ⁸¹Kr AND THE CONSEQUENCES FOR A ⁸¹Br SOLAR NEUTRINO DETECTOR¹

D. Krofcheck ²	R. C. Byrd ⁵
E. Sugarbaker ²	C. C. Foster ⁵
A. J. Wagner ²	C. D. Goodman ⁵
J. Rapaport ³	C. Gaarde ⁶
D. Wang ³	D. J. Horen
J. N. Bahcall ⁴	T. Carey ⁷
T. N. Taddeucci ⁷	

Neutron time-of-flight measurements have been performed on the ⁸¹Br(p,n)⁸¹Kr reaction at $E_p = 190$ and 200 MeV. Gamow-Teller transition strengths have been deduced for final ⁸¹Kr states accessible through solar neutrino capture on ⁸¹Br. For the standard solar model, ⁸¹Br neutrinos, not — as previously believed — ⁷Be neutrinos.

-
1. Abstract of published paper: Phys. Lett. B189, 299 (1987).
 2. Ohio State University, Columbus, OH 43210.
 3. Ohio University, Athens, OH 45701.
 4. Institute for Advanced Study, Princeton, NJ 08540.
 5. Indiana University, Bloomington, IN 47405.
 6. Niels Bohr Institute, Copenhagen, Denmark.
 7. Los Alamos National Laboratory, Los Alamos, NM 87545.

THE $^{52,54}\text{Cr}(p,n)^{52,54}\text{Mn}$ AND $^{57,58}\text{Fe}(p,n)^{57,58}\text{Co}$
REACTIONS AT $E_p = 120 \text{ MeV}^1$

D. Wang ²	C. Gaarde ⁴
J. Rapaport ²	C. D. Goodman ⁵
D. J. Horen	E. Sugarbaker ⁶
B. A. Brown ³	T. M. Taddeucci ⁷

Differential cross sections for the (p,n) reaction on $^{52,54}\text{Cr}$ and $^{57,58}\text{Fe}$ have been measured for angles up to $\theta_L = 10.5^\circ$ and 14.6° , respectively, using 120-MeV protons. The observed angular distributions are used to evaluate the location and strength of Gamow-Teller resonances. A shell-model calculation of this strength distribution is presented and compared with the experimental results. The M1 strength for ^{52}Cr is also calculated and compared with available results from (e,e') and (p,p') experiments. A comparison is made with other $1f_{7/2}$ nuclei.

1. Abstract of paper to be submitted to Nuclear Physics.
2. Ohio University, Athens, OH 45701.
3. Michigan State University, East Lansing, MI 48824.
4. Niels Bohr Institute, Copenhagen, Denmark.
5. Indiana University, Bloomington, IN 47405.
6. Ohio State University, Columbus, OH 43215.
7. Los Alamos National Laboratory, Los Alamos, NM 87545.

NUCLEAR STRUCTURE STUDIES
VIA TRANSFER AND CAPTURE REACTIONS

SINGLE-NUCLEON TRANSFER REACTIONS INDUCED
BY 376-MeV ^{170}O ON $^{208}\text{Pb}^1$

M. A. G. Fernandes ²	D. J. Horen
F. E. Bertrand	E. E. Gross
R. L. Auble	J. L. Blankenship ⁴
R. O. Sayer ³	D. Shapira
B. L. Burks	M. Beckerman ⁵

The one-nucleon $^{208}\text{Pb}(^{170}\text{O},^{160})$ and $^{208}\text{Pb}(^{170}\text{O},^{16}\text{F})$ transfer reactions have been investigated at $E_{\text{lab}}(^{170}\text{O}) = 376 \text{ MeV}$. The data were analyzed in terms of the distorted-wave Born approximation. The DWBA predictions reproduce fairly well the bell shape of the various angular distributions and the relative inten-

sities of the various single-particle and single-hole transitions.

1. Abstract of published paper: Phys. Rev. C 36, 108 (1987).
2. University of Sao Paulo, Sao Paulo, Brazil.
3. Computing and Telecommunications Division, ORNL.
4. Instrumentations and Controls Division, ORNL.
5. Engineering Physics and Mathematics Division, ORNL.

QUASI-ELASTIC INTERACTIONS BETWEEN HEAVY IONS
AT SUBBARRIER ENERGIES

H. J. Kim	J. Gomez del Campo
P. H. Stelson	D. Shapira
	M. Hindi ¹

This investigation was undertaken to study quasi-elastic reactions between massive ($A > 46$) nuclei near and below the interaction barrier, of which very little is known. This study complements our earlier fusion study.² In our study, we adopted the inverse-kinematics technique: quasi-elastic events between ^{90}Zr projectiles and ^{50}Ti targets occurring at large center-of-mass angles were studied by detecting target and targetlike particles ejected forward with the split-pole magnet and its associated heavy-ion detector. The momentum, energy and energy-loss resolutions of the detection system were sufficient for a complete identification of the ejectiles, allowing the study of various reaction channels, e.g., $1n$, $2n$, $1p$, etc.

At the lowest energy (276 MeV), only ^{50}Ti (target ejectile) and ^{49}Ti ($1n$ -transfer product) were observed; however, ejectiles from many additional channels were observed at higher energies. Representative results from our recent (summer, 1987) experiment are shown in Fig. 2.34. Here, the ratios $d\sigma_{qe}/d\sigma_R$ and $P_n = d\sigma_{1n}/d\sigma_{qe}$ are displayed as a function of R ; where $d\sigma_{qe}$, $d\sigma_R$, and $d\sigma_{1n}$ are quasi-elastic (sum of target and all targetlike ejectiles), Rutherford, and $1n$ -transfer cross sections, respectively, and R is the classical distance of closest approach of the colliding nuclear pair in their pure Coulomb field (in the absence

Fig. 2.34. Top: Yield of target and targetlike ejectiles relative to corresponding Rutherford cross section as a function of distance of closest approach,

$$R = \frac{Z_p Z_t e^2}{E} \left(1 + \frac{1}{\sin^2 \theta/2} \right).$$

The normalization of $\sum_i \frac{d\sigma_i}{d\Omega_i}(E, \theta) / \frac{d\sigma_R}{d\Omega}(E, \theta)$ is chosen so that the ratios are unity at larger (>12.7 fm) R . Bottom: Yield of ^{49}Ti relative to all ejectiles as a function of R .

of specifically nuclear fields). Results for four different incident energies are displayed together in this figure. Using the semiclassical approach³ $d\sigma_{qe}/d\Omega = 1 - P_a$, where P_a is the probability of removing incident flux from the quasi-elastic channels by absorption into others (fusion and deep inelastic channels).

P_n , at first, rises monotonically as the colliding pair approach each other closer in a manner (exponential) expected for semiclassical cases (transfer via tunnelling while on Coulomb trajectories). But this trend ceases or gets interrupted at about $R = 12.25$ fm, indicating that the transfer no longer proceeds via the above simple tunnelling for closer approaches. This distance is much larger than conventional estimates of the strong-interaction distance for the pair. The ratio $d\sigma_{qe}/d\Omega$ also begins to depart discernibly from unity (see Fig. 2.34) at or near the same separation, implying that the flux absorption from the quasi-elastic channels into the fusion and other, nonquasi-elastic channels becomes a significant process for closer collisions. Further analyses to uncover how the fusion and transfer channels interact in more detail are in progress.

1. Tennessee Technological University, Cookeville, Tennessee.
2. P. H. Stelson et al., Phys. Div. Prog. Rep., Sept. 30, 1985, ORNL-6233 (April 1986), p. 122.
3. H. Siekmann et al., Z. Phys. A307, 113 (1982); W. von Oertzen et al., Z. Phys. A326, 463 (1987).

DIRECT THERMAL NEUTRON CAPTURE¹

S. Raman S. Kahane²
J E Lynn³

We discuss the direct capture theory pertaining to primary electric dipole (E1) transitions following slow neutron capture. For light nuclides that we have studied (including ^9Be , ^{12}C , ^{13}C , ^{24}Mg , ^{25}Mg , ^{26}Mg , ^{32}S , ^{33}S , ^{34}S , ^{40}Ca , and ^{44}Ca), estimates of direct capture cross sections using optical model potentials with physically realistic parameters are in reasonable agreement with the data. Minor disagreements that exist are consistent with extrapolations to light nuclides of generally accepted formulations of compound nucleus capture. We also discuss the channel capture approximation which is, in general, a good representation of these cross sections in heavier nuclei particularly if the scattering

lengths are not different from the corresponding potential radii. We also draw attention to cases where the use of this formula leads to inaccurate predictions.

1. Abstract of an invited paper presented at the Sixth International Symposium on Capture Gamma-Ray Spectroscopy, Leuven, Belgium (Aug. 31-Sept. 4, 1987).

2. Visitor at ORNL from the Nuclear Research Centre-Negev, Beer-Sheva, Israel.

3. Los Alamos National Laboratory, Los Alamos, NM.

ANALYSIS OF PRIMARY ELECTRIC DIPOLE GAMMA RAYS FROM SLOW-NEUTRON CAPTURE BY Ca ISOTOPES¹

S. Kahane² J. E. Lynn³
S. Raman

We have analyzed the available data on the primary E1 transitions in the thermal-neutron capture by even isotopes of calcium with the aim of determining the relative importance of direct and compound-nucleus mechanisms of capture in these nuclides. In some of these cases, the thermal-neutron scattering length, as well as the spectroscopic factors of the final states, is known, and an absolute estimate of the direct capture cross sections can be made. In these cases (⁴⁰Ca, ⁴⁴Ca), the estimates made from a specialized optical model (which reproduces the scattering length precisely) and a global optical model with a valency contribution from a local level are in agreement and are also generally close in absolute value to the experimental cross sections. The detailed deviations can be accounted for as a compound-nucleus contribution to the transitions, which fluctuates, but has an overall magnitude in agreement with Cameron's semiempirical relationship for this mechanism. In both nuclides the compound-nucleus contribution to the capture can plausibly be attributed to a bound local level. For ⁴⁰Ca there is some indirect evidence for the value of the thermal-neutron scattering length, and the use of this value in the calculations of direct capture leads to agreement with the data. There is no evidence for an

important compound-nucleus contribution in this magic number nucleus. In ⁴²Ca and ⁴⁶Ca the thermal-neutron scattering length can be adjusted to "best fit" the calculation of direct capture from the optical model to the experimental data. After this adjustment the detailed agreement between theory and the data is very good, indicating the major predominance of the direct mechanism in capture at thermal-neutron energies by these nuclides.

1. Abstract of published paper: Phys. Rev. C 36, 533 (1987).

2. Nuclear Research Centre, Negev, Beer-Sheva, Israel.

3. Los Alamos National Laboratory, Los Alamos, NM.

NUCLEAR STRUCTURE OF ²⁰⁸Pb FROM ²⁰⁷Pb + n RESONANCES¹

R. Köhler² L. Mewissen³
J. A. Wartena² F. Poortmans³
H. Weigmann² J. P. Theobald⁴
S. Raman

Resonance structure in the ²⁰⁷Pb + n system has been investigated by measuring the neutron total cross section with high energy resolution and the partial radiative cross sections for transitions to the ground-state and the first-excited state in ²⁰⁸Pb. A detailed analysis of resonance parameters was carried out up to a neutron energy of 700 keV. The nuclear level density shows a strong parity dependence. The doorway in the s-wave neutron strength function has been firmly established with an escape width equal to the corresponding widths in the neighboring isotopes. The total magnetic dipole strength detected between the neutron separation energy and 8.0 MeV is $B(M1)_{\uparrow} = 5.8 \mu_N^2$, thus smaller than the lowest theoretical estimate for that region. Above this energy an additional $1 \mu_N^2$ is observed, but more strength may have escaped detection because the sensitivity of the experiment decreases; thus the "missing" strength may be partly hidden at these higher energies. Radiative widths for the E1 decay of resonances to the first-excited state of ²⁰⁸Pb

show a doorway structure which can be related to the properties of known bound states.

1. Abstract of published paper: Phys. Rev. C 35, 1646 (1987).

2. Commission of the European Communities, Joint Research Center, Geel Establishment, Central Bureau for Nuclear Measurements, Geel, Belgium.

3. Studiecentrum voor Kernenergie/Centre d'Etude de l'Energie Nucleaire, Mol, Belgium.

4. Institut für Kernphysik, Technische Hochschule, Darmstadt, Federal Republic of Germany.

POPULATION OF HIGH-SPIN STATES IN THE ACTINIDE REGION BY HEAVY-ION TRANSFER REACTIONS¹

C. Y. Wu ²	W. J. Kernan ³
X. T. Liu ²	E. Vogt ³
S. P. Sorensen ²	T. Czosnyka ³
R. W. Kincaid ²	A. E. Kavka ³
M. W. Guidry ²	M. A. Stoyer ⁴
D. Cline ³	J. O. Rasmussen ⁴
M. L. Halbert	

Population of states with spin as high as 24^+ (26^+) in ^{234}U is observed in the one-nucleon pickup reaction $^{235}\text{U}(^{58}\text{Ni}, ^{59}\text{Ni})^{234}\text{U}$ at $E_{\text{lab}} = 325$ MeV. The total γ -ray energy and multiplicity measured in this reaction channel indicate that transfer is populating mostly "cold" states, without appreciable fission competition. The prospect of studying high-spin states in the actinide region using even heavier projectiles is discussed, and we conclude that discrete states with spin higher than 30 may be accessible by these methods.

1. Abstract of published paper: Phys. Lett. B188, 25 (1987).

2. University of Tennessee, Knoxville, TN 37996-1200.

3. University of Rochester, Rochester, NY 14627.

4. Lawrence Berkeley Laboratory, Berkeley, CA 94720.

OSCILLATING TWO-NEUTRON TRANSFER PROBABILITIES AT LARGE RADIAL SEPARATION IN HEAVY-ION REACTIONS¹

C. Y. Wu ²	B. Kotlinski ⁴
S. P. Sorensen ³	X. T. Liu ²
M. W. Guidry ³	R. W. Kincaid ²
W. J. Kernan ⁴	D. Cline ⁴
T. Czosnyka ⁴	E. Vogt ⁴
A. E. Kavka ⁴	

Several groups have investigated one- and two-nucleon heavy-ion transfer cross sections as a function of radial separation between the ions in the collision.²⁻⁷ At large ion-ion separations the radial behavior of the formfactor is governed by the exponential form of the bound-state wavefunctions and the probability for transfer is expected to be

$$p \sim e^{-\alpha R_{\text{min}}}, \quad (1)$$

where $\alpha = 2 \cdot (2\mu E_B)^{1/2}/\hbar$, E_B is the effective binding energy, μ the reduced mass of the transferred particles, and R_{min} the classical distance of closest approach. If (1) is valid, then one expects that the one- and two-neutron transfer slope parameters α are related by

$$\alpha_{2n} \approx 2\alpha_{1n} \quad (2)$$

for transfer between low-lying states.

For a variety of heavy-ion reactions the data exhibit an exponential dependence on distance of closest approach as given in Eq. (1). The one- and two-neutron transfer slope parameters obey Eq. (2) when both collision partners are spherical,^{1,2} whereas a large departure from the expected behavior is observed for neutron transfer reactions with very heavy ions in which at least one of the collision partners is deformed,^{3,4,6} that is, in these cases, $\alpha_{2n} < \alpha_{1n}$.

This puzzling behavior has been observed for many deformed systems, and we will term it the two-neutron transfer (TNT) slope anomaly. Initial attempts to explain the anomaly invoked large intrinsic excitation energies (≈ 10 MeV) associated with the TNT process. It has been demonstrated⁶ that this explanation of the TNT slope anomaly in terms of intrinsic excitation

was not likely to be correct, and that the slope anomaly exhibits a sharp dependence on the angular momentum of the state populated in the transfer. In this paper we report on the resolution of this puzzle.

The experiments were carried out by bombarding 540-600 $\mu\text{g}/\text{cm}^2$, self-supporting ^{162}Dy targets with 285- and 345-MeV ^{58}Ni and 637-MeV ^{116}Sn ions in the Spin Spectrometer of the ORNL Holifield Heavy Ion Research Facility.

Figure 2.35 shows the sum-energy spectra of the MaI elements of the Spin Spectrometer gated on the $4^+ \rightarrow 2^+$ transitions in the Ge spectrum for both ^{162}Dy (inelastic channel) for ^{160}Dy (2-neutron pickup reaction channel). Two distinct areas are observed for the two-neutron transfer channel. The discrete states observed in the lower energy region (<1.5 MeV), which resemble those of the inelastic channel, correspond to the population of the ground-state band and the continuous structure in the higher energy region corresponds to the population of two-quasiparticle (2-qp) states.⁷

Also shown in Fig. 2.36a-c are the transfer probabilities vs the distance of closest approach assuming Rutherford trajectories. The

Fig. 2.35. Projected total γ -ray energies for the inelastic channel (top) and two-neutron pickup reaction channel (bottom) for $^{58}\text{Ni}+^{162}\text{Dy}$ at 285 MeV.

two-neutron transfer probability to 2-qp bands falls exponentially with radial distance at large separations in all three cases, and the experimental slope parameters (≈ 2) approach the values (≈ 2.4) expected using 2-neutron separation energies. This is in contrast with the transfer probability to the ground band which exhibits an oscillatory behavior and the envelope of the oscillations appears to fall more slowly with distance than does the 2-qp probability. Also shown in Fig. 2.36a-c are the sums of the 2-qp and ground-band probabilities. A comparison of the total, ground band, and 2-qp curves indicates the source of the apparent slope anomaly observed in earlier inclusive TNT measurements which have failed to resolve the two components.

The cause of the oscillatory behavior shown in Fig. 2.36 is not apparent since the probabilities for the transfer to the ground-band shown are the sum of the populations of states with the spin $> 4^+$. Plotted in Fig. 2.37 is the differential cross section for the 4^+ state obtained by subtracting the yield of $6^+ \rightarrow 4^+$ transition from that of the $4^+ \rightarrow 2^+$ transition after taking into account the absolute detection efficiency and internal conversion. A more pronounced oscillatory structure is seen in the differential cross section for the 4^+ state.

In conclusion, we have shown that the large-distance behavior for two-neutron transfer in the reactions $^{162}\text{Dy}(^{58}\text{Ni}, ^{60}\text{Ni})^{160}\text{Dy}$ and $^{162}\text{Dy}(^{116}\text{Sn}, ^{118}\text{Sn})^{160}\text{Dy}$ exhibits the expected exponential dependence for transfer to the 2-quasiparticle bands, but pronounced oscillations are observed for transfer to the ground band. The superposition of these two disparate behaviors is shown to be responsible for previously reported anomalies in these reactions. The oscillation is found to be more pronounced for population of individual states than for the yields.

1. Summary of paper submitted to Physics Letters B.

2. University of Tennessee, Knoxville, TN 37996.

Fig. 2.36. Radial behavior for two-neutron transfer reactions. Shown for each case are $d\sigma/d\sigma_R$ and the probability for two-neutron transfer to the ground-state band, the 2-q.p. bands, and the sum of the probabilities for the ground and 2-q.p. cases. The probabilities are defined using equation (3), and the distance scale is determined from the angular distributions assuming classical Rutherford trajectories. The cuts between the populations of the ground-state and 2-q.p. bands were varied between 1.1 and 1.4 MeV for the above cases. The dashed and solid lines are best-fit straight lines through the total and 2 q.p. data, respectively. The probabilities are plotted on an arbitrary scale and displaced by the factors shown for clarity.

Fig. 2.37. The differential cross section vs. the scattering angle for the $^{162}\text{Dy}(^{116}\text{Sn}, ^{118}\text{Sn})^{160}\text{Dy}$ 2-neutron pickup reaction, at 637 MeV, leading to the 4^+ state.

3. Adjunct staff member from University of Tennessee, Knoxville, TN.
4. University of Rochester, Rochester, N.Y.
5. H. Siekmann et al., Zeit. Phys. A307, 113 (1982).
6. W. von Oertzen et al., Z. Phys. A313, 189 (1983).
7. G. Himmele et al., Nucl. Phys. A404, 401 (1983).
8. A. O. Macchiavelli et al., Nucl. Phys. A432, 436 (1985).
9. K. Sapotka et al., Phys. Rev. C31, 1297 (1985).
10. S. Juutinen et al., Phys. Lett. B192, 307 (1987).

TWO-NEUTRON PAIRING ENHANCEMENT FACTORS¹

X. T. Liu ²	M. W. Guidry ⁴
C. Y. Wu ²	D. Cline ⁵
X. L. Han ^{2,3}	W. J. Kernan ⁵
R. W. Kincaid ²	E. Vogt ⁵
S. P. Sorensen ⁴	T. Czosnyka ⁵
A. E. Kavka ⁵	

The enhancement of two-nucleon transfer cross sections by factors of approximately 50 over that expected from uncorrelated transfer of two particles is well documented in (t,p) or

(p,t) reactions on superfluid nuclei.⁶ In the collision of two superfluid heavy ions it is expected that the enhancement could be considerably larger due to the strong pairing correlation in both interacting nuclei.⁷ Various experimenters have attempted to study two-particle transfer in the collision of two heavy nuclei,⁸⁻¹² and typically have concluded that the enhancement factors for these collisions are comparable to those for (t,p) or (p,t) reactions. These experiments had low energy resolution and thus there was little information as to which states were being populated in the reaction. In this paper we report on the first measurement of enhancement factors with sufficient resolution to distinguish transfer to the ground-state band from transfer to other bands.

The reactions studied were ^{162}Dy ($^{116}\text{Sn}, ^{118}\text{Sn}$) ^{160}Dy and $^{161}\text{Dy} (^{116}\text{Sn}, ^{117}\text{Sn}) ^{160}\text{Dy}$ at $E_{\text{lab}} = 637$ MeV. Experiments were performed using the Spin Spectrometer of the Holifield Heavy Ion Research Facility. The Spin Spectrometer consisted of 8 Compton-suppressed Ge detectors and 61 NaI elements, and was operated in coincidence with two position-sensitive parallel-plate avalanche counters (PPAC's).

Figure 2.38 shows the projected total energy of the gamma rays from the NaI elements of the Spin Spectrometer for the one- and two-neutron pickup reactions, and for the corresponding inelastic scattering reaction $^{162}\text{Dy} (^{116}\text{Sn}, ^{116}\text{Sn}) ^{162}\text{Dy}$. In each case the relevant channel was selected by gating on the $4^+ \rightarrow 2^+$ transition of the exit-channel Dy ion. These projections of the total gamma-ray energy indicate a reasonable separation of the ground-band transfer from that populating 2-qp bands in the transfer reactions.

Figure 2.39 shows the enhancement factor F as a function of separation distance for transfer to the ground-band and 2-qp bands. Various definitions exist in the literature for the enhancement factor. We have taken the simplest:

$$F = P_{2n}/P_{1n}^2 \quad (1)$$

Fig. 2.38. Summed γ -ray energies for NaI detectors in the inelastic and transfer channels. The separation of ground-band and 2-qp population is indicated by the dashed line.

Fig. 2.39. Two-neutron enhancement factors deduced from Fig. 2.38 using the definition(1).

where the one- and two-neutron probabilities are denoted by P_{1n} and P_{2n} respectively. This definition ignores possible differences in ground-state Q-values and the number of states involved.

At distances smaller than 16 fm the 2 qp-enhancements are typically $\sim 7-8$ but the corresponding ground-band enhancements are $\sim 50-80$, suggesting pairing effects in the transfer to the ground-state band of ^{164}Dy . At distances larger than 16 fm the enhancements increase markedly, to around 500 for the ground-band.

In summary, we have presented the first conclusive evidence that the pairing enhancement of two-particle transfer in the collision of two heavy ions is appreciably larger than the corresponding enhancement in light-ion reactions. The enhancements are found to increase at more forward scattering angles, which would suggest larger enhancements for large ion-ion separations. The dramatic difference between the ground-band and 2-quasiparticle band enhancements calls into question any discussion of pairing effects in nuclei based on heavy-ion reactions which fail to resolve the ground band from other bands, a category which includes all previous attempts to measure the enhancement factors. These results suggest that the collision of two heavy nuclei with structures far from closed shells may be reasonably approximated as the collision of two superfluid pieces of matter if attention is focused on transitions to low-lying states.

TWO-NEUTRON TRANSFER IN Sn+Sn COLLISIONS

X. L. Han ¹	D. Cline ⁴
C. Y. Wu ¹	W. J. Kernan ⁴
X. T. Liu ¹	T. Czosnyka ⁴
R. W. Kincaid ¹	A. E. Kavka ⁴
S. Juutinen ²	M. A. Stoyer ⁵
S. P. Sorensen ³	J. O. Rasmussen ⁵
M. W. Guidry ³	M. L. Halbert
	D. C. Hensley

Pairing enhancement factors in neutron transfer reactions between Sn isotopes have been measured to be 20 - 40 by von Oertzen et al.,⁶ in experiments where there was little information on the states being populated in the reactions. However, theoretical estimates of such enhancement factors for ground-state transitions have been found to be between 100 and 1600 by Broglia et al.⁷ The use of the Spin Spectrometer to identify the population of the ground-state band in deformed nuclei and to measure the neutron pairing enhancement factors by isolating the low-lying discrete states from the quasicontinuum states has been described separately in this progress report. There we found that the total enhancement is small (~ 10) but the enhancement for ground-band population is much larger ($\sim 80-500$). We extended such measurements to reactions with spherical superfluid nuclei in Sn+Sn collisions. The goal of this experiment is to measure pairing effects with a definite identification of the final states being populated.

The reactions studied were $^{117}\text{Sn}(^{112}\text{Sn}, ^{113}\text{Sn})^{116}\text{Sn}$ and $^{118}\text{Sn}(^{112}\text{Sn}, ^{114}\text{Sn})^{116}\text{Sn}$ at $E_{\text{lab}} = 570$ MeV. The Spin Spectrometer, consisting of 17 Compton-suppressed Ge detectors and 52 NaI elements, was operated in coincidence with two position-sensitive parallel-plate avalanche counters (PPAC's) which were used to measure the scattering angles and time-of-flight for beamlike and targetlike ions in kinematic coincidence. The Ge spectra were corrected, on an event-by-event basis, for Doppler shifts using the measured kinematics. The timing of the NaI detectors was sufficient to discriminate between neutrons and γ rays by time-of-flight and a neutron multiplicity was established.

1. Summary of paper submitted to Physics Letters B.
2. University of Tennessee, Knoxville, TN.
3. Joint Institute for Heavy Ion Research, HHIRF, Oak Ridge, TN.
4. Adjunct staff member from University of Tennessee, Knoxville, TN.
5. University of Rochester, Rochester, N.Y.
6. R. Broglia, O. Hansen, and C. Riedel. *Adv. Nucl. Phys.* 6, 287 (1973).
7. R. A. Broglia et al., *Phys. Lett.* 73B, 401 (1978).
8. W. von Oertzen et al., *Z. Phys.* A313, 189 (1983).
9. A. O. Macchiavelli et al., *Nucl. Phys.* A432, 436 (1985).
10. H. Siekmann et al., *Zeit. Phys.* A307, 113 (1982).
11. G. Himmele et al., *Nucl. Phys.* A404, 401 (1983).
12. W. Dunnwaber, H. Morinaga, and D. E. Alburger, *Phys. Lett.* 106B, 47 (1981).

The similar mass for projectile and recoil in these reactions caused difficulty in distinguishing the γ rays emitted by projectiles from those by recoils for some Ge detectors, and only 7 of 17 Ge detectors were actually selected for final analysis. The summed spectrum from those Ge detectors is shown in Fig. 2.40. The

Fig. 2.40. The total γ -ray spectrum (a) gated on the 2Q-band, (b) gated on the G-band.

projected total energy of NaI elements by gating on $2^+ \rightarrow 0^+$ transition belong to the transfer channel is shown in Fig. 2.41. The prescan of the data is finished, and the final analysis is in progress.

Fig. 2.41. Projected total γ -ray energies for the two-neutron pickup reaction channel at 570 MeV.

NUCLEAR STRUCTURE STUDIES VIA COMPOUND NUCLEUS REACTIONS

GAMMA-RAY MEASUREMENTS ON THE HIGH-SPIN STATES OF ^{172}Os

J. C. Wells¹ M. Riley³
A. Virtanen² F. K. McGowan
W. R. Johnson C. Baktash
I. Y. Lee

In 1985, we carried out spectroscopy studies of the nucleus ^{172}Os in an effort to understand an anomaly in the yrast sequence moment of inertia at low spin, first reported by Durell et al.⁴ In a plot of the moment of inertia versus the rotational frequency, one sees a discontinuity at $\hbar\omega = 0.27$ MeV, and this is presumably due to rotation alignment of $i_{13/2}$ neutrons. In addition, our earlier work⁵ confirmed the second discontinuity reported⁴ at $\hbar\omega = 0.24$ MeV. However, cranking model calculations⁵ were unable to provide any insight on the nature of this observation.

To investigate the band structure further, we have repeated the experiment with considerably better statistics. In our earlier work,⁵ we observed weak γ rays which appeared to originate in at least two side bands. It was felt that

1. University of Tennessee, Knoxville, TN.
2. University of Jyväskylä, Finland.
3. Adjunct staff member from the University of Tennessee, Knoxville, TN.
4. University of Rochester, Rochester, NY.
5. Lawrence Berkeley Laboratory, Berkeley, CA.
6. W. von Oertzen, et al., Z. Phys. A313, 189 (1983).
7. P. A. Broglia, et al., Phys. Lett. 73B, 401 (1978).

documenting the properties of these and possibly other side bands in this nucleus may aid in an understanding of the anomalous behavior observed in the yrast sequence.

The reaction employed was the same as before: $^{144}\text{Nd}(^{32}\text{S}, 4n)$ using 162-MeV ^{32}S ions from the HHIRF tandem accelerator. For the measurements, we used our Compton Suppression Spectrometer which consists of 19 Compton-suppressed large-volume Ge detectors. This system was incorporated into the Spin Spectrometer where we were able to collect γ - γ coincidence data while recording the associated total energy and γ -ray multiplicity.

The γ -ray spectra from the 19 Ge detectors were gain-matched, and a $4k \times 4k$ channel coincidence histogram was generated using coincidences between all possible pairs of detectors. The quality of the data is illustrated in Fig. 2.42, which shows the sum of the $2^+ \rightarrow 0^+$ and $4^+ \rightarrow 2^+$ gates. The yrast transitions are identified by initial spin, and the other important transitions by energy in keV. Although the analysis is still in progress, it appears that most of these transitions can be grouped by

coincidence relationships into the yrast sequence and three side bands.

1. Adjunct staff member from Tennessee Technological University, Cookeville, TN.
2. On leave from University of Jyväskylä, Finland.
3. Partial support provided by JIHIR and the University of Tennessee.
4. J. L. Durell et al., Phys. Lett. 155B, 367 (1982).
5. J. C. Wells et al., Phys. Rev. C 36, 431 (1987).

SPIN AND EXCITATION ENERGY DEPENDENCE OF CONTINUUM GAMMA-RAY CORRELATIONS

I. Y. Lee	D. C. Hensley
C. Baktash	N. R. Johnson
J. R. Beene	F. K. McGowan
M. L. Halbert	D. G. Sarantites ¹

Recent studies of the gamma-gamma energy correlations of the continuum gamma rays have generated better understanding of the properties of the collective E2 gamma rays which produce the well-known hump in the continuum. From experiments performed with the Spin Spectrometer, we have determined that in ^{172}Os the amount of the correlation is about 20% with a

Fig. 2.42. Coincidence spectrum of ^{172}Os obtained from the sum of the $2^+ \rightarrow 0^+$ and $4^+ \rightarrow 2^+$ gates. Yrast sequence transitions are identified by initial spin, and other important transitions by energy in keV.

spreading width of a few hundred keV. These correlated gamma rays originate from a region about 0.5 MeV about the yrast line as determined from a comparison of the spin and excitation energy dependence of the correlation intensity with statistical model calculations. However, the low resolution of the NaI elements of the Spin Spectrometer prevented our studying the detailed shape of the correlation and its dependence on spin and excitation energy. Previous high-resolution studies have been carried out, but without spin and excitation energy selection of the entry states.

We have performed a high resolution gamma-gamma energy correlation study using 18 anti-Compton shielded Ge detectors in the Spin Spectrometer along with 52 NaI elements. The fusion reaction $^{130}\text{Te} + ^{40}\text{Ca}$ was produced with a 200-MeV ^{40}Ca beam from the MHIRF tandem accelerator. A total of 5×10^6 two- and higher-fold Ge coincidence events, along with the associated information from the 52 NaI detectors of the Spin Spectrometer were recorded. The data were first corrected for the variation in gains of the detectors and then the total pulse height of the gamma ray (H) and the coincidence fold (k) for each event were calculated. From these data, we can extract the spin and excitation energy dependence of the correlation properties of the continuum gamma rays.

Coincidence spectra of Ge detectors were generated by gating on gamma rays in an energy range from 0.7 to 1.1 MeV in 3 keV steps and by using six different gates on H and k. To improve the statistics, several gated spectra were shifted to align the gating gamma ray and then these were added. Singles spectra, gated by (H,k), were also generated and they were shifted and added by using the same procedure. Figure 2.43 shows single and coincidence spectra gated with (H,k) region.

A comparison of the gated and singles spectra shows many interesting features. First of all, in the gated spectrum a dip is clearly seen centered at the energy of the gating gamma ray. Secondly, two well-defined peaks are observed at the edge of the dip. Finally, beyond the

Fig. 2.43. Singles and gated Ge spectra with entry-state selection $13 < k < 16$ and $0 < H < 5$ MeV. The gating gamma ray has an energy of 0.7 MeV. The gated spectra show a dip centered at 0.7 MeV and peaks on both sides of this dip.

peaks, additional dips and peaks can be seen, but with much reduced intensity. The two strong peaks are separated by 0.12 MeV, and from this separation we can determine the value of the dynamic moment of inertia $\mathcal{J}^{(2)}/\hbar^2 = 67 \text{ MeV}^{-1}$.

The areas of the peaks and the dip (Fig. 2.43), defined as the area in the gated spectra above and below the normalized singles spectra, respectively, are shown in Table 2.7 for several (H,k) gates. The widths of the peaks are also shown in Table 2.7. The average width of the peak is about 12 keV which is considerably larger than the energy resolution of the detector (3 keV). This increased width represents the spreading width of these continuum gamma rays. The area of the dip is larger than the area of the peaks. From our simulation calculations it was found that as the spreading width increases, the evidence for the peak vanishes long before that for the dip. This may indicate that there are contributions to the dip from correlated gamma rays with a spreading width much larger than 12 keV. From the shape of the dip one may be able to determine the associated spreading width. The fact that the areas of the

Table 2.7. Properties of peaks and valleys in the gated spectra from $^{130}\text{Te} + ^{40}\text{Ca}$ reaction

k	H ^a (MeV)	Lower Peak		Higher Peak		Valley
		relative area	width (keV)	relative area	width (keV)	relative area
13-16	0-5	3.5	10	2.2	13	15.2
	5-10	3.5	10	2.3	14	17.1
17-25	0-5	2.8	13	1.5	12	12.4
	5-10	3.0	10	1.5	14	13.5

dips and peaks seem to be independent of the (H,k) selection probably indicates that the correlated gamma rays are emitted from a region close to the yrast line.

1. Washington University, St. Louis, MO 63130.

TRANSITION QUADRUPOLE MOMENTS OF HIGH-SPIN STATES IN ^{170}W

F. K. McGowan
N. R. Johnson
M. N. Rao¹
I. Y. Lee

C. Baktash
J. C. Wells²
M. Kortelahti³
V. P. Janzen⁴

Transition quadrupole moments from lifetime measurements of states with spins up to about 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. The reduction of collectivity at high spins has been observed in several $N = 90$ nuclei.⁵⁻⁷ This effect is understood qualitatively in terms of the cranked-shell-model theory⁸ as a result of rotational alignment of two $i_{13/2}$ neutrons. The reduction of the 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 nucleus changes from a prolate shape at low spin or rotational frequency to a triaxial shape that is oriented so as to reduce the collectivity of the rotation at high spin by the deformation driving forces of the aligned neutrons.

The calculated systematics⁹ 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 different for the Fermi level near the middle of the $i_{13/2}$ shell. Bengtsson and Xing in Ref. 10 substantiated these general predictions by a full cranked-shell-model calculation for $^{172}\text{W}_{98}$ using a deformed Woods-Saxon potential. Measurements¹⁰ of lifetimes in ^{172}W by the Doppler-shift recoil-distance method showed, however, 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. A three-band mixing calculation¹⁰ with band interaction matrix elements and some other parameters fitted empirically to the energy levels of ^{172}W gave rise to a reduction of the transition quadrupole moments, Q_t , at high spin. Thus, the participation of $h_{9/2}$ protons in the upbend for ^{172}W explains the reduction of the measured Q_t values at high spin.

A systematic look at the aligned angular momentum plots for the tungsten nuclei revealed a curious pattern. The tungsten isotopes below mass 172 showed alignment gains¹¹ $\Delta = 10\hbar$ which confirms that the crossings originate from the lowest $i_{13/2}$ neutron orbitals only. For mass 172 and higher, the evidence points to the participation of a third band in the first crossings of the yrast levels.¹⁰ Thus, it appeared that a study of the nucleus ^{170}W with $N = 96$ may

be an appropriate case to test the cranked-shell-model predictions for the Fermi surface at the middle of the $i_{13/2}$ neutron shell.

Lifetimes of high-spin states in $^{169,170,171}\text{W}$ have been measured by the Doppler-shift recoil-distance method using the reaction $^{122}\text{Sn}(52\text{C}^{12}, \text{xn})^{170}\text{W}$ at a bombarding energy of 230 MeV. At this incident energy the dominant reaction channel was $4n$ and the average value of the recoil velocity, determined from positions of shifted and unshifted γ -ray peaks, was $7.67 \pm 0.04 \mu\text{m/ps}$ which corresponds to $(0.02559 \pm 0.00014)c$.

The recoil-distance data were collected in the γ - γ coincidence mode rather than the customary singles mode in order to reduce the complexities of the γ -ray spectra and to avoid some of the problems associated with side feeding to excited states. Data were recorded with a bismuth germanate-Compton suppressed Ge detector at 0° with respect to the beam under the coincidence requirement that at least one of an array of six Ge detectors positioned at 90° to the beam be triggered. The target-to-detector separations were 9.7 and 5.9 cm for the 0° and 90° detectors, respectively. This close geometry provides a high-efficiency coincidence system. Coincidence spectra were obtained for 20 target-stopper separations ranging from 0 to 7000 μm . Figure 2.44 shows the unshifted and shifted peaks from a portion of the total-projected coincidence spectra of ^{170}W at six target-stopper separations. These spectra are of good statistical quality and reveal a favorable peak-to-background ratio in the 0° detector as a result of using the Compton-suppression shield and of collecting data in the coincidence mode.

So far, only the total projected data and the sum gated below 2^+ to 10^+ data for the yrast sequence of ^{170}W have been analyzed. In Fig. 2.45 the transition quadrupole moments, Q_t , deduced from the lifetime results are presented as a function of spin. Aside from the 12^+ , 14^+ , and 18^+ states, the Q_t values for all other states are near a value of 6.3 eb. The low values for the 12^+ and 14^+ states can probably be understood in terms of perturbations of $B(E2)$

Fig. 2.44 Unshifted and shifted γ -ray peaks from a portion of the total-projected coincidence spectra of ^{170}W at six target-stopper separations.

Fig. 2.45 Transition quadrupole moments, Q_t , as a function spin for the yrast sequence of ^{170}W .

values for states in the vicinity of the band crossing. It is quite possible that when we analyze the gated above data in ^{170}W , there may

be some minor modifications to Fig. 2.45. However, at this time, it seems reasonable to say that the cranked-shell-model-predictions for a nucleus with the Fermi surface near the middle of the $i_{13/2}$ neutron shell are borne out by these results from ^{170}W .

1. On leave from University of São Paulo, São Paulo, Brazil.
2. Adjunct staff member from Tennessee Technological University, Cookeville, TN.
3. Louisiana State University, Baton Rouge, LA.
4. University of Tennessee, Knoxville, TN 37996-1200.
5. H. Emling et al., Nucl. Phys. A419, 187 (1984).
6. M. P. Fewell et al., Phys. Rev. C 31, 1057 (1985).
7. M. Oshima et al., Phys. Rev. C 33, 1988 (1986).
8. R. Bengtsson et al., Nucl. Phys. A405, 221 (1983).
9. S. Frauendorf and F. R. May, Phys. Lett. 125B, 245 (1983).
10. M. N. Rao, et al., Phys. Rev. Lett. 57, 667 (1986).
11. J. Recht et al., Nucl. Phys. A440, 366 (1985).

SHAPE CHANGES, BAND TERMINATIONS AND TRANSITION RATES IN ^{157}Tm

M. A. Riley ¹	M. R. Johnson
C. Baktash	I. Y. Lee
Y. A. Ellis-Akovali	F. K. McGowan
M. L. Halbert	V. P. Janzen ²
D. C. Hensley	L. Riedinger ²
L. Chaturvedi ³	

The use of large arrays of Compton-suppressed germanium gamma-ray spectrometers has made it possible to study states of very high angular momentum ($I > 40 \hbar$). Such studies reveal much information about the physical structure of nuclei, in particular the mapping of the nuclear shape with increasing angular momentum and the nature of the particle alignments that occur. The most prolific region for such spectroscopy has been in the transitional rare-earth region near $N = 88-90$.

The $N = 88$ isotones are weakly prolate in their ground states and are expected to be soft with respect to shape changes with increasing spin. Calculations predict a transition along

the yrast line from prolate collective rotation to oblate noncollective rotation (or band termination) near spin 40. Experimental evidence for such a shape transition has been made for the $N = 88$ even-even nuclei ^{158}Yb , ^{156}Er and ^{154}Dy between spins $I = 30-40\hbar$. However, as yet this shape change has not been observed in an odd proton $N = 88$ nucleus.

It is important to study the odd- Z , $N = 88$ nuclei since we expect a systematic behavior with respect to proton number and also because these nuclei have a special characteristic not found in the even-even cases. The yrast sequence in the odd-proton nuclei is composed of two strongly coupled bands based on the two signatures of the $h_{11/2}$ proton shell. With such bands it is possible to obtain from $\Delta I = 1$ to $\Delta I = 2$ branching ratios, electromagnetic $B(M1)/B(E2)$ transition rates which give sensitive information on the alignment processes taking place and their effect on the nuclear shape. At high spins it is expected when approaching a band termination that the $B(E2)$ transition strength will decrease and that in strongly coupled bands the $M1$ strength could dominate. This information will be most valuable since details of transition rates close to a band termination are exceedingly scarce.

High spin states in the $Z = 69$ $N = 88$ ^{157}Tm were populated via the $^{110}\text{Pd}(^{51}\text{V}, 4n)$ fusion evaporation reaction at a beam energy of 220 MeV. Gamma-rays were detected in coincidence by using our Compton-Suppression Spectrometer System. The 19 suppressed Ge detectors were inserted into a corresponding number of NaI positions in the Spin Spectrometers for these measurements. Approximately 165 million suppressed gamma-gamma coincidence events were recorded. The analysis of these data is in progress. The high quality of these data may be observed in Fig. 2.46 which shows gamma-rays in coincidence with the main low-energy yrast gamma-ray, 394 keV, in ^{157}Tm . Previously, only 6 gamma rays, indicated by an asterisk, had been assigned⁷ to this nucleus. Clearly, from this

Fig. 2.46. Gamma-rays in coincidence with the main low-energy yrast gamma-ray, 34 keV, in ^{157}Tm . Previously observed transition. In this nucleus are indicated by an asterisk. (Ref. 7)

figure it can be seen that the present data contain a wealth of new information about ^{157}Tm .

1. Partial support provided by JIHR and the University of Tennessee.
2. University of Tennessee, Knoxville, TN 37996.
3. Vanderbilt University, Nashville, TN 37235.
4. C. Baktash et al., Phys. Rev. Lett. 54, 978 (1985).
5. F. Stephens et al., Phys. Rev. Lett. 54, 2584 (1985).
6. H. W. Cramer-Gordon et al., Nucl. Phys. A465, 506 (1987).
7. R. Kossakowski et al., Phys. Rev. C32, 1612 (1985).

SEARCH FOR SUPERDEFORMED SHAPES IN ^{144}Gd

Y. Schutz ²	R. Ribas ⁴
C. Baktash	J. C. Lisle ⁵
I. Y. Lee	L. Adler ⁶
M. L. Halbert	K. Honkanen ⁶
D. C. Hensley	D. G. Sarantites ⁶
N. R. Johnson	A. J. Larabee ⁷
M. Oshima ³	J. X. Saladin ⁸

Two-dimensional γ - γ transition energy correlation measurements were made in ^{144}Gd using Compton-suppressed Ge detectors in the Spin Spectrometer. A ridge-valley structure was observed and shown to originate from discrete, fast transitions. The deduced moment of inertia is less than that of the superdeformed collec-

tive bands that have been predicted by Strutinsky cranking calculations.

1. Abstract of published paper: Phys. Rev. C 35, 348 (1987).
2. Grand Accelérateur National d'Ions Lourds, Caen France.
3. Japan Atomic Energy Research Institute, Tokai, Japan.
4. Universidade De Sao Paulo, Sao Paulo, Brazil.
5. Schuster Laboratory, University of Manchester, Manchester M13 9PL, England.
6. Washington University, St. Louis, MO 63130.
7. University of Tennessee, Knoxville, TN 37916.
8. University of Pittsburgh, Pittsburgh, PA 15260.

HIGH-SPIN SPECTROSCOPY IN $^{179,181}\text{Ir}$ AND ^{181}Au

V. P. Janzen ¹	L. Zhou ¹
C. R. Bingham ²	C. Baktash
M. P. Carpenter ¹	M. L. Halbert
K. Hart ³	N. R. Johnson
H. Q. Jin ¹	I. Y. Lee
L. L. Riedinger ²	F. K. McGowan
M. A. Riley ⁴	

Experiments have been performed in the past year on the high-spin states in $^{179,181}\text{Ir}$ and ^{181}Au , prolate-deformed nuclei in the transitional region approaching the spherical nuclei below Pb. The Spin Spectrometer loaded with 19 Compton-suppressed Ge counters was used for these measurements. The purpose of this program has been to investigate the low-frequency alignment processes in the bands built on high-j quasiproton states. While the first backbend throughout the rare-earth deformed region is based upon the rotational alignment of $i_{13/2}$ neutrons, our recent measurements on $N = 106$ isotones ^{185}Au , ^{184}Pt , and ^{183}Ir (Refs. 5, 6, 7, respectively) have demonstrated that there exist two very low-frequency band crossings, one due to the alignment of $\pi h_{9/2}$ at $\hbar\omega = 0.23$ MeV and the other due to $\nu i_{13/2}$ at $\hbar\omega = 0.29$ MeV. It is extraordinary to observe the $\pi h_{9/2}$ band crossing at such low frequency, and self-consistent calculations of the Total Routhian Surfaces (TRS) are under way to explain it. In this transitional region of soft nuclear shapes, the deformation parameters are dependent upon the

particular orbitals occupied by the valence nucleons, and the measurement of the crossing frequencies can be one measure of the success of these calculations in mapping the broad trend of the deformations.

These particular measurements on $^{179,181}\text{Ir}$ were spurred by our interesting results on ^{183}Ir .⁶ In this odd-Z nucleus, rotational bands were assigned to the $1/2[541]$ and $5/2[402]$ Nilsson states, which are built on primarily the $h_{9/2}$ and $d_{5/2}$ proton levels, respectively. The former exhibits one strong band crossing, where a total of $6.5 \hbar$ of aligned angular momentum is gained rapidly at $\hbar\omega = 0.28 \text{ MeV}$. The $d_{5/2}$ band, however, shows two band crossings, at $\hbar\omega = 0.21$ and 0.30 MeV , with a total alignment gain of at least $10 \hbar$. The presence of two crossings in the latter and one in the former is compatible with both the $\pi h_{9/2}$ and $\nu i_{13/2}$ alignments occurring in the $d_{5/2}$ band, with only the $\nu i_{13/2}$ crossing in the $\pi h_{9/2}$ band.

The measurements on the lighter Ir nuclei were performed to learn if this anomalously low-frequency $\pi h_{9/2}$ crossing persists for $N = 102$ and 104 nuclei. High-spin states had been previously observed by Kaczarowski et al.⁸ in ^{181}Ir . In our experiment, excitation-function measurements were first performed to find whether and at which energy a $(^{27}\text{Al}, 4n)$ or $(^{35}\text{Cl}, 4n)$ reaction would be best for producing ^{181}Ir . The latter seemed to result in no higher peak gamma-ray fold compared to the former (likely due to fission), and so our main experiment was performed with the $^{158}\text{Gd}(^{27}\text{Al}, 4n)^{181}\text{Ir}$ reaction at a beam energy of 134 MeV , using a lead-backed target. A preliminary analysis of the data indicate that $1/2[541]$ band can be extended from the previously known $I = 37/2$ up to at least the $53/2$ level, while the $9/2[514]$ structure can be extended from $I = 27/2$ up to $43/2$. The results for these two bands are shown in the alignment diagram of Fig. 2.47. Whereas the $\pi h_{9/2}$ band exhibits one crossing at $\hbar\omega = 0.3 \text{ MeV}$ (presumably the $\nu i_{13/2}$ backbend), the $\pi h_{11/2}$ structure seems to show two crossings. If this is true, then it would be evidence of a

ORNL-DWG 87-18957

Fig. 2.47. Plot of aligned angular momentum (i) versus rotational frequency for the $1/2[541]$ band (triangles) and the $9/2[514]$ band in ^{181}Ir . The rotational reference was subtracted as indicated.

still very low-frequency $\pi h_{9/2}$ crossing, below $\hbar\omega = 0.26 \text{ MeV}$.

Another measurement was performed by our group to establish for the first time, high-spin states in $N = 102$ nuclei ^{179}Ir and ^{181}Au . Due to the absence of any previously assigned medium to high spin states in either nucleus, excitation function measurements were performed to carefully follow the formation of these two products by a $(^{27}\text{Al}, 4n)$ reaction in the former case and a $(^{35}\text{Cl}, 4n)$ reaction in the latter. A long measurement was performed on the $^{156}\text{Gd}(^{27}\text{Al}, 4n)^{179}\text{Ir}$ reaction at 134 MeV , and it is felt that at least a band built on the $1/2[541]$ orbital has been established. A shorter measurement was performed on the $^{150}\text{Sm}(^{35}\text{Cl}, 4n)^{181}\text{Au}$ reaction, at beam energies of 160 and 172 MeV . This has led to a preliminary placement of both the $1/2[541]$ and $1/2[660]$ bands. The $13/2$ to $9/2$ transition in the former band apparently has an energy of 228.9 keV in ^{181}Au , compared to values of 219 , 212 , and 233 keV in the $A = 183$, 185 , 187 isotopes of Au , respectively. This trend is reasonable, as the deformation of $N = 102$ nuclei is calculated to be slightly less than that of the $N = 104$ and

106 isotopes, according to our TRS calculations. These measurements give us the first possibility to learn about high-spin effects in the $N = 102$ nuclei in this region. Detailed analysis of these results is continuing.

1. University of Tennessee, Knoxville, TN.
2. Adjunct staff member from University of Tennessee, Knoxville, TN.
3. Summer student from Transylvania College at the University of Tennessee, Knoxville, TN.
4. Partial support provided by JINR and the University of Tennessee.
5. A. J. Larabee et al., *Physics Lett.* 169B, 21 (1986).
6. M. P. Carpenter et al., submitted to *Phys. Rev. C*.
7. V. P. Janzen et al., private communication.
8. R. Kaczarowski, E. G. Funk, J. W. Mihelich, and U. Garg, *University of Notre Dame Biennial Rep.*, 1981 - 1983, p. 91.

NUCLEAR STRUCTURE STUDIES VIA RADIOACTIVE DECAY

IDENTIFICATION OF ^{182}Pb IN ^{40}Ca IRRADIATIONS OF ^{147}Sm ¹

K. S. Toth F. Blonnigen²
D. M. Moltz² F. T. Avignone, III³

The α decay of ^{182}Pb was identified in bombardments of ^{147}Sm with ^{40}Ca ions. Its α -decay energy and half-life were determined to be 6.919 ± 0.015 MeV and 55^{+40}_{-35} ms, respectively.

Figure 2.48 shows portions of the spectra accumulated at 194 (Fig. 2.48a) and 222 MeV (Fig. 2.48b). The two energies were selected on the basis of compound-nuclear evaporation calculations⁴ to maximize the production yields of ^{184}Pb and ^{182}Pb , respectively. One sees in Fig. 2.48a that the particle spectrum, as had been expected, is dominated by the single α group known⁵ to belong to ^{184}Pb . Peaks that have been assigned⁵ to the $(^{40}\text{Ca}, 2n)$ and $(^{40}\text{Ca}, 4n)$ products, i.e., ^{185}Pb and ^{183}Pb , are also seen in Fig. 2.48a; in addition, α groups of isotopes with $Z < 82$ are present. The reader will note that the spectrum measured at 222 MeV is strikingly different in appearance. Here only a vestige of the ^{184}Pb peak remains while the main ^{183}Pb group (6.718 MeV), clearly visible in Fig. 2.48a, is greatly reduced in intensity [the

incident energy is above the maximum of the $(^{40}\text{Ca}, 4n)$ excitation function]. In Fig. 2.48b it is isotopes with $Z < 80$ that are predominant. At this higher incident energy, reaction channels involving the evaporation of two or more protons and/or α particles are obviously much more probable than the $(^{40}\text{Ca}, xn)$ and $(^{40}\text{Ca}, pxn)$ channels. The peak at 6.919 ± 0.015 MeV, above those of ^{184}Pb and ^{183}Pb , is present in Fig. 2.48b but not in Fig. 2.48a. Based on excitation-function and cross-bombardment ($^{39}\text{K} + ^{147}\text{Sm}$) data and on decay-energy systematics, we assign the peak to the α decay of ^{182}Pb .

The mass excess of ^{178}Hg is listed in Ref. 6 as (-16323 ± 19) keV. With this value and our measurement of the ^{182}Pb α -decay energy we deduce a mass excess of (-6823 ± 25) keV for ^{182}Pb . Also, the previously not available half-life of ^{183}Pb was determined to be 300 ± 80 ms.

1. Summary of published paper: *Phys. Rev. C* 35, 233 (1987).
2. Lawrence Berkeley Laboratory, Berkeley, CA 94720.
3. University of South Carolina, Columbia, SC 29208.
4. M. Blann and F. Plasil, *ALICE: A Nuclear Evaporation Code*, U.S. Atomic Energy Commission Report COO-3594-10 (1973); also W. G. Minn, H. H. Gutbrod, and M. Blann, *Nucl. Phys.* A188, 423 (1972).
5. U. J. Schrewe, et al., *Phys. Lett.* 91B, 46 (1980).
6. A. H. Wapstra and G. Audi, *Nucl. Phys.* A432, 1 (1985).

OBSERVATION OF ^{149}Tm DECAY TO ^{149}Er LEVELS AND β -DELAYED PROTON EMISSION¹

K. S. Toth P. A. Wilmarth²
J. Gilat² K. Vierinen²
J. M. Nitschke² F. T. Avignone, III³

With the use of the OASIS on-line isotope separator,⁴ ^{149}Tm ($T_{1/2} = 0.9 \pm 0.2$ s) was identified in ^{58}Ni bombardments of ^{94}Mo . Seven γ rays were observed to follow the isotope's (β^+ + electron capture) decay, including the 111.3-keV transition known from $^{149}\text{Er}^m$ isomeric decay to be the $d_{3/2}$ (111.3 keV) $\rightarrow$ $s_{1/2}$ (0.0 keV) γ ray in ^{149}Er . In addition to the previously known levels at 111.3 ($d_{3/2}$) and 741.5 ($h_{11/2}$) keV in ^{149}Er , our data establish

Fig. 2.48 Alpha-decay energies for isotopes of elements ranging from Hf ($Z = 72$) to Pb ($Z = 82$) plotted as a function of neutron number. Points representing nuclides with even Z are connected by full lines, while dashed lines connect points that indicate nuclides with odd Z .

three other excited states at 907.4 ($d_{5/2}$), 1066.2 ($f_{7/2}$), and 1492.9 ($9/2^-$, $11/2^-$) keV.

Figure 2.49 shows systematics of levels below 1.5 MeV in the three known $h = 81$ even- Z isotones with $Z > 64$, i.e., ^{145}Gd , ^{147}Dy , and

^{149}Er . One sees the smooth trends with proton number of the $s_{1/2}$, $d_{3/2}$, $h_{11/2}$, $d_{5/2}$, $f_{7/2}$, and $g_{7/2}$ neutron hole states. Note that, due to a low production cross section for ^{149}Tm (calculated⁵ to be 1.5 mb), we were unable to

Fig. 2.49 Systematics of neutron-hole states in the $N = 81$ nuclei ^{145}Gd , ^{147}Dy , and ^{149}Er .

observe γ rays deexciting the $g_{7/2}$ state in ^{149}Er .

Coincidences observed between Er K X rays and protons in the $A = 149$ mass chain show that ^{149}Tm is a β -delayed proton precursor. By using the total ^{149}Tm β decay intensity derived from our data, we estimate the β -delayed-proton branch of ^{149}Tm to be about 2×10^{-3} with an uncertainty factor of two.

1. Summary of published paper: Phys. Rev. C 36, 826 (1987).
2. Lawrence Berkeley Laboratory, Berkeley, CA 94720.
3. University of South Carolina, Columbia, SC 29208.
4. J. M. Nitschke, Nucl. Instrum. Methods Phys. Res. 206, 341 (1983).

S. W. G. Winn, H. H. Gutbrod, and M. Blann, Nucl. Phys. A188, 423 (1972); also, M. Blann and J. Bisplinghoff, Code ALICE/Livermore 1982, US DOE Report UCID-19614 (1982).

MASSSES OF ^{77}Kr AND ^{75}Kr

D. M. Moltz² C. A. Gagliardi³
 A. C. Betker³ R. E. Tribble³
 J. P. Sullivan³ K. S. Toth
 R. H. Burch³ F. T. Avignone, III⁴

As part of our program (see Refs. 5 and 6) of obtaining accurate masses of neutron deficient nuclei located between the $1f_{7/2}$ and $1g_{9/2}$ shells we measured the masses of ^{77}Kr and ^{75}Kr . This was done by determining the Q -values of the $^{80}\text{Kr}(^3\text{He}, ^6\text{He})^{77}\text{Kr}$, $^{78}\text{Kr}(d,t)^{77}\text{Kr}$, and $^{78}\text{Kr}(^3\text{He}, ^6\text{He})^{75}\text{Kr}$ reactions. We found that the ^{77}Kr and ^{75}Kr mass excesses are $-70.160(10)$ and $-64.231(16)$ MeV, respectively. These new results are summarized in Table 2.8 where they are compared with values in the literature.^{7,8}

1. Summary of published paper: Phys. Rev. C 35, 1275 (1987).
2. Lawrence Berkeley Laboratory, Berkeley, CA 94720.
3. Texas A&M University, College Station, TX 77843.
4. University of South Carolina, Columbia, SC 29208.
5. D. K. Moltz, K. S. Toth, F. T. Avignone, III, H. Noma, B. G. Ritchie, and B. D. Kern, Phys. Lett. 113B, 16 (1982).

Table 2.8 Summary of the ^{77}Kr and mass ^{75}Kr measurements (All values are in MeV.)

	^{77}Kr	^{75}Kr
Measured Q -value:		
$(^3\text{He}, ^6\text{He})$ reaction	-10.398(24)	-12.581(14)
(d,t) reaction	- 5.804(7)	
Mass Excess	-70.160(10)	-64.231(16)
Literature	-70.227(29) ^a	-64.16 ^b

^aRef. 7.

^bRef. 8. This value is deduced from systematics.

6. D. M. Moltz, K. S. Toth, R. E. Tribble, R. E. Neese, and J. P. Sullivan, Phys. Rev. C 26, 1914 (1982).

7. A. H. Wapstra and G. Audi, Nucl. Phys. A432, 1 (1985).

8. A. H. Wapstra and K. Bos, At. Data Nucl. Data Tables 19, 177 (1977).

THE α -DECAY REDUCED WIDTH OF ^{194}Pb AND LOW-SPIN LEVELS IN ^{194}Tl POPULATED IN ^{194}Pb β DECAY¹

Y. A. Ellis-Akovi¹ C. R. Bingham³
K. S. Toth I. C. Girit⁴
H. K. Carter² M. O. Kortelahti⁵

The α decay of ^{194}Pb [$E_\alpha = 4.64 \pm 0.02$ MeV, α branch = $(7.3 \pm 2.9) \times 10^{-6}\%$] was identified for the first time and a comprehensive decay scheme was constructed for the isotope's β -decay branch. This scheme consists of 29 excited levels built on the 2^- ^{194}Tl ground state and incorporates 91 γ -ray transitions. (A preliminary version of the ^{194}Pb β -decay scheme was presented and discussed in the previous Physics Division Progress Report.⁶) Based on the decays of several strong transitions, the

half-life of ^{194}Pb was measured to be 12.0 ± 0.5 minutes.

From the half-life of 12.0 ± 0.5 min, the α branch of $(7.3 \pm 2.9) \times 10^{-6}\%$, and the α -decay energy of 4.64 ± 0.02 MeV, the α reduced width, δ^2 , for ^{194}Pb was calculated to be 0.011 ± 0.004 MeV. Figure 2.50 shows δ^2 values for s-wave (ground-state-to-ground-state) transitions of even-even nuclei with Z from 78 to 100. They exhibit a regular behavior as a function of N with an extremely sharp discontinuity at N = 126. This break has been shown to be a shell structure effect. Note that for N = 122-126, the δ^2 values for given neutron numbers decrease as Z decreases from 90 toward 82. In contrast to an expected shell effect at Z = 82, however, the widths for 186, 188, 190, 192^{Pb} (N = 104-110) are larger than those of neighboring Hg nuclei. This result may be due to a predicted⁷ disappearance of the Z = 82 gap midway between N = 82 and N = 126. A related explanation may be the existence of different

Fig. 2.50 Reduced widths for s wave α transitions plotted as a function of N for isotopes with Z from 78 to 100. Widths for 184, 186, 188, 190, 192, 194^{Pb} nuclei are indicated by open points.

ground-state shapes in Pb, Hg, and Pt isotopes in this mass region.

The width for ^{194}Pb is much less than those of nuclei with $N < 110$ and less than the δ^2 for ^{190}Pt ($N = 112$), indicating that perhaps the $Z = 82$ gap is being restored for $N > 112$. We also show in Fig. 2.50 an estimated width (0.060 MeV) for ^{184}Pb based on the data of Schrewe et al.⁸ and on the assumption of an α branch of 100%. [From gross β -decay theory⁹ the calculated partial half-life for ^{184}Pb ($\beta^+ + \text{EC}$) decay is 5-10 seconds, which yields an α branching of 89 - 96% and a smaller δ^2 value of 0.053-0.057 MeV.] This δ^2 value is appreciably less than the $^{186,188,190}\text{Pb}$ widths and may indicate that the influence of the $Z = 82$ shell reappears and retards the α decay of extremely neutron-deficient Pb isotopes.

1. Summary of published paper: Phys. Rev. C 36, 1529 (1987).
2. UNISOR, Oak Ridge Associated Universities, Oak Ridge, TN 37831.
3. University of Tennessee, Knoxville, TN 37916 and Oak Ridge National Laboratory, Oak Ridge, TN 37831.
4. Vanderbilt University, Nashville, TN 37325 and Joint Institute for Heavy-Ion Research, Oak Ridge, TN 37831.
5. Louisiana State University, Baton Rouge, LA 70803.
6. Y. A. Ellis-Akovi, et al., Phys. Div. Prog. Rept., Sept. 30, 1986, ORNL-6326, p. 99.
7. R. A. Sorensen, Nucl. Phys. A420, 221 (1984).
8. U. J. Schrewe, et al., Phys. Lett. 91B, 46 (1980).
9. K. Takahashi, et al., At. Data Nucl. Data Tables 12, 101 (1973).

STRONGLY DAMPED HEAVY-ION REACTIONS FUSION, FISSION

ARE PIONS EMITTED IN THE SPONTANEOUS FISSION OF ^{252}Cf ?

J. R. Beene C. E. Bemis, Jr.
M. L. Halbert

The provocative suggestions of pionic radioactivity, and other exotic radioactive decay modes, made by Ion, Ivascu, and Ion-Mihai,¹ is supported by their considerations of the energetics of the process and by phase-space arguments based on statistical ideas proposed by

Fermi.^{2,3} Two-body pionic radioactivity, i.e. the spontaneous creation and emission of pions from the nuclear ground state, is forbidden by conservation of energy and momentum, but three- or more-body decay modes are possible. The total energy release in the fission of the heaviest elements exceeds 200 MeV, sufficient to create pions. This energy appears mainly in fragment kinetic energy, arising from Coulomb repulsion of the fission fragments. For pions to be created, the total energy release in normal two-body spontaneous fission, the fission Q value, must be reduced by the pion rest mass (134.96 MeV for a π^0). Pion emission is energetically possible for all elements with Z greater than about 80 where the two-body fission Q values exceed the pion rest mass.

Although the details of the dynamics of pion-accompanied spontaneous fission, with a substantially reduced fragment kinetic energy release, are obscure, the application of "phase-space" statistical arguments as was done by Ion et al.¹ seems appropriate. This technique demonstrates that the likelihood of pion accompanied fission increases with increasing fission Q value, thus the very heaviest elements would be the most likely candidates for study. The statistical arguments, without further knowledge of the exact mechanism, do not allow the extraction of a decay branching ratio.

We have made a sensitive search for the neutral-pion-accompanied spontaneous fission of ^{252}Cf . Approximately 9 ng of isotopically pure (>99.99%) ^{252}Cf was incorporated into a fast fission-ionization chamber initially developed at Oak Ridge National Laboratory for the purpose of permitting fission measurements on intensely alpha-active isotopes like ^{252}Cf .^{4,5} Since neutral pions decay with a mean life of 8.7×10^{-17} s, predominantly (98.799%) via the two-photon decay mode, a sensitive method to search for this decay mode is: the detection of a pair of correlated high energy gamma rays, a determination of their energy and correlation angle in prompt coincidence with a fission event and the reconstruction of the invariant mass. We have used the HHIRF Spin Spectrometer,

a spherical 4 π array of NaI(Tl) detectors with the fast fission-ionization chamber mounted in the center, to search for this decay mode.

Sub-nanosecond time resolution for the detection of high energy photons ($E > 10$ MeV) allowed us to discriminate against cosmic ray events, i.e., minimum ionizing particles with $v \approx c$ originating outside the Spin Spectrometer and traversing its center. For this case, the minimum arrival time difference for detectors on opposite sides of the sphere is 1.78 nanoseconds. We observed no events in prompt coincidence (± 2 ns) with a fission trigger which could be taken as a candidate for neutral pion decay originating in the center of the Spin Spectrometer. We recorded more than 2×10^9 individual fission trigger events and conclude that neutral-pion-accompanied spontaneous fission of ^{252}Cf is $< 1 \times 10^{-3}$ of the normal fission decay mode at the 90% confidence level. We would contemplate additional experiments if more detailed theoretical investigations provided some realistic optimism. Using the present apparatus and exploiting the virtues of the Spin Spectrometer in the "self-shielding" mode to discriminate against cosmic ray background, we could expect to reduce the upper limit as given above, by approximately two orders of magnitude.

A more complete description of our experiment and result is being prepared for a short formal publication.

1. D. B. Ion, M. Ivascu, and R. Ion-Mihai, *Ann. Phys.* 171, 237 (1986); D. B. Ion, R. Ion-Mihai, and M. Ivascu, *Rev. Roum. Phys.* 31, 205 (1986); D. B. Ion, R. Ion-Mihai, and M. Ivascu, *Rev. Roum. Phys.* 31, 209 (1986); D. B. Ion, R. Ion-Mihai, and M. Ivascu, *Rev. Roum. Phys.* 31, 551 (1986); D. B. Ion, R. Ion-Mihai, and M. Ivascu, *Rev. Roum. Phys.* 32, 299 (1986).
2. E. Fermi, *Prog. Theor. Phys.* 5, 570 (1950).
3. R. Hagedorn, *Relativistic Kinematics*, W. A. Benjamin, Inc., New York, 1963; Chapter 7, pp. 80-115 and references therein.
4. J.W.T. Dabbs et al., *Proc. Int. Conf. Nuclear Cross Sections and Technology*, Washington, D.C., March 3-7, 1975, CONF-750303, NBS Special Publication 425, edited by R. A. Schrack and C. D. Bowman, Vol. I, p. 81, U.S. National Bureau of Standards (1975).
5. J.W.T. Dabbs et al., *Nucl. Sci. Eng.* 84, 1 (1983).

STUDIES OF GIANT RESONANCES IN HOT NUCLEI

J. R. Beene	D. C. Hensley
R. L. Varner	I. Y. Lee
R. L. Auble	H. P. Morsch ²
F. E. Bertrand	D. G. Sarantites ³
B. L. Burks ¹	R. O. Sayer ⁴
M. L. Halbert	M. Spang ²
D. W. Stracener ³	

We have begun a program to measure the gamma emission strength function of highly excited nuclear systems in the region of the gamma spectrum dominated by the isovector giant dipole resonance (IVGDR). Much data now exists on the IVGDR at low and moderate nuclear excitation energy.⁵ We intend to study the IVGDR strength from the gamma decay of hotter systems ($T \approx 3$ to 7 MeV), to explore the limits of nuclear collectivity as the temperature approaches the binding energy of individual nucleons. It may even be possible to define the range of temperatures for which a hot aggregation of nucleons may be considered to be a nucleus. Such data will also test the current predictions that the width and mean energy of the IVGDR should remain relatively stable with increasing temperature above $T \approx 3$ MeV.⁶ If these predictions are correct, experiments might even provide a window on detailed nuclear structure properties of very hot nuclei. These experiments face a number of difficulties, including the necessity of characterizing the mean excitation energies of composite systems accurately in spite of complex reaction mechanisms, and the difficulty imposed at higher bombarding energies by the background of proton-neutron bremsstrahlung.

To date we have performed two measurements of high energy gamma decays in hot, compound systems. The hot nuclei were produced by fusion-like heavy-ion reactions, using the MHIRF Spin Spectrometer as the gamma detector. The experiments used different beam-target combinations, and differed in the experimental information used to characterize the hot composite reaction products, as discussed below.

The first experiment was a study of the systems $^{32}\text{S} + ^{120}\text{Sn}$ and $^{32}\text{S} + ^{197}\text{Au}$ using a beam of 450-MeV ^{32}S ions. Symmetric fission of the system was used to characterize the reaction process and thus identify the temperature of the

compound system. Fission kinematics were used to determine the fraction of the projectile momentum transferred to the fissioning system. The trigger detectors were thin, position-sensitive gas counters with an angular acceptance of $\Delta\theta = 35^\circ$, and placed on opposite sides of the beam, at a mean angle of 60° for the Au experiment. For the Sn experiment, the mean angles were 45° and 55° . The experimental trigger required a coincident event in the two position-sensitive detectors. From time of flight and position, transverse velocities were determined for each fragment and used to select nearly symmetric fissions. The angle between the fission fragments was calculated and used to determine the momentum transfer to the fissioning system.

The second experiment was a study of the system $^{160}\text{Gd} + ^{159}\text{Tb}$ with 400- and 300-MeV ^{160}Gd . The identification of the momentum transfer was made using position-sensitive Breskin detectors placed 40 cm downstream from the target, with which the energy and time of flight (TOF) of the recoiling reaction products were measured. The angles accepted by the detectors were between 3.5° and 19.3° . The recoil momentum spectrum for the 400 MeV experiment can be seen in Fig. 2.51. In addition to the recoil detectors, several sections of the new "dwarf ball" detector, a compact, 72 segment, 4 π , CsI detector array being developed at Washington University, were used to detect light charged particles ($A < 4$) evaporated from the compound nucleus.

Both of these experiments are being processed into gamma spectra. Clear evidence for a strong IVGDR is seen in the fission gated $^{32}\text{S} + ^{120}\text{Sn}$ data. The fission gated data on the ^{197}Au target shows a much weaker IVGDR. The recoil gated data acquired show evidence for significant IVGDR strength for full momentum transfer events at both the 300- and 400-MeV ^{160}Gd bombarding energies. Another significant result from the recoil gated data is information on the high energy gamma production ($E_\gamma > 20$ MeV) as a function of linear momentum transfer (impact parameter). At 300 MeV this yield is significant only for full momentum transfer events, and

Fig. 2.51. Time of flight vs energy of recoiling particles from 400-MeV $^{160}\text{Gd} + ^{159}\text{Tb}$ reactions. The time resolution is sufficient to clearly distinguish the different classes of reaction products: quasi-elastic, deep inelastic or fission-fragment, and compound-like recoils.

drops precipitously with decreasing linear momentum transfer. At 400 MeV this relative yield is almost constant over a range of linear momentum transfer from 100% to almost 50%, and then falls rapidly.

1. Engineering Physics and Mathematics Division, ORNL.
2. Institut für Kernphysik, D-5170 Jülich, West Germany.
3. Washington University, St. Louis, MO 63110.
4. Computing and Telecommunications Division, ORNL.
5. J. O. Newton et al., Phys. Rev. Lett. 46, 1383 (1981). K. A. Snover, Ann. Rev. Nucl. Part. Sci. 36, 545 (1986).
6. R. A. Broglia and G. F. Bertsch, private communication.

REACTIONS WITH ^{40}Ar AND ^{84}Kr LEADING TO THE SAME COMPOUND NUCLEUS, ^{200}Po ¹

R. L. Hahn² Y. LeBeyec³
K. S. Toth B. Lagarde³
M. W. Guidry⁴

Excitation functions were measured for the deexcitation by neutron evaporation of the compound nucleus ^{200}Po formed in the interactions of $^{84}\text{Kr} + ^{116}\text{Cd}$ and $^{40}\text{Ar} + ^{160}\text{Dy}$. In general, the results are consistent with the predictions^{5,6} of the statistical model of nuclear

reactions, including effects of angular momentum and deexcitation by fission. However, few-neutron ($2n,3n$) evaporation is more favored in ^{84}Kr induced reactions than in those involving ^{40}Ar , a result that is not predicted by the statistical model. In fact, neither code^{5,6} reproduces our observation that the $(\text{HI},2n)$ product, ^{198}Po , is seen in the Kr reactions but not in the Ar reactions.

1. Summary of a paper to be published in Physical Review C.
2. Chemistry Division, Oak Ridge National Laboratory.
3. Institut de Physique Nucléaire, Orsay, France.
4. University of Tennessee, Knoxville, TN 37996.
5. M. Blann, Overlaid Alice, report COO-3494-29 (unpublished); F. Plasil, OPNL Alice, report ORNL-TM-6054 (unpublished, 1977).
6. M. Hillman and Y. Eyal, Julian, Brookhaven National Laboratory Report 22846 (unpublished, 1976); see also, A. Gavron, Phys. Rev. C 21, 230 (1980).

NUCLEAR SHAPES FROM ALPHA - GAMMA-RAY ANGULAR CORRELATIONS¹

Z. Majka ²	Li Ze ²
D. G. Sarantites ²	M. L. Halbert
L. G. Sobotka ²	J. R. Beene
K. Honkanen ³	D. C. Hensley
E. L. Dines ²	R. P. Schmitt ⁴
L. A. Adler ²	G. Nebbia ⁴

The angular distribution of alpha particles with respect to the spin direction of the residual nuclei is used to probe the shapes of the emitting systems. Two compound systems have been studied: ^{170}Yb and ^{110}Sn . Deformed emission shapes are required in order to understand the alpha-gamma correlations in the ^{170}Yb system, but not for the ^{110}Sn compound system. These conclusions are identical to those reached by the study of giant resonances built on excited states for very similar systems.

1. Abstract of published paper: Phys. Rev. Lett. 58, 322 (1987).
2. Washington University, St. Louis, MO 63130.
3. Deceased.
4. Texas A&M University, College Station, TX 77840.

NUCLEAR TEMPERATURE MEASUREMENTS AND FEEDING FROM PARTICLE UNBOUND STATES¹

H. M. Xu ²	J. Pochodzalla ²
D. J. Fields ²	D. G. Sarantites ³
M. G. Lynch ²	L. G. Sobotka ³
M. B. Tsang-	M. L. Halbert
C. K. Gelbke ²	D. C. Hensley
M. R. Maier ²	D. Hahn ⁴
D. J. Morrissey ²	H. Stocker ⁵

Inclusive fragment cross sections and cross sections of coincident γ -ray transitions from the decay of ^6Li , ^7Be , ^{10}B , ^{12}B , and ^{13}C fragments were measured for ^{32}S induced reactions on Ag at 715 MeV. These measurements are compared to quantum statistical model calculations which include sequential feeding from particle unbound states of heavier fragments. When the uncertainties in the sequential feeding calculations are taken into account, although the measured γ -ray fractions are consistent with temperature, $T > 4$ MeV; the calculations demonstrate that the investigated γ -ray transitions cannot be used to determine the temperature of highly excited systems.

1. Abstract of published paper: Phys. Lett. B182, 155 (1986).
2. Michigan State University, East Lansing, MI 48824.
3. Washington University, St. Louis, MO 63130.
4. Lawrence Berkeley Laboratory, Berkeley, CA 94720.
5. Institut für Theoretische Physik, J. W. Goethe Universität, Frankfurt am Main, Federal Republic of Germany.

CHARGE AND MASS DISTRIBUTION OF PROJECTILELIKE FRAGMENTS IN THE REACTION $^{58}\text{Ni} + ^{165}\text{Ho}$ AT 15.7 MeV/NUCLEON

V. Penumetcha ¹	R. L. Ferguson
G. A. Petitt ¹	F. E. Obenshain
T. C. Awes	F. Plasil
	G. R. Young

Charge, energy, and time-of-flight (TOF) information for projectilelike fragments (PLF) from the reaction $^{58}\text{Ni} + ^{165}\text{Ho}$ was obtained at 910-MeV bombarding energy. Charge and energy were determined using a multi-element ionization chamber detector, and PLF masses were obtained with the time-of-flight facility using a 2.4-meter flight path. PLF charges ($4 < Z < 28$)

were measured with a resolution of ~ 0.6 charge units, and PLF masses ($12 < A < 60$) were measured with a resolution of ~ 0.8 amu. The data are being analyzed together with neutron measurements for the same system to obtain mass, charge, and excitation energy distributions as a function of energy loss.

1. Georgia State University, Atlanta, Georgia.

NEUTRON FLOW BETWEEN NUCLEI AS THE PRINCIPAL ENHANCEMENT MECHANISM IN HEAVY-ION SUBBARRIER FUSION¹

P. H. Stelson

We have studied the distributions of barriers required to fit experimental heavy-ion fusion cross sections at energies in the barrier region. Best fits were generally obtained with distributions which were flat, broad, and characterized by a sharp cutoff value at the low-energy end. The cutoff barrier is correlated with the distance at which merged neutron potentials just allow neutrons to flow between the nuclei. These features suggest that fusion initiated by neutron flow is the principal enhancement mechanism and that coupling to collective states plays a secondary role.

1. Abstract of paper submitted for publication in Physics Letters B.

EMISSION OF COMPLEX FRAGMENTS AND NUCLEAR TEMPERATURE MEASUREMENTS IN THE $^{58}\text{Ni} + ^{58}\text{Ni}$ FUSION REACTION AT 11-MeV/NUCLEON

J. Gomez del Campo	R. L. Auble
J. L. Charvet ¹	J. R. Beene
A. D'Onofrio ²	M. L. Halbert
H. Kim	

The emission of complex fragments, also referred to as intermediate mass fragments (IMF) or cluster fragments, is a subject of strong interest in heavy-ion reactions in the intermediate energy domain of 10 to 100 MeV/nucleon.^{3,4} The yield distributions as a function of Z and/or A has been used as a tool to search for the predicted liquid-gas phase tran-

sition,⁴ although a series of experimental difficulties exist for the determination of the temperature at the critical point. Recently several authors have pointed out some of these difficulties^{5,6} in studying the population of excited states of the IMF's.

In the present work we have chosen to study the IMF emissions for nuclear charges Z from 4 to 12 for the system $^{58}\text{Ni} + ^{58}\text{Ni}$ to avoid projectile-fragmentation contaminations of the IMF cross sections. We also measured the cross sections for excited states for ^{12}C , ^{15}N , and ^{16}O isotopes since for these fragments the sensitivity to high temperatures will be the greatest. The experiment was performed at the NHIRF using 630-MeV ^{58}Ni beams extracted from coupled operation of the tandem and cyclotron. A total of six surface-barrier detector telescopes were used to measure IMF in the range $Z = 4-28$. Two of the telescopes had sufficient resolution to identify also the mass of the fragments from Be to Me. The detector telescopes were placed inside the 34-cm spherical scattering chamber of the Spin Spectrometer. Sixty-four NaI detectors (out of the 72 NaI that the spectrometer has) were used to determine γ -ray and n multiplicities as well as to measure individual γ -ray transitions of excited states of the IMF's. This report shows only the γ -ray results; the neutron data are still under analysis.

Figure 2.52 shows the results for the angular distributions ($d\sigma/d\Omega$) in the center-of-mass system for fragments of $Z = 4-13$. The differential cross sections measured in the laboratory system were transformed to the center of mass using two-body kinematics. As can be seen from the figure, the angular distributions from $Z = 4-9$ are essentially isotropic, which is a strong indication that they result from emissions of a fully equilibrated system. In contrast, it should be noted that the angular distributions for fragments of $Z = 10-13$ are strongly forward-peaked. This feature is characteristic of more peripheral processes like deep-inelastic scattering or fragmentation. In addition, the centroids of the energy spectra

Fig. 2.52. Angular distributions for emitted fragments of $Z = 4-13$ resulting from $^{58}\text{Ni} + ^{58}\text{Ni}$ collisions at 11 MeV/nucleon. The solid lines are to guide the eye.

for fragments of $Z = 4-9$ are consistent with compound nucleus emission, whereas those of $Z > 9$ are not.

Figure 2.53 shows the angle-integrated cross sections for the data of Fig. 2.52 obtained with the assumption that $(d\sigma/d\Omega)$ is constant outside the angular range measured. The open circles correspond to the estimated equilibrium cross sections for fragments of $Z > 9$. They were obtained by fitting an isotropic angular distribution to the largest measured angles ($\sim 120^\circ$). The histogram is the result of a Hauser-Feshbach⁷ calculation which assumes a complete-fusion reaction with a critical angular momentum, J_c , of 68 $\hbar$. The decay of the compound nucleus includes all possible energetically open channels from $Z = 0-20$. Also, for every emitted fragment, ground and excited states have been included and all particle unstable levels have been followed in their decay. Thus the calculations of Fig. 2.53, in general, contain a mixture of primary (particle stable) and secondary (particle unstable) emitted fragments. The critical

Fig. 2.53. Angle-integrated cross sections obtained from the data of Fig. 2.52. The histogram is the result of a Hauser-Feshbach calculation.

angular momentum of 68 $\hbar$ is the same as that predicted by a Sierk-Nix calculation for the vanishing of the symmetric fission barrier for the compound nucleus ^{116}Ba . Also, it should be noted that the critical angular momentum extracted from evaporation residue measurements of a compound nucleus of mass 111 ($^{84}\text{Kr} + ^{27}\text{Al}$)⁸ is 69 $\hbar$, which compares very well with the value of 68 used in the calculations of Fig. 2.53. From the data and analysis given in Figs. 2.52 and 2.53, we conclude that the fragments of $Z < 10$ are consistent with the emission of a completely fused system (^{116}Ba) formed at an excitation energy of 250 MeV and a critical angular momentum of 68 $\hbar$. The 250 MeV excitation energy corresponds to a temperature of 4.1

MeV calculated with the expression $T = \sqrt{Ex/a}$ for $a = A/8$.

The idea of extracting nuclear temperatures from highly excited systems by studying the population of excited states has been discussed in detail in Refs. 5 and 6. In a simple statistical approach it is expected that the ratio of two states 1,2 of an emitted fragment is given by:

$$\sigma_1/\sigma_2 = (2S_1 + 1)/(2S_2 + 1) \exp(-\Delta E/T) \quad (1)$$

where s_1 and s_2 are the spins of the two states and ΔE is their difference in excitation energy. T is, in principle, the temperature of the emitting system, provided that the emitted fragments in the states 1,2 are primary fragments. In the present experiment, we have used the 64 NaI detectors to study the γ -ray emission of the first excited states in $^{12}\text{C}(2^+, Ex = 4.439 \text{ MeV})$, $^{15}\text{N}(5/2^+, Ex = 5.2704 \text{ MeV} + 1/2^+, Ex = 5.2988 \text{ MeV})$ and in $^{16}\text{O}(3^-, Ex = 6.1304)$. The kinetic energies of the fragments were measured with the array of particle telescopes and their emitted γ -ray energies were corrected event-by-event for Doppler-shifts. The results, summed over the 64 NaI detectors for the γ -rays of ^{12}C , ^{15}N , and ^{16}O , are shown in Fig. 2.54 where the photo-peak and the first escape peak are indicated.

The results of the ground state and excited states for the angle-integrated cross sections are shown in Table 2.9. Column 1 gives the

Fig. 2.54. The γ -ray energy spectra for ^{12}C , ^{15}N , and ^{16}O measured with the NaI detectors of the Spin-Spectrometer. The vertical lines indicate the energy of the photo peak and first escape peak for the indicated fragment.

Table 2.9. Cross sections and effective temperatures deduced for ^{12}C , ^{15}N , and ^{16}O ejectiles from 11-MeV/nucleon $^{58}\text{Ni} + ^{58}\text{Ni}$. Cross sections are given in mb, and T_{eff} in MeV, extracted from Equation 1. Typical cross section errors are 15%.

	Experiment			Calculation		
	σ (g.s.)	σ (exc.)	T_{eff}	σ (g.s.)	σ (exc.)	T_{eff}
^{12}C	20.5	16.5	2.4	17.4	9.0	1.94
^{15}N	8.0	3.0	1.9	6.5	4.0	2.3
^{16}O	14.0	6.0	2.2	14.0	3.0	1.75

nuclei studied, column 2 the angle-integrated cross sections in mb for the ground state, and the third column gives the cross section for the excited state. The fourth column, labeled T_{eff} , gives the extracted temperature using Eq. (1). The next three columns are from the Hauser-Feshbach calculations. The main conclusion to be drawn from the experimental and theoretical values given in Table 2.9 is that the extracted temperature of about 2 MeV is lower by a factor of two than the temperature of the fused system; however, the Hauser-Feshbach calculation is able to reproduce the observed value of T_{eff} . This result indicates that, even for fragments which have excited states of several MeV, the secondary effects coming from the deexcitation of particle-unbound states are a dominant factor. Hence, the temperatures extracted from Eq. (1) can agree with the compound nucleus temperature only for low excitation energies, where the population of IMF in particle-unbound states should be small.

1. Joint Institute for Heavy Ion Research and Centre d'Études de Bruyères-le Chatel, France.
2. Joint Institute for Heavy Ion Research and Istituto Nazionale di Fisica Nucleare, Napoli, Italy.
3. A. N. Panagiotou et al., Phys. Rev. Lett. 52, 496 (1984).
4. P. J. Siemens, Nucl. Phys. A428, 189c (1984).
5. H. M. Xu et al., Phys. Lett. B182, 155 (1986).
6. D. J. Morrissey et al. Phys. Rev. C 32, 877 (1985).
7. Phys. Div. Prog. Rep. for Period Ending Sept. 30, 1985, ORNL-6233, p. 120.
8. W. F. W. Schneider et al. Nucl. Phys. A371, 493 (1981).

HEAVY RESIDUE MASSES AS POSSIBLE INDICATORS OF THE IMPACT PARAMETER IN THE REACTION $^{20}\text{Ne} + ^{60}\text{Ni}$ at 742 MeV¹

A. D'Onofrio ²	F. Andreozzi ²
B. Delaunay ³	A. Brondi ²
J. Delaunay ³	R. Moro ²
H. Dumont ³	M. Romano ²
J. Gomez del Campo	F. Terrasi ²
J. F. Brundet ⁴	

Mass and charge distributions for heavy residues in the reaction $^{20}\text{Ne} + ^{60}\text{Ni}$ at 37.1

MeV/nucleon were measured by both in-beam and radioactivity gamma-ray spectrometry. The general features of the experimental data are well reproduced by a massive transfer model. The heavier residues are also interpreted in the framework of a participant spectator model.

1. Abstract of published paper in Phys. Rev. C 35, 1167 (1987).
2. Dipartimento di Fisica Nucleare, Struttura della Materia e Fisica applicata dell'Università, Napoli, Italy and Istituto Nazionale di Fisica Nucleare, Napoli, Italy.
3. Service de Physique Nucleaire-Basse Energie, Centre d'Études Nucleaires de Saclay, France.
4. Institut des Sciences Nucleaires Grenoble, France.

EVIDENCE FOR EQUILIBRATION OF HOT NUCLEI¹

A. D'Onofrio ²	A. Brondi ²
B. Delaunay ³	R. Moro ²
J. Delaunay ³	M. Romano ²
H. Dumont ³	F. Terrasi ²
J. Gomez del Campo	J. F. Brundet ⁴

The production cross sections of ^7Li in its ground and first excited states have been measured at 14, 120, 150 for the 742 MeV $^{20}\text{Ne} + ^{60}\text{Ni}$ reaction. Hauser-Feshbach calculations show that the backward angle data are consistent with an emission temperature greater than 6 MeV. This is in agreement with the values extracted from the slope of the energy spectra and indicates that the emitting source is equilibrated.

1. Abstract of published paper in Z. Phys. A326, 335 (1987).
2. Dipartimento di Fisica Nucleare, Struttura and Istituto Nazionale di Fisica Nucleare, Napoli, Italy.
3. Service de Physique Nucleaire-Basse Energie-Cen Saclay, France.
4. I.S.N. Grenoble, France.

CRYSTAL BLOCKING IN HEAVY ION REACTIONS¹

J. Gomez del Campo

The crystal blocking technique for measuring short lifetimes (10^{-18} s) was developed during the 1960s from the study of the channeling

effect. Early blocking measurements involved light ion resonance reactions yielding typical lifetime values of the order of 10^{-17} s. Recently, studies on heavy-ion induced fission and fusion have extended the technique into the 10^{-18} to 10^{-19} s scale. In this work measurements of fusion for ^{160}Ge are presented for bombarding energies around 8 MeV/nucleon. Also, measurements of the projectile fragmentation of 44-MeV/nucleon $^{40}\text{Ar} + \text{Ge}$ are discussed. In all reactions studied, the presence of particle evaporation is the dominant mechanism that determines the reaction times of $\sim 10^{-18}$ s measured with the blocking technique.

1. Abstract of paper published in Nucl. Instr. and Meth. B24, 447 (1987).

THE ANGULAR MOMENTUM DEPENDENCE OF COMPLEX FRAGMENT EMISSION¹

L. G. Sobotka ²	D. C. Hensley
D. G. Sarantites ²	R. P. Schmitt ³
Ze Li ²	Z. Majka ³
E. L. Dines ²	G. Nebbia ³
M. L. Halbert	H. C. Griffin ⁴
A. J. Sierk ⁵	

Large fragment ($A > 4$) production at high angular momentum is studied via the reaction, 200 MeV $^{45}\text{Sc} + ^{65}\text{Cu}$. Comparisons of the fragment yields from this reaction (high angular momentum) to those from $^{93}\text{Nb} + \text{Be}$ (low angular momentum) are used to verify the strong angular momentum dependence of large fragment production predicted by equilibrium models. Details of the coincident γ -ray distributions not only confirm a rigidly rotating intermediate but also indicate that the widths of the primary L-wave distributions decrease with increasing symmetry in the decay channel. These data are used to test the asymmetry and L-wave dependence of emission barriers calculated from a rotating, finite-range-corrected, liquid drop model.

1. Abstract of invited paper to be published in Nuclear Physics A (Proceedings, American Chemical Society Symposium on Central Collisions and Fragmentation Processes, Denver, CO, April 5-10, 1987) (in press).

2. Washington University, St. Louis, MO 63130.

3. Texas A&M University, College Station, TX 77843.

4. University of Michigan, Ann Arbor, MI 48109.

5. Los Alamos National Laboratory, Los Alamos, NM 87545.

PARTICLE-BOUND EXCITED STATE YIELDS PRODUCED IN THE REACTION OF 181-MeV $^{19}\text{F} + ^{159}\text{Tb}$ ¹

L. G. Sobotka ²	M. L. Halbert
D. G. Sarantites ²	J. H. Barker ³
H. Puchta ²	J. R. Beene
F. A. Dillmanian ²	R. L. Ferguson
M. Jaaskelainen ²	D. C. Hensley
G. R. Young	

The yield of particle-bound excited states of ejectiles produced in the reaction 9.5-MeV/nucleon $^{19}\text{F} + ^{159}\text{Tb}$ has been determined by use of particle γ -ray coincidence techniques. The bound excited-state population fraction for most projectilelike fragments shows no dependence on particle kinetic energy. In these cases the fractions are inconsistent with a Boltzmann population distribution, but they support the hypothesis of a substantial sequential decay component with a strong preference for the ground state of the residual fragment. For a few detected ejectiles there is a strong dependence of the excited state fraction on particle kinetic energy. This dependence is in agreement with that expected for a binary process in which the projectilelike fragment gets a small but constant fraction of the total available excitation energy.

1. Abstract of published paper: Phys. Rev. C 34, 917 (1986).

2. Washington University, St. Louis, MO 63130.

3. South Carolina Electric & Gas Co., Columbia, SC 29218.

EXCITATION ENERGY DIVISION IN THE QUASIELASTIC REGION FROM REACTIONS OF 12 MeV/NUCLEON ^{48}Ti WITH ^{150}Nd

T. M. Semkow ²	M. Ross ²
D. G. Sarantites ²	J. R. Beene
K. Honkanen ³	M. L. Halbert
Z. Li ²	D. C. Hensley

Internal excitation of projectilelike fragments and targetlike fragments was investigated for the system 12-MeV/nucleon $^{48}\text{Ti} +$

^{150}Nd , by measuring the discrete γ rays emitted by both fragments in coincidence with the charge-separated projectilelike fragments. Two quasielastic exit channels were studied: 2 proton stripping and inelastic scattering/neutron transfer. Each of the above exit channels was assumed to have an average primary mass split independent of the total kinetic energy loss. The characteristic γ rays were then used to determine the average masses of products resulting from neutron evaporation as a function of total kinetic energy loss. Comparisons between the deduced and known values of the neutron separation energies, as well as detailed statistical-model calculations, show that the excitation energy is divided approximately equally between the projectile- and the target-like fragments for both exit channels. The result for 2p stripping remains in agreement with predictions made by the stochastic nucleon-exchange models. The result for inelastic scattering/neutron transfer may be due to averaging over several exit channels. The excitation energy appears to be divided equally up to ~ 104 MeV of the total kinetic energy loss, corresponding to $\sim 24\%$ of total kinetic energy damping.

1. Abstract of a paper submitted to Physical Review C.

2. Washington University, St. Louis, MO 63130.

3. Deceased.

ANGULAR MOMENTUM EFFECTS IN SUBBARRIER FUSION¹

M. L. Halbert	T. M. Semkow ³
J. R. Beene	V. Abenante ³
D. C. Hensley	D. G. Sarantites ³
K. Honkanen ²	Z. Li ³

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 and $^{160} + ^{140}\text{Sm}$. At the lowest bombarding energies the σ_L extend to higher L values than do predictions 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 an energy-dependent real potential fitted to the excitation function fails to reproduce the experimental σ_L distribution. No effects attributable to superdeformation were observed.

1. Abstract of paper to be published in Proceedings of the 6th Adriatic International Conference on Nuclear Physics, Dubrovnik, Yugoslavia, June 15-19, 1987.

2. Deceased.

3. Washington University, St. Louis, MO 63130.

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

TWO-PROTON CORRELATIONS IN ^{32}S -INDUCED REACTIONS AT 22.3 MeV/NUCLEON

T. C. Aves	F. E. Obenshain
Z. Chen ¹	F. Plasil
R. L. Ferguson	J. Pochodzalla ¹
C. K. Gelbke ¹	S. Pratt ²
W. G. Lynch ¹	H. M. Xu ¹
G. R. Young	

Two-particle correlations between light particles emitted in heavy-ion reactions may be used to extract information on the spatial extent and excitation of the emission source.³ Such measurements have provided evidence for the formation and decay of localized regions of high excitation.

We have measured light-particle correlations for reactions of $^{32}\text{S} + \text{Al}$, Ag , and Au at 22.3 MeV/nucleon at WHIRF. Light particles from protons through ^7Li were measured in coincidence with one another using a hodoscope consisting of 13 Si-NaI telescopes centered at a laboratory angle of 30° . The correlation function $R(q)$ is extracted from the ratio of the coincidence yield Y_{12} to the singles yields Y_1 and Y_2 according to

$$Y_{12}(\vec{p}_1, \vec{p}_2) = C_{12} * Y_1(\vec{p}_1) * Y_2(\vec{p}_2) * [R(q) + 1],$$

where $\vec{p}_1$ and $\vec{p}_2$ are the laboratory momenta of particles one and two and q is the relative momentum of the pair. The normalization constant C_{12} is determined at large relative momenta by the requirement that $R(q) = 0$.

Already with the first proton-proton correlation measurements, it was observed that the higher energy protons were emitted from sources of smaller apparent dimensions.⁴ This observation has been interpreted as due to a lifetime effect, the lower energy particles being emitted in the later equilibrated stage of the reaction. Koonin³ had pointed out that information on the source lifetime may be obtained by measuring the correlation function for relative momenta transverse and longitudinal to the momenta of the emitted pair. For a long-lived emission source, the correlation is expected to give an apparently elongated source in the longitudinal direction since the particles may be separated "further back" in time. This then leads to a characteristically suppressed correlation in the transverse direction due to the Pauli blocking in the relatively smaller transverse direction.

We have studied the dependence of the correlation function on the angle of the relative momentum for the Al, Ag, and Au targets as a function of the laboratory total kinetic energy (TKE) of the outgoing protons. As previously observed, it is found that the high-energy protons exhibit a strong correlation characteristic of emission sources of sizes comparable to the compound nucleus or smaller. However, with decreasing proton energies, the correlation becomes significantly weaker, indicating emission sources which exceed the dimensions of the compound nucleus. In order to determine whether the large apparent source sizes might be due to a lifetime effect, we have studied the directional dependence of the two-proton correlation. An example of the results is shown in Fig. 2.55 for the $^{32}\text{S} + \text{Au}$ reaction for two protons with TKE between 60 and 70 MeV. Contrary to expectations, the longitudinal and transverse correlations are observed to be essentially the same, even at small proton TKE.

A calculation is shown in Fig. 2.55 for the longitudinal and transverse correlations expected for an emission source of prolate spatial dimensions with $R_T = 5 \text{ fm}$ and $R_L = 12 \text{ fm}$ or equivalently, as would be expected for a spheri-

Fig. 2.55. Two-proton correlation function for two protons with total kinetic energy between 50 and 75 MeV emitted in ^{32}S -induced reactions on Au at 22.3 MeV/nucleon. The correlation function is shown for relative momenta parallel (solid squares) and transverse (open squares) to the direction of emission. Calculated correlation functions are shown for $R_T = 5 \text{ fm}$ and $R_L = 12 \text{ fm}$.

cal source of 5-fm radius with lifetime $(v\tau)^2 = R_L^2 - R_T^2$. Although such a calculation reproduces the observed decrease of the longitudinal correlation, it predicts that the transverse correlation should be substantially suppressed, contrary to observation. Instead, the experimental results indicate that the low-energy protons are emitted from a source which exceeds the compound nucleus dimensions. [For a uniform distribution the radius R_0 is related to the extracted gaussian radii by $R_0 = \sqrt{5/2} R$; for comparison $R(\text{Au}) = 4.4 \text{ fm}$.] This result suggests that the low-energy protons continue to interact during emission from the diffuse surface of the heated nucleus.

1. National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan.

2. University of Tennessee, Knoxville, Tennessee.

3. S. E. Koonin, Phys. Lett. 70B, 43 (1977).

4. W. G. Lynch et al., Phys. Rev. Lett. 51, 1850 (1983).

ENERGETIC PHOTON EMISSION ($E_\gamma > 50$ MeV)

N. Alamanos ¹	P. Paul ¹
T. C. Aves	F. Plasil
P. Braun-Munzinger ¹	K. Smith ²
R. L. Ferguson	J. Stachel ¹
R. Freifelder ¹	L. Waters ¹
F. E. Obenshain	G. R. Young

We continued analysis of the high-energy ($E_\gamma > 50$ MeV) photon production in reactions of 22-MeV/nucleon ^{32}S with Al, Ni, and Au targets. A full reanalysis of in-beam background was made, which required resetting time cuts on all prompt peaks for the lead-glass detectors relative to the cyclotron rf and looking at effects of walk. We have examined events falling in the gamma and neutron peaks in order to check that the observed angular distributions for the neutrons are sharply forward peaked, as they are found to be. A check of the response of the lead-glass detectors against that of a calibrated 10-inch NaI(Tl) crystal was made at SUNY with ^{160}Ta reactions. Using the measured spectrum in the NaI to define a reference spectrum and then folding that with the lead-glass response previously measured at the Mainz microtron, correcting for differing geometrical acceptances, and using the previously measured NaI(Tl) efficiency, it was possible to reproduce quite well the spectrum observed in the lead-glass detector. This gives considerable reassurance that the lead-glass response has been measured correctly and thus can be accounted for in later analysis of the present results.

Angular distributions in the lab frame for photons with $E_\gamma > 50$ MeV are shown in Fig. 2.56. The increase in cross section near $\theta_{\text{lab}} = 90^\circ$ is most pronounced for the Au target, less so for the Al and Ni targets. The angular distributions measured are consistent with a form

$$\left. \frac{d\sigma}{dE d\Omega} \right|_{\text{lab}} = \frac{K}{x} e^{-E_{\text{lab}}/E_0} \left(1 - \alpha + \frac{\alpha \sin^2 \theta_{\text{lab}}}{x^2} \right),$$

which is a superposition of an isotropic and dipole term, where $x = 1 - \frac{V_s}{c} \cos \theta_{\text{lab}}$, E_0 is a slope constant, V_s is a source velocity, and α represents the fraction of dipole yield. In all experiments where angular distributions are published, examination of the results shows $\alpha \sim$

Fig. 2.56. Angular distribution (lab frame) for photons with $E_\gamma > 50$ MeV, measured in reactions of $E/A = 22 \text{ MeV } ^{32}\text{S}$ with Al, Ni, and Au targets.

0.3-0.5 reproduces the results best. This, plus the failure to observe a quadrupolar component, could be consistent with the first few nucleon-nucleon scatterings dominating the production cross section for these photons. However, the contributions from evaporation still need to be

considered. The inverse slope parameters measured by various groups are shown in Fig. 2.57 as a function of bombarding energy (compiled in V. Metag's summary talk³ at the 1987 Gull Lake Conference). The measurements with NaI-telescope results are somewhat below those found using lead glass (present data and Grosse et al.) and range telescopes. The integrated cross sections as scaled following U. Mosel's³ prescription are shown in Fig. 2.58, where discrepancies among the various techniques used are apparent for $E_p/A_p < 50$ MeV. The present results are now being analyzed with an unfolding procedure to correct for the lead-glass response function.

1. State University of New York, Stony Brook, New York.
2. GLCA Science Semester Student. Present address: Department of Physics, Yale University, New Haven, Connecticut.

Fig. 2.57. Inverse exponential slopes for photon spectra at $\theta_{lab} = 90^\circ$ and for $E_\gamma > 50$ MeV, as a function of E_p/A_p for various experiments. (From V. Metag's compilation at Gull Lake, 1987.)

Fig. 2.58. Scaled angle- and energy-integrated cross sections for $E_\gamma > 50$ MeV, as a function of E_p/A_p for various experiments. The scaling rule is from a suggestion by U. Mosel. (From V. Metag's compilation at Gull Lake, 1987.)

3. Gull Lake Conference on Energetic Photon and Particle Emission in Heavy-Ion Reactions, Gull Lake, Michigan, May 17-20, 1987.

NEUTRON EMISSION IN DAMPED REACTIONS OF $^{58}\text{Ni} + ^{165}\text{Ho}$ AT 15.5 MeV/NUCLEON

G. A. Pettit ¹	R. L. Ferguson
C. Butler ¹	F. E. Obenshain
V. Penumetchal	F. Plasil
T. C. Awes	S. P. Sorensen ²
J. R. Beene	G. R. Young

Neutrons emitted in and out of the reaction plane have been measured in coincidence with projectilelike fragments resulting from damped

reactions of $^{58}\text{Ni} + ^{165}\text{Ho}$ at 15.5 MeV/nucleon. Neutrons were detected using 12 detectors, 2 of which were 1 meter long and position sensitive. The charge, energy, and angle of the projectilelike fragments were measured in a gas- ΔE silicon-E ionization chamber. The results are being analyzed to extract the characteristics of the nonequilibrium neutron contribution as a function of the velocity of the outgoing projectilelike fragment, and will be compared with the predictions of two-body nucleon-nucleon collision models and time-dependent external field-induced emission.

1. Georgia State University, Atlanta, Georgia.

2. Adjunct research participant from the University of Tennessee, Knoxville, Tennessee.

LIGHT-PARTICLE MULTIPLICITY ACCOMPANYING PROJECTILE BREAKUP AT 20 MeV/NUCLEON¹

T. C. Awes D. Leach²
R. C. Connolly² S. P. Sorensen³
S. Gil² R. Vandenbosch²
C. L. Wu²

In previous experiments^{4,5} it has been demonstrated that projectile breakup into fragments of approximately one-half the projectile charge is due to a sequential decay rather than to prompt fragmentation. The first study of coincident fragments with Z between 3 and 8 from breakup of ^{37}Cl at 20 MeV/nucleon revealed energy-energy correlations which could be understood only if the projectile breakup occurred outside the range of the Coulomb field of the targetlike reaction partner. A second, more detailed, study showed that the relative energy spectra of these breakup events were consistent with statistical model expectations for decay of excited nuclei. One puzzle that remained after these studies was the fact that the most probable sum of the nuclear charges of the observed coincident events was appreciably less than that of the projectile ^{37}Cl . This could arise from transfer of protons from the projectile to the target at an early stage of the collision, or it could result from either (or both) preequilibrium emission of protons and alphas or addi-

tional proton or alpha evaporation from the projectilelike or final fragments.

The most recent experiment was designed to distinguish between these possibilities by determining the number of protons and alpha particles accompanying events in which two heavier coincident fragments were emitted. The observed angular distributions of coincident protons and alpha particles are Gaussian distributions which are centered near the beam direction on the opposite side of the beam from the heavy fragments. These observations are consistent with the majority of the protons and alpha particles being emitted at an early stage of the reaction, rather than by sequential decay of projectilelike fragments or their breakup products. The energy spectra exhibited many high-energy particles, with the proton spectra, in particular, having a considerable number of particles with velocities greater than the beam velocity.

A lower limit to the nuclear charge carried off by the light charged particles accompanying projectile breakup can be obtained by integrating the yields of particles with $Z > 1$ and $Z > 2$ over all angles, using a Gaussian fit to extrapolate to large angles. This yields an average charge carried away by the accompanying light particles of $Z = 3.4$. When this is added to the average total charge of the triggering coincident breakup fragments of $Z = 12.5$, one obtains a total charge of $Z = 15.9$, which is rather close to the projectile charge ($Z = 17$). Thus, we conclude that most of the charge not appearing in the breakup fragments is lost to accompanying light charged particles rather than transferred to the target nucleus.

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

2. University of Washington, Seattle, Washington.

3. Adjunct research participant from the University of Tennessee, Knoxville, Tennessee.

4. M. J. Murphy et al., Phys. Rev. Lett. 53, 1543 (1984).

5. M. J. Murphy et al. Phys. Rev. C 33, 165 (1986).

NUCLEAR PHYSICS WITH ULTRARELATIVISTIC PROJECTILES

PERFORMANCE OF THE CALORIMETERS FOR THE RELATIVISTIC HEAVY-ION EXPERIMENT WA80 AT CERN

T. C. Awes	I. Y. Lee
C. Baktash	F. E. Obenshain
J. L. Blankenship	A. Oskarsson ²
R. P. Cumby	I. Otterlund ²
R. L. Ferguson	S. Persson ²
A. Franz ¹	F. Plasil
S. Garpman ²	A. M. Poskanzer ¹
H. A. Gustafsson ²	H. G. Ritter ¹
J. M. Johnson	S. P. Sorensen ³
P. Kristiansson ¹	E. Stenlund ²
G. R. Young	

The experiment WA80 is a large collaborative experiment being carried out at CERN. The primary physics goals of the experiment are (1) to search for indications of formation of a quark-gluon plasma, (2) to determine nuclear stopping power, and (3) to survey and compare nucleus-nucleus and proton-nucleus collisions. It is described more completely elsewhere.⁴⁻⁶ Two calorimeters have been built for this experiment under the supervision of ORNL. The Wall or Mid-Rapidity Calorimeter (MIRAC) is one of the main detector systems of the experiment. It is a joint venture with LBL, Lund University, and GSI of Darmstadt. The Zero-Degree Calorimeter is primarily a trigger calorimeter of ORNL design and construction.

The Wall Calorimeter has been designed to provide calorimetric coverage of the mid-rapidity participant region (rapidity >2). In addition, it is also to be used as a specialized trigger, capable of selecting events with a high associated transverse energy, E_t . Physically,⁷ the Wall Calorimeter is a lead-scintillator electromagnetic, and a steel-scintillator hadronic, sampling calorimeter. It consists of thirty 20 cm x 120 cm stacks arranged in five six-packs with each stack subdivided into six 20 cm x 20 cm towers with separate readout.

Initial tests and calibrations of MIRAC were performed at the T9 beam line of the CERN Proton Synchrotron (PS) during March and April of 1986 and have been described elsewhere.⁸ Further linearity and resolution measurements were made

at the X1 beam line of the CERN Super Proton Synchrotron (SPS). Mixed, negative beams of electrons and pions from 4 to 50 GeV/c were used to study the linearity and resolution of the calorimeters. In addition, all 180 calorimeter towers were exposed to the beam in order to set the gain of the photomultipliers and to calibrate the laser pulser signal relative to the actual particle signal for each photomultiplier. For these calibrations each six-pack of calorimeters was placed on a moveable platform, and the beams of electrons and pions were allowed to impinge onto the center of each tower. Electrons were identified in an upstream threshold Cerenkov counter, and muons were identified in a plastic scintillator located behind an iron absorber behind the calorimeters.

The response of the calorimeters to electrons was observed to be linear to within 2% over the momentum range of 10 to 50 GeV/c. The electron resolution σ/E is plotted against $1/\sqrt{E}$ in Fig. 2.59 for electrons of 4 to 50 GeV/c. A linear fit of the data gives an energy resolution of $\sigma/E = 0.014 + 0.11/\sqrt{E}$ for electrons. The contribution to the electromagnetic resolution due to sampling fluctuations can be estimated to be about $\sigma/E = 0.09/\sqrt{E}$; thus, the electromagnetic resolution is dominated by sampling fluctuations.

Fig. 2.59. The calorimeter resolution (σ/E) versus $1/\sqrt{E}$ for electrons of incident momenta of 4 to 50 GeV/c. The curve is a least squares fit to the data.

Due to the fact that all 144 photomultipliers of a six-pack were summed to produce the data of Fig. 2.59, one expects a non-negligible contribution to the electromagnetic resolution due to photomultiplier noise and pedestal resolution. These effects should add directly to σ and therefore should contribute to the resolution scaled like $1/E$. This contribution is estimated to be about 5% at 1 GeV/c.

From the PS calibration of MIRAC, it was observed that the response of the calorimeters to protons and pions of incident momenta from 2 to 10 GeV/c is linear over this range of energies with a similar response for pions and protons. At low kinetic energy the response to protons is observed to be slightly higher than to pions, despite the fact that pions should also deposit a substantial fraction of their rest mass as visible energy. It is also observed that protons begin to shower in the electromagnetic section more frequently than pions, due to their larger interaction cross section.

From the XI calibration results, the response of the calorimeters to pions with incident momenta of 4 to 50 GeV/c is observed to be linear to within 7%. The hadron resolution σ/E is plotted against $1/\sqrt{E}$ in Fig. 2.60 for pions

Fig. 2.60. The calorimeter resolution (σ/E) versus $1/\sqrt{E}$ for pions of incident momenta of 4 to 50 GeV/c. The curve is a least squares fit to the data.

of 4 to 50 GeV/c. A linear fit of the data gives an energy resolution of $\sigma/E = 0.034 + 0.34/\sqrt{E}$ for hadrons. The contribution to the hadronic resolution due to sampling fluctuations⁹ in the hadronic section can be estimated to be about $\sigma/E = 0.27/\sqrt{E}$. For hadronic showers the obtainable resolution is limited, in general, by the intrinsic resolution due to fluctuations in the portion of the shower energy which is lost due to effects of nuclear binding and neutron emission. For iron/scintillator calorimeters similar to MIRAC, the intrinsic contribution has been calculated¹⁰ to be $\sigma_{\text{intr}} = 0.20/\sqrt{E}$. Thus, the observed energy dependence of $0.34/\sqrt{E}$ of the resolution is entirely explained as the quadratic sum of the sampling and intrinsic resolution contributions. The constant term of 3.4% contributing to the hadronic energy resolution is similar to previous observations. Such a constant contribution is expected for calorimeters which are not fully compensating, that is, for calorimeters which do not have an equal response to electromagnetic and hadronic particles such that $(e/h)_{\text{intr}} = 1$. With the measured e/h ratio of the hadronic section of MIRAC (see below), the constant term contributing to the resolution is expected to be somewhat larger than observed. This may be due partly to the fact that a portion of the hadronic energy is deposited in the rather deep electromagnetic section which has a lower e/h ratio and, therefore, better hadronic resolution.

The ratio $(e/h)_{\text{intr}}$, which is the relative response of the calorimeter to electromagnetic energy as compared to purely hadronic energy, plays a crucial role in understanding the resolution achieved for hadronic showers. In practice, it is not possible to directly measure the intrinsic e/h ratio since the hadronic showers typically contain an electromagnetic component within the shower. The measured e/h ratios for the MIRAC are shown as a function of energy in Fig. 2.61 and tabulated in Table 2.10. They are shown for the lead-scintillator electromagnetic section and the iron-scintillator hadronic section. The ratios are obtained from the observed or extrapolated signals in which the energy of

Fig. 2.61. The ratio of electromagnetic to hadronic energy response as a function of incident momentum for the lead-scintillator electromagnetic section and the iron-scintillator hadronic sections of the mid-rapidity calorimeters.

Table 2.10. Momentum dependence of e/h ratio for electromagnetic and hadronic sections of MIRAC

Momentum (GeV/c) (PS calibration)	(e/h) _E	
2.	1.14 ± 0.06	
3.	1.20 ± 0.06	
4.	1.30 ± 0.07	
5.	1.18 ± 0.06	
6.	1.31 ± 0.07	
7.	1.21 ± 0.06	
8.	1.16 ± 0.06	
10.	1.18 ± 0.06	

Momentum (GeV/c) (X1 calibration)	(e/h) _E	(e/h) _H
4.	1.26 ± 0.06	
10.	1.12 ± 0.06	
20.	1.15 ± 0.06	1.39 ± 0.14
30.	1.19 ± 0.06	1.38 ± 0.14
40.	1.14 ± 0.06	1.55 ± 0.16
50.	1.09 ± 0.05	1.44 ± 0.14

the electron or pion is totally contained within the electromagnetic or hadronic section. The $(e/h)_E$ ratio is easily extracted for the electromagnetic section in which both electrons and pions leave sizeable signals, making the determination of the intercepts E^E and E^H straightforward. On the other hand, due to the fact that electrons typically deposit very little energy in the hadronic section, the extrapolation to deduce HE , the signal expected for an electron depositing all of its energy in the hadronic section, is rather uncertain with consequent uncertainty in extracting the $(e/h)_H$ ratio for the hadronic section. It was deemed reasonable to extract $(e/h)_H$ only for momenta of 20 GeV/c and above, where, on average, the incident electron deposits 5% or more of its energy in the hadronic section. The $(e/h)_H$ ratio is found to be about 1.4 for the hadronic section, in agreement with expectations for an 8-mm iron-3-mm scintillator sampling calorimeter. It is interesting to note that, although the e/h ratio is rather large as compared with other iron-scintillator calorimeters, the resolution obtained is nearly optimum due to the relatively small contribution from sampling fluctuations. The electromagnetic section $(e/h)_E$ ratio of about 1.25 is found to be in good agreement with the design calculations. The ratio is observed to have the expected energy dependence, decreasing at high energies due to the increasing electromagnetic component of the hadronic showers and at low energies due to the increasing contribution from ionization energy loss for the hadrons.

To prepare for the data-taking with the 200-GeV/nucleon ^{16}O beam in the SPS, it was determined from LUND model simulations that it was necessary to reduce the photomultiplier gains from the calibration gains by factors of from 2.5 to 50 depending on the pseudorapidity of the photomultiplier's tower. This was accomplished using the MIRAC laser calibration system by reducing the voltage on the photomultiplier until the laser peak was reduced by the required factor. Due to the very large extrapolation in the gain setting (a factor of

50 gain reduction) for the four innermost towers, it was deemed wise to verify the calibration of these towers during the heavy-ion run by directing the 60-GeV/nucleon ^{16}O beam into the center of each tower. For this calibration run the ^{16}O beam was fragmented upstream to produce the full range of $A = 2Z$ products from deuterons through oxygen at the same momentum/charge and at a reduced intensity of 10^6 /second. The total energy signal of the fragmented beam as measured in MIRAC for the beam incident on each of the four inner towers was found to be correct to within 5% after a factor of 50 extrapolation in gain from the calibration gain settings. It is also interesting that the resolution obtained in MIRAC for the ^4He , ^{12}C , and ^{16}O peaks, gated by identified charge in one of the WA80 beam counters, is $\sigma/E = 4.4\%$, 3.1% , and 3.2% , respectively. This is somewhat better than the hadron resolution values of $\sigma/E = 5.7\%$, 4.7% , and 4.6% expected, based on the calibration results obtained at lower incident energies.

FIRST HEAVY-ION EXPERIMENTS WITH THE WA80 SETUP

WA80 Collaboration

R. Albrecht ¹	I. Y. Lee
T. C. Awes	H. Lohner ²
C. Baktash	I. Lund ¹
P. Beckmann ²	F. E. Obenshain
F. Berger ²	A. Oskarsson ⁴
R. Bock ¹	I. Otterlund ⁴
G. Claesson ¹	T. Peitzmann ²
L. Dragon ²	S. Persson ⁴
R. L. Ferguson	F. Plasil
A. Franz ³	A. M. Poskanzer ³
S. Garpman ⁴	M. Purschke ²
R. Glasow ²	H. G. Ritter ³
H. A. Gustafsson ⁴	R. Santo ²
H. H. Gutbrod ¹	H. R. Schmidt ¹
J. W. Johnson	T. Siemiarczuk ¹
K. H. Kampert ²	S. P. Sorensen ⁵
B. W. Kolb ¹	E. Stenlund ⁴
P. Kristiansson ³	G. R. Young

During this reporting period, several years of planning and of equipment construction and calibration came to fruition when the first heavy-ion experiments at ultrarelativistic energies were performed at CERN. We present here a brief account of the CERN runs and a status report of the WA80 experiment.

The goals of WA80, as well as the experimental arrangement, have been described earlier.^{6,7} Elsewhere in this section we present results on transverse and longitudinal energy measurements in ^{16}O -induced reactions at 60 A GeV and 200 A GeV, together with estimates of the degree of nuclear stopping and of attained energy densities, and describe the performance of the calorimeters, which are the responsibility of the ORNL group.

The first production run with ^{16}O projectiles at 60 and 200 GeV/nucleon took place at CERN from November 19 to December 3, 1986. (In September 1986, a 3.2-TeV ^{16}O test beam was made available briefly in the North Area of the SPS. This test beam, however, was not available to WA80, which is located in the West Area.) Prior to the November run with heavy ions, proton reference data were obtained during October and early November. During this time most problems associated with the various detector systems were solved. One of the important questions remaining to be settled was the determination of calorimeter gains appropriate to operation with heavy-ion beams and consistent with earlier

1. Lawrence Berkeley Laboratory, Berkeley, California.

2. University of Lund, Lund, Sweden.

3. Adjunct research participant from the University of Tennessee, Knoxville, Tennessee.

4. "Status of the CERN WA80 Experiment," Phys. Div. Prog. Rep., Sept. 30, 1986, ORNL-6326 (March 1987), p. 120.

5. "Study of Nucleus-Nucleus Collisions at Relativistic Energies: CERN-SPS WA80 Experiment," Phys. Div. Prog. Rep., Sept. 30, 1985, ORNL-6233 (April 1986), p. 149.

6. "Experiment WA80," GSI preprint GSI-85-32 and CERN document CERN/SPSC/85-39; SPS 6/M 406, August 15, 1985.

7. H. H. Gutbrod et al., Proc. XV Int. Workshop on Gross Properties of Nuclei and Nuclear Excitations, Hirschegg, Austria, January 12-17, 1987, GSI and Institut für Kernphysik, Darmstadt, 1987, p. 42.

8. "Performance and Calibration of the WA80 Calorimeters," Phys. Div. Prog. Rep., Sept. 30, 1986, ORNL-6236 (March 1987), p. 126.

9. C. W. Fabjan and T. Ludlam, Ann. Rev. Nucl. Part. Sci. 32, 335 (1982).

10. R. Wigmans, Nucl. Instrum. Methods Phys. Res. A259, 389 (1987).

calibration measurements. In addition, the hardware transverse-energy trigger was improved with the installation of a new set of 1080 resistors in the ORNL-designed summing modules.

The first 160 particles were incident on the target during the night of November 19 to 20. At first, a number of particles with different Z values were observed in the Zero-Degree Calorimeter, which was used in the role of a "beam quality monitor." These turned out to be fragmentation products (e.g., carbon ions) from an improperly tuned beam line. In due course, a stable, well-focused beam with almost no halo was obtained. The beam was found to have a contamination level of less than 3%. Data-taking was initiated within 24 hours of the start of the run. The beam level at the WA80 setup was limited to less than 2×10^6 particles/SPS spill. In a prior agreement with other experiments sharing the beam, the projectile energy was 200 A GeV from November 19 to December 3 and 60 GeV/nucleon from December 3 until the end of the run on December 8. The beam-energy change-over was accomplished within three shifts.

Targets of Au, Ag, Cu, and C were used. Great care had been taken to keep all extraneous material out of the reaction zone, resulting in negligible background levels during target-out operation. Most of the data were accumulated with the Au target, although at least 500,000 events were obtained with each target at each energy. While some minimum-bias data were obtained, during most of the running time mainly central collision events were recorded. A total of 300 data tapes were generated during the run. First conference talks, using preliminary data, were presented in January 1987 at the meetings in Hirschegg⁷ and Bormio.⁸

The 160 run was considered to be a great success by all collaborations, with the exception of NA36, which did not have its equipment fully operational. The performances of the CERN, GSI, and LBL accelerator groups, which made the heavy ions available at CERN, were outstanding. The sustained smooth and reliable operation of the CERN accelerator complex with the new beam was very impressive.

From January to May 1987, intense activity was focused on the generation of programs, calibration constants, unfolding procedures, etc., needed for the conversion of the raw data tapes to data summary tapes (DSTs). The DSTs contain the results of transformations of such raw quantities as pulse heights, etc., to physical quantities such as energies. DST production requires a large amount of computing time. In the WA80 collaboration, only LBL and ORNL have a sufficiently large VAX-based computing capability to be able to handle the needs of DST production, and the task was split equally between the two institutions. DST tape production was performed during June and July at LBL and from late June through September at ORNL. At ORNL, DST production took place at the STC VAX cluster, using off-peak rates. The total ORNL cost for DST production was about \$75K. Various spectra and distributions were generated from the DSTs. These include transverse and longitudinal energy distributions (see separate contribution to this report), photon spectra, and multiplicity distributions. Correlations between various observables were also obtained. First WA80 results were presented in a series of four talks at the Quark Matter 1987 Meeting at Nordkirchen, West Germany, at the end of August.

In August 1987, 201-GeV proton beams were made available for the production of reference data. With the exception of the multiplicity arrays, the WA80 detector systems were essentially unchanged from their original configuration. The multiplicity arrays, however, had to be reconfigured after it was discovered that only data obtained with a double layer of streamer tubes were trustworthy. Thus, during the summer of 1987, modifications were made to provide double-layer coverage over the entire detection region, and not only in front of SAPHIR and the calorimeters. Due to start-up difficulties associated with the multiplicity arrays and due to a variety of other minor equipment problems, the proton data obtained during August were rather limited.

The second run with heavy ions, 6.4-TeV ^{32}S , took place in late September 1987. The start-up

with the sulphur beam was in no way as smooth as the start-up with the oxygen beam less than one year earlier. A major factor that contributed to this slow start-up was the low intensity of the sulphur ions, compared to the oxygen ions, produced by the source. In order to tune the SPS, accelerator operations decided to return to oxygen. This decision enabled us to obtain a small amount of data with the same conditions as those of the previous year. The operation with the sulphur beam never reached the high degree of stability that was achieved with the oxygen beam. However, the operation was satisfactory, and the statistics obtained with the four targets (Au, Ag, Cu, and Al) were adequate. Aluminum was chosen because its mass is close to that of sulphur, and the other three targets were used during the oxygen run.

Preliminary results from the sulphur run appear to be reasonable. The location of the shoulder in the transverse energy spectra for the Au target increases in energy, as anticipated, from 100 GeV with 160 projectiles to 160 GeV with ^{32}S projectiles. Preliminary indications are that charged-particle multiplicities also increase by a similar ratio. The estimated maximum energy density attained in central collisions, however, seems to be in disagreement with expectations based on the convolution models used by other groups. From the oxygen data, a value of approximately 2.7 GeV/fm^3 was deduced in the tail of the transverse energy distribution, where the yield has decreased to 0.1% of the yield on the plateau. The sulphur data yield a value of about 2.6 GeV/fm^3 in the same region of the spectrum. This result can be understood on the assumption that the transverse energy is generated in a volume corresponding to the overlap of the projectile and target, and provided that the transverse energy scales linearly with the number of participating baryons, as is suggested by our 160 results. Based on the convolution picture, a factor of two increase in the transverse energy is predicted as the projectile mass is increased from 160 to ^{32}S ; whereas, a factor of 1.6 (the change in the number of participating baryons) is, in

fact, observed. This important result is preliminary, pending further analysis.

Plans for 1988 and 1989 indicate that only 200-GeV protons are likely to be available in the first year, while sulphur beams may again be available in the second year.

1. Gesellschaft für Schwerionenforschung (GSI), D-6100 Darmstadt, West Germany.
2. University of Münster, D-4400 Münster, West Germany.
3. Lawrence Berkeley Laboratory, Berkeley, California 94720.
4. University of Lund, S-22362 Lund, Sweden.
5. Adjunct research participant from the University of Tennessee, Knoxville, Tennessee 37996.
6. Phys. Div. Prog. Rep., Sept. 30, 1985, ORNL-6233 (April 1986), p. 149 and Phys. Div. Prog. Rep., Sept. 30, 1986, ORNL-6326 (March 1987), p. 120.
7. H. H. Gutbrod et al., Proc. Int. Workshop on Gross Properties of Nuclei and Nuclear Excitations XV, Hirschegg, Austria, January 12-17, 1987, GSI and Institut für Kernphysik, Darmstadt, 1987, p. 42.
8. F. Plasil et al., Proc. XXV Int. Winter Meeting on Nuclear Physics, Bormio, Italy, January 19-24, 1987, University of Milano, Italy, 1987, p. 34.

ENERGY MEASUREMENTS IN OXYGEN-INDUCED REACTIONS AT 60 A GeV AND 200 A GeV

WA80 Collaboration

R. Albrecht ¹	I. Y. Lee
T. C. Awes	H. Lohner ²
C. Baktash	I. Lund ¹
P. Beckmann ²	F. E. Obenshain
F. Berger ²	A. Oskarsson ⁴
R. Rock ¹	I. Otterlund ⁴
G. Claesson ¹	T. Peitzmann ²
L. Dragon ²	S. Persson ⁴
R. L. Ferguson	F. Plasil
A. Franz ³	A. M. Poskanzer ³
S. Garpman ⁴	M. Purschke ²
R. Glasow ²	H. G. Ritter ³
H. A. Gustafsson ⁴	R. Santo ²
H. H. Gutbrod ¹	H. R. Schmidt ¹
J. W. Johnson	T. Siemiarczuk ¹
K. H. Kampert ²	S. P. Sorensen ⁵
B. W. Kolb ¹	E. Stenlund ⁴
P. Kristiansson ³	G. R. Young

The ultimate goal of the WA80 experiment is to search for the transition from hadronic matter to deconfined quark matter, referred to as the quark-gluon plasma (QGP). Such a transition may occur in the finite volume of hadronic matter that is formed with high energy density in very high-energy nucleus-nucleus collisions. At the

CERN SPS energies of 200 GeV/nucleon, it is estimated that the required critical energy density, believed to be between 2-3 GeV/fm³, may be reached in central collisions between nuclei, provided that the degree of nuclear stopping is high enough to concentrate a large fraction of the available c.m. energy at mid-rapidity. Thus, an important, immediate goal of the collaboration is to study the extent of stopping and to estimate the energy density that has been attained. The primary experimental quantity used for estimating the energy density is the transverse energy, E_T . We present here transverse energy measurements, together with energies measured at zero degrees. It is shown that, in nucleus-nucleus collisions at ultra-relativistic energies, the transverse energy appears, to first order, to be determined by the number of participating nucleons. Estimates of nuclear stopping and of attained energy densities are also presented.

The experiment was performed with the WA80 experimental arrangement at the CERN SPS. The setup includes two calorimeters: the Mid-Rapidity Calorimeter (MIRAC) and the Zero-Degree Calorimeter (ZDC). The design and construction of the calorimeters have been the responsibility of ORNL. Both the experimental arrangement and the calorimeters have been described earlier.^{6,7} MIRAC has full azimuthal coverage in pseudorapidity, η , from 2.4 to 5.5 and, in addition, covers approximately 10% of the azimuthal angles in the range $1.6 < \eta < 2.4$. The ZDC is located 11 m from the target and measures the energy of particles that pass through the beam hole in MIRAC. This hole has an inscribed cone angle of 0.3° , corresponding to $\eta > 6.0$. The ZDC is both a key component of the trigger system and an important measuring device from which the total energy of projectile spectators and/or of the leading particles is obtained.

An important aspect of high-energy nucleus-nucleus collisions is the nuclear collision geometry, as determined by the relative sizes of the target and projectile nuclei, the overlap volume in the collision, and the impact

parameter. As a consequence, simple geometrical considerations can be used as a key for a qualitative understanding of the ZDC energy spectra shown in Fig. 2.62. It is seen that at 200 A GeV the $^{16}\text{O} + ^{12}\text{C}$ reaction has essentially no cross section for events depositing a small amount of energy in the ZDC. This is because, in a simple participant spectator picture — even in the most central collisions — several projectile spectator nucleons, each with an energy of 200 GeV, proceed in the beam direction. In contrast to this, a pronounced peak is seen at small ZDC energies in the spectrum from the $^{16}\text{O} + ^{197}\text{Au}$ reaction. In this case, events with low ZDC energies result from central collisions in which the oxygen projectile is engulfed by the massive

Fig. 2.62. Energy spectra measured in the Zero-Degree Calorimeter (filled circles) in ^{16}O -induced reactions. Histograms give the results of the FRITIOF model.⁸ The vertical error bars represent statistical errors.

Au nucleus, resulting in the emission of only a few leading particles at angles less than 0.3° . Furthermore, in this case, a wide range of impact parameters gives rise to collisions in which the entire projectile interacts with a nearly constant number of target nucleons, thus producing the peak at low ZDC energies.

In going from 200 A GeV to 60 A GeV, the nucleon-nucleon c.m. rapidity decreases from 3.0 to 2.4. As a consequence, if there is no significant change in the reaction mechanism, the beam hole in MIRAC results in a more restricted ZDC coverage at the lower beam energy, and the measured integrated energy of the reaction products is correspondingly lower. This is clearly seen in the 60 A GeV $^{160} + ^{197}\text{Au}$ spectrum, which has an even more pronounced peak at the lowest energies. In the 60 A GeV $^{160} + ^{12}\text{C}$ reaction, there are many more events with low ZDC energies as compared to the 200 A GeV case. These events may originate from collisions in which the oxygen projectile fragments so violently that one or more of the projectile spectators has a pseudorapidity lower than 6 and is thereby intercepted by MIRAC.

In an effort to isolate characteristic features of nucleus-nucleus collisions (e.g., collective phenomena) from those that may be expected on the basis of nucleon-nucleon or nucleus-nucleus collisions, we compare measured quantities with calculations that reproduce data from nucleon-induced reactions and that make predictions for nucleus-nucleus reactions. While several models for this procedure are available, none has as yet been demonstrated to have clear advantages over the others. Consequently, we have chosen to make comparisons with the LUND model for high-energy nucleus-nucleus interactions (FRITIOF).⁸ Effects of detector acceptance and of trigger bias have been included in all FRITIOF calculations shown in this work.

The absolute cross section predictions of the FRITIOF model are shown as histograms in Fig. 2.62. At 200 A GeV, the ZDC energy spectra are well reproduced by the calculation; whereas, at 60 A GeV, FRITIOF underestimates the cross

sections, especially for the lighter targets. As discussed above, this discrepancy at 60 A GeV might be caused by projectile spectator fragmentation, which is not included in the FRITIOF model. The agreement at 200 A GeV indicates that the model provides a good description of the impact-parameter dependence of the longitudinal momentum transfer.

The transverse energy produced in the reaction is measured on an event-by-event basis in MIRAC. The transverse energy is calculated as $E_T = \sum E_i \sin(\theta_i)$, where E_i and θ_i are the observed energy and the effective angle of each element i of MIRAC, respectively. The transverse energy distributions for $2.4 < \eta < 5.5$ are shown in Fig. 2.63. As in the case of the ZDC spectrum, the shapes of the E_T spectra are dominated by effects of the nuclear collision geometry. The spectra for the heaviest nuclei, Ag and Au, show a large "plateau" extending out to 80-100 GeV at 200 A GeV beam energy and to 40-45 GeV at 60 A GeV. The Au spectra have a broad peak at the high-energy end of the plateau. This peak is closely correlated with the low-energy peak in the Au ZDC spectra, as can be seen from the contour plot of $d^2\sigma/dE_T dE_{ZDC}$ in Fig. 2.64. This correlation demonstrates that the peak in the E_T distribution, corresponding to low ZDC energies, originates from the most central collisions, in which the entire projectile interacts with a nearly constant number of target nucleons. As the target becomes smaller, the peak and the plateau become less pronounced. For $^{160} + ^{12}\text{C}$, the E_T spectra have shapes similar to those of the E_T spectra measured in proton-induced reactions.

At 60 A GeV the high-energy tails of the E_T distributions for Cu, Ag, and Au targets almost coincide with one another at a value of approximately 60 GeV. This phenomenon can be caused by "complete stopping." However, at our beam energies, this finding is more likely due to a combination of two opposing effects. As the target mass or number of target participants increases, the maximum transverse energy increases. At the same time, however, the rapidity of the effective c.m. system decreases,

ORNL-DWG 87-18601

Fig. 2.63. Transverse energy distributions measured in the pseudorapidity range of $2.4 < \eta < 5.5$ for 60 A GeV and 200 A GeV ^{16}O projectiles incident on targets of C, Cu, Ag, and Au. The experimental results (filled circles) are presented with their statistical errors. Histograms give the results of the FRITIOF model.

leading to decreased coverage by MIRAC. At 60 A GeV these two effects tend to cancel each other; whereas, at 200 A GeV the increase in E_T dominates over the decreasing coverage, resulting in a net increase of the observed transverse energy. This demonstrates that the precise shapes of the observed E_T spectra are a sensitive function of the pseudorapidity region in which they are measured. The histograms in Fig. 2.63 are the results of FRITIOF calculations. For all targets and projectile energies, the model gives a good description of the shapes of the E_T spectra but consistently underesti-

ORNL-DWG 87-18602

200 A GeV $^{16}\text{O} + \text{Au}$

Fig. 2.64. Yield distributions as a function of the transverse energy (for $2.4 < \eta < 5.5$) and of the energy measured in the Zero-Degree Calorimeter. The distance between the contours corresponds to a factor of two in yield.

mates the transverse energy scale in the tail region by 10% to 15%.

In view of the importance of the nuclear collision geometry, it is desirable to develop a simple method by means of which the impact parameter and the number of participating nucleons can be determined. Two alternative methods have been used to obtain an estimate of the average number of participating nucleons. First, since the ZDC data are reasonably well described by FRITIOF, the model has been used to establish a relationship between ZDC energies and the number of participants. Second, the average number of participants as a function of ZDC energy was deduced from a sharp-sphere model, on the assumption of a monotonic increase of the impact parameter with ZDC energy. The results from the two methods are consistent with

each other. With a relationship established between the total number of participants and the ZDC energy, the E_T distributions can be examined as a function of the number of participating nucleons. In Fig. 2.65 the average E_T per participant is shown as a function of the ZDC energy. This $\langle E_T/\text{participant} \rangle$ is calculated using the azimuthal-acceptance-corrected E_T measured in the pseudorapidity interval $1.6 < \eta < 5.5$ and the average number of participants corresponding to the observed ZDC energy. The striking feature of Fig. 2.65 is that, at a given bombarding energy, the $\langle E_T/\text{participant} \rangle$ remains nearly constant as a function of target

mass and decreases only slowly with decreasing collision centrality. Based on the above analysis, the transverse energies in central Pb + Pb collisions at 200 A GeV can be expected to be five to six times larger than those in $^{160} + ^{197}\text{Au}$ collisions. This does not, however, necessarily imply a higher energy density since the volume associated with the transverse energy production will be correspondingly larger.

The degree of nuclear stopping and the attained energy densities are two of the key quantities that relate to the probability of quark-gluon plasma formation. Estimates of these quantities based on our data are given here. Due to difficulties associated with a precise definition of "nuclear stopping," our stopping results are presented in terms of "mid-rapidity energy stopping," S_{mid} , defined as the ratio between $[dE_T(\text{experiment})/d\eta]_{\text{max}}$ and $[dE_T(\text{theory})/d\eta]_{\text{max}}$. The value of $[dE_T(\text{theory})/d\eta]_{\text{max}}$ is taken to be equal to half of the available center-of-mass energy $E_{\text{c.m.}}$, which is, in turn, estimated under the assumption that in central collisions all the projectile nucleons react with a cylinder of the target nucleus that has a base area equal to the cross section of the projectile. The systematics of S_{mid} are shown in Table 2.11. At 60 A GeV, S_{mid} is about 1/3, decreasing to only 1/4 at 200 A GeV. S_{mid} appears to be only very weakly dependent on the target mass.

At present, no generally accepted method exists for the determination of the energy density, ϵ , from experimental results. We estimate

Fig. 2.65. Average values of $E_T/\text{participant}$ as a function of the energy measured in the Zero-Degree Calorimeter. The pseudorapidity range used in the E_T determination is $1.6 < \eta < 5.5$. The dashed lines indicate the estimated systematic error limits.

Table 2.11. "Mid-rapidity energy stopping" for $^{160} + \text{C, Cu, Ag, and Au}$ at 60 and 200 A GeV

	60 A GeV	200 A GeV
C	31(3)%	21(2)%
Cu	32(3)%	26(3)%
Ag	35(4)%	26(3)%
Au	35(4)%	27(3)%

ϵ from the following formula, which is based on the work of Bjorken.⁹

$$\epsilon = \frac{1}{\tau_0 \pi R^2} \frac{dE_T}{dt}$$

Here τ_0 was taken to be 1 fm/c, and the sharp-surface electron-scattering value of 3.0 fm was used for R , the radius of ^{16}O . Rapidity was replaced by pseudorapidity, and an interval of $2.4 < \eta < 4.0$ was used. Values of ϵ obtained with this prescription, which is believed to underestimate true energy densities attained, were found to extend to 1.3 GeV/fm³ at 60 A GeV and as high as 2.7 GeV/fm³ at 200 A GeV, reaching, in this case, the region of energy densities that are believed to be required for the formation of the quark-gluon plasma.

1. Gesellschaft für Schwerionenforschung (GSI), D-6100 Darmstadt, West Germany.

2. University of Münster, D-4400 Münster, West Germany.

3. Lawrence Berkeley Laboratory, Berkeley, California 94720.

4. University of Lund, S-22362 Lund, Sweden.

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

6. R. Albrecht et al., *Phys. Div. Prog. Rep.*, Sept. 30, 1986, ORNL-6326 (March 1987), p. 120 and H. M. Gutbrod et al., *Proc. Int. Workshop on Gross Properties of Nuclei and Nuclear Excitations XV*, Hirschegg, Austria, January 12-17, 1987, GSI and Institut für Kernphysik, Darmstadt, 1987, p. 42.

7. R. Albrecht et al., *Phys. Div. Prog. Rep.*, Sept. 30, 1986, ORNL-6326 (March 1987), p. 126.

8. B. Andersson et al., *Phys. Scr.* 34, 451 (1986) and B. Nilsson-Almqvist and E. Stenlund, *Com. Phys. Comm.* 43, 387 (1987).

9. J. D. Bjorken, *Phys. Rev. D* 27, 140 (1983).

MISCELLANEOUS TOPICS

STUDIES OF THE CHANNELING CHARACTERISTICS OF 400 MeV/NUCLEON URANIUM IONS IN SINGLE CRYSTALS OF Si AND Fe

C. E. Bemis, Jr.	C. R. Vane
J. Gomez del Campo	H. Gould ¹
C. A. Ludemann	B. Feinberg ¹
N. Clayton ¹	

The initial channeling experiments as described previously,²⁻⁴ have been completed successfully at the Bevalac accelerator at Lawrence Berkeley Laboratory. We have

demonstrated and investigated the characteristics of transmission axial channeling of relativistic heavy ions, 112 MeV/nucleon Fe(+24) and 407 MeV/nucleon U(+88,+89,+90,+91 and +92), in the $\langle 110 \rangle$ axis of Si and alpha-Fe single crystals. For the U ions, both 110- and 370-micron-thick Si crystals and 100-micron-thick Fe single crystals were investigated. The channeling "signatures" were determined on an ion-by-ion basis using a brute-force collimated beam from the Bevalac, collimated to match the half-angle channeling acceptance of approximately 0.02 degrees. The uranium ions, accelerated as U(+40), were extracted and passed thru a selection of stripper foils of appropriate thickness and atomic number, chosen to optimize a particular emergent charge state. Magnetic analysis selected this charge state, and this beam was then passed thru a collimator assembly to achieve the desired angular divergence. Under optimum conditions, approximately 100 ions per Bevalac "spill," 1 spill every 6 seconds, were available for our experiments.

As a function of crystal orientation, we measured the magnetic rigidity of each ion using position-sensitive proportional detectors mounted in the focal plane of a large beam-analyzing magnet assembly (QQQD) which was operated as a spectrometer. Channeling characteristics for well channeled ions include a reduction in the energy loss (by a factor of 2-3), and a reduction in the electron capture and ionization from that experienced by unchanneled ions. As an example, we show in Fig. 2.66, the experimental histogrammed data for U(+89) ions transmitted thru a 110-micron-thick single crystal of Si for the crystal oriented for channeling in the $\langle 110 \rangle$ axis and, for a "random" crystal orientation. In this example, the effects are most dramatic because the highest yield emergent charge state for channeling is +89, the same as the incident charge state. For the "random" orientation, the emergent charge states are substantially higher. We are in the process of extracting the charge changing cross sections for U(+88-92) ions in channeling, where we expect the processes to be

Fig. 2.66. Experimental histogrammed transmitted ion intensity vs magnetic rigidity (channel number) for incident 407 MeV/nucleon U(+89) ions on a Si single crystal sample 110 microns in thickness. In the upper spectrum, the crystal sample is oriented for axial channeling along the $\langle 110 \rangle$ direction; in the lower spectrum, the crystal sample is oriented in a random direction.

simpler than those experienced by ions passing thru amorphous solids. In particular, we expect the dominant electron pickup or capture process to be radiative capture, and expect the dominant electron loss or ionization process to be electron impact ionization. These particular processes are thought to be the dominant processes because small impact parameter collisions with the crystal target atoms are suppressed in axial channeling.

In one aspect of our experiments, we attempted to demonstrate the pickup of polarized electrons for U(+92) ions channeled in the $\langle 110 \rangle$ axis of alpha-Fe single crystals. We placed our goniometer, and Fe single-crystal sample, at the center of an air-cored coil array where uniform magnetic fields of 500 gauss could be applied in a direction perpendicular to the beam direction. Magnetic fields of this strength are more than sufficient to fully saturate Fe samples thus aligning the magnetic domains which are normally "randomized" in orientation. In Fe single crystals of the type and thickness used here, fields of 500 gauss are more than sufficient to achieve alignment. The basic idea relies on the

expectation that polarized electrons would be picked up by the radiative capture process, preferentially in the uranium K shell, and that further pickup processes would be suppressed due to the Pauli principle. Thus the yield of emergent U(+90) ions in the presence of the applied external magnetic field would be lower than that in the absence of the applied external field. Model calculations indicated that this effect would be of the order of a few percent under our experimental conditions. Unfortunately, the statistical accuracy of our measurements was not sufficient to conclusively demonstrate this process. We have not addressed the magnitude of the electron "spin-flip" capture process which would mask the polarization effects as described above.

A brief description of these experiments has been presented.⁵

1. Lawrence Berkeley Laboratory, Berkeley, CA 94720.
2. H. Gould and C. E. Bemis, Jr., Bevalac Proposal #719H, "Polarized Hydrogenlike Uranium", Oct. 21, 1983 (unpublished).
3. C. E. Bemis, Jr. et al., *Phys. Div. Prog. Rep. for Period Ending Sept. 30, 1985*, ORNL-6233, p. 148 (1986).
4. C. E. Bemis, Jr. et al., *Phys. Div. Prog. Rep. for Period Ending Sept. 30, 1986*, ORNL-6326, p. 129 (1987).
5. H. Gould et al., *Bull. Am. Phys. Soc.* 32, 1244 (1987).

SEARCH FOR AXIONS FROM THE 1115 keV TRANSITION OF $^{65}\text{Cu}^1$

F. T. Avignone, III ²	W. C. Haxton ⁴
C. Baktash	D. Kahana ³
W. C. Barker ²	R. T. Kouzes ³
F. P. Calaprice ³	H. S. Miley ²
R. W. Dunford ³	D. M. Moltz ²

Two independent axion searches have been carried out near a well-shielded radioactive ^{65}Zn source (~ 15 kCi). One experiment used four NaI(Tl) scintillators to detect coincident photons generated in the decay $\alpha + \gamma\gamma$. The second used a shielded 145 cm³ low-background intrinsic Ge detector to detect single photons produced by axion "Compton" interactions with detector electrons and by Primakoff conversion off Ge nuclei and off Pb nuclei in the detector

shield. We determine general constraints imposed by these experiments on axions that couple to nucleons and to either the electron or two photons. In the case of light axions, the limits obtained in the second experiment are new. For the standard axion, we determine the ranges of f_ϕ and χ that are ruled out by our measurements.

-
1. Abstract of paper submitted to Phys. Rev. D.
 2. University of South Carolina, Columbia, South Carolina 29208.
 3. Princeton University, Princeton, New Jersey 08544.
 4. University of Washington, Seattle, Washington 98195.

INSTRUMENTATION

DEVELOPMENT OF ADVANCED CALORIMETERS

F. E. Obenshain G. R. Young

As part of the effort to prepare a proposal for a relativistic heavy-ion experiment at the BNL AGS accelerator and to develop needed in-house expertise with detectors that would be useful at the proposed RHIC collider at BNL, a program has been started to develop calorimetric detectors that significantly exceed the performance of those built for the CERN WA80 experiment. Two efforts will be pursued. One involves designing, constructing, and testing a sandwich-type calorimeter that is read out in several depth-segments by waveshifter plates that are themselves read out by waveshifter-doped optical fibers placed in grooves along the waveshifter plate edges. The second involves building a calorimeter made of alternating layers of lead and scintillating optical fiber. This has the nice property of bringing the scintillation light directly to its back face, where it can be viewed by a highly segmented readout device. The potential exists for a very fine grading of showers according to their transverse development. A grant of seed money from the ORNL Director's funds has been obtained in order to pursue this project.

COMPUTER NETWORK CONNECTIONS TO HEPNET/PHYSNET

C. E. Bemis, Jr.

The Physics Division at Oak Ridge National Laboratory conducts basic research, both experimental and theoretical, in Heavy Ion Nuclear Physics, Heavy Ion Atomic Physics, research in support of controlled fusion, is engaged in data compilation activities such as the Controlled Fusion Atomic Data Center and the Nuclear Data Project, operates the Holifield Heavy Ion Research Facility which is a national user facility, and has smaller programs in applications and in high energy physics. In addition, an accelerator design effort in support of the HISTRAP project is also performed by the Division staff. Physics Division staff members conduct research not only at our extensive facilities in Oak Ridge but also at other facilities throughout the world in collaborative efforts. As an example, staff members are in residence at CERN in Geneva for an international high energy heavy ion experiment, staff members have ongoing programs at other sites such as Brookhaven National Laboratory, Argonne National Laboratory, Lawrence Berkeley Laboratory, as well as at unique foreign accelerator facilities. Approximately 300 researchers from U.S. universities, other U.S. national laboratories and from non-U.S. institutes used facilities operated by the Physics Division at ORNL during FY 87. Thus the Physics Division's involvement with other institutions is extensive and requires external links for both communications and data exchange.

To improve the Division posture with respect to wide-area computer networking, which will support the various activities within the Division, a link between the Division's Vax computers and the DECnet portion of the High Energy Physics network, HEPnet, is being implemented. The DECnet portion of HEPnet is often called PHYSnet, and this network reaches most of DOE's national laboratories, many U.S. university sites, and provides international connections to similar sites outside the U.S. This network links the many "de facto" standard Digital

Equipment Corporation computers with the DECnet network protocol to provide file transfer capability, remote terminal access, communications between tasks running on different computers, utilize distributed data base techniques and to provide electronic mail communications. The Division's link will be provided initially by a leased synchronous data line to Fermi National Accelerator Laboratory, one of the central hubs for this network. Synchronous line communications equipment and a micro-Vax-II network server will complete the connection to the Division's DECnet'd computers, all of which exist on a segment of the Oak Ridge National Laboratory's baseband ethernet network. Our connectivity to HEPnet/PHYSnet, which provides minimal impact and security to the remainder of the ORNL network, has required careful planning and coordination and has been the most time-consuming aspect of this project. Our connection will be completed in November 1987.

PROCUREMENT OF ACP FARM

W. T. Milner G. R. Young

A severe need for more computing power in data replay has arisen over the past two years in the Division. This has arisen largely because of the program to upgrade the Spin Spectrometer with 17 Compton-suppressed germanium detectors and because of the program at CERN to study reactions of ultrarelativistic 160 and ^{32}S with nuclear targets. Both these experimental efforts generate several hundred magnetic tapes of raw data per run. The pre-scanning job alone for one experiment amounts to over 1 thousand hours of cpu time for a typical Spin Spectrometer run or over 10 thousand hours cpu (VAX 11/780 equivalents) for one CERN run. This seriously impedes our ability to analyze results of the experiments.

A neat solution to the problem has been developed over the past four years at Fermilab by the Advanced Computer Project (ACP) Group under Tom Nash. This is to recognize the inherent parallelism of the prescanning job and apply a multitude of microprocessors to the scan,

giving each processor one event at a time to analyze. The recent availability of 32-bit microprocessors operating at speeds in excess of 10 MHz has meant that a single board processor can be constructed, with processing power nearly equal to that of a VAX 11/780 at a cost of a few \$K. FNAL has developed such processors and related boards in the VME standard, together with needed software designed to run under a microVAX-II VMS host. The components of such a system can now be purchased commercially.¹

To alleviate the prescan problem, an initial small system of eight processors plus host and peripherals is being assembled. After some initial experience is gained, more processors will be added as Division resources permit, to expand the farm into the 100-processor range. The ultimate goal is to implement two or three such farms in a range of sizes, and have these run by hosts that are part of a Division-wide VAX cluster, so that peripheral resources may be shared. One farm will be developed with local high-speed I/O support using a cassette tape or optical disk to help with the other pressing problem in data reduction, that of scanning in order to prepare histograms from a large set of prescan output tapes. The associated software effort will involve porting the existing VAXPAK routines so that a user may link a given set of routines into either a VAX-based or a microprocessor-farm-based executable image in a transparent way. This will allow short test scans to be carried out on the VAX (or Concurrent) computers and the corresponding long jobs to be run directly on the farm with no changes to the user routines.

1. Omnibyte Corporation, West Chicago, Illinois.

EVALUATION OF 50-MM-DIAMETER PHOTOMULTIPLIER TUBES FOR BaF₂ SCINTILLATOR SPECTROSCOPY AND TIMING APPLICATIONS

J. L. Blankenship¹

Barium fluoride scintillator crystals emit both a fast-decaying component of light centered

at 220 nm and a slow-decaying component centered about 310 nm. Both light components require a quartz window on the photomultiplier tube. For fast coincidence timing applications, the photomultiplier tubes must have a risetime of less than 2 ns, and a transit time spread of less than 600 ns. Under such conditions, timing coincidence measurements of the ^{60}Co gamma rays have yielded 350 ps FWHM.

The slower decaying light constitutes about 90 per cent of the total emitted light. The energy resolution of BaF_2 equals or exceeds that of NaI(Tl) for energies above 2 MeV. Therefore, the photomultiplier tubes must have the gain stability as a function of both counting rate and time that is normally associated with tubes used with NaI . The decay time of NaI is 230 ns, and most photomultiplier tubes made for gamma ray spectroscopy have a modest pulse risetime, typically 10 ns. The fast-pulse-response tubes are typically used with fast plastic scintillators, where gain stability is not a problem. Good energy resolution also requires high photocathode quantum efficiency in the 200-350 nm wavelength region.

Several tubes from Amperex, Thorn-EMI, and Hamamatsu have been tested for the desirable properties described above. All tubes have risetimes of 2 ns or less. Some samples from each manufacturer have provided good energy resolution when used with BaF_2 , thus demonstrating good quantum efficiency in the emission range of interest, and have demonstrated good timing resolution. A very small number of tubes demonstrated good gain stability as a function of time and count rate changes. The Hamamatsu type R2059 has demonstrated the best stability characteristics up to this time. It is hoped that other vendors will modify their manufacturing processes to achieve gain stability comparable to that of the Hamamatsu tube.

PROGRESS ON HILI

D. Shapira	J. W. McConnell
H. Kim	R. Novotny ²
J. Mitchell ¹	K. Teh ³
	M. Hindi ⁴

Phase I of the HILI detector is now complete. The mechanical details were described in previous contributions.⁵⁻⁶ The HILI has been used in a study of the $\text{Ni} + \text{C}$ reaction. The signal processing and data acquisition are described in this contribution. The signal processing scheme for a single quadrant of the HILI detector is shown in Fig. 2.67. There are 48 ΔE -E channels from the phoswich scintillators as well as timing signals for horizontal and vertical position determination of heavy fragments stopped in the gas filled detector.

Processing this large number of signals is accomplished with a combination of CAMAC and FASTBUS modules. In the current setup, the CAMAC modules process signals from the heavy-ion detector and the MMPC. The FASTBUS modules are devoted solely to processing the plastic hodoscope signals. Among the reasons for adopting the FASTBUS standard are the low cost and high channel density. Other reasons involve special features available on the modules. The CAMAC leg of the data acquisition system services the high density data components; the FASTBUS handles the sparse component. Although there are 96 individual detectors in each hodoscope, it is expected that less than ten detectors will fire in any single event. The fast data transfer rate across the FASTBUS segment, coupled with the pedestal subtraction and zero compression features available on the LeCroy Segment Manager, is particularly suited for handling such data. Another problem the FASTBUS QDCs address is the different dynamic range of the ΔE and E signals from the phoswich detector. Since the light output is viewed with a single photomultiplier, the ranges cannot be adjusted separately. This problem is alleviated through the use of the high- and low-range feature on the LeCroy 1885 QDCs.

Data acquisition and processing at HHIRF is built around the Event Handler — a CAMAC based

1. Instrumentation and Controls Division, ORNL.

Fig. 2.67. Block diagram of signal processing scheme for HILI.

front-end processor. By retaining overall control of the HILI's data acquisition system in the Event Handler, access to the large amount of data processing software at the Holifield facility is maintained with the present system. Data read and stored by the FASTBUS Segment Manager is read into the CAMAC dataway by the Event Handler through a specially built memory lookup unit. Besides serving as the CAMAC-FASTBUS interface, the lookup unit also maps the geographical address field of the 32-bit FASTBUS word to the corresponding parameter tag in the LOO2 format used at HHIRF. The CAMAC-based processor is also used for further event selection and trigger. The HILI will see a large number of quasielastic events; these are events from 'soft' collisions and therefore, of limited interest. Such events can be scaled

down or rejected by converting a select number of parameters with fast ADCs (LeCroy 3551's). Based on the outcome, the decision to accept or reject the event is made within 25 microseconds. The data acquisition logic and the handshake between the Event Handler and the LeCroy Segment Manager is indicated on the flow chart shown in Fig. 2.68. A method for retrieving operational errors was also built into the processor software.

1. Yale University, New Haven, CT.
2. University of Giessen, West Germany.
3. Joint Institute for Heavy Ion Research.
4. Tennessee Technological University, Cookeville, TN.
5. D. Shapira et al., *Phys. Div. Prog. Rep.* Sept. 30, 1984, ORNL-6120, p. 114.
6. D. Shapira et al., *Phys. Div. Prog. Rep.* Sept. 30, 1985, ORNL-6233, p. 160.

Fig. 2.68. A chart showing the data acquisition logic and protocol.

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. Theoretical research performed by UNISOR staff and collaborators is described briefly in this section and in more detail in the Theoretical Physics Section of this report. Research and development activities at UNISOR by Physics Division staff members are included in the Nuclear Physics Section.

SEPARATOR DEVELOPMENT

M. L. Simpson ¹	J. Kormicki ²
H. K. Carter ¹	I. C. Girit ³
D. Abraham ¹	W. B. Newbolt ⁴

Testing begun last year of the new FEBIAD-B2 ion source was completed and the source was put into routine operation. The original design⁵ has been modified in order to be more compatible with the UNISOR separator. We have mounted all components of the ion source on the same mounting flange, in contrast to the original design. The construction of the new ion source incorporates a new arrangement for a test gas inlet and a mini-oven for evaporation of preselected calibration elements. The working conditions of the new source have been examined for both off-line and on-line modes. The source is now used routinely, having shown in all experiments very stable running conditions, long life-time, and high efficiency. In comparison to other sources used at UNISOR, the production rate was improved by a factor of 6 for ^{139}Sm and about 10 for ^{190}Hg and ^{185}Au . The source has been run for 14 shifts without failure, showing the significant source life-time improvement. Under development now is a UNISOR version of the storage-bunched version⁶ of this source.

Construction and installation of the new telemetry and control system (begun and reported in 1986) has been completed. The new system has been used in several on-line experiments, and linearity and reliability have been excellent. The modular design concept used has allowed needed modifications to be made with ease.

Development of a high-sensitivity beam profile monitor has been completed. This instrument uses a commercially available scanning-wire beam profile monitor, but a low noise preamplifier and a compensation circuit were designed to extend the range of the device down to 3.7 pA/cm^2 . In addition, a method was developed to make a measurement of the total beam intensity from the beam profile signal, thus allowing a constant, nondestructive measurement of the beam intensity.

Two new power supplies were developed which improved the operation of the FEBIAD-B2 ion source. An ion source magnet supply was designed which exhibited less than 0.05% current ripple at full load and shows excellent regulation stability with temperature and time. A current-regulated filament supply was also developed, which also exhibits low ripple and drift.

A current supply, which supplies current to the mini-oven described above, was designed and is now being tested. This supply will operate in a switching mode at 50 kHz and will use a MOS output stage to maximize efficiency at current levels above 60 A. Another use will be to provide single-shot, manually triggered, current pulses with an amplitude of 120 A and a rise time of less than 1 μ s. This feature will be used in a second approach to developing a storage-bunched version of the FEBIAD-82 source.

A lens control system for the nuclear orientation facility beam line was developed and is fully operational. This system consists of control circuits for an electrostatic quadrupole, a 50-kV electrostatic 90-degree deflector and an electrostatic x and y deflector. The quadrupole is powered by two +30 kV and two -30 kV Glassman switching power supplies. Each negative supply is the slave in a master/slave pair with one of the positive supplies. The x and y deflectors are powered by a positive and a negative 5-kV NIM power supply. Again, the negative supplies are slaved to the positive supplies. The 90-degree deflector is driven by a 50-kV Glassman switching power source. The control circuits for all the power supplies are remotely located at the separator control console, while the power supplies are located close to the beam line to minimize stored energy.

UNISOR NUCLEAR ORIENTATION FACILITY

I. C. Girit ¹	J. H. Hamilton ⁵
D. Abraham ²	B. D. Kern ⁶
G. D. Alton	P. F. Mantica ⁷
C. R. Bingham ³	C. A. Reed ²
H. K. Carter ²	M. L. Simpson ²
J. D. Cole ⁴	E. F. Zganjar ⁸

All of the hardware for the UNISOR On-Line Nuclear Orientation (NO) Facility was installed during this year and tests have been made on its performance. The UNISOR NO facility consists of three sections: the existing mass separator and the beam line to the refrigerator; the He₃/He₄ dilution refrigerator; and the data acquisition system. In the following, results of tests on each section will be described.

The beam line to the refrigerator installed this year is an addition to the horizontal central beam line of the mass separator and consists of a section for beam monitoring devices on the horizontal plane, a 90-degree electrostatic beam deflector (ED), a quadrupole triplet lens (QTL), and a system of x-y deflectors (XYD). The beam is monitored by low noise, particle beam scanners (PBS) and Faraday cups placed at several positions of the beam line. The beam size is controlled by an externally adjustable iris inside the vertical cold beam line. Because of the high background observed during an experiment with a radioactive beam, a fixed aperture in the 4°K beam line is being designed. After the separator's magnet, the beam is conditioned by two Einzel lenses and deflected 90° by the ED. This deflector is placed at 45 degrees to the horizontal beam line and consists of 7 parallel plates spaced one inch apart. A voltage equal to the beam acceleration voltage (50 kV) is applied to the bottom plate and degraded by 200 M Ω resistors to provide the necessary electric field. The horizontal beam is then focused by a quadrupole triplet working at approximately 18 kV. The focused beam can be further manipulated by a set of x-y deflectors. The actual position of the beam on the target foil is monitored by a special Faraday cup, consisting of three circular plates with varying apertures, which

1. UNISOR, Oak Ridge Associated Universities, Oak Ridge, Tennessee.

2. Vanderbilt University, Nashville, Tennessee.

3. Vanderbilt University, Nashville, Tennessee and Joint Institute for Heavy Ion Research, Oak Ridge, Tennessee.

4. Washington and Lee University, Lexington, Virginia.

5. R. Kirchner and E. Roeckle, Nucl. Instrum. Methods 133, 187 (1976).

6. R. Kirchner, O. Klepper, D. Marx, G.-E. Rathke and B. Sherril, Nucl. Instrum. Methods Phys. Res. A247, 265 (1986).

monitors the beam size. Using Faraday cups to monitor the beam, we are able to obtain > 90% transmission to the target position from the separator's focal plane.

The Oxford Instruments Model 400 helium dilution refrigerator was installed, after repairs necessitated by damage in transit. While initial performance tests by the manufacturer indicated a small problem in achieving the warranted base temperature of 6°mK, a more serious problem was discovered. When the baffles separating the refrigerator from the beam line were opened, the base temperature rose from 7.6° to 56°mK. The warranted temperature is 12°mK under these conditions. While the company has successfully made two other similar systems (more than three years ago), they have now discovered that the three systems currently being delivered have the same problem as the UNISOR system. Additional tests on the UNISOR system showed that the 77°K heat shields are not at 77°K but approximately 300°K. These heat shields and the beam lines have been returned for necessary modifications.

The $^{57}\text{CoFe}$ and $^{54}\text{MnFe}$ NO thermometer sources have been fabricated in our facility and a computer program written to monitor the temperature during the experiments. Results from these secondary thermometers were checked against the single crystal $^{60}\text{CoCo}$ thermometer and found to be consistent.

During the test experiments, up to four Ge or Ge(Li) detectors were used. When the polarizing field at the center of the magnet was 0.8 T, all of the intrinsic detectors were adversely affected; their resolutions deteriorated and they stopped functioning after prolonged exposure to the field. The reason for this effect is now thought to be the "Penning Discharge" of ions in the crystal enclosure of the detector. Two detector manufacturers are working on supplying detectors capable of operation in a 0.1-T field. Tests on the one detector supplied so far were encouraging. It appears that both manufacturers will be able to supply field-hardened detectors. We also have determined that operating at lower bias voltage enables

satisfactory operation, although at poorer energy resolution.

At this point, solutions to these problems appear imminent. After the modification of the shields and cold beam line, the refrigerator will be tested prior to the first on-line experiments. By this time, it is expected that the detectors will be sufficiently shielded against the magnetic field. A test on-line experiment with ^{189}Au showed that it is possible to attain a high degree of nuclear orientation with the UNISOR system when the above-mentioned problems are solved.

The first on-line experiment will be on ^{189}Au , which has been studied by the Leuven group. This test will allow us to compare results with a previous experiment and, because of our unique 3-angle detector arrangement, will allow us to obtain new information on the mixing ratios.

1. Vanderbilt University, Nashville, Tennessee and Joint Institute for Heavy Ion Research, Oak Ridge, Tennessee.

2. UNISOR, Oak Ridge Associated Universities, Oak Ridge, Tennessee.

3. Adjunct staff member from the University of Tennessee, Knoxville, Tennessee.

4. Idaho National Engineering Laboratory, EG&G Idaho, Inc., Idaho Falls, Idaho.

5. Vanderbilt University, Nashville, Tennessee.

6. University of Kentucky, Lexington, Kentucky.

7. University of Maryland, College Park, Maryland.

8. Louisiana State University, Baton Rouge, Louisiana.

DEVELOPMENT OF A LASER ION SOURCE FOR THE SEPARATOR

W. M. Fairbank, Jr.¹

S. M. Fischer²

G. A. Barrera²

J. P. Judish³

S. L. Allman³

H. K. Carter⁴

This summer experimental work was begun on the development of a laser ion source for the UNISOR separator. The main features of the source are: (1) stopping of fast recoils from the target in helium gas, (2) transport of the stopped atoms, through a capillary to an accumulation plate, (3) laser vaporization of the

deposited atoms, and (4) laser resonance ionization of the selected species at the entrance to the acceleration region of the separator.⁵ The use of laser vaporization and ionization is expected to allow almost any element to be studied, even the most refractory ones, since heating of the whole source is not required. Thus recent work on the Pb, Tl, Hg and Au group could be extended into the neighboring refractory group where shape coexistence and intruder ground states are expected.⁶

Previous experimental work at UNISOR has demonstrated a 50% efficiency for steps (1) and (2) of the process. The goal of the current work is to learn about steps (3) and (4), which are more complicated and less well-known. Eventually, we want to establish experimentally the predicted efficiency of 2-20% for steps (3) and (4), so that an overall efficiency of 1-10% can be demonstrated.

A simple time-of-flight mass spectrometer was adapted for laser ablation studies. Gridded electrodes allowed ablated ions to be accelerated, if desired, or suppressed when ablated neutral atoms were resonantly ionized by a second laser passing crosswise above the first grid. In the latter mode a mass resolution of 300 was achieved.

Initial studies of the ablation process were performed with a YAG laser at 1.06 microns, green and orange YAG-pumped dye lasers, doubled dye lasers and a XeCl excimer laser. Each laser had a pulse width of $\sim 10^{-8}$ sec and operated at 10 Hz. It was found, as expected, that the amount of ablation was a very steep function of the laser intensity. A twenty percent increment in pulse energy increased the ablation signal by more than an order of magnitude. The YAG and YAG-dye lasers produced very erratic ablation signals, probably due to varying hot spots in the beam. In contrast, the excimer ablation was remarkably steady, consistent with its uniform spatial profile. From the time spectra observed at low acceleration voltages, temperatures on the order of 4000°K were measured for both the ablated neutral atoms and the ions. All experiments were done with low energy densities of

0.5-3 mJ/mm² in order to avoid the complicating effects of plasma formation.

One interesting effect which we observed, but did not explore at length, was resonance enhancement of the ablated ion signal. When ablating indium with the doubled plus visible dye laser output, a ten times enhancement of the direct ablated ion signal was observed as the laser frequency was scanned through a UV resonance in indium. This effect has also been seen in France in a few other elements. It is conceivable that the proposed laser ion source could be simplified, based on this effect.

The major thrust of the last month of the summer was an attempt to establish an efficiency for the ablation and transverse resonance ionization process. Quantified In samples were prepared by depositing small drops of acid solution containing In on a tantalum foil. From the roughly calibrated counts recorded in time-of-flight mode, an efficiency of 6×10^{-6} was established.

In order to get a more reliable measure, 10^8 - 10^{11} atoms of radioactive ^{111}In or ^{115}In were deposited on a sample and the γ -ray activity counted. After the ablation experiment the count was repeated on the sample and the removable conversion dynode of the electron multiplier. We did prove that at least 75% of the In atoms could be ablated. However, the γ -counts of the conversion dynode were disappointingly low. With ^{115}In , an efficiency limit of $< 0.3\%$ was established. In a separate ^{111}In run, an efficiency of 3×10^{-6} may have been found, although ablated and nonionized neutral atoms could have been responsible for most of this signal.

During these experiments, each time the laser power was increased, very large and broad ion signals were observed, perhaps indicating plasma formation or space charge problems. It could be that most of the indium evaporated during these large pulses and was mostly lost. This problem may be exacerbated by the large amount of unidentified material deposited from the acid with the indium. We are constructing an apparatus in which further tests can be conducted by

the graduate students at Colorado State University. In addition to continued experiments with evaporated samples, tests are planned for samples deposited by a helium jet, which may be much cleaner.

1. DOE Faculty Research Participant, Colorado State University, Fort Collins, Colorado.
2. Colorado State University, Fort Collins, Colorado.
3. Health and Safety Research Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee.
4. UNISOR, Oak Ridge Associated Universities, Oak Ridge, Tennessee.
5. W. M. Fairbank, Jr. and H. K. Carter, "A Completely Cold Laser Ion Source for Separators," Nucl. Inst. & Methods Phys. Res. B26, 357 (1987).
6. J. H. Hamilton, "Structures of Nuclei Far from Stability," in Treatise on Heavy-Ion Science, Vol. 8, "Nuclei Far from Stability," ed. D. A. Bromley, Plenum Press (in press).

ENERGY LEVELS AND STRUCTURE OF LIGHT RARE-EARTH
NUCLEI. $^{136}, ^{138}, ^{140}\text{Sm}$. VIA BETA DECAY

B. D. Kern¹ E. F. Zganjar⁴
G. A. Leander² R. A. Braga⁵
R. L. Mlekodaj³ R. W. Fink⁵
H. K. Carter² C. P. Perez⁵
M. O. Kortelahti⁴ P. B. Semmes⁶
W. Nazarewicz⁷

A transition from spherical to deformed shape in increasingly neutron-deficient Sm and Nd isotopes with $N < 82$ has long been predicted on the basis of elementary shell structure considerations and was borne out by recent systematic measurements of yrast level energies in these nuclei. The detailed nature of this shape transition is of special interest for the study of nuclear structure in view of the unusual nature of the analogous shape transition in the Sm isotopes at $N > 82$. Deformed shell model calculations agree with the observation that experimentally available nuclear species with $50 < N < 82$ are softer with respect to triaxial gamma-deformation than their $N > 82$ counterparts.

The tandem accelerator at the Holifield Heavy Ion Research Facility provided beams that were used to produce radioactive ions through the $^{92}\text{Mo}(^{46},^{48}\text{Ti}, \text{ypxn})$ and $^{112}\text{Sn}(^{28}\text{Si}, \text{ypxn})$ reactions at energies from 170 to 250 MeV. The

radioactive ions were introduced into a high-temperature ion source and passed through the UNISOR mass separator. Also, in order to enhance the yields, He-jet measurements were carried out without mass separation. In both experimental arrangements, radioactive ions were transported on a continuous plastic tape from a collection point to a counting location which was situated between two Ge detectors. The counting time intervals were equal to the collection time intervals; these time intervals were varied from 5 to 75 s.

In this work, level schemes for the $N = 74$, 76, 78 isotopes of Sm were established by observing γ rays following the β decay of $^{136,138,140}\text{Eu}$, and for the $N = 72, 74, 76$ isotopes of Md, following the β decay of $^{132,134,136}\text{Pm}$. Gamma bands were observed in each nucleus. The level diagram of ^{136}Sm is shown in Fig. 3.1.

The potential energy of the β_2 , γ , and β_4 deformation was calculated using the triaxially deformed "Warsaw" Woods-Saxon potential.⁸ The potential-energy surfaces shown in Fig. 3.2 were calculated with a square lattice of 0.05 and at steps of 0.04 in β_4 . The contour line separation is 250 keV. Spectroscopic properties were calculated at the interpolated minima in β_2 , γ ,

Fig. 3.1. Partial level diagram of ^{136}Sm .

Fig. 3.2. Potential-energy surfaces in the β, γ quadrupole deformation plane.

84. Quadrupole transition moments, $B(E2: 2^+ \rightarrow 0^+)$ reduced transition rates, rotational moments of inertia with respect to the three principal axes, and the energy levels of $^{138,140}\text{Sm}$ were calculated. Details of these calculations will be available in a future publication.⁹

The prediction of triaxiality in this region was made by several workers.⁹ Here, in Fig. 3.2, the transition from a well-deformed prolate shape in ^{138}Sm to near-spherical shape in ^{142}Sm is seen to proceed via triaxial shapes in $^{138,140}\text{Sm}$.

The triaxial rotor Hamiltonian, without adjustment of parameters, reproduces the energies of levels of $^{138,140}\text{Sm}$ rather well (Fig. 3.3). The experimental energies of the lowest 2^+ states are compared in Fig. 3.4 with the "1-axial" values which are derived by cranking the nucleus around one axis, as is appropriate semiclassically or for an axial shape, and with the "3-axial" values which were obtained from quantal triaxial rotation. The triaxial theory fits the $^{138,140}\text{Sm}$ energies and the axial symmetry theory fits the ^{138}Sm energy. The energies of the 2_2^+ and 3_1^+ members of the γ band are reasonable. The states of spin 4 and higher are systematically lower in experiment than in theory due to the variable moment of inertia effect.

Fig. 3.3. Comparison between the experimental and calculated levels of the triaxial nuclei.

Fig. 3.4. Comparison between the experimental and calculated energies of the first 2^+ levels. The "1-axial" energies are those of a semiclassical rotor.

Finally, it is noted that the large change in the energy of the 2_1^+ levels between ^{134}Sm (163 keV) and ^{140}Sm (531 keV) can be understood since the triaxial rotation tends to increase the 2_1^+ level energy of ^{140}Sm .

1. University of Kentucky, Lexington, Kentucky.

2. UNISOR, Oak Ridge Associated Universities, Oak Ridge, Tennessee.

3. Environmental Compliance and Health Protection Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

4. Louisiana State University, Baton Rouge, Louisiana.

5. School of Chemistry, Georgia Institute of Technology, Atlanta, Georgia.

6. Joint Institute for Heavy Ion Research, Oak Ridge, Tennessee. Present address: Lund Institute of Technology, Lund, Sweden.

7. Joint Institute for Heavy Ion Research, Oak Ridge, Tennessee.

8. W. Nazarewicz et al., Nucl. Phys. A435, 397 (1985).

9. R. D. Kern et al., Phys. Rev. C 36, 1514 (1987).

ENERGY LEVELS OF LIGHT RARE-EARTH NUCLEI, $^{132}, ^{134}, ^{136}\text{Nd}$, VIA BETA DECAY

B. D. Kern ¹	R. A. Braga ⁵
G. A. Leander ²	R. W. Fink ⁵
R. L. Mlekodaj ³	P. B. Semmes ⁶
M. O. Kortelahti ⁴	W. Nazarewicz ⁷

Improved decay schemes have been constructed for the decay of $^{132}, ^{134}, ^{136}\text{Pm}$ to $^{132}, ^{134}, ^{136}\text{Nd}$ from data collected by means of He-Jet and mass separator experiments (Figs. 3.5-3.7). The gamma bands have been identified in each of the three daughter nuclei. The spin-parities of the gamma-band members in ^{136}Nd have been determined in an in-beam measurement.⁸ The spin assignments in ^{134}Nd are consistent with the observed gamma-ray intensities and with the systematic trends exhibited in ^{138}Nd and ^{136}Nd . The 823.5-keV level of ^{132}Nd is assumed here to be the 2^+ member of the gamma band.

In ^{132}Nd , the second 2^+ level is higher in energy than the 4^+ level of the ground-state band. This follows the trend, which can be observed in ^{138}Nd , ^{136}Nd , and ^{134}Nd , wherein the

Fig. 3.5. Partial decay scheme of ^{132}Nd . The level at 823.5 keV is assumed to be the 2^+ of the γ band.

Fig. 3.6. Partial decay scheme of ^{134}Nd .

Fig. 3.7. Partial decay scheme of ^{136}Nd .

2_2^+ level energy converges upward toward the 4^+ level energy.

1. University of Kentucky, Lexington, Kentucky.
2. UNISOR, Oak Ridge Associated Universities, Oak Ridge, Tennessee.
3. Environmental Compliance and Health Protection Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee.
4. Louisiana State University, Baton Rouge, Louisiana.
5. School of Chemistry, Georgia Institute of Technology, Atlanta, Georgia.
6. Joint Institute for Heavy Ion Research, Oak Ridge, Tennessee. Present address: Lund Institute of Technology, Lund, Sweden.
7. Joint Institute for Heavy Ion Research, Oak Ridge, Tennessee.
8. E. S. Paul et al., Phys. Rev. C 36, 153 (1987).

STUDY OF ODD MASS Pr, Nd, AND Pm NUCLEI IN THE $A = 135$ REGION

M. O. Kortelahti¹ R. A. Braga³
B. D. Kern² C. P. Perez³
R. W. Fink³ H. K. Carter⁴
J. Kormicki⁵

We have continued our study of the level structure of rare earth nuclei in the very neutron-deficient region around $A = 135$. In

addition to the $^{28}\text{Si}(190\text{--}210\text{ MeV}) + ^{112}\text{Sn}$ reaction, the $^{48}\text{Ti}(240,250\text{ MeV}) + ^{92}\text{Mo}$ reaction was also used. The produced activities were transported to the detection station either by a He-jet system or through the UNISOR mass-separator. In the case of the $^{48}\text{Ti} + ^{92}\text{Mo}$ reaction, the mass-separated activities were obtained with the FEBIAD-B2 ion source.

The assignment of different decaying isotopes was based on measured half-lives and on the observation of appropriate characteristic X rays in coincidence with γ rays. The level schemes were constructed based on γ - γ -coincidence data.

$A = 135$

The following γ rays were assigned to the decay of ^{135}Pm and are located in the level scheme of ^{135}Nd (energies are in keV and the γ intensities are in parentheses): 98.1(15), 128.7(135), 177.4(10), 190.3(8), 198.8(100), 208.0(122), 249.3(16), 270.1(124), 306.1(58), 342.0(27), 362.8(16), 366.8(8), 398.5(76) doublet, 409.1(21), 439.3(14), 463.8(60), 471.1(16), 514.0(5), 518.0(5), 627.5(3), 644.8(5), 713.2(22), 978.1(36), 1016.4(5), and 1158.2(4).

$A = 133$

The following γ rays are located in the level scheme of ^{133}Pr from the decay of ^{133}Nd (energies in keV and the γ intensities in parentheses): 59.2(10), 61.6(100), 104.9(64), 164.0(220), 197.0(27), 225.6(28), 250.4(21), 262.0(15), 367.0(18), 414.4(81), 476.7(22), and 637.3(4).

Further analysis is still in progress.

1. Louisiana State University, Baton Rouge, Louisiana.
2. University of Kentucky, Lexington, Kentucky.
3. School of Chemistry, Georgia Institute of Technology, Atlanta, Georgia.
4. UNISOR, Oak Ridge Associated Universities, Oak Ridge, Tennessee.
5. Vanderbilt University, Nashville, Tennessee.

DECAY OF ^{155}Pb TO LEVELS IN ^{155}Tl : TESTS OF PARTICLE-CORE COUPLING

C. R. Bingham ¹	J. L. Wood ⁴
H. V. Carmichael ²	M. O. Kortelahti ⁵
V. F. Janzen ²	E. F. Zganjar ⁵
L. L. Riedinger ¹	I. C. Girit ⁶
W. Schmitz ²	H. K. Carter ⁷
R. A. Braga ³	P. B. Semmes ⁸
R. W. Fink ³	R. L. Mlekodaj ⁹

By making two measurements in which Pb and Bi compound nuclei were formed, respectively, separate relative intensities were obtained for decays of both the $13/2^+$ isomer and the $(3/2^-)$ ground state of ^{155}Pb .¹⁰ The analysis of these decay data is almost complete and a decay scheme with 169 transitions between 89 levels has been constructed. Conversion electron coefficients were measured and compared with theoretical values to deduce the multipolarity of almost every transition observed. We are in the process of checking each deduced number for final publication.

The light Tl isotopes are in the middle of a region exhibiting a variety of nuclear structure properties, e.g., normal shell structure associated with the closed $Z = 82$ proton shell, coexistence of different nuclear shapes in single nuclei, and the intrusion of proton particle states across the closed shell gap. A majority of the levels observed in ^{155}Tl have spins and parities consistent with being a proton hole in a closed $Z = 82$ lead core. However, one strongly populated band apparently consists of configurations containing a proton in the $h_{9/2}$ orbital which lies above the $Z = 82$ energy gap of the spherical shell model. This band can be described by a model which couples a $h_{9/2}$ proton with a ^{154}Hg core, as will be discussed further, below. The $h_{9/2}$ single particle level is at an excitation of 482.7 keV and about forty additional levels decay through it. The remainder of the negative parity states consist of an $11/2^-$ state at 1361 keV, which decays with a high intensity to the low-lying $9/2^-$ state at 482.7 keV, and fifteen other states which have a significant direct feeding of the 1361 keV level. To some extent this pattern is characteristic of a weak coupling model in which a

$h_{11/2}$ proton hole is coupled to a spherical Pb core. Since Pb has a closed shell of protons, its ground state is believed to be spherical. Indeed, the first excited state in ^{196}Pb is 2^+ at an excitation energy of 1049 keV. However, recent conversion electron measurements on the decay of ^{196}Bi has revealed another 0^+ level in ^{196}Pb at an excitation energy of 1143 keV and the start of a band based on it, which suggests that this level is somewhat deformed.¹¹ Thus, if we consider an $h_{11/2}$ hole coupled to an excited ^{196}Pb core, seven ^{155}Tl levels should decay strongly with about 1-MeV γ rays to the 1361-keV level. Since we see 15 such states it is obvious that these levels mix with a number of other levels, the character of which we are still uncertain. Also, if the core were excited to the deformed 0^+ state, the transition from the resulting $11/2^-$ state to the 1361-keV level should have a large component of E0 strength. A strong E0 component was not apparent in any of the observed transitions. Of course, in analysis of conversion electron data, mixed E0 + E2 transitions could be misinterpreted as M1 or M1 + E2 transitions. Additional data are required to determine if that is the case here.

Frequently, states in odd-A nuclei are described in terms of a particle-core coupling model of Donau and Frauendorf. For the states observed in ^{155}Tl the cores would be in Pb and Hg. While we do not have a good model calculation for Pb, both IBA and triaxial rotor calculations have been utilized to describe light Hg isotopes. We have made calculations using the Donau-Frauendorf code in which $h_{9/2}$ protons were coupled to both IBA and triaxial rotor cores. The cores were described with parameters which fit the general structural trends in the light Hg isotopes. As shown in Fig. 3.8, both of these models do reasonably well in predicting energy levels in the $9/2^-$ band in ^{155}Tl . Several members of the band decay by more than one transition and thus relative branching through the various transitions provide another test of the calculations. The calculated relative intensities for a number of levels are compared with the experimental values in Table 3.1.

Fig. 3.8. A comparison of experimentally observed levels in the $h_9/2$ band with calculations utilizing the Donau-Fraendorf particle-core coupling model with triaxial rotor and IBA cores. The spin of the level labeled with an asterisk is uncertain but falls in the range of $9/2-13/2$.

Neither of these models reproduces the experimental relative intensities very well. Sample calculations were made in which protons in $h_{9/2}$, $f_{7/2}$, and $f_{5/2}$ orbitals were coupled to the IBA core. The second $9/2^-$ state was then predicted to be at 925 keV in much better agreement with experiment, but the second $7/2^-$ came at 1131 keV which is over 100 keV above the experimental value. The relative intensities between several band members are listed for this calculation in the last column of Table 3.1. The improvement in agreement with the experimental relative intensities is not striking. Mixing with other types of structure is probably necessary to achieve a good description of these states and transitions in ^{195}Tl .

1. Adjunct staff member from the University of Tennessee, Knoxville, Tennessee.
2. University of Tennessee, Knoxville, Tennessee.
3. School of Chemistry, Georgia Institute of Technology, Atlanta, Georgia.
4. School of Physics, Georgia Institute of Technology, Atlanta, Georgia.

Table 3.1. Comparison of experimental relative intensities with particle-core coupling calculations

Transition	I_{expt}	CORE* $^{19}\text{F}_2$		CORE* $(^{19}\text{F}_2 + ^{17}\text{F}_2 + ^{15}\text{F}_2)$
		I_{TR}	I_{IBA}	I_{IBA}
$13/2^- \rightarrow 9/2^-$	100	100	100	100
$\rightarrow 11/2^-$	49	3	5	13
$9/2^- \rightarrow 9/2^-$	100	100	100	100
$\rightarrow 11/2^-$	57	18	18	19
$\rightarrow 7/2^-$	16	2	1	14
$7/2^- \rightarrow 9/2^-$	100	100	100	100
$\rightarrow 11/2^-$	---	94	119	6
$\rightarrow 7/2^-$	---	2	4	16
$\rightarrow 5/2^-$	32	21	69	10
$\rightarrow 9/2^-$	---	---	1	1
$13/2^- \rightarrow 11/2^-$	100	100	100	100
$\rightarrow 9/2^-$	14	10	2	31
$\rightarrow 13/2^-$	---	4	3	1
$15/2^- \rightarrow 11/2^-$	100	100	100	100
$\rightarrow 13/2^-$	82	20	35	26
$17/2^- \rightarrow 13/2^-$	100	100	100	100
$\rightarrow 15/2^-$	51	3	5	8

5. Louisiana State University, Baton Rouge, Louisiana.

6. Vanderbilt University, Nashville, Tennessee and Joint Institute for Heavy Ion Research, Oak Ridge, Tennessee.

7. UNISOR, Oak Ridge Associated Universities, Oak Ridge, Tennessee.

8. Joint Institute for Heavy Ion Research, Oak Ridge, Tennessee. Present address: Lund Institute of Technology, Lund, Sweden.

9. Environmental Compliance and Health Protection Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

10. Phys. Div. Prog. Rep., Cont. 30, 1986, ORNL-6326, p. 151.

11. P. Van Duppen et al., Phys. Rev. Lett. 52, 1974 (1984).

POSSIBLE SHAPE COEXISTENCE IN ^{195}Pb

J. C. Griffin ¹	J. L. Wood ³
C. R. Bingham ²	M. O. Kortelahti ⁴
R. W. Fink ¹	H. V. Carmichael ⁵

Recently, additional low-lying states have been found in neutron-deficient even-even Pb isotopes other than the virtually pure single-particle states.⁶ These new states, found in $^{190}\text{--}^{198}\text{Pb}$, are excited 0^+ levels that descend in energy with decreasing neutron number, becoming the first excited state in ^{194}Pb . In ^{196}Pb , the associated 2^+ and 4^+ states have also been found^{6,7} in a pattern that appears more rotational than vibrational. These states and their associated band structure have been interpreted as deformed bands⁷ resulting from proton-pair excitations across the $Z = 82$ closed shell. These deformed bands are called shell-model intruder states⁸, and their presence in the even-even Pb nuclei implies shape coexistence similar to that observed in the singly closed shell even-even Sn nuclei ($Z = 50$).^{9,10}

The presence of these low-lying intruder states in the even-even Pb isotopes suggests the possibility of a new degree of freedom in the description of the low-energy structure of the neighboring odd-A Pb isotopes. Though the presence of low-energy intruder states in the neutron-deficient, odd-A Pb nuclei has not been observed previously, the close relationship in structure that exists between adjacent even- and odd-mass nuclei certainly indicates that such states should exist.

The lightest odd-A Pb isotope for which detailed experimental data are available on the single-particle states is ^{197}Pb .¹¹ The reported experimental data on ^{195}Pb are limited primarily to high-spin results from in-beam reaction studies.¹²⁻¹⁴ The information on low-energy states in ^{195}Pb is restricted to the placement of the $13/2^+$ level at approximately 200 keV, based on alpha-decay studies of $^{199}\text{m, gPo}$.¹⁵ The assignment of $3/2^-$ as the ground-state spin-parity is based on analogy with ^{197}Pb .

The present study of the decay of 180 s ^{195}gBi to excited states in ^{195}Pb was therefore undertaken to (1) map out the systematics of the single-particle states and (2) search for evidence of shape coexistence in a singly closed shell odd-A nucleus. Radioactive decay is the only way to study low-spin, low-energy states in nuclei far from stability.

The 180 s ^{195}gBi sources were produced via the $\text{natRe}(^{160}\text{O}, \text{xn})^{195}\text{gBi}$ reaction using 140-MeV ^{160}O ions from the MHIRF tandem accelerator. The natural Re target consisted of a stack of thin, self-supporting, Re-Mo alloy foils, with total thickness of 19.2 mg/cm², mounted inside the UNISOR version of the FEBIAD-F ion source, in which the target also serves as catcher. All data in the present experiment were acquired with a collection/counting time of 350 s. Time-sequenced singles γ -ray, ce spectra and yrt , xrt , and ce-yt coincidence data were acquired at two counting stations.

The transitions assigned to the decay of ^{195}gBi to ^{195}Pb are found to be divided into two major groups; transitions in each group show only coincidences among themselves, indicating that they belong to a band sequence not connected (or very weakly connected) to the other group. The first group of transitions are assigned to the negative-parity states (shown in Fig. 3.9), based on coincidences with the 134.6-keV ground-state transition and on energy sums. The second group of transitions observed are those we assign to the positive-parity states (Fig. 3.10). These transitions feed into the $i_{13/2}$ single-particle state, which is tentatively placed at 203.9 keV above the ground

Fig. 3.9. Decay scheme for $^{195}\text{Bi} \rightarrow ^{195}\text{Pb}$: negative-parity states.

Fig. 3.10. Decay scheme for $^{195}\text{Bi} \rightarrow ^{195}\text{Pb}$: positive-parity states.

state. An M4 transition has been observed in other neutron-deficient Pb isotopes between the $13/2^+$ and $5/2^-$ states ($^{197,199}\text{Pb}$), but no evidence was found for its presence in ^{195}Pb . We observe another transition, however, which appears to connect the positive- and negative-parity bands. This transition, a 499.4-keV

γ ray placed by coincidence as feeding the 830.3-keV negative-parity level (Fig. 3.9), is assigned E1 multipolarity based on its conversion coefficient.

A particularly interesting aspect of the positive-parity states (Fig. 3.10) is the presence of two highly converted transitions at

317.7 and 401.3 keV. The 317.7-keV transition has a K-shell conversion coefficient greater than expected for M3 transitions, while that of the 401.3-keV transition is greater than expected for M4 transitions. Since there is no evidence for the presence of high multipolarity transitions at these excitation energies in neutron-deficient, odd-A Pb isotopes, we assign the E0 + M1 + E2 multipolarity to both of these transitions.

These transitions at 317.7 and 401.3 keV are assigned, respectively, as transitions between $9/2^+(11/2^+)$ and $11/2^+(9/2^+)$ levels (see Fig. 3.10). The appearance of these transitions with an E0 component is a strong indicator for shape coexistence, suggesting that these are transitions from states arising from the coupling of the $i_{13/2}$ orbital to the deformed-band core states. The presence of transitions with an E0 component among the negative-parity states, indicative of a strongly deformed negative-parity band, is expected but not observed in the present work.

LOW-ENERGY E0 TRANSITIONS IN ODD-A NUCLEI: $180 < A < 200$

E. F. Zganjar¹ J. L. Wood²
M. O. Kortelahti¹ C. D. Papanicolaopolos²

Nuclei in the far-from-stability region between $78 < Z < 83$ and $104 < N < 109$ have been discussed by many authors (see, e.g., Refs. 3, 4) as the most extensive region known exhibiting coexisting nuclear shapes. We reported earlier on the observation in $^{185,187}\text{Au}$ ($Z = 79$; $N = 106, 108$) of a systematic pattern of bands interconnected with low-energy, very converted transitions.^{5,6} In contrast to other reports (e.g., Ref. 7), which indicated that the very converted cases were anomalous M1 transitions, we have clearly shown that these very converted transitions are entirely consistent with an E0 multipole component and that they closely match low-energy E0 transitions in the neighboring doubly even isotopes (see also "Very Converted Transitions in the Neutron Deficient Au Isotopes," Papanicolaopolos et al., this report). The systematic pattern of transitions with E0 components in ^{185}Au (and ^{187}Au , see Ref. 6) bears a close resemblance to E0 and E0 admixed transitions in the neighboring doubly even Pt and Hg isotopes which are considered cores for certain configurations in the odd-mass Au isotopes. This is shown in Fig. 3.11 for the case of ^{185}Au .

The $9/2^-$ state at 9 keV (see Fig. 3.11) is the proton $h_{9/2}$ particle (intruder) state. The particle character has the consequence that the appropriate core for this configuration in ^{185}Au is ^{184}Pt . The $11/2^-$ state at 220 keV is the proton $h_{11/2}$ hole state. The appropriate core for proton hole configurations in ^{185}Au is ^{186}Hg . A discussion of the coupling of these configurations to Pt and Hg cores for the case of ^{189}Au is given in References 8 and 9. The association between ^{185}Au states and ^{184}Pt , and ^{186}Hg states, shown in Fig. 3.11 by dashed lines, is suggested as reflecting the major components of the particle- and hole-coupled wave functions. Such a pattern of bands connected by low-energy transitions with E0 components is

1. School of Chemistry, Georgia Institute of Technology, Atlanta, Georgia.

2. Adjunct staff member from the University of Tennessee, Knoxville, Tennessee.

3. School of Physics, Georgia Institute of Technology, Atlanta, Georgia.

4. Louisiana State University, Baton Rouge, Louisiana.

5. University of Tennessee, Knoxville, Tennessee.

6. P. Van Duppen et al., Phys. Rev. Lett. 52, 1974 (1984); Phys. Lett. 154B, 354 (1985).

7. J. Penninga et al. in Nuclei Off the Line of Stability, Am. Chem. Soc. Sympo. Series 324 (1986).

8. K. Heyde et al. Phys. Repts. 102, 291 (1983); Nucl. Phys. A466, 189 (1987).

9. A. Baklin et al., Nucl. Phys. A351, 490 (1981).

10. N. G. Jonson et al., Nucl. Phys. A371, 33 (1981).

11. J. L. Wood, private communication (1986).

12. H. Helppö et al., Phys. Lett. 67B, 279 (1977).

13. H. Richel et al., Z. Physik A284, 425 (1978).

14. M. Pautrat et al., Phys. Ser. 34, 378 (1986); J. Phys. (London) G12, 1285 (1986).

15. R. E. Stone et al., Phys. Rev. C31, 582 (1985).

Fig. 3.11. (a): Portions of the $h_{9/2}$ and $h'_{9/2}$ bands in the ^{185}Au compared with the 0^+ and 0^+ bands in ^{184}Pt . (b): Portions of the $h_{11/2}$ and $h'_{11/2}$ bands in ^{185}Au compared with the 0^+ and 0^+ bands in ^{186}Hg . Only transitions with $\alpha_K > \alpha_K(M1)$ are shown. All energies are in keV. The numbers in parentheses following the transition energy are the ratios $\alpha_K(\text{expt})/\alpha_K(M1)$ theory for transitions where $I \neq 0$. The data are from Refs. 5, 6, 8, and 11. The $^{185}\text{m}, ^{186}\text{Hg}$ decay contains three 347-keV transitions and thus a multipolarity for the 1029 keV + 682 keV 347 keV transition (b) could not be determined.

suggested to reflect a new type of particle-core coupling in nuclei.

Low-energy transitions with E0 components between states with $I^\pi \neq 0^+$ are fairly common in doubly even nuclei. However, in odd-mass nuclei, low-energy transitions with E0 components are very rare; and even relaxing the low-energy criterion, they are still uncommon. In Table 3.2, we list (in increasing value by energy) all the cases known to us in odd-mass nuclei of low-energy transitions ($E < 430$ keV) with E0 components. While it is surprising that only 16 cases below 430 keV are known, one immediately notes that 13 of the 16 cases are odd-mass neighbors of the even-even nuclei $^{186-188}\text{Hg}$ and $^{184-188}\text{Pt}$. Low-lying (< 600 keV) excited 0^+ states are not commonly known in nuclei. We list all the cases known to us in Table 3.3. Note that all the isotopes listed in Table 3.2 are odd-mass neighbors of even-even nuclei listed in Table 3.3. Table 3.3 can be used to suggest other odd-mass candidates for low-energy E0 admixed transitions.

The unique occurrence of E0 and E0 admixed low-energy transitions in both even- and odd-mass-nuclei for $78 < Z < 80$, $104 < N < 109$, together with the systematic features for $^{185,187}\text{Au}$ observed at ISOCEL⁹ and UNISOR¹⁰,

Table 3.2. The lowest-energy transitions with E0 components known between low-lying levels in odd-mass nuclei. All known cases with $E_\gamma < 430$ keV are shown. The individual references are given in Reference 11.

Isotope	$E_\gamma(\text{keV})$	$E_i(\text{keV})$	I_i^π
^{185}Au	205	497	$5/2^+$
^{187}Pt	260	260	$3/2^-$
^{187}Pt	262	288	$5/2^-$
^{185}Au	281	515	$5/2^+$
^{183}Au	284	----not certain----	
^{185}Au	289	289	$5/2^-$
^{183}Au	297	----not certain----	
^{185}Au	313	322	$9/2^-$
^{195}Pb	318	1126	$11/2^+$
^{187}Au	323	444	$9/2^-$
^{185}Au	330	371	$3/2^+$
^{185}Pt	340	521	$3/2^-$
^{187}Au	388	742	$13/2^-$
^{195}Pb	401	1177	$9/2^+$
^{185}Au	427	648	$13/2^-$
^{231}Th	429	634	$7/2^-$

Table 3.3. The lowest first excited 0^+ states known in doubly-even nuclei. All known cases with $E_x < 635$ keV are shown. The individual references are given in Reference 11.

Isotope	E_x	Comments
^{98}Sr	215	
^{100}Zr	331	
^{184}Hg	375	
^{178}Pt	(422)	0^+ spin inferred
^{176}Pt	(433)	0^+ spin inferred
^{186}Pt	472	
^{184}Pt	492	
^{182}Pt	500	
^{180}Pt	(500)	estimate from systematics
^{186}Hg	522	
^{152}Gd	615	
^{230}Th	635	

leads us to propose a new type of multiple band structure in odd-mass nuclei (Fig. 3.11 for ^{185}Au). The essential features are: two bands interconnected by transitions with strong E0 components, a small (< 500 keV) energy separation between the bands, and the absence of well-defined strong coupling in the bands.

1. Louisiana State University, Baton Rouge, Louisiana.

2. School of Physics, Georgia Institute of Technology, Atlanta, Georgia.

3. J. H. Hamilton et al., Rep. Prog. Phys. 48, 631 (1985).
4. K. Heyde et al., Phys. Rep. 102, 291 (1983).
5. E. F. Zganjar et al., in *Nuclei Off the Line of Stability*, eds. R. A. Meyer and D. S. Brenner, ACS Symp. Series 324, page 245 (1986).
6. E. F. Zganjar et al., in *Nuclear Structure Reactions and Symmetries*, Vol. 2, eds. R. A. Meyer and V. Paar (World Scientific Publ. Co., Singapore), p. 716 (1986).
7. C. Bourgeois et al., Nucl. Phys. A386, 308 (1982).
8. C. D. Papanicolaopolus et al., J. Phys. G, preprint.
9. V. Berg et al., Nucl. Phys. A244, 462 (1975).
10. J. L. Wood et al., Phys. Rev. C14, 682 (1976).
11. E. F. Zganjar et al., Proceedings, Fifth International Conference on Nuclei Far from Stability, Rosseau Lake, Ontario, Canada September 14-19, 1987 (in press).

VERY CONVERTED TRANSITIONS IN THE NEUTRON DEFICIENT Au ISOTOPES

C. D. Papanicolaopolus¹ E. F. Zganjar³
 M. A. Grimm² M. O. Kortelahti³
 J. L. Wood¹ J. D. Cole⁴
 H. K. Carter⁵

Excited states of $^{185,187}\text{Au}$ have been studied through the mass-separated radioactive decay of $^{185\text{m},9}\text{Hg}$ and $^{187\text{m},9}\text{Hg}$. Gamma-ray and conversion-electron spectrum multiscaling and γ - γ -t, γ -x-t, γ -ce-t, and ce-x-t coincidence measurements were conducted on-line.

Decay schemes for the high-spin ^{185}Au and low-spin ^{187}Au β^+ /EC decays were constructed using γ - γ and γ -ce coincidence data. Because of the high γ -ray and conversion-electron line densities, great care was taken in separating multiplets. All assignments of γ -ray and internally converted transitions have been made on the basis of coincidence information. The major features seen in common with the in-beam spectroscopy studies^{6,7} are shown in Fig. 3.12. Our data are in substantial disagreement with the data of Bourgeois et al. for both ^{185}Au (Ref. 8) and ^{187}Au (Ref. 9).

The very converted transitions observed in the $^{185,187}\text{Au}$ -level schemes are shown as $\text{E0} + \text{M1} + \dots$ in Fig. 3.13. The 313-, 427-, and 429-keV transitions in ^{185}Au and the 323-, 388-, and 657-keV transitions in ^{187}Au all have

Fig. 3.12. The systematic features of low-lying states in $^{185,187}\text{Au}$ with $J > 9/2$ seen both in the decay of $^{185\text{m},187\text{m}}\text{Hg}$ (the present work) and by in-beam reaction spectroscopy (see Refs. 6 and 7).

$\alpha_K(\text{expt}) > \alpha_K(\text{M1})$. The locations of all transitions with $\alpha_K(\text{expt}) > \alpha_K(\text{M1})$, shown in Fig. 3.13, are consistent with $\Delta J = 0$. Thus, these α_K values can be interpreted as $\text{E0} + \text{M1}$, $\text{E0} + \text{M1} + \text{E2}$, or $\text{E0} + \text{E2}$. [The interpretation of the 313- and 323-keV transitions as high multipolarity ($\Delta L > 3$) would require that the parent levels be long-lived. This is excluded by prompt coincidences with feeding transitions (see Fig. 3.13) of 326 and 299 keV, respectively.] Bourgeois et al., however, have suggested⁸ that the occurrence of $\alpha_K(\text{expt}) > \alpha_K(\text{M1})$ might be due to abnormalities in the M1 internal conversion

Fig. 3.13. The band structures associated with the E0 enhanced transitions of 313, 427, 492 keV (^{185}Au) and 323, 388, 657 keV (^{187}Au). The level at 322 keV in ^{185}Au was not reported in Ref. 8, and the level at 444 keV in ^{187}Au was not reported in Ref. 9.

process. In their ^{185}Au level scheme, this abnormality was demanded for transitions of 321 and 330 keV which were assigned to de-excite a level at 330 keV to the $5/2^-$ ground state and $9/2^-$ first excited state, respectively (see Fig. 3.14). Clearly, E0 transitions to $5/2^-$ and $9/2^-$ final states cannot proceed from a single initial state. Thus, the 330-keV level was assigned by them to be $J^\pi = 7/2^-$, and the 321- and 330-keV transitions were assigned M1 multipolarity, albeit with $\alpha_K(\text{expt}) > \alpha_K(\text{M1})$. Consequently, while the spin assignments to the levels shown in Fig. 3.13 are consistent with the data, if the transitions with $\alpha_K(\text{expt}) > \alpha_K(\text{M1})$ are abnormally converted M1 transitions, they are not unique. For example, the 322-keV level in ^{185}Au could have $J^\pi = 7/2^-$ or $9/2^-$ (see Fig. 3.13).

Fig. 3.14. A portion of the level scheme of ^{185}Au showing the location of the 321- and 330-keV transitions from the 330-keV level. These transitions are discussed in the text.

A careful analysis of our γ - γ and γ -ce data shows that the 321- and 330-keV transitions, de-exciting the 330-keV level, both have $\alpha_K(\text{expt}) < \alpha_K(\text{M1})$. Evidently, the electron intensities assigned⁸ to the 321- and 330-keV conversion lines by Bourgeois et al. do not correspond to transitions de-exciting the 330-keV level (see Fig. 3.14). Multiplet structure is indicated for these lines. A detailed discussion of this will appear¹⁰ in a comprehensive article; however, it can be noted here that we find all transitions with $\alpha_K(\text{expt.}) > \alpha_K(\text{M1})$ in ^{185}Au (and ^{187}Au) to be consistent with $\Delta J = 0$ and thus consistent with the schemes shown in Fig. 3.13. Additionally, unique spin assignments can be made when one dispenses with the idea of abnormal M1 transitions.

1. School of Physics, Georgia Institute of Technology, Atlanta, Georgia.
2. Georgia Institute of Technology, Atlanta, Georgia. Present address: University of Louisville, Louisville, Kentucky.
3. Louisiana State University, Baton Rouge, Louisiana.
4. Idaho National Engineering Laboratory, EG&G Idaho, Inc., Idaho Falls, Idaho.
5. UNISOR, Oak Ridge Associated Universities, Oak Ridge, Tennessee.
6. A. J. Larabee et al., Phys. Lett. 169B, 21 (1986); and private communication.
7. M. A. Deleplanque et al., J. de Phys. 36, L205 (1975); and J. C. Waddington, private communication.

8. C. Bourgeois et al., Nucl. Phys. A386, 308 (1982).
 9. C. Bourgeois et al., Nucl. Phys. A295, 424 (1978).
 10. C. D. Papanicopolulos, J. L. Wood, E. F. Zganjar, and M. Kortelahti, to be published.

LOCATION OF THE EXCITED DEFORMED BAND IN ^{190}Hg

M. O. Kortelahti ¹	R. W. Fink ⁶
E. F. Zganjar ¹	J. L. Wood ⁷
C. R. Bingham ²	L. Chaturvedi ⁸
H. K. Carter ³	J. Kormicki ⁸
H. V. Carmichael ⁴	W. B. Newbolt ⁹
D. Brown ⁵	E. van Walle ¹⁰
K. S. Toth	

The early studies of the far-from-stability Hg isotopes $^{184}\text{--}^{188}\text{Hg}$ at UNISOR provide a classic example of the coexistence of bands of levels built on well-deformed and near-spherical shapes. This is summarized¹¹ in Fig. 3.15 where we have added the points (open circles) for the 0^+ , 2^+ , 4^+ and 6^+ members of the deformed band in ^{190}Hg . These studies as well as the hyperfine structure measurements on $^{180}\text{--}^{198}\text{Hg}$, which

Fig. 3.15. The energies of the spherical (solid lines) and deformed (dashed lines) states in $^{182}\text{--}^{198}\text{Hg}$. With the exception of the ^{190}Hg deformed energies, which come from this work, the remaining data is taken from Ref. 11. States above 6^+ in ^{190}Hg are not known since in-beam data is not available on that isotope.

showed that the very light odd-mass Hg isotopes ($A < 185$) become deformed in their ground state, are summarized in Ref. 11. Most theoretical calculations indicate that the near spherical shape is oblate and the well-deformed shape is prolate, although these oblate and prolate associations are not established experimentally.

Prior to this work it was believed that the deformed band suddenly appeared in ^{188}Hg . This view was supported by an earlier experiment¹² on the $^{190}\text{Tl} \rightarrow ^{190}\text{Hg}$ decay which did not observe the deformed states. However, no theory¹³⁻¹⁶ predicts the "sudden" appearance of a deformed band in ^{188}Hg . Indeed, the picture¹⁶ based on the promotion of a proton pair into the $h_{9/2}$ "intruder state" as giving rise to the deformed structure demands¹⁶ the existence of the deformed structure in ^{190}Hg as well, albeit at a significantly higher energy than that observed in ^{188}Hg . The correspondingly decreased Q-value is partly responsible for the failure to locate the deformed states in the earlier experiment.¹²

The earlier measurements¹² on the ^{190}Hg decay were done at a time when UNISOR beams were less intense and before the development of our present methods for e^- - γ - t spectroscopy which enable one to make precise measurements on even weak branches. Additionally, the present work utilized a reaction (^{160}W on ^{182}W) to produce ^{190}Pb rather than ^{190}Tl . The ^{190}Pb (0^+ ground state) β -decays predominantly to ^{190}Hg (2^-) which in turn preferentially β -decays to low-spin states in ^{190}Hg and thus enhances the population of the deformed band relative to the spherical band. This is in contrast to that of ^{190}mTl (7^+) decay which favors the high-spin members of the ^{190}Hg spherical ground band when ^{190}Tl is produced directly in the heavy-ion reaction.

Detailed γ - γ - t and γ - e^- - t spectroscopy was performed on the $^{190}\text{Pb} \rightarrow ^{190}\text{Hg}$ decay. While the full details of the decay scheme are presented elsewhere,¹⁷ the parts relevant to the specification of the deformed band are given in Fig. 3.16. In addition to the data presented there (see the caption), the $B(E2)$ branching ratios for intraband/interband transitions are $314 \pm$

Fig. 3.16. Portions of the ground state and deformed bands in ^{190}Hg obtained from the ^{190}Pb , $^{190}\text{Tl} \rightarrow ^{190}\text{Hg}$ decay. All energies are in keV. The numbers in parentheses represent the gamma-ray intensities. The numbers in brackets are the ratios $\alpha_{\gamma}(\text{expt})/\alpha_{\gamma}(\text{M1 theory})$ for the $I^{\pi} \rightarrow I^{\pi}$ transitions. These ratios demonstrate that the $I^{\pi} \rightarrow I^{\pi}$ transitions contain significant E0 strength. Transitions of 863 keV (1279 keV $0^+ \rightarrow 416$ keV 2^+) and 529 keV (1571 keV $2^+ \rightarrow 1042$ keV 4^+) are not shown for reasons of clarity.

20, 73 ± 15 , and > 323 for the 535/1468, 404/1559, and 292/1571 keV transitions respectively. The $^{184-188}\text{Hg}$ isotopes have recently been studied to spins of the order 24^+ (see e.g., Ref. 18). A variety of band crossings are observed, and it is therefore critical to obtain an understanding of the shape coexistence observed at low energy in these proton magic ($Z = 80$) nuclei. The present work, when added to the previous body of data, makes it clear that the promotion of two protons into the $h_{9/2}$ intruder orbitals gives rise to the shape coexistence observed at low energy in these nuclei.

1. Louisiana State University, Baton Rouge, Louisiana.

2. Adjunct staff member from the University of Tennessee, Knoxville, Tennessee.
3. UNISOR, Oak Ridge Associated Universities, Oak Ridge, Tennessee.
4. University of Tennessee, Knoxville, Tennessee.
5. Oregon State University, Corvallis, Oregon.
6. School of Chemistry, Georgia Institute of Technology, Atlanta, Georgia.
7. School of Physics, Georgia Institute of Technology, Atlanta, Georgia.
8. Vanderbilt University, Nashville, Tennessee.
9. Washington & Lee University, Lexington, Virginia.
10. Katholieke Universiteit Leuven, Belgium. Present address: Princeton University, Princeton, New Jersey.
11. J. H. Hamilton et al., Rep. Prog. Phys. 48 (1985).
12. C. R. Bingham et al., Phys. Rev. C14, 1586 (1976).
13. S. Frauendorf et al., Phys. Lett. 55B, 365 (1975).
14. P. D. Duval et al., Phys. Lett. 100B, 223 (1981).
15. A. F. Barfield et al., Z. Phys. A311, 205 (1983).
16. K. Heyde et al., Nucl. Phys. A466, 189 (1987).
17. M. O. Kortelahti et al., preprint.
18. A. V. Ramayya et al., Proc. Int. Symp. on Ion-Beam Nucl. Spect. (Budapest, 1984).

SYSTEMATICS OF THE LOW-LYING EXCITED STATES OF $^{185,187,189}\text{Au}$

M. O. Kortelahti¹ C. D. Papanicolaopolos³
E. F. Zganjar¹ M. A. Grimm⁴
H. K. Carter² J. L. Wood³

A remarkable similarity exists⁵ between the low-lying excited states of $^{189,191,193,195}\text{Au}$. This similarity persists into the lighter Au isotopes for near-yrast negative-parity states, a close resemblance being evident between the excited states of ^{189}Au (Ref. 6), ^{187}Au (Refs. 7, 8), and ^{185}Au (Ref. 9) populated by in-beam reaction spectroscopy. The decay schemes of the high-spin ($J^{\pi} = 13/2^+$) isomers of ^{189}Hg (Refs. 10, 11), ^{187}Hg (Refs. 12, 13) and ^{185}Hg (Ref. 14) agree well with the in-beam data where spin populations overlap. The limited information available on low-medium spin states in ^{189}Au and ^{187}Au (populated in the decays of low-spin ($J^{\pi} = 3/2^-$) ^{189}Hg and ^{187}Hg , respectively) suggests that this resemblance between ^{189}Au , ^{187}Au , and ^{185}Au should also persist for

low-spin states. However, this similarity is lacking in the ^{185}Au -level scheme of Bourgeois et al.¹⁴ Recently, a large isotope shift has been observed¹⁵ between ^{187}Au and ^{186}Au . The shift is consistent with a deformation $\delta = 0.25$ for ^{186}Au ; and a similar large deformation is also inferred for ^{185}Au . This sudden large change in the Au isotope shifts is comparable to the shift in the mercury isotopes (see, e.g., Ref. 16). These are the largest isotope shifts known anywhere on the mass surface. Thus, it is critical to clarify the low-energy details of the ^{185}Au -level scheme.

The excited states of $^{185,187,189}\text{Au}$ were studied through the mass-separated radioactive decay of $^{185\text{m}}\text{Hg}$ and $^{187\text{m}}\text{Hg}$, $^{189\text{m}}\text{Hg}$. Gamma-ray and conversion-electron spectrum multiscaling and γ - γ -t, γ -x-t, γ -ce-t, and ce- γ -t coincidence measurements were conducted on-line. Because of the high γ -ray and conversion-electron spectral line densities, all assignments of transitions are based on coincidence data.

Samples of the systematics of the excited states of $^{185,187,189}\text{Au}$ are shown in Figs. 3.17, 3.18, and 3.19. All spin parity assignments are deduced from our conversion electron data together with $^{\text{m}}\text{Hg}$ (high-spin) and $^{\text{g}}\text{Hg}$ (low-spin)

Fig. 3.17. The systematics of the bands built on the $h_{11/2}$ proton hole configuration in $^{185,187,189}\text{Au}$. Data are taken from this work and references are given in the text. (The $19/2^-$ states have only been seen in the in-beam studies.) The spin assignment in square brackets is suggested by these systematics. The spin assignments in parentheses are tentative.

Fig. 3.18. The systematics of the bands built on the $hg_{7/2}$ and $i_{13/2}$ proton particle configurations in $^{185,187,189}\text{Au}$. Only one state of each spin-parity is shown and states with $1 < 5/2$ are omitted. Data are taken from this work and referenced in the text.

Fig. 3.19. The systematics of the bands built on the positive-parity proton hole configurations ($s_{1/2}$, $d_{3/2}$, $d_{5/2}$) in $^{185,187,189}\text{Au}$. Data are taken from this work and references given in the text. In ^{185}Au the only agreement in 1^+ assignments between this work and Bourgeois et al.¹⁵ for these levels is the $1/2^+$ level at 24 keV.

beta decay feeding patterns. The excited states of ^{185}Au , established in the present work, differ in a major way from the scheme proposed¹⁴ by Bourgeois et al. The ^{185}Au positive-parity states shown in Fig. 3.19 were (with the exception of the $1/2^+$ state at 24 keV) assigned negative parity by Bourgeois et al. Conversely, states at 36, 259, 280, and 388 keV which we assign as negative parity, were assigned¹⁴ positive parity by Bourgeois et al. In the present

work, however, we have established key coincidences which unambiguously determines, via measurements of the corresponding α values, the correct assignments.

Evidently, the distinctive systematic patterns seen^{5,6} for bands in ¹⁸⁹Au and the heavier odd-mass Au isotopes persists in ¹⁸⁷Au and ¹⁸⁵Au. Most notable, the positive-parity states (Fig. 3.19) and the low-spin members in the $h_{11/2}$ band (Fig. 3.17) show smooth systematic behavior. Contrary to the ¹⁸⁵Au-level scheme of Bourgeois et al.,¹⁴ we find no significant departures in the low-energy systematics of this very neutron-deficient odd-mass Au isotope.

1. Louisiana State University, Baton Rouge, Louisiana.
2. UNISOR, Oak Ridge Associated Universities, Oak Ridge, Tennessee.
3. School of Physics, Georgia Institute of Technology, Atlanta, Georgia.
4. Georgia Institute of Technology, Atlanta, Georgia. Present address: University of Louisville, Louisville, Kentucky.
5. E. F. Zganjar et al., Phys. Lett. 588, 159 (1975).
6. Y. Gono et al., Nucl. Phys. A327, 269 (1979).
7. M. A. Deleplanque et al., J. de Phys. 36, L205 (1975).
8. J. C. Waddington, private communication, 1986.
9. A. J. Larabee et al., Phys. Lett. 169B, 21 (1975).
10. V. Berg et al., Nucl. Phys. A244, 462 (1975).
11. J. L. Wood et al., Phys. Rev. C14, 682 (1976).
12. C. Bourgeois et al., Nucl. Phys. A295, 424 (1978).
13. M. A. Grimm, 1978 Ph.D. Thesis, Georgia Institute of Technology.
14. C. Bourgeois et al., Nucl. Phys. A386, 308 (1982).
15. K. Wallmeroth et al., Phys. Rev. Lett. 58, 1516 (1987).
16. G. Ulm et al., Z. Phys. A325, 247 (1986).

STRONGLY COUPLED BANDS IN THE LIGHT Au ISOTOPES

C. D. Papanicolaopolous¹ M. O. Kortelahti²
J. L. Wood¹ E. F. Zganjar²
H. K. Carter³

Shape isomerism at low energy in the neutron-deficient even-even Pt and Hg isotopes is now well established. In the neighboring odd-mass

Ir, Pt, Au, Hg, and Tl isotopes, evidence for shape isomerism resulting from the even-even Pt- and Hg-core isomerism is almost unknown. In ¹⁸⁵Au, a strongly coupled sequence of levels is observed^{4,5} to feed the $h_{11/2}$ -decoupled band. This is shown in Fig. 3.20. No spin assignments were made in Reference 4. In ¹⁸⁷Hg a strongly coupled sequence of levels is observed⁶ to feed the $i_{13/2}$ -decoupled band. There is experimental evidence in both ¹⁸⁵Au (Ref. 7) and ¹⁸⁷Hg (Ref. 8) that the heads of these bands lie below the decay sequences seen in the in-beam studies.^{4,6}

We have observed a third example of this type of shape isomerism in ¹⁸⁵Au in studies of the decays of ^{185m}9Hg. The relevant part of the ¹⁸⁵Au decay scheme is shown in Fig. 3.21. A strongly coupled sequence of levels is evident. The level which constitutes the head of the band is not easily identified, but the low-energy E0 enhanced transitions (205 and 330 keV) are evidence⁵ that the 371- and 496-keV levels form the

Fig. 3.20. Portions of the $h_{11/2}$ structure in ¹⁸⁵Au as seen in decay and in-beam spectroscopy. All energies are in keV. The levels and transitions with energies to 0.1 keV are seen in decay spectroscopy.⁵ The upper levels with energies to 1-keV are seen only by in-beam spectroscopy.⁴ The 1209.4-, 682.3-, and 220.1-keV levels and the 527.1-keV transitions are seen both in-beam and in the ^{185m}9Hg decay.

Fig. 3.21. Continuation of the positive-parity band based on the 371- and 496-keV levels. All energies are in the keV. The numbers in parentheses following the 330- and 205-keV transition energies are the ratios $\alpha_k(\text{expt})/\alpha_k(\text{M1 theory})$. These ratios are given to show the E0 contribution to the transitions.

bottom of such a shape isomeric band. It is not yet clear, however, if it is the same band as that formed by the 559-, 683-, 861-, and 1014-keV levels. The existing data on these three examples of odd-mass core shape isomerism imply that the situation at low spin is complex, probably due to mixing. This is a new type of degree-of-freedom in odd-A nuclei and needs to be clarified further in order to facilitate the search for other cases.

1. School of Physics, Georgia Institute of Technology, Atlanta, Georgia.

2. Louisiana State University, Baton Rouge, Louisiana.

3. UNISOR, Oak Ridge Associated Universities, Oak Ridge, Tennessee.

4. A. J. Larabee et al., Phys. Lett. 169B, 21 (1986).

5. E. F. Zganjar et al., Proceedings, Fifth International Conference on Nuclei Far from Stability, Rosseau Lake, Ontario, Canada, Sept. 14-19, 1987 (in press).

6. F. Hannachi et al., Z. Phys. A325, 371 (1986).

7. E. F. Zganjar et al., in Nuclear Structure Reactions and Symmetries, Vol. 2, eds. R. A. Meyer and V. Paar, World Scientific Publ. Co., Singapore, page 716 (1986).

8. J. L. Wood et al., Bull. Am. Phys. Soc. 25, 739 (1980).

STUDY OF HIGHLY CONVERTED TRANSITIONS IN ^{185}Pt

J. Schwarzenberg¹ E. F. Zganjar³
R. W. Fink¹ M. O. Kortelahti³
J. L. Wood² E. van Malle⁴

Recently, it has been claimed that highly converted transitions in ^{185}Au (Ref. 5) and ^{185}Pt (Ref. 6) are anomalous M1 transitions, i.e., M1 transitions with "penetration" matrix elements that are 100 times anything observed previously. In earlier UNISOR experiments in the light Au isotopes (see "Very Converted Transitions in the Neutron Deficient Au Isotopes," Papanicolaopolos et al., this report), we showed that all the very converted transitions can be understood as occurring by the well-known E0 transition process. While our assignments were based on e- γ coincidence measurements, no such measurements were made in the previous work.⁵ A similar situation exists in ^{185}Pt , where the strong electron lines have been assumed⁶ to correspond to γ lines located by γ - γ coincidence measurements. The result is a decay scheme⁶ in which the highly converted transitions appear between states of different spin (implying the exclusion of the E0 process). Furthermore, the spins and parities in ^{185}Pt have been determined uniquely in a recent nuclear orientation study⁷ of the $^{185}\text{Au} \rightarrow ^{185}\text{Pt}$ decay. Thus, the situation in ^{185}Pt is similar to that which existed in ^{185}Au , with the more compelling factor that the spin and parity assignments are uniquely determined.

Clarification of the structure of ^{185}Pt is the crucial (structural) consideration that E0 transitions are a signature of shape coexistence. If states in coexisting bands are not

correctly assigned, any theoretical description is meaningless. Also, at present, there are no heavy odd-neutron nuclei in which bands of coexisting states have been established. (However, bands of coexisting states have been established in the odd-proton nucleus ^{185}Au at UNISOR.; Measurements on the multipolarity of these transitions in order to resolve this conflict has implications well beyond that of these Au or Pt nuclei.

The decay of ^{185}Au to ^{185}Pt and subsequently to ^{185}Ir has been studied via the $^{181}\text{Ta}(^{12}\text{C},8n)^{185}\text{Au}$ reaction at 140 MeV, using the UNISOR facility. The $\gamma\gamma$ and $\text{ce-}\gamma\gamma$ coincidences as well as the singles spectra were obtained. Our data feature excellent statistics (approximately 500 million coincidence events) and thus make possible a critical reassignment of the levels and transitions in ^{185}Pt , as well as in ^{185}Ir .

Preliminary results in the ^{185}Au to ^{185}Pt decay show strong disagreement in the assignment of the 542-keV transition which had been published as highly converted.⁵ Some strong lines crucial to the correct assignment of this transition had not been reported. The construction of the decay scheme is in progress.

Studies of the decay of the granddaughter ^{185}Ir are also being investigated. The superior amount of data obtained, compared to previous publications, provides many new transitions, in addition to the enhanced population of low-spin levels. A decay scheme is being constructed.

SPECTROSCOPIC MODEL ANALYSIS OF DATA ON ^{195}Tl AND ^{185}Au

P. B. Semmes¹

UNISOR measurements from the decay of $^{195}\text{Pb} \rightarrow ^{195}\text{Tl}$ have provided more data on the negative parity states; in particular, a few members of the $K=\pi=7/2$, $K=\pi=5/2$ and $K=\pi=13/2$ bands were observed in addition to the previously known $K=\pi=9/2$ band. These states, all expected in a triaxial rotor model, were then used together with previous quadrupole moment data² to pin down all the coupling parameters in such a description. It is then found that the calculations underestimate the observed $I+1 \rightarrow I-1$ relative transition rates in the $K=9/2$ band by a factor of 5-10. The experimental $M1/E2$ mixing ratios are not known well enough to indicate whether the difficulty lies in the $M1$ or $E2$ part, but it is interesting to note that similar difficulties in the $I+1 \rightarrow I-1$ $E2$ rates have been observed recently, e.g. in ^{157}Ho (Ref. 3).

The particle-triaxial rotor model was also applied to the low-spin negative parity states ($h_9/2$ bands) in ^{185}Au for which additional UNISOR data has become available. This nucleus is of particular interest due to the shape coexistence observed in studies both at low spin⁴ and high spin.⁵ Therefore, it is important to determine which shapes coexist, and which states can be correlated with a given shape. Furthermore, in the high spin work quoted above, a band assigned as predominantly (intruder) $f_{7/2}$ in character was observed, which led to new Nilsson parameters for proton orbitals in this region.⁶ Calculations with these proposed Nilsson parameters at a deformation of $\epsilon_2=0.23$, $\gamma=20^\circ$, indeed gave good agreement levels. In particular, very low $7/2$ and $3/2$ levels, a source of difficulty in Ref. 4 appear quite naturally with the new Nilsson parameters, and with large $f_{7/2}$ components (and thus can be identified as the low spin continuation of the $f_{7/2}$ band seen in Ref. 5. The recently measured magnetic moment of the $5/2$ ground state (+2.14

1. School of Chemistry, Georgia Institute of Technology, Atlanta, Georgia.

2. School of Physics, Georgia Institute of Technology, Atlanta, Georgia.

3. Louisiana State University, Baton Rouge, Louisiana.

4. Katholieke Universiteit Leuven, Belgium. Present address: Princeton University, Princeton, New Jersey.

5. C. Bourgeois et al., Nucl. Phys. A386, 308 (1982).

6. B. Roussiere et al., Nucl. Phys. A438, 93 (1985).

7. E. van Walle, Ph.D. Thesis, Katholieke Universiteit Leuven, Belgium (unpublished).

n.m.) is well reproduced (2.0 n.m. calc.) as is the $B(E2; 9/2 \rightarrow 5/2)$ ($1.25 e^2 b^2$ exp, 1.21 calc). However, there remain some difficulties concerning these low-lying states, e.g. the $B(E2; 3/2 \rightarrow 5/2)$ is underestimated by a factor of about 6 ($2.3 e^2 b^2$ exp, 0.37 calc), and the $3(M1; 7/2 \rightarrow 5/2)$ is overestimated by a factor of about 8 (0.0015 n.m. exp, 0.017 n.m. calc.). The asymmetry parameter has little effect on the low spin results, but mainly affects the higher spin states (15/2-21/2). Overall, the agreement is certainly improved with the proposed Nilsson

parameters, which in turn supports the $f_{7/2}$ assignment made by Larabee.⁵

-
1. Joint Institute for Heavy Ion Research, Oak Ridge, Tennessee. Present address: Lund Institute of Technology, Lund, Sweden.
 2. J. A. Bounds et al., Phys. Rev. Lett. 55, 2269 (1985).
 3. G. B. Hagemann et al., Nucl. Phys. A424, 365 (1984).
 4. C. Ekstrom et al., Nucl. Phys. A348, 25 (1980).
 5. A. J. Larabee et al., Phys. Lett. 169B, 21 (1986).
 6. J.y. Zhang et al., J. Phys. G13, L75 (1987).

4. EXPERIMENTAL ATOMIC PHYSICS

The experimental atomic physics program within the Physics Division is carried out by two groups, whose reports are given in this section. Work of the accelerator atomic physics group is centered around the 6.5-MV EN Tandem accelerator; consequently, most of its research is concerned with atomic processes occurring to, or initiated by, few MeV/nucleon heavy ions. Additional activities of this group are concerned with lower energy atomic collision physics in support of the Fusion Energy Program. These studies utilize the multiply charged ion beams obtained from an electron cyclotron resonance source. In addition to these two activities in experimental atomic physics, other chapters of this report describe the progress in related activities of these groups in theoretical atomic physics experimental, plasma diagnostic development, and atomic data center compilation.

ACCELERATOR-BASED ATOMIC PHYSICS

INELASTICITY AND ANGULAR DISTRIBUTIONS FOR CHARGE CORRELATED MULTIPLE IONIZATION OF Ne AND Ar BY C IONS¹

R. Schuch	H. F. Krause
S. Datz	P. D. Miller
P. F. Dittner	H. Schöne ²
R. E. Olson ³	

We have measured the energy loss of 10 MeV carbon projectiles (initial charge 3+, 5+, and 6+) associated with a given degree of multiple target ionization of Ne and Ar rare gas atoms. The projectile ions were analyzed by an Elbek high-resolution magnetic spectrograph.⁴ Using a two-dimensional position-sensitive channel-plate detector, placed in the focal plane of the Elbek, where the magnification is almost one, the energy loss of the projectiles could be determined in the plane of dispersion with a FWHM of 1.2 keV. In the direction perpendicular to the dispersion plane the projectile scattering angle could be determined from less than 0.01° up to about 0.4°, with a resolution of 0.005°. Different incoming and outgoing projectile ion charge states were selected in order to select target ion coincidences with single electron capture, single electron loss, or target ionization with no change in projectile charge.

The recoil ions were extracted from the interaction region by an electric field of about 300 V/cm and detected with channel plates. The recoil-ion charge states were determined by time-of-flight with the analyzed projectile ions supplying the starting time signal.

Unlike the case for pure target ionization, the recoil-ion charge distributions in coincidence with either capture or loss did not peak at $q = 1$. Instead, the distribution appeared binomial with a most probable charge of, e.g., 3+ for the Ne target. At the velocity in question, both capture and loss with, e.g., C⁵⁺ on a Ne target require small impact parameters well within the L-shell radius. Thus distributions similar to those observed in K-L X-ray satellite spectra should be expected.

The results clearly show an increasing inelasticity (Q-value) with increasing recoil-ion charge state and we found Q values which exceed by far the ionization potentials necessary for producing the respective recoil ions. This indicates a large loss of energy by multiple ionization to the continuum (average values reach approximately 200 eV/electron). The width of the angular distribution, W , increases with increasing recoil-ion charge state for a given projectile channel. Further, for a given recoil

charge state, W is larger for the electron loss or capture channels than for ionization. For fixed entrance and exit charge states of projectile and recoil ions, however, there is no change of Q -values observed with scattering angle (impact parameter).

1. Abstracts of Contributed Papers of the XV International Conference on the Physics of Electronic and Atomic Collisions, p. 433, July 22-28, 1987, Brighton, England.

2. Graduate student on assignment from the University of Heidelberg, Heidelberg, West Germany.

3. Department of Physics, University of Missouri-Rolla, Rolla, MO 65401.

4. J. Borggreen, B. Elbek, and L. Perch Nielsen, Nucl. Instr. Meth. 24, 1 (1963).

ELECTRON CAPTURE, IONIZATION, AND TRANSFER IONIZATION IN RAPID (0.1 - 1.0 MeV/NUCLEON) HIGHLY CHARGED ION COLLISIONS WITH HELIUM¹

S. Datz	H. F. Krause
R. Hippler ²	P. D. Miller
L. H. Andersen ³	P. L. Pepmiller
P. F. Dittner	T. Rosseel ⁴
H. Knudsen ³	N. Stolterfoht ⁵
C. R. Vane	

The interaction of bound-target atom electrons with the strong Coulomb field supplied by an oncoming highly charged ion has been a subject of considerable study. At low and medium velocities, if the ion is of sufficiently high charge, the binding energy match with the electrons in the target atom's outer shell leads to transfer into high n (Rydberg) states of the projectile ion. The large field also gives rise to large release distances and to multiple electron interactions. Scaling rules for single electron capture and ionization have been developed, but for two-electron processes the situation is not clear. An example is the case of "transfer" ionization (TI) where charge transfer is accompanied by additional electron loss from the target, i.e., are these two independent events or are they correlated? To determine the details of the transfer process and to test scaling models, we measured: (1) Cross sections for single- and double-charge transfer, transfer ionization, single and double ionization from He targets using I^{q+} ions ($q = 5+$ to $24+$) at ener-

gies of 0.1 and 0.25 MeV/nucleon, and U^{q+} at 0.25, 0.50, and 1.0 MeV/nucleon ($q = 17+$ to $44+$). These are compared with previous results from 0.1 MeV/nucleon Au^{q+} .⁶ (2) Zero-degree electron spectra in coincidence with transfer ionization for 0.25 - 1.0 MeV/nucleon U^{q+} on He. Our results are similar to those previously obtained for 0.1 MeV/nucleon Au^{q+} projectiles,⁷ i.e., the transfer ionization process leads predominantly to bound capture of a single electron accompanied by an electron released from the rest frame of the projectile ion with a velocity distribution similar to that observed for projectile ionization. In addition, projectile Rydberg electrons ($n > 500$) are observed in coincidence with bound charge capture (i.e., transfer ionization) indicating a possible correlation in the electron pair transfer mechanism in which one electron is transferred to a high n Rydberg state and the other to deeply bound states. (3) VUV photons in coincidence with single capture and with transfer ionization. Results here indicate charge transfer to lower n states with transfer ionization than with single capture.

1. Abstracts of Contributed Papers of the XV International Conference on the Physics of Electronic and Atomic Collisions, p. 439, July 22-28, 1987, Brighton, England.

2. Universität Bielefeld, Fakultät für Physik, Postfach 8640, 4800 Bielefeld 1, West Germany.

3. Institute of Physics, University of Aarhus, DK-8000, Aarhus C, Denmark.

4. Analytical Chemistry Division, ORNL.

5. Hahn-Meitner-Institut für Kernforschung Berlin GmbH, Bereich Kern- und Strahlenphysik, D-1000, Berlin 39, West Germany.

6. H. Damsgaard, H. K. Haugen, P. Hvelplund, and H. Knudsen, Phys. Rev. A 27, 112 (1983).

7. L. H. Andersen, M. Frost, P. Hvelplund, H. Knudsen, and S. Datz, Phys. Rev. Lett. 52, 518 (1984).

PARTIAL CROSS SECTIONS FOR CAPTURE TO SPECIFIC n STATES IN COLLISIONS OF 0.1 and 0.25 MeV/NUCLEON I^{q+} IONS WITH MOLECULAR HYDROGEN¹

P. D. Miller	P. F. Dittner
R. Hippler ²	H. F. Krause
S. Datz	P. L. Pepmiller

Experiments at Aarhus with highly charged gold ions (Au^{14+} at 0.1 MeV/nucleon) incident on

H_2 have demonstrated that electron capture to n states of the projectile in the range $n = 9 - 13$ takes place with partial cross sections in the range of $\sim 10^{-16} \text{ cm}^2$ [Ref. 3]. A number of calculations have been made at this energy for charge $14+$ ions colliding with atomic hydrogen. Qualitatively, these results were in better agreement with classical-trajectory Monte Carlo (CTMC) calculations⁴ and the calculations of Ryufuku and Watanabe⁵ (RW), than they were with OBK or the eikonal model.⁶ The observed cross sections were, however, smaller than any of the calculations by factors ranging from 2 to 20. If the measured cross sections were to drop steeply for low n , the sum of the partial cross section would be much less than the total charge-transfer cross section. For the case in question, the OBK and eikonal calculations predict that the partial cross sections σ_n should have a maximum at $\sigma_n = q = 14$. The CTMC and RW calculations predict a maximum of σ_n at $n = q^{2/3}$ (8 or 9). The Aarhus measurements spanned the range $n = 10 - 13$, and were monotonically decreasing with n .

We have extended the measurements to lower n values to investigate the question of whether these partial cross sections do indeed have a maximum in the vicinity of $n = q^{2/3}$. A VUV spectrometer (McPherson 234) was equipped with a gas cell and a channeltron to detect photons in the wavelength range 40 - 120 nm. Cascade contributions were subtracted using lifetimes and transitions probabilities from Lindgard and Nielsen⁷ and Bethe and Salpeter.⁸ Partial cross sections, for populating these higher cascading states, were taken from Ref. 3 in correcting the 0.1 MeV/nucleon data; the 0.25 MeV/nucleon data were corrected assuming σ_n proportional to n^{-3} .

An example of our experimental results for I^{14+} incident on H_2 at 0.1 MeV/nucleon is shown in Fig. 4.1. The projectile velocity was too low for a good comparison of the data to the OBK or eikonal calculations. The magnitudes of the partial cross sections are in good agreement with the CTMC calculations, but a smooth curve drawn through the present data and the Aarhus data is much steeper than any of the theoretical

Fig. 4.1. Partial cross sections for capture of an electron into specific n states by 0.1 MeV/nucleon $14+$ ions incident on H_2 . Present experimental results for I^{14+} are given by the solid circles. The results from Ref. 1 are shown by open circles. The dashed line is a guide to the eye. The theoretical curves are: — [Ref. 5], $\triangle$ — $\triangle$ [Ref. 4], — — — [Ref. 6], and — — — — — [OBK].

calculations. Three factors should be considered in comparing these data with calculations:

- (1) The calculations were done assuming bare ions. However, for capture into Rydberg states, the effect of an ionic core has been shown to be small.
- (2) The calculations were made for an atomic hydrogen target, instead of H_2 . Since the total-capture cross sections for H and H_2 are nearly equal, one may argue that a valid comparison can be made.
- (3) The experimental measurements include not only single-electron transfer but also contributions from the two-electron process of transfer ionization. Such contributions are known to be substantial for the case of an He target.⁹

The separation of the n -dependence of these two processes is an important subject for future experimental and theoretical investigations.

1. Abstracts of Contributed Papers of the XV International Conference on the Physics of Electronic and Atomic Collisions, p. 522, July 22-28, 1987, Brighton, England.

2. Universität Bielefeld, Fakultät für Physik, Postfach 8640, 4800 Bielefeld 1, West Germany.

3. P. Hvelplund et al., Phys. Scripta T 3, 176 (1983).

4. R. E. Olson, Phys. Rev. A 24, 1726 (1981).

5. H. Ryufuku and T. Watanabe, Phys. Rev. A 21, 745 (1980).

6. J. Eichler and F. T. Chan, Phys. A 20, 104 (1979).

7. A. Lindgard and S. E. Nielsen, Atomic Data and Nuclear Data Tables 19, 533 (1977).

8. H. A. Bethe and E. E. Salpeter, Quantum Mechanics of One- and Two-Electron Atoms, Plenum, New York (1977).

9. L. H. Andersen et al., Phys. Rev. Lett. 52, 518 (1984).

ATTEMPTED MEASUREMENT OF DIELECTRONIC RECOMBINATION VIA A $\Delta n = 1$ TRANSITION

P. F. Dittner	P. D. Miller
S. Datz	P. L. Pepmiller
H. F. Krause	C. M. Fou ¹

Using the previously described apparatus and technique,² we have extended our investigations of dielectronic recombination (DR). Our published results for Li-like, Be-like, and Na-like ions and the results (unpublished) for B-like ions are all DR via $\Delta n = 0$ transitions, i.e., the core excitation accompanying electron capture is either $2s-2p$ or $3s-3p$. These DR cross sections, $\sigma(0)$, all have one common feature: the largest contribution occurs for electron capture to high n -values of the final state. The $\sigma(0)$ of the high n -states is field dependent, making comparison with calculations more difficult, since the magnitude of the electric field is not well known, nor is it spatially uniform in our interaction region.

DR cross sections involving a $\Delta n = 1$ transition, $\sigma(1)$, have large contributions for low or intermediate n -states which are much more insensitive to the field in the interaction region,

thus providing a better test of the calculations. However, the magnitude of the $\sigma(1)$'s are much smaller than the field enhanced $\sigma(0)$'s making the experiments much more difficult. We have previously attempted to measure DR in Ne-like Cl^{17} but the high background from slit-edge scattering has obscured the expected signal. In order to decrease the background, we have changed the ion to P^{+5} . The DR process involved can be written as,

where $n\ell$ are the quantum numbers of the captured electron. The measured rate, v_d , should have prominent peaks³ when $n\ell = 4d$ and $4f$ at a relative energy of about 130 eV and for very high n -values at a relative energy of about 160 eV. The results of our efforts are summarized in Fig. 4.2 where we plot the DR rate v_d versus the relative energy. The error bars shown are relative errors only. The solid curve is a fold of our relative energy distribution with

Fig. 4.2. Solid points are the experimental data with typical relative error bars shown for a few points. The solid curve is a fold of our relative energy distribution with arbitrary amplitude σ 's but located at the expected relative energy.

arbitrary amplitude σ 's but located at the expected relative energy. Theoretical results of the P^{+5} DR σ which are expected shortly will be compared with our measurements.

In order to increase our confidence in the peaks observed, we have proposed a new experiment utilizing the WHIRF to supply Cl^{+7} ions at much higher energies than are available at the EN tandem. The increased laboratory energies should decrease the background and decrease the uncertainty of our measurements.

1. Department of Physics, University of Delaware, Newark, DE 19711.
2. For the experimental apparatus and procedure, see pp. 134-135 in *Phys. Div. Prog. Rep.*, Sept. 1984, ORNL-6120.
3. Y. Hahn, private communication.

RESONANT TRANSFER AND EXCITATION CROSS SECTION MEASUREMENTS OF THE SYSTEM $F^{6+} + H_2$

M. Schulz R. Schuch
S. Datz P. D. Miller
 H. Schöne¹

We have measured the energy dependence of the resonant transfer and excitation (RTE) cross section for Li-like F^{6+} ions on H_2 . Using the ORNL EN tandem, we covered the energy range from 15 MeV to 33 MeV. The K-X rays produced by the decay of excited projectile states were detected by two gas proportional counters, each in coincidence with the charge exchanged projectile ion. The results shown in Fig. 4.3 have a defined maximum for the cross section at about 24 MeV and are in agreement with the calculated RTE cross section for the KLM-resonance. Non-resonant transfer and excitation (NTE), which is not distinguishable from RTE in this X-ray-particle coincidence experiment, is expected to be consistently less than 25% of RTE in this energy region. The various KL_n ($n = 2, \dots, \infty$) resonances (indicated by arrows) cannot be resolved because of the Compton broadening by the target electron energy profile. A surprising result is the shoulder in the energy region of 27 - 31 MeV; it fits the position of the Kmn ($m, n > 3$) resonances. Estimated cross section

Fig. 4.3. Energy dependence of the transfer and excitation (TE) cross section for F^{6+} incident on an H_2 target. The arrows labeled KXY indicate the resonant energies for electron impact excitation of K electron and simultaneous capture of the exciting electron into states X and Y.

values for Kmn resonances are much too small to fit the data. A new transfer and excitation process eTE ,² in which one of the target electrons excites the electron originally bound to the projectile and a second electron is captured, has been proposed. This process could contribute to transfer plus excitation mechanisms in this energy region and makes further studies on similar systems desirable.

1. Graduate student on assignment from the University of Heidelberg, Heidelberg, West Germany.
2. Y. Hahn, private communication.

HIGH RESOLUTION SPECTROSCOPY OF HEAVY-ION INDUCED X RAYS

C. R. Vane S. Raman
T. Walkiewicz¹ S. Kahane³
T. Rosseel² S. Stewart⁴

In ongoing studies of environmental effects on X rays emitted from chemically complex targets under heavy-ion impact, we have measured complete aluminum K-X-ray spectra from a variety of aluminum alloys and compounds excited by 84-MeV Si^{9+} ions. These spectra were obtained

at the highest resolution to date using the von Hamos broad-band crystal spectrometer⁵ in an attempt to observe variations in the numerous individual multiplet transitions which make up the separate K_L^n satellite peaks. The spectrometer was mounted on HIRF beam line 22 (commissioned this year), which permits projectile charge-state selection, using a stripping foil and a small bending magnet at the beginning of the beam line.

Normally, third-row elements excited by heavy-ion impact show distinctive variation in the intensity distributions of the $K_{\alpha}L^n$ satellite peaks as a function of the outer electron distribution near the emitting atom. Aluminum is the puzzling exception to this rule, displaying almost no changes (except for normal chemical energy shifts) independent of the target chemical environment.⁶ Interestingly, excitation by predominantly single-vacancy forming mechanisms, such as fluorescence or electron impact ionization, leads to aluminum and aluminum-oxide spectra with particular features having relative intensities which differ by as much as 100%. Historically, this was one of the first systems studied because the differences in components α_3 and α_4 of the first satellite peak, KL^1 , are so obvious. The observed chemical insensitivity for aluminum-compound spectra induced by heavy-ion impact is not yet understood. In fact, even identification of the specific transitions involved has been questioned.⁷

With minor exceptions, our data show that all alloys have spectra similar to aluminum metal, and all compounds have spectra like Al_2O_3 . Therefore, only the metal and oxide results will be discussed explicitly here. Data for thick aluminum metal and aluminum-oxide targets are displayed in Fig. 4.4. These Al K-X-ray spectra include: The intense $K_{\alpha}L^n$ distribution extending from $K_{\alpha_{1,2}}$ at 1.487 keV up to the K absorption edge at 1.56 keV; low energy, very low-intensity structures lying below $K_{\alpha_{1,2}}$, labeled RER and RAE, which arise from two-electron, one-photon transitions;⁸ $K_{\beta}L^n$ satellites which are highly attenuated by X-ray self-absorption

Fig. 4.4. Aluminum K-X-ray spectra from thick targets of aluminum metal (top spectrum) and aluminum oxide (bottom spectrum) excited by 84-MeV Si ions.

in the target; and $K_{\alpha}^2L^n$ hypersatellites which overlap in energy the $K_{\beta}L^n$ satellites. As in previous studies, the relative differences in the near binomial $K_{\alpha}L^n$ intensity distributions are small. There are stronger variations apparent at this resolution in specific spectral features, but they are still relatively weak compared with similar regions in other third-row elements, e.g., sulfur. Similarly, the low-energy RER and RAE features show little variation with chemical environment. The greatest differences occur in the $K_{\beta}L^n + K_{\alpha}^2L^n$ region between 1.56 and 1.75 keV, where the $K_{\beta}L^n$ component is almost completely absent in the oxide spectrum.

The extreme difference in the relative yields of $K_{\beta}L^n$ X rays in aluminum metal and aluminum oxide is the first strong variation observed in heavy-ion induced X-ray spectra for these targets. This must result from differences in the degree to which M-shell electrons (which are necessary for K_{β} transitions and are almost certainly all initially ionized in these violent K-vacancy forming collisions) are re-established in the metals and compounds within the Al K radiative lifetime of approximately 10^{-15} sec.

1. Edinboro University, Edinboro, PA 16444.
2. Analytical Chemistry Division, ORNL.

3. Nuclear Research Center-Negev, Beer-Sheva, Israel.
4. ORAU Summer Research Participant, Western Kentucky University, Bowling Green, KY 42101.
5. C. R. Vane et al., *Phys. Div. Prog. Rep.*, Sept. 1986, ORNL-6326, p. 219.
6. F. Hopkins et al., *Phys. Rev. A* 14, 1907 (1976).
7. W. J. Kuhn and B. L. Scott, *Phys. Rev. A* 34, 1125 (1986).
8. T. Aberg, *Phys. Rev. A* 4, 1735 (1971), and K. A. Jamison, et al., *J. Phys. B* 8, L485 (1975).

A NOVEL HIGH-RESOLUTION EXPERIMENTAL APPROACH FOR STUDYING LASER PHOTODETACHMENT IN A MAGNETIC FIELD¹

H. F. Krause

Studies of the photodetachment process ($A^- + h\nu \rightarrow A + e$) performed in the presence of a strong magnetic field (1 – 8 Tesla) have been reported for atomic negative ions of sulfur and selenium.^{2,3} When low-density ions contained in a Penning ion trap were illuminated by a narrow-band CW dye laser, the photodetachment yield was observed to increase periodically near threshold whenever the laser was tuned to quantized states of the free electron (Landau states separated by the classical electron cyclotron frequency). In spite of the improvements in the Penning trap design and in the overall experimental layout that have occurred, the effective experimental frequency resolution, $f/\Delta f$, has remained in the range $2 - 5 \times 10^5$. The spectral bandwidth, Δf , has not been reduced below about 2 GHz for the Penning trap design.³ The Doppler and Stark limited resolution is a consequence of the temperature of the cooled ions and motional electric fields that occur in the ion trap. Resolution of the transitions between different magnetic substates of the same fine structure transition is barely possible at such a low resolution, even at the relatively high magnetic fields employed.

In a recent theoretical study, Crawford⁴ found that the cross section is enhanced by orders of magnitude in the narrow frequency band (10 MHz) surrounding each Landau state. The Landau resonances are predicted to display a characteristic asymmetric shape that should be observable for spectral bandwidths below about

300 MHz. The predictions could not be tested without the design of an improved experimental configuration capable of high to ultrahigh frequency resolution (300 – 30 MHz). Such an improvement in resolution of 10 – 100x would also allow most fine-structure and hyperfine transitions (such as in the case of H^-) to be resolved (6 transition frequencies corresponding to a unique alignment of the electron and nuclear spins of H). Spectroscopic studies at this resolution performed in a beam arrangement, in combination with the cross section enhancement in the case of H^- , might also permit the copious production of electron and nuclear spin-aligned neutral beams at greatly reduced laser power. No studies of this most fundamental ion have been performed to date.

The design of a novel high-resolution beam apparatus that should be capable of achieving these goals has been completed. The beam arrangement chosen allows the effects of Doppler and Stark broadening to be reduced well below those experienced in a Penning trap (by a factor 10 – 100x) at the same magnetic field strength. The underlying physical principles for the beam design and some results from Monte Carlo simulations that address the spectral bandwidth issues have been discussed elsewhere.⁵ Several interesting consequences that would arise if the apparatus were used to produce spin-polarized neutral beams also have been discussed.⁵

Construction of the apparatus is now nearing completion. In the experiment, negative ions from an Alton source will be accelerated to about 2 keV and then momentum analyzed before injection into an E x B photoneutralizer maintained under ultrahigh vacuum conditions. The laser beam from a pulsed tunable dye laser, outfitted with a Fabry-Perot interferometer to obtain a bandwidth below 100 MHz, will intersect the focal point of the ion beam inside the photoneutralizer. In the initial test configuration involving the use of S^- ions, the laser beam propagation direction will be perpendicular to the incident ion beam and parallel to the electrostatic field of the photoneutralizer. The laser beam also will be linearly polarized

in a direction that is either parallel or perpendicular to the plane of the intersecting beams. The ion beam will be deflected into a Faraday cup after leaving the photoneutralizer. Neutrals will be detected downstream on a high-resolution two-dimensional position-sensitive detector. The (X,Y) positions of neutral particles detected in delayed coincidence with the pulsed laser will be used to accumulate high-resolution spectral information that lie within the Doppler tuning range of the negative ion beam (typically 5 – 10 GHz). The high resolution photodetachment spectroscopy of S^- will be investigated before any studies of H^- in the infrared are attempted.

1. Work supported by the U.S. Army SDC, Huntsville, Alabama.
2. W. A. M. Blumberg, W. M. Itano, and D. J. Larson, Phys. Rev. Lett. 40, 1320 (1978).
3. R. E. Elmquist, C. J. Edge, G. D. Fletcher, and D. J. Larson, Phys. Rev. Lett. 58, 333 (1987).
4. O. H. Crawford, Proc. 4th Int. Symp. on Production and Neutralization of Negative Ions and Beams, ed. James G. Alessi, Brookhaven National Laboratory, AIP Conf. Proc. No. 158 (1987) p. 663.
5. H. F. Krause, *ibid.*, p. 673.

NEGATIVE-ION STRUCTURE MEASUREMENTS USING CROSSED-BEAM PHOTOELECTRON DETACHMENT SPECTROSCOPY

D. J. Pegg¹ G. D. Alton
J. S. Thompson² R. M. Compton³

During the past year, a new crossed-beam photodetachment apparatus has been built and tested. We have used this apparatus to determine, for the first time, that the negative ion of calcium is stably bound in the $(4s^2 4p)^2P$ state.⁴ The electron affinity of calcium has been measured to be 43 ± 7 meV. Photodetachment signals also have been observed for He^- and B^- ions.

The photoelectron detachment spectroscopy measurements were made using the crossed-beam apparatus shown in Fig. 4.5. A beam of negative ions is produced by passing a positive ion beam, in the energy range from ~20 to 100 keV, through an alkali vapor charge-exchange cell. After a

Fig. 4.5. Schematic of the cross-beam photodetachment spectroscopy apparatus.

delay of a few microseconds, the beam leaving the charge-exchange cell is charge-state analyzed. The negative component is deflected through 10° into a beam line containing a spherical sector electron energy analyzer. Just prior to the entrance of this analyzer, the negative ion beam is crossed perpendicularly with a photon beam from a flashlamp-pumped, pulsed, dye laser. The laser is operated at a repetition rate of 10 Hz and the pulse duration is 2.2 μs . The linear polarization vector of the laser beam is established by a Glan-Thompson prism. The direction of the vector can be varied by the use of a double Fresnel rhomb arrangement. The ~2 Å bandwidth of the laser beam is determined by an intra-cavity etalon device. A 10-cm focal length lens is used to focus the laser beam onto the ion beam. Photoelectrons ejected from the field-free interaction region in the direction of the ion beam can enter the energy analyzer and be detected. The data is stored in a CAMAC-based multichannel-analyzer data acquisition system. Four multichannel scalars (MCS) are used to record the data. The first MCS is triggered by the laser pulse using a fast PIN detector and gated on for 4 μs to count the electron signal

associated with the laser firing. The second MCS, which has the same gate width as the first, was triggered 2 μ s after the first MCS was turned off. This enables us to sample, with the laser off, the continuously distributed background associated with electrons generated by ion impact with apertures and, to a lesser extent, electrons resulting from collisional detachment of the ions with the residual gas. (If the ion under study is metastable, autodetachment processes will also contribute to the background.) By subtracting the contents of the two MCS's, one can effectively discriminate against the background and obtain the true photoelectron signal. The third and fourth MCS's are used to monitor the intensities of the ion and laser beams, respectively, so that the photodetachment signal can be normalized to fluctuations in either of these beams.

The apparatus was first tested on the metastable ion, He^- . In this case, we observed two peaks corresponding to photodetachment leaving the He atom in either the $(1s2s)^3S$ or $(1s2p)^3P$ states. The electron affinity that we measured was in good agreement with a previous experiment and with theory. We have also photodetached the stable B^- ion and obtained an electron affinity in agreement with an earlier measurement. The apparatus was then used for the experiment for which it was designed, i.e., to determine the structure of Ca^- . Figure 4.6 shows the photoelectron spectrum obtained by laser detaching a 60 keV beam of Ca^- ion at a photon wavelength of 635.2 Å. The low energy doublet at 0.62 eV and 1.06 eV is the result of the photodetachment process in which the residual Ca atom is left in the $(4s4p)^3P$ excited state. The two peaks correspond to photoelectrons being ejected, in the rest frame of the ion, in the backward and forward directions, respectively. The higher energy peak at 5.24 eV is the result of photodetachment in which the residual atom is left in the $(4s^2)^1S$ ground state. The presence of this peak clearly shows that the Ca^- is stable and the presence of the lower energy peaks strongly suggest that Ca^- is formed in the $4s^2 4p$ configuration as opposed,

Fig. 4.6. Photoelectron spectrum produced by laser photodetaching a 60 keV beam of Ca^- ions. The pair of low energy peaks, whose origin is described in the text, is the result of the photodetachment of the $(4s^2 4p)^2P$ levels of Ca^- into the $(4s4p)^3P$ levels of Ca while the higher energy peak corresponds to the Ca atom being left in the $(4s^2)^1S$ ground state.

for example, to the $4s^2 3d$. The stability of Ca^- is somewhat unexpected since the lighter Group IIA elements are known to be metastable. The electron affinity of the Ca^- atom was determined in a novel way, by determining the separation of the forward- and backward-directed peaks.⁴ The final result is $\text{EA}(\text{Ca}) = 43 \pm 7$ meV. A recent calculation involving extensive correlation by Froese-Fischer et al.⁵ is in good agreement with our measurement. Efforts are in progress to search for stable negative ions of the heavier Group IIA elements.

We are now in the process of trying to make angular distribution measurements on the photodetached electrons. These measurements are to be made by rotating the linear polarization vector of the laser beam keeping the emission direction fixed.

During the past year, an effort was also made to confirm the existence of metastable Ar^- reported by Bae et al.⁶ We essentially duplicated the experimental conditions used by these

investigations but were unable to detect Ar^- ions. We conclude that if metastable Ar^- ions are formed their lifetimes must be less than ~ 100 ns and not as long as 350 ns, reported by Bae et al.

1. Adjunct staff member from the University of Tennessee, Knoxville, TN 37996.
2. Department of Physics, University of Tennessee, Knoxville, TN 37996.
3. Health and Safety Research Division; Prof. of Chemistry, University of Tennessee, Knoxville, TN 37996.
4. D. J. Pegg, J. S. Thompson, R. N. Compton, and G. D. Alton, Phys. Rev. Lett. 59, 2267 (1987).
5. C. Froese-Fischer, J. B. Lagowski, and S. H. Vosko, Phys. Rev. Lett. 59, 2263 (1987).
6. Y. K. Bae, J. R. Peterson, A. S. Schlachter, and J. W. Stearns, Phys. Rev. Lett. 54, 789 (1985).

COINCIDENT DETECTION OF TWO HIGHLY EXCITED/IONIZED ELECTRONS IN FAST ION ATOM/SOLID COLLISIONS¹

M. Breinig² H.-P. Hülskötter³
T. Underwood⁴

The study of the threshold behavior of scattering cross sections, that is, the study of the energy dependence of these cross sections in the vicinity of the threshold for the scattering process under consideration, has attracted considerable interest in recent years. Threshold laws describe the dependence of the cross sections (E) on the asymptotic energy of the final state, E , as E approaches zero. This dependence is determined by the long range interactions in the final state.

Of great fundamental interest is the behavior of three charged particles with near zero energy above the dissociation limit. Here different threshold-theories differ not only in their predictions for (E) but also in their predictions for various correlations between the charged particles, such as energy partition and angular distributions.⁵ Most studies so far have concentrated on the double escape of two electrons from a positive ion. Double escape, however, can be viewed as an evolution of doubly excited states towards higher and higher excitations

until finally both electrons become unbound. Recent experimental and theoretical work explores this connection.^{6,7}

In previous experimental studies, the final doubly excited or doubly ionized state is reached by photon or electron impact. We have explored the formation of such states in fast ion-atom/solid collisions by detecting projectile exiting from a collision with one electron excited to a high Rydberg state and one electron excited to a low-lying continuum state. We have detected such doubly excited states and, in a preliminary study, have investigated the dependence of the cross section for their formation on the energy of the Rydberg electron for zero energy continuum electrons, and on the energy of the continuum electron for fixed energy Rydberg electrons.

We have coincidentally detected free electrons moving with near zero velocity in the projectile rest frame and field ionized Rydberg electrons from the same projectile using apparatus described in Ref. 8. For C projectiles on a C foil, we have detected $\sim 5 \times 10^{-9}$ coincidences per incident ion, indicating that in ion solid collisions the formation of such doubly excited states is rare.

In Fig. 4.7, the coincidence rate is shown as a function of the voltage across the Rydberg

Fig. 4.7. Coincidence rate normalized to the total number of Rydberg electrons versus ionizing potential.

ionizer for zero velocity free electrons in the projectile frame. Higher ionizer voltages allow stripping of lower n -states. Figure 4.7 shows at most a weak dependence of the coincidence rate on the n -state of the Rydberg electron, as expected for the $q \gg 1$ projectile ions exiting the foil. At present, experiments involving capture and loss events in ion-atom collisions are being prepared, and first results indicate that the formation of states with one electron in a high Rydberg state and one in a low-lying continuum state under single collision conditions is more probable than in ion-solid collisions.

1. Abstracts of Contributed Papers of the XV International Conference on the Physics of Electronic and Atomic Collisions, p. 607, July 22-28, 1987, Brighton, England.

2. Adjunct staff member from the University of Tennessee, Knoxville, TN 37996.

3. Department of Physics, University of Tennessee, now at Stanford University, Palo Alto, CA 94305.

4. Department of Physics, University of Tennessee, Knoxville, TN 37996.

5. See, for example, Symposium on "Threshold Laws" in *Electronic and Atomic Collisions*, Invited Papers of the XIII ICPEAC, eds.

J. Eichler, I. V. Hertel, and N. Stolterfoht (North-Holland, Amsterdam, 1984).

6. A. R. P. Rau in *Atomic Physics*, Vol. 9, eds. R. S. VanDyke and E. N. Fortson (World Scientific, Singapore, 1984).

7. F. H. Read, *J. Phys. B* 17, 3965 (1984).

8. H.-P. Hülskötter et al., "Threshold Laws for Simultaneous Rydberg Electron and Convoy Electron Production," in *Electronic and Atomic Collisions*, Abstracts of Contributed Papers, ed. by M. J. Coggiola, D. L. Huestis, and R. P. Saxon (Palo Alto, 1983).

DOUBLY DIFFERENTIAL CONVOY ELECTRON EMISSION DISTRIBUTIONS IN HIGH VELOCITY ION-SOLID COLLISIONS: TARGET THICKNESS DEPENDENCE¹

S. B. Elston²

G. E. Gonzalez Lepera³

J. P. Gibbons³

M. Breinig²

R. DeSerio³

O. Heil⁴

H.-P. Hülskötter³

I. A. Sellin²

C. R. Vane

We have extended previous measurements² of the doubly differential convoy electron emission cross section for high impact velocities to include target thickness dependence studies. The experiment we report also adds doubly differen-

tial detail to recent investigations of the target thickness dependence of the total convoy electron yield.⁶

The present measurements are for 115-MeV oxygen projectiles (velocity 17 a.u.) incident on thin amorphous carbon foils over a thickness range from a few percent of that required to achieve charge state equilibrium to near charge state equilibrium. Incident charge states include fully stripped, one-electron, and three-electron ions to probe the dependence on the principal quantum number of a bound electron. The data were acquired by means of a previously described⁷ spherical-sector electrostatic spectrometer equipped with a position-sensitive electron detector to provide simultaneous emission velocity selection and emission angle detection. A preliminary sample of results is shown in Fig. 4.8 for one- and three-electron ions incident on the thinnest and thickest targets used. While the data shown are actually contours of equal emission intensity plotted in emission polar angle and emission energy space, to a reasonable degree of approximation the limited range of these parameters permits interpretation in terms of equal emission intensity contours plotted versus velocity components transverse (v_t) and longitudinal (v_l) with respect to the incident ion beam.

The results can be interpreted in terms of a primary production event dominated by electron loss from excited states to the continuum of the projectile, which determines the multipole moments of the initial emission distribution as has been suggested previously. Transport phenomena occurring in the remainder of the foil target appear to broaden the initial distribution in a manner that can be modeled with Monte Carlo calculations such as recently reported by Burgdörfer and Böttcher.^{8,9}

1. Abstracts of Contributed Papers of the XV International Conference on the Physics of Electronic and Atomic Collisions, p. 606, July 22-28, 1987, Brighton, England.

2. Adjunct staff member from the University of Tennessee, Knoxville, TN 37996.

3. Department of Physics, University of Tennessee, Knoxville, TN 37996.
4. Institute für Kernphysik, University of Frankfurt, Frankfurt, West Germany.
5. S. D. Berry et al., J. Phys B 19, L149 (1986).
6. Y. Yamazaki et al, Phys. Rev. A 34, 4493 (1986).
7. S. B. Elston, "Doubly Differential Cross Sections of Collision-Produced Forward Electron Emission," in *Electronic and Atomic Collisions, Invited Papers of the XIV ICPEAC*, eds. D. C. Lorents, W. E. Meyerhof, and J. R. Peterson (North-Holland, Amsterdam, 1986), p. 331.
8. J. Burgdörfer, Phys. Rev. Lett. 51, 374 (1983); J. Burgdörfer et al., Phys. Rev. A 28, 3277 (1983).
9. J. Burgdörfer and C. Böttcher, private communication and to be published.

OBSERVATION OF STEEP VARIATION OF RECOIL-ION ENERGY ON SCATTERED ION CHARGE STATE IN COINCIDENT MULTIELECTRON PROJECTILE AND TARGET IONIZATION EVENTS¹

C. S. O ²	S. B. Elston ³
J. C. Levin ²	J. P. Gibbons ²
R. T. Short ²	I. A. Sellin ³
H. Cederquist ²	H. Schmidt-Böcking ⁴

Production of slow, highly-charged recoil ions by fast heavy-ion beams⁵ continues to provide a rich source of novel data on ion-atom collision phenomena. In addition, use of such beams to produce a powerful parasitic source of slow, few-electron ions,⁶ has been conjectured. However, virtually no data have been available concerning the energy and angular distributions of the primary-recoil ions themselves. Here, we discuss quantitative measurements of the mean energies E_r of slow, highly charged recoil ions produced in collisions of MeV/nucleon ions undergoing extensive, simultaneous ionization of both projectile and target. The observed recoil-ion energies show a steep dependence on the product (qr) of final projectile and recoil-charge states. From these data, it is possible to infer useful information concerning the impact parameter dependence of single and multiple electron-transfer processes.

The measurements were performed using a time-of-flight (TOF) technique⁷ already demonstrated in determination of energies of ions produced by inner-shell photoionization. Since recoil-ion energies for high-charge-state recoils produced by heavy-ion impact can be > two orders of magnitude higher, the present method's intrinsic accuracy improves on upper limits set in previous "hammer" experiments. In these measurements, beams of 23, 27.6, 33 MeV Cl^{5+} ions traversed a dilute Ar target maintained in the extraction region at the front end of the TOF analyzer. Recoil Ar^{r+} ($r = 4 - 9$) were extracted and detected in coincidence with Cl^{q+} ($q = 6 - 8$), which were sorted electrostatically and detected by a parallel-plate avalanche detector. Widths of individual ion peaks in the TOF spectra obtained for various TOF analyzer fields were used to deduce E_r . The strong dependence of E_r on qr is illustrated in Fig.

Fig. 4.8. Contours of equal electron emission intensity in the vicinity of the convoy peak plotted with respect to velocity components transverse (v_t) and longitudinal (v_l) to the incident projectiles. Shown are results for a thin (lower row) and thick (upper row) targets (nominally 0.5 and 32 g/cm, respectively) and for incident charge states 5+ (left column) and 7+ (right column). The displayed contours are a 95, 80, 65, 50, and 35% of the peak intensity.

4.9. The linear dependence of $\log(E_r)$ on $\log(qr)$ [Fig. 4.9 (b)] suggests a power dependence $E_r \sim (qr)^n$, where $n \sim 5$.

Fig. 4.9. (a) Recoil energies of Ar^{r+} produced by 23 MeV Cl^{9+} . (b) Ar^{r+} recoil energies produced by 23, 27.6, 33 MeV Cl^{9+} plotted as a function of qr . Both scales are logarithmic.

Using a classical screened-Coulomb scattering calculation, in conjunction with two-body energy-momentum conservation, it is possible to relate the recoil-ion energy to an appropriate b for the relevant collision event. For the impact parameter range of greatest importance for simultaneous projectile and target ionization the mean recoil energies observed are about an order of magnitude greater than previous estimates based on half-collision Rutherford scattering of projectile and recoil ion in their emergent charge states. The present approach is

complementary to the standard method of resolving the projectile scattering angle in coincidence with one or more collision products because the difficult requirement of high scattering-angle resolution is avoided.

1. Abstracts of Contributed Papers of the XV International Conference on the Physics of Electronic and Atomic Collisions, p. 432, July 22-28, 1987, Brighton, England.
2. Department of Physics, University of Tennessee, Knoxville, TN 37996.
3. Adjunct staff member from the University of Tennessee, Knoxville, TN 37996.
4. Institute für Kernphysik, University of Frankfurt, Frankfurt, West Germany.
5. L. Liljeby et al., Phys. Scr. 33, 310 (1986); S. Kelbch et al., J. Phys B 18, 323 (1985); and Proceedings of International Symposium on Production and Physics of Highly Charged Ions, ed. L. Liljeby (Phys. Scr. 13, (1983)).
6. J. Ullrich et al., J. Phys. B 17, L785 (1984).
7. R. T. Short et al., Phys. Rev. Lett. 56, 2614 (1986).

EN TANDEM OPERATIONS

P. D. Miller and P. L. Pepmiller

During the last year, the EN tandem accelerator was operated 2100 hours in support of the accelerator-based atomic physics program. Operation was extremely reliable up to about 5.8 MV, but at the highest voltages difficulties were encountered with excessive high-energy column currents. A thorough cleaning of the tube and column structure near the high energy end of the accelerator, has, at least temporarily, improved the performance. New acceleration tubes were received, and will be installed before the end of the calendar year. The vacuum system between the accelerator tank and the analyzing magnet is being upgraded to ultrahigh vacuum standards. All of the components have been received, and assembly is about 75% complete. This beam line unit will be installed at the same time that the acceleration tubes are being replaced. It is anticipated that these improvements will allow operation of the accelerator at terminal voltages up to 7.0 MV.

ATOMIC PHYSICS FOR FUSION PROGRAM

ELECTRON CAPTURE CROSS SECTIONS FOR $O^{5+} + H$ AND $N^{5+} + H$ AT eV ENERGIES USING MERGED BEAMS

C. C. Havener M. S. Huq¹
R. A. Phaneuf

Electron capture collisions of multiply charged ions with H atoms in the 1 to 500 eV/amu energy range play an important role in astrophysics and in the edge plasma of magnetic fusion devices. At such low energies, theoretical models of many inelastic processes remain essentially untested. Our objective is to perform benchmark measurements of independently absolute total cross sections for electron capture which result from collisions of various multicharged ions with H atoms in the relative energy range extending from tenths of an eV to several hundred eV. During the past year absolute cross section measurements were completed for the $O^{5+} + H(D)$ systems and preliminary measurements were made for the $N^{5+} + H(D)$ systems at relative energies ranging from 0.8 to 800 eV/amu. This extends the previous measurements² for these systems to lower energies by two orders of magnitude, allowing comparison with theory for the first time in this energy range.

Experimentally, a 99% pure ground-state beam of H or D atoms is produced by passing a 6- to 9-keV beam of H^- or D^- ions through the optical cavity of a 1.06- μm Nd:YAG laser, where up to 1 kW of power circulates. Typically, 0.5 to 1% of the negative ions in the beam are neutralized by photodetachment. A 50- to 90-keV, 2- to 4- μA beam of O^{5+} ions produced by the ORNL-ECR ion source is merged electrostatically with this neutral beam. The 80-cm-long interaction path of the beams is maintained at an average pressure of 2×10^{-10} torr. The product H^+ (D^+) ions are magnetically separated from the primary beams and are deflected and focused onto a channel electron multiplier where they are counted. Typical neutral beams of 15 nA (equivalent) produce $60 s^{-1}$ of beam-beam signal, and $12,000 s^{-1}$ of background due to stripping on residual gas. A fast two-beam chopping scheme is used to

separate the signal from the backgrounds. In order to quantify the spatial overlap of the beams, two-dimensional intensity profiles of each beam are measured at four different positions along the merged path.

Several improvements to the original apparatus were made during the last year. These include modifications of two beam scanners which are used to measure the beam-beam spatial overlap and introduction of a one-inch-diameter channel electron multiplier. The new electron multiplier increased the angular acceptance of the reaction products by 50%, ensuring complete collection of products at the lowest center-of-mass energies. Furthermore, the larger detector essentially eliminated the sensitivity of the method to spurious signals produced by space-charge modulation, allowing measurements to be performed below 1 eV/amu. Modifications of the beam scanners helped improve the accuracy of the cross-section measurements.

The present results for absolute total cross sections for electron capture for collisions of $O^{5+} + H(D)$ are shown in Fig. 4.10 as a function of relative collision energy. Data shown correspond to several different laboratory-frame conditions which provide important diagnostic tests of the method: the hydrogen beam was interchanged with a heavier deuterium beam, the neutral beam was prepared at a higher or lower velocity than the multicharged ion beam, and the laboratory-frame energies of all beams were significantly changed. Figure 4.10 also shows

Fig. 4.10. Cross sections for total electron capture of O^{5+} from H and D.

the previous ion-beam gas target measurements² for the same system and the recent unpublished theoretical calculations by Bottcher and Heil³ and Gargaud and McCarroll.⁴ As can be seen from the figure, the cross sections rise with decreasing energy in the 20 to 200 eV/amu range, consistent with previous measurements down to 80 eV/amu, and with the calculations. However, below 20 eV/amu, the experimental cross section turns over and decreases with decreasing energy. Below 3 eV/amu, the measured cross section rises again with decreasing energy, consistent with the $1/v$ dependence and cross-section magnitude predicted by the classical orbiting model.⁵

Preliminary measurements for $N^{5+} + H$ and $N^{5+} + D$ collisions are shown in Fig. 4.11. The

Fig. 4.11. Cross sections for total electron capture of N^{5+} from H and D.

energy dependence of N^{5+} collisions is significantly different from that for the O^{5+} case. Evidence suggestive of the role of the orbiting mechanism is also apparent in the lowest energy data for this system.

1. ORNL Postdoctoral Research Associate.
2. R. A. Phaneuf et al., Phys. Rev. A 26, 1892 (1982).
3. C. Bottcher and T. G. Heil (unpublished).
4. M. Gargaud and R. McCarroll (unpublished).
5. G. Gioumousis and D. P. Stevenson, J. Chem. Phys. 29, 294 (1958).

ELECTRON-IMPACT IONIZATION OF MULTIPLY CHARGED NI IONS

L. J. Wang¹ K. Rinn²
D. C. Gregory

Nickel is an important impurity element in modern fusion devices, especially in those where the vessel walls are made of high-nickel-content alloys (e.g., JET, the Joint European Torus). A good knowledge of atomic processes involving nickel ions is essential in order to understand and accurately model these plasmas, but detailed calculations and measurements are available for ionization of only the first three charge states of nickel. The present work involves the measurement of cross sections for electron-impact ionization of Ni^{5+} , Ni^{6+} , Ni^{7+} , Ni^{8+} , Ni^{12+} , and Ni^{14+} .

The absolute cross section measurements reported here utilized the ORNL-ECR ion source³ and the electron-ion crossed beams apparatus.⁴ The results and interpretation of the data can most easily be considered by dividing the measurements into two parts, with Ni^{5+} through Ni^{8+} forming one group, and Ni^{12+} and Ni^{14+} the other. One example from each group will be discussed, and general trends will be noted.

The cross section data for Ni^{6+} are plotted in Fig. 4.12 along with a calculation for direct

Fig. 4.12. Electron-impact ionization measurements for Ni^{6+} , with calculated direct ionization.

ionization based on the semiempirical Lotz formula.⁵ The measured cross sections are up to 40% larger than theory. The difference is attributed to excitation-autoionization (excitation of an inner electron followed by autoionization of the resulting highly excited ion). The influence of this process is observed over the entire energy range studied here, with no sharp onsets which would indicate a single transition dominating the indirect contribution. Excitation-autoionization from hundreds of transitions add together to produce the smooth enhancement observed in this case.

The electronic configurations of these four ions are similar ($3p^6 3d^n$, where $n = 5, 4, 3$, and 2 for Ni^{5+} through Ni^{8+} , respectively) and this accounts for the similarities in cross section observed in these measurements. In each case, indirect ionization contributes a featureless enhancement to the cross section over the entire energy range. Since the direct ionization cross section decreases fairly rapidly with increasing charge and the contribution of excitation-autoionization remains more or less constant, indirect ionization becomes relatively more important as the charge state increases along this sequence. This trend is predicted to end abruptly as the ion reaches an inert-like electron configuration, where indirect contributions must come from excitation of more tightly bound inner electrons.

Figure 4.13 shows the cross section measurements for ionization of Ni^{12+} along with Lotz calculations representing direct ionization of outer-shell $3s^2 3p^4$ electrons. In contrast to the Ni^{6+} data discussed above, direct ionization accounts for about 75% of the measured cross section up to about 850 eV, where an abrupt change in slope is observed. This feature is the signature for excitation of inner-shell 2p electrons to autoionizing excited configurations. These $\Delta n = 1$ (or more) transitions contribute up to 40% of the total at the peak cross section, in contrast to recent predictions⁶ that excitation-autoionization due to $\Delta n = 1$ transitions would be insignificant for higher charge

Fig. 4.13. Electron-impact ionization measurements for Ni^{12+} , with calculated direct ionization.

states of nickel. An additional feature of this curve is the onset of ionization below the threshold for direct ionization of ground-configuration $3p^4$ electrons. This indicates the presence of metastable ions in the beam at the collision volume. Based on the observed low-energy behavior of the cross section (and making certain assumptions about the energy-dependence of the cross section for ionization of the metastable ions), we estimate that 20% of the ion beam was in $3p^3 3d$ metastable levels.

As predicted above, the direct ionization cross section for Ni^{12+} is considerably smaller than that of Ni^{6+} . Indirect ionization is no larger proportionally for Ni^{12+} than for Ni^{6+} , which again is expected since more tightly-bound inner-shell electrons must be excited to autoionizing configurations for the higher-charged ions. As the sequence continues up in charge, Ni^{14+} (with a $3s^2 3p^2$ electron configuration) has relatively more indirect contribution to its total cross section than is observed for Ni^{12+} .

These measurements provide an extended data base for ionization of nickel ions as well as a basis for comparison of accurate experimental data with planned detailed calculations for this sequence. This work may also be combined with similar measurements and calculations for the

iron isonuclear sequence to study the scaling of cross sections along isoelectronic sequences.

1. On assignment from Department of Physics, Wesleyan University, Middletown, CT 06457.
2. Joint Institute for Laboratory Astrophysics, Boulder, CO 80309, and ORNL.
3. F. W. Meyer, Nucl. Instrum. Methods 9, 532 (1985).
4. D. C. Gregory et al., Phys. Rev. A 34, 3657 (1986).
5. W. Lotz, Z. Phys. 220, 466 (1969).
6. P. G. Burke, W. C. Fon, and A. E. Kingston, J. Phys. B 20, 2579 (1987).

SEARCH FOR RECOMBINATION RESONANCES IN ELECTRON-IMPACT IONIZATION OF O^{5+}

K. Rinn¹ L. J. Wang²
D. C. Gregory R. A. Phaneuf
 A. Müller³

Li-like ions, with a $1s^2 2s$ electron configuration, are prime candidates for detailed experimental and theoretical studies of electron-impact ionization. A number of experiments and theoretical studies in the last ten years have focused on O^{5+} as an example of the Li isoelectronic sequence. Recent major improvements in the ORNL crossed-beams apparatus and improved stability and intensities of beams from the ORNL-ECR ion source made further study⁴ of this ion worthwhile. The two primary aims of this work were to measure the excitation-autoionization contribution to the total cross section with improved accuracy and to search for isolated recombination resonances which were beyond the resolution of previous studies. The present summary will concentrate on the latter effort.

In addition to direct ionization (the "knock-out" of an outer electron in an electron collision) and excitation-autoionization (the excitation of an inner-subshell electron, leaving the ion in a highly excited configuration which autoionizes), an ionization event may be produced by more exotic processes. One of these, termed Resonant Excitation Double Auger (REDA) by its originators,⁵ was predicted to make a significant contribution to the total cross section for ionization of Na-like Fe^{15+} .

The variation of this process sought in this study is illustrated by the sequence

In this example, the incoming projectile electron excites a $1s$ target electron to the $2p$ subshell and is captured in the process to the $2p$ subshell. This is a resonant process (since the energy levels must match exactly) and may decay through a number of channels, one of which is illustrated above. This is the only exit channel which produces a net ionization event, and it requires that two electrons be ejected from the target ion simultaneously (i.e., in a correlated event). The other resonance considered here involves the $O^{4+}(1s^2 2s^2 2p)$ intermediate state, which also requires a correlated double-autoionization to produce a net ionization. These two intermediate states produce isolated ionization resonances which would be observed as sharp enhancements in the ionization cross section at 436.3 and 449.0 eV.

In order to increase the sensitivity of the experiment to the presence of resonance structures, a special computer program was written to control the experiment and data collection. Measurements were made at each of up to 30 closely spaced electron energies for approximately four seconds each, with this scan repeated for hours in order to obtain data with good statistics and a common background at all energies. Any features in the data produced by drifting experimental parameters will cancel in such a scan, producing a solid baseline which will reveal any resonance structures.

The data are shown in Fig. 4.14, with the energies where resonances are expected marked by arrows and identified by the O^{4+} intermediate state. Although the features observed at these energies cannot be cleanly resolved from the background cross section, there are suggestions of structures at the predicted energies. We place an upper limit of 10^{-20} cm^2 on the cross sections for the resonant processes, with an experimental energy spread of 2.4 eV. This

Fig. 4.14. Electron-impact ionization of $O5^+$, with predicted resonance features indicated by the arrows.

result is in good agreement with more recent detailed calculations for this process.⁶

1. Joint Institute for Laboratory Astrophysics, Boulder, CO 80309, and ORNL.
2. On assignment from Department of Physics, Wesleyan University, Middletown, CT 06457.
3. Justus-Liebig-Universität, Giessen, West Germany.
4. K. Rinn et al., Phys. Rev. A 36, 595 (1987).
5. K. J. LaGattuta and Y. Hahn, Phys. Rev. A 24, 2273 (1981).
6. D. C. Griffin and M. S. Pindzola, Bull. Am. Phys. Soc. 32, 1274 (1987).

HIGH RESOLUTION AUGER-ELECTRON SPECTROSCOPY OF LOW-ENERGY DOUBLE-ELECTRON CAPTURE COLLISIONS OF MULTIPLY CHARGED IONS WITH NEUTRAL ATOMS AND MOLECULES

F. W. Meyer D. C. Griffin²
C. C. Havener M. S. Huq¹
J. K. Swenson¹ R. A. Phaneuf
M. Stolterfoht³

Our investigation of double-electron capture by multiply charged ions into autoionizing final states has continued. The experimental apparatus was moved to a newly completed beamline of the ORNL ECR source facility that delivered factors of 10 to 20 times more beam current to the experiment than was available during previous runs. This enhanced capability made

possible an extension of earlier measurements to He-like F and Ne incident ions, as well as improved measurements of spectra for He-like O incident ions. The focus of study during this reporting period was a series of systematic, high-resolution measurements of the production of L and M Coster-Kronig, as well as L and M Auger electrons in double-electron capture collisions involving He-like multiply charged ions as a function of projectile charge and target species. The Coster-Kronig electrons result from the decay of non-equivalent electron configurations, whose production has been shown to involve electron-electron correlation effects.⁴ Comparison of Coster-Kronig electron production to total Auger electron production provides a relative measure of the importance of correlation effects in double-electron capture collisions of multiply charged ions.

Figure 4.15 shows a sample L Coster-Kronig electron spectrum for 60 keV O^{6+} colliding with

Fig. 4.15. High resolution spectrum of L Coster-Kronig electrons produced in 60 keV $O^{6+} + He$ collisions, after low-energy background subtraction. The energy scales of all spectra shown refer to the projectile frame.

He, showing a well defined Rydberg series starting at principal quantum number $n=6$, at which the $1s^2 2pn\ell$ configurations become autoionizing, and terminating at a series limit of 12 eV. Figure 4.16 shows high resolution scans of the first two members of the $1s^2 2pn\ell$ Coster-Kronig series measured for 30 keV projectile energy;

Fig. 4.16. High resolution spectrum of the first two members of the $1s^2 2p n l$ Coster-Kronig series produced in 30 keV $O^{6+} + He$ collisions. The vertical lines are calculated transition energies of the levels belonging to the 6l and 7l configurations; heights of the lines are proportional to singlet purity.

partially resolved structures are seen within the $n=6$ and $n=7$ transition manifolds. Also shown in Fig. 4.16 are calculated Hartree-Fock transition energies for those levels belonging to the $2p 6 l$ and $2p 7 l$ electron configurations that have significant singlet content. The calculations are being used⁵ together with the high resolution experimental spectra to obtain information about the l -distributions characterizing double-electron capture into non-equivalent electron configurations.

Figure 4.17 shows electron spectra in the range 0 to 20 eV for Ne^{8+} incident on He and H_2 . The figure illustrates the increasing complexity of the spectra as the projectile charge is increased due to the increased number of final channels populated. The magnitude of the electron emission cross sections is enhanced in the case of the H_2 target, since the positions of the relevant curve crossings are shifted to larger internuclear separations due to the reduced total initial binding energy of the two target electrons.⁶ The doubling of the L Coster-Kronig peaks is due to the fine structure splitting of the Ne^{8+} 2p core level.

1. ORAU Postdoctoral Research Associate.
2. Consultant, Rollins College, Winter Park, Florida.
3. Permanent address: Hahn-Meitner-Institut für Kernforschung GmbH, Berlin, FRG.

4. N. Stolterfoht et al., Phys. Rev. Lett. 57, 74 (1986).

5. F. W. Meyer et al., manuscript in preparation.

6. F. W. Meyer et al., "Correlation Effects on Double Electron Capture in Highly-Charged, Low-Energy Ion-Atom Collisions," presented at the XV International Conference on the Physics of Electronic and Atomic Collisions, Brighton, U.K., July 22-28, 1987; to be published in Book of Invited Papers.

Fig. 4.17. Low energy electron spectra for 90 keV Ne^{8+} ions incident on (a) He and (b) H_2 .

STUDIES OF LOW-ENERGY MULTICHARGED ION-SURFACE INTERACTIONS BY EJECTED-ELECTRON SPECTROSCOPY

F. W. Meyer S. H. Overbury²
C. C. Havener K. J. Snowdon³
D. M. Zehner¹ W. Heiland³

Observation of the ejected-electron energy spectra from ion-surface collisions provides information on the dynamics of the neutralization of the ion as it interacts with the solid. This year's activity in this area consisted of analyzing measurements made last fiscal year for multiply charged N, O, F, Ne, and Ar ions with energies of a few keV/amu incident at grazing angles on Au and Cu surfaces. The detailed analysis has led to new proposals for understanding the interaction of multicharged ions with surfaces.

The multicharged ion beams from the ECR ion source were incident at 5° on the (110) surfaces of gold and copper single crystals (see Fig. 4.18) mounted in an ultrahigh vacuum chamber

Fig. 4.18. Schematic illustration of the experimental and detection geometries. The CMA axis is located at 90° to the incident ion beam direction.

(1×10^{-10} torr). The surfaces were sputter cleaned using 1 keV Ne^+ at 10° incident to the surface, annealed, and their cleanliness monitored using electron-induced Auger-electron spectroscopy. The energy distributions of emitted electrons arising from the multicharged ion surface interaction were measured using a cylindrical mirror analyzer (CMA). The CMA pass energy and data collection were controlled by a minicomputer-based multichannel scaler.

Figure 4.19 shows the electron emission spectra for H-, He-, and Li-like O ions on Au. As is typical in all the spectra, most of the electrons are ejected at low energies (<10 eV) by the mechanism of kinetic electron emission, which is quite sensitive to surface effects. Above about 50 eV the emission has been proposed⁴ to result from quasielastic scattering

Fig. 4.19. Electron kinetic energy distributions for collisions of $\text{O}^{7+}, \text{O}^{6+}$ projectiles with Au metal target, for the geometry of Fig. 4.17.

processes which involve promotion of bound electrons in the target and projectile to the continuum.

Superimposed on the low energy emission and giving information about the dynamics of the neutralization of the projectile are one-center Auger decay features of both projectile and target vacancies. One way that neutralization can proceed is by capture of valence-band electrons to the projectile excited states followed by one-center Auger decay.⁵ Figure 4.19 shows broad peaks at 500 eV which are identified as Doppler-broadened KLL-Auger peaks resulting from filling the projectile 1s vacancy by the above process. This structure is absent in the Li-like O^{5+} spectra since these projectiles contain no initial inner-shell vacancies and apparently produce none during the interaction with the surface. For the He-like O^{6+} spectra the high energy structure is still present, pointing to the existence of $1s2s^3S$ metastables in the beam. The correlation between the Auger peaks and the initial vacancies in the incident ion beam allowed the metastable fraction to be determined for the beams listed in Table 4.1. This technique is the basis for a proposed simple meta-

Table 4.1. Metastable fractions of several beams from the ORNL ECR multicharged ion source.⁶

Ion	Metastable Fraction (%)
N^{5+}	6.2 ± 0.6
O^{6+}	2.6 ± 0.5
Ar^{8+}	15.5 ± 0.7
Ar^{7+}	10 ± 1

stable detector⁶ suitable for use with low-energy ion beams.

In Fig. 4.19, the additional structures at 69 and 239 eV are due to the transfer of the projectile inner-shell vacancy to the target Au $\text{M}_{IV,V}$ level and subsequent decay by Auger emission. The presence of these target vacancies suggests an additional mode for neutralization of the incident ion. Long-lived projectile inner-shell vacancies survive until close encounters with the atoms in the solid. At these binary collisions, pseudocrossings of molecular orbitals can transfer the vacancy from the projectile to the target.

Further evidence of the survival of the vacancies until close encounters with the atoms in the solid is in the electron emission for various F^{q+} ions on Cu (not shown). The Doppler-broadened KLL-Auger peak resulting from the filling of the 1s vacancy is observed not only in the F^{8+} spectra, but also with diminishing intensity, for charge states F^{6+} down to F^{2+} , for which no initial K-shell vacancies exist. By constructing the correlation diagram for the F-Cu system, one finds that initial 2p-subshell vacancies which are always present even for the lower charge state F ions, can be transferred to the K-shell of the projectile by means of rotational coupling between the $3d\pi$ and $3d\sigma$ molecular orbitals of the F-Cu system. These molecular orbitals correlate with the 2p and 1s levels of F, respectively.

4. K. J. Snowden et al., submitted to Physical Review A.

5. F. W. Meyer et al., Phys. Rev. A 35, 3176 (1987).

6. K. J. Snowden et al., submitted to Review of Scientific Instruments.

ECR ION SOURCE UPGRADE: ADDITION OF NEW USER BEAM LINES

J. K. Swenson¹ F. W. Meyer
J. W. Hale

A new user beam line has been installed recently at the ORNL ECR ion source facility. This upgrade increases to four the number of user ports available for experiments. Figure 4.20 shows the new beam line configuration and the location of the user ports.

The new user beam line starts with a half-scale version of the main 90° double-focusing charge analyzing magnet followed by an x-y micrometer slit assembly and a biased Faraday cup. The magnet is designed to transport the entire beam envelope into the new beam line. A large-bore electrostatic einzel lens images the magnet exit slit onto the entrance aperture of a 90° spherical sector deflector shown positioned at the end of the beam line. This deflector allows switching the beam to either 90° port #3 or #4 as indicated in Fig. 4.20. It can also be positioned out of the beam path via the UHV rotation feed-through to permit the beam to travel undeflected into the straight-through port #2. An experiment may be positioned at each of these three beam ports. The beam line pressure is typically a few $\times 10^{-8}$ torr and the deflector chamber is a few $\times 10^{-9}$ torr. The deflector chamber is pumped by a 2000 l/sec cryopump and acts as a differential pumping section between experiments and the rest of the beam line. A beam profile monitor at the entrance of the spherical deflector chamber facilitates positioning and shaping of the ion beam before being directed into one of the online experiments.

The new beam line has already been used to perform a second series of Auger electron spectroscopy measurements in which electrons emitted at zero degrees to the beam axis were energy-

1. Solid State Division, ORNL.

2. Chemistry Division, ORNL.

3. Universität Osnabrück, FRG.

Fig. 4.20. Schematic representation of ECR ion source and beam transport showing location of main experimental port #1 and new user beam line ports #2-4.

analyzed in high resolution, following collisions of He-like second row ions (O^{6+} , F^{7+} , Ne^{8+}) with He, H_2 , and Ne. The only location at which beam was available for the first series of these measurements was downstream of the merged-beams and crossed-beams experiments, semi-permanently in place at port #1, and suffered from poor upstream beam transport. Factors of

10-20 increase in usable beam currents were obtained at the new port. Thus, the addition of the new beam lines has already demonstrated enhanced flexibility and overall accessibility of the ECR ion source facility.

1. ORAU Postdoctoral Research Associate.

5. THEORETICAL PHYSICS

The theoretical physics program in the Physics Division at ORNL encompasses activities in two major areas — nuclear and atomic physics. The theoretical nuclear physics program involves activity in low-energy, heavy-ion collisions, nuclear structure, and intermediate-energy and relativistic heavy-ion physics. In atomic physics, the major topics of investigation are dielectronic recombination, electron correlation effects in ion-atom collisions, and the development of methods to obtain numerical solutions for the three-body Coulomb problem. The research areas complement many of the experimental programs in the Division; i.e., programs at MHIRF, the EN Tandem, the atomic cross sections for the fusion energy center, and the relativistic heavy-ion experiments at CERN and Brookhaven.

In the last several years, there has been an increasing interdisciplinary effort in computational physics relevant to both nuclear and atomic physics. In the past year, this effort has concentrated on the development of algorithms which are particularly relevant to strong field effects and which utilize the FPS-164/MAX attached vector processor on the Physics Division computing system, as well as the Cray systems at ORNL and the OER computer system at Livermore. As one example of this program, an algorithm to obtain an accurate numerical solution for the 3-D time-dependent Dirac equation has been developed which executes at a rate of 40 mflops on the FPS-164. It is anticipated that these interdisciplinary computational physics efforts will be an important component of the program in the coming years.

Again this past year, the theory program has benefited greatly from an extensive visitor program supported by the Joint Institute for Heavy-Ion Research.

COMPUTATIONAL AND MATHEMATICAL PHYSICS

RELATIVISTIC THEORY OF FERMIONS AND CLASSICAL FIELDS ON A COLLOCATION LATTICE¹

C. Bottcher M. R. Strayer

We present a novel numerical method for solving dynamical strong field problems in quantum mechanics and classical field theory based on expansion of functions in terms of splines. The method differs from traditional approaches by the introduction of a mapping onto a collocation lattice, which is generally nonuniform and time-dependent, depending on the particular physical application. This approach results in a set of finite matrix transformations of a type which can be evaluated rapidly on supercomputers

possessing either vector or matrix co-processors. As an example of the method, we present a study of the relativistic quantum-mechanical many-electron problem interacting via very strong time-dependent classical fields.

1. Abstract of paper: Ann. Phys. 175, 64 (1987).

ATOMIC TIME-DEPENDENT HARTREE-FOCK CALCULATIONS IN THREE SPACE DIMENSIONS

C. Bottcher M. R. Strayer

We have now completed a suite of codes which follow the course of an ion-atom collision in the independent particle approximation with a common, self-consistent field. The electronic

wavefunctions are represented by basis splines on a Cartesian lattice in three dimensions with periodic boundary conditions. When the time evolution is completed, the wavefunctions are projected on complete sets of bound and continuum states in the projectile and target frames. Thus, all possible excitation, capture, and ionization processes are described, insofar as they are meaningfully represented on the finite lattice.

The first comprehensive studies are being carried out on $p + H$. Well-established results on, for example, the variation of capture probability with impact parameter are readily confirmed. However, the probabilities of ejecting electrons at angles defined with respect to the collision plane reveal intricate alignments not described by earlier formalisms.

The codes run at around 70 Mflops in the NMFEC Crays, sufficient to produce useful results in a reasonable time. It is clear that the possible applications of these codes are almost unlimited, particularly if one considers that molecular projectiles and targets can be represented on the lattice with the same facility as atoms.

CALCULATION OF CONTINUUM EXCITATION AMPLITUDES FOR TIME-DEPENDENT EXTERNAL FIELD PROBLEMS¹

C. Bottcher A. S. Umar²
M. R. Strayer V. E. Oberacker²

A large class of problems in nuclear and atomic physics involves the excitation of continuum states by a time-dependent external field acting on a complex many-body system.³ Examples include the semiclassical description of nuclear and atomic collisions where the internal degrees of freedom of one of the ions are frozen, while the other ion is treated quantum mechanically and continuum excitations caused by fields acting on an isolated atom or nucleus. Continuum excitation problems occur also in non-perturbative quantum field theories, e.g., the lepton-pair production in relativistic heavy-ion collisions. Although we will confine ourselves

to nonrelativistic problems, the method discussed below is readily applicable to relativistic systems.⁴

The calculation of scattering amplitudes requires the knowledge of both bound and continuum states for the system. In general, the calculation of scattering states for a many-body system is far more difficult than the calculation of bound states. In most practical calculations, the Hamiltonian is represented on a discrete numerical mesh. In principle, the continuum excitation problem can be solved by diagonalizing the resulting finite-size Hamiltonian matrix, which yields a finite number of bound states and discretized continuum states (with standing wave boundary conditions). However, this straightforward approach gives rise to serious problems:⁵

- i) For a realistic two- or three-dimensional calculation, the size of the matrix to be diagonalized is prohibitively large. Choosing a smaller number of mesh points (or a one-dimensional approximation) yields an inadequate description of the continuum spectrum.
- ii) Other methods for the calculation of scattering states, such as the solution of the Lippmann-Schwinger scattering equation and the R-matrix approach, are also impaired by the requirement of a small Hamiltonian matrix. Due to numerical inaccuracy, the calculated scattering states are no longer orthogonal to the bound states, and they do not satisfy the Schrödinger equation.

Therefore it is highly desirable to develop a formalism which makes effective use of the discretized Hamiltonian to calculate scattering information for complex systems. In our new formalism, the Hamiltonian matrix is actually never stored. Rather, it is known implicitly through its action on the state vectors. In this way, the problem becomes tractable.

As we consider an isolated many-body system which is described by the free Hamiltonian H_0 and during the time interval $-T < t < +T$, the system is subjected to an external time-dependent potential $V(t)$. The time evolution of the system is given by the state vector $|\psi_\alpha(t)\rangle$ and the continuum excitation probability,

$$P_\alpha(\epsilon_k) = |\langle \psi_\alpha(T) | \phi_k \rangle|^2, \quad (1)$$

is given by

$$P_\alpha(\epsilon) = \langle \psi_\alpha(T) | F^\dagger(\epsilon) F(\epsilon) | \psi_\alpha(T) \rangle \quad (2)$$

$$F(E) = \left(\frac{1}{\sqrt{\pi}\Delta} \right)^{1/2} e^{-(H_0 - E)^2 / 2\Delta^2}, \quad (3)$$

and where Δ is an energy width over which the probability is evaluated.

We have applied the method to the problem of prompt nucleon emission in low-energy, heavy-ion collisions. Numerical computations were performed to study neutron emission⁶ in the deep-inelastic reaction $^{160}\text{Gd} + ^{93}\text{Nb}$ at $E_{\text{lab}} = 204$ MeV. Figure 5.1 shows the differential cross section (in the laboratory frame) obtained from

$$\frac{d\sigma}{d\epsilon} = 2\pi \sum_{\alpha=1}^N \int_{b_{\min}}^{b_{\max}} db b P_\alpha(\epsilon_k, b). \quad (4)$$

The theoretical differential cross section peaks around 8 MeV and decays exponentially at higher energies, as observed in the experiment. The curve can be approximated by a function of the form $N e^{-\epsilon/T}$ with a temperature $T = 4.8$ MeV and $N = 250$.

In summary, we have introduced a method for the calculation of continuum excitation probabilities in external field problems represented by discretized Hamiltonians.

1. Summary of paper to be published in Physical Review C.

2. Consultant from Vanderbilt University, Nashville, TN 37235.

3. A. S. Umar, M. R. Strayer, D. J. Ernst, and K.R.S. Devi, Phys. Rev. C 30, 1934 (1984).

4. C. Bottcher and M. R. Strayer, Ann. Phys. 175, 64 (1987).

5. M. L. Goldberger and K. M. Watson, Collision Theory (John Wiley & Sons, New York, 1975).

6. A. Gavron, R. L. Ferguson, F. E. Obenshain, F. Plasil, G. R. Young, D. G. Sarantites, and C. F. Maguire, Phys. Rev. Lett. 46, 8 (1981).

Fig. 5.1. Energy spectrum $d\sigma/d\epsilon$ (mb/MeV) of prompt nucleons emitted in the deep-inelastic reaction $^{160}\text{Gd} + ^{93}\text{Nb}$, using the new projection method discussed here.

PERIODIC TRAJECTORIES FOR A TWO-DIMENSIONAL NONINTEGRABLE HAMILTONIAN¹

M. Baranger² K.T.R. Davies

A numerical study is made of the classical periodic trajectories for the two-dimensional, nonintegrable Hamiltonian

$$H = \frac{1}{2} (p_x^2 + p_y^2) + \left(y - \frac{1}{2} x^2 \right)^2 + 0.05 x^2. \quad (1)$$

In addition to x-y pictures of the trajectories, E- τ (energy-period) plots of the periodic families are presented. Efforts have been made to include all trajectories with short periods and all simple branchings of these trajectories. The monodromy matrix has been calculated in all cases, and from it the stability properties are

derived. The topology of the E - τ plot has been explored, with the following results. One family may have several stable regions. The plot is not completely connected; there are islands. The plot is not a tree; there are cycles. There are isochronous branchings, period-doublings, period-multiplying of higher orders, and examples of each of these are presented. There is often more than one branch issuing from a branch point. Some general empirical rules are inferred. In particular, the existence of isochronous branchings is seen to be a consequence of the symmetry of the Hamiltonian. All these results agree with a general classification scheme of possible branchings recently derived. Finally, some non-periodic trajectories are calculated to illustrate the fact that stable periodic trajectories lie in "regular" regions of phase space, while unstable ones lie in "chaotic" regions.

-
1. Abstract of paper: Ann. Phys. (N.Y.) 177, 330 (1987).
 2. Massachusetts Institute of Technology, Cambridge, MA 02139.

BIFURCATIONS OF PERIODIC TRAJECTORIES IN NON-INTEGRABLE HAMILTONIAN SYSTEMS WITH TWO DEGREES OF FREEDOM: NUMERICAL AND ANALYTICAL RESULTS¹

M.A.M. de Aguiar² M. Baranger³
C. P. Malta² K.T.R. Davies

Numerical and analytical studies are made of the types of period multiplying bifurcations undergone by classical periodic trajectories of nonintegrable Hamiltonians with two degrees of freedom. The Hamiltonians studied possess time reversal and reflection symmetries, and we found that these symmetries give rise to additional types of period multiplying bifurcations. The analytical study explains most of the numerically observed bifurcations.

-
1. Abstract of paper to be published in Annals of Physics.
 2. Universidade de São Paulo, 01498 São Paulo, SP, Brazil.
 3. Massachusetts Institute of Technology.

COMPLEX-PLANE METHODS FOR EVALUATING INTEGRALS WITH HIGHLY OSCILLATORY INTEGRANDS¹

K.T.R. Davies

Calculations in momentum space often involve transformations whose integrands are highly oscillatory. By deforming the contour of integration in the complex plane, such an integral can be made to converge rapidly. All oscillatory terms are converted into pure damping terms which decrease exponentially. Examples are given for simple integrals, for the integral of three spherical Bessel functions, and for the Fourier and spherical Bessel function transforms of the Woods-Saxon potential (Fermi-Dirac distribution function). We also show that oscillatory principal-value integrals can usually be accurately evaluated using this method. Convergence with respect to the number of Gaussian points is studied. It is shown that the method normally converges much better than ordinary integration along the real axis, especially as the frequency of the oscillations increases relative to the damping. A comparison is made with the method of steepest descent.

-
1. Abstract of paper submitted to Journal of Computational Physics.

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 submitted to Journal of Computational Physics.

2. GTE Laboratories, Inc., Waltham, MA 02254.

LOW-ENERGY, HEAVY-ION REACTIONS

ISOSPIN AND MACROSCOPIC MODELS FOR THE EXCITATION OF GIANT RESONANCES AND OTHER COLLECTIVE STATES¹

G. R. Satchler

Recently there has been some confusion over the excitation of "isovector" giant resonances by isoscalar probes. We present a unified theoretical description of macroscopic models that may be used to calculate the excitation of giant resonances by inelastic scattering so as to clarify this and related questions. Particular attention is given to the relative phase of the Coulombic and hadronic contributions. After describing models for the transition densities that are based upon certain sum rules, a folding model and a deformed optical potential model for the transition potentials are discussed. Applications are made to some examples of inelastic α -particle scattering and the two models are compared. The cross sections obtained for the breathing-mode monopole resonance are smaller than the measured values, so that more than 100% depletion of the sum rule appears to be required in these cases.

1. Abstract of paper to be published in Nuclear Physics A.

EFFECTS OF DENSITY DEPENDENCE OF THE EFFECTIVE INTERACTION IN A MACROSCOPIC FOLDING MODEL FOR THE EXCITATION OF GIANT RESONANCES AND OTHER COLLECTIVE STATES

M. El-Azab Farid¹ G. R. Satchler

It was speculated recently² that a transition potential would be particularly sensitive to any

density dependence of the effective interaction³ if the corresponding transition density has a node near the surface, such as occurs for the giant monopole resonance.² The expected density dependence strongly dampens the interaction in the interior and reduces the cancellation that would otherwise occur between contributions from small and large radii. When data for the excitation of giant monopole states have been interpreted by using a simple folding model, more than 100% depletion of the sum rule seemed to be required.^{2,4} It was hoped that introducing density dependence would remove this apparent discrepancy. We have now studied this for $\alpha + {}^{208}\text{Pb}$ scattering at 172 MeV. At the same time, we explored the consequences of a consistent treatment of the density dependence⁵ for the excitation of macroscopic density oscillations. Similar studies are being made for the ${}^{16}\text{O} + {}^{12}\text{C}$ system.

Giant monopole, dipole, and quadrupole excitations of ${}^{208}\text{Pb}$ were considered, as well as the first 3^- state, using the DWBA and macroscopic transition densities.² We employed the M3Y effective interaction and its density-dependent generalization called DDM3Y.³ Corresponding optical potentials were obtained from the folding model using the same interactions, normalized to give equivalent elastic scattering for angles $\theta < 20^\circ$. The same normalizations were used for the transition potentials; this is an important constraint. In the usual simple approach,³ which we call SDD, only the ground state density ρ is included in the DDM3Y effective interaction $v(\rho)$ when it is folded with the transition density $\delta\rho$. However, in a consistent treatment (CDD) of macroscopic density oscillations, the deformation of the density $\rho \rightarrow \rho + \delta\rho$ also affects $v(\rho) \rightarrow v(\rho + \delta\rho)$. For harmonic oscillations, this can be included exactly by using the modified interaction

$$\tilde{v}(\rho) = v(\rho) + \rho \partial v(\rho) / \partial \rho. \quad (1)$$

This results in a further reduction of the interaction for nonzero density, as Fig. 5.2 illustrates for a typical example of DDM3Y. (Other forms of density dependence⁵ behave in a similar way.)

Fig. 5.2. The density dependence of the DDM3Y interaction³ at $E/A = 43$ MeV compared to that obtained when modified as in Eq. (1) for the excitation of harmonic density oscillations. The $f(\rho)$ are normalized to unity at $\rho = 0$, and $\rho_0 = 0.17$ nucleons fm^{-3} approximates normal nuclear matter density.

The results will be discussed in detail elsewhere, but in summary, the differences in forward-angle cross sections predicted for these various cases are only of order 10-20%. This is so even for the monopole and the hadronic part of the dipole, despite the nodes in their transition densities. This occurs because of the relatively short range of v and because strong absorption restricts the reaction to large radii.⁴ Simple inclusion of the density dependence (SDD) led in all cases to increases in cross sections of ~10 to 20% at the most forward angles, relative to those obtained with the M3r, but use of the consistency requirement (COD) expressed in Eq. (1) generally reduced them again by similar amounts. These effects become more marked at larger angles, particularly as the region of the nuclear rainbow is approached ($\theta \geq 40^\circ$, say), where the scattering becomes more sensitive to conditions in the nuclear interior.

1. Guest Assignee from Teachers Training College, Salalah, Sultanate of Oman.
2. G. R. Satchler, Nucl. Phys. A (in press).
3. A. M. Kobos, B. A. Brown, R. Lindsay, and G. R. Satchler, Nucl. Phys. A425, 205 (1984).
4. F. E. Bertrand, G. R. Satchler, D. J. Horen, J. R. Wu, A. D. Picher, G. T. Emery, W. P. Jones, and D. W. Miller, Phys. Rev. C 22, 1832 (1980).

5. T. Cheon, K. Takayanagi, and K. Yazaki, Nucl. Phys. A437, 301 (1985); D. K. Srivastava and H. Rebel, Z. Phys. A316, 225 (1984).

THE THRESHOLD ANOMALY AND THE EFFECTIVE INTERACTION FOR NUCLEAR NONELASTIC SCATTERING¹

G. R. Satchler

Previously a dispersion relation has been used to elucidate the energy dependence of one-channel optical potentials, especially the "threshold anomaly" that is observed at low energies. We show that this dispersion relation is also applicable to the elements of the potential matrix which is needed for a coupled-channels treatment. Consequently, the off-diagonal couplings which produce nonelastic transitions may also exhibit such anomalies. We discuss how the energy dependences of the various matrix elements may be related, and provide some arguments that the potential in an excited state is similar to that in the ground state, evaluated at a bombarding energy reduced by the excitation energy. We also examine the collective, or deformed potential, model to see whether the way it is commonly applied is consistent with the dispersion relation.

1. Abstract of paper to be published in Nuclear Physics A.

AN OPTICAL MODEL ANALYSIS OF $^{16}\text{O} + ^{12}\text{C}$ ELASTIC SCATTERING AT $E/A = 94$ MeV¹

A. M. Kobos² G. R. Satchler

An analysis of experimental data for $^{16}\text{O} + ^{12}\text{C}$ elastic scattering at an ^{16}O bombarding energy of 1503 MeV is presented, including the use of "model-independent" and "semi-model-independent" techniques. We conclude that the data unambiguously indicate an optical potential whose real part is approximately 80-MeV deep in the interior, but which is more attractive in the surface region than that given by a folding model with a "realistic" nucleon-nucleon interaction.

1. Abstract of paper to be published in the Proceedings of Supercomputing Symposium '87, Calgary, Alberta, Canada, June 15-16, 1987.
2. Myrias Research Corporation, Edmonton, Alberta T6J 2P7 Canada.

FURTHER OPTICAL MODEL STUDIES OF ^{16}O SCATTERING AT $E/A = 94$ MeV

A. M. Kobos¹ M. E. Brandan²
G. R. Satchler

It is now established that the interactions between target nuclei and light, heavy ions, such as ^{12}C and ^{16}O , become more "surface transparent" as the energy is increased to $E/A \geq 25$ MeV. Consequently, optical model analyses of measurements made at higher energies can reveal the characteristics of the optical potentials at shorter distances and over a wider domain. Such optical model studies have been made using real potentials with either simple functional forms, such as the Woods-Saxon (WS) or Woods-Saxon-squared (WS2), or from folding models which also result in simple monotonic shapes. The main purpose of the present work was to explore the use of more general shapes for the real potential in analyses of recent³ data for ^{16}O scattering at $E/A = 94$ MeV. In particular, we took one of the folding models⁴ to provide reference potentials V_0 and added various correction terms $\Delta V(r)$. One choice treated the values of $\Delta V(r)$ at specified radii as variables, with a cubic spline interpolation used in between. The reference potentials, by themselves, have already been shown³ to reproduce quite well the cross sections measured at this energy, while the same model has given a good account⁵ of other data for $^{12}\text{C} + ^{12}\text{C}$ and $^{16}\text{O} + ^{12}\text{C}$ at a number of energies from $E/A = 13$ to 84 MeV.

The data³ we used are confined to very forward scattering angles. However, their angular distributions are dominated by refractive effects. (The imaginary potential plays a much less important role.) There is strong interference between nearside and farside scattering at the smaller angles, followed by an almost featureless falloff at the larger angles where the farside scattering dominates, although even there some residual far-near interference modulates the angular distributions. It is by fitting these features in detail that we can learn more about the refractive potential.

No significant improvement in fitting the $^{16}\text{O} + ^{40}\text{Ca}$ data was obtained by introducing ΔV

over that already found,³ using the WS or folded potentials alone. This system exhibits the characteristics of "strong absorption": the scattering in the observed range is sensitive to the potential over only a relatively narrow region (at most, $r = 6$ to 9 fm), and the low partial waves are strongly absorbed (S-wave scattering matrix elements of magnitude $|S_0| = 10^{-4}$ to 10^{-3}).

The $^{16}\text{O} + ^{28}\text{Si}$ scattering data imply somewhat less strong absorption ($|S_0| = 10^{-2}$ to 10^{-3}), although sensitivity is still confined to a surface region of $r = 5$ to 8 fm. Some reduction in χ^2 was obtained by adding the supplementary potential ΔV , but its significance is not clear. Consequently, the significant results primarily concern $^{16}\text{O} + ^{12}\text{C}$, where it seems possible to draw some less ambiguous conclusions. The results for this case are summarized in "An Optical Model Analysis of $^{16}\text{O} + ^{12}\text{C}$ Elastic Scattering at $E/A = 94$ MeV" by Kobos and Satchler in this report. Figure 5.3 shows a typical example

Fig. 5.3. Comparison of the measured³ differential cross sections for $^{16}\text{O} + ^{12}\text{C}$ at $E/A = 94$ MeV with the fits obtained with the folded potential⁴ alone (FOLD) and with the addition of a $\Delta V(r)$ comprised of two Woods-Saxon derivative terms.

of the improvement obtained by adding ΔV to the reference potential.

1. Myrias Research Corporation, Edmonton, Alberta, T6J 2P7 Canada.

2. Universidad Nacional Autonoma de Mexico, 01000 Mexico DF, Mexico.
3. P. Roussel et al., Phys. Rev. Lett. 54, 1779 (1985); Phys. Lett. 185B, 29 (1987).
4. M. El-Azab Farid and G. R. Satchler, Nucl. Phys. A438, 525 (1985).
5. M. E. Brandan, J. Phys. G 9, 197 (1983); Proceedings 10th Oaxtepec Symposium on Nuclear Physics, Notas de Física, Vol. 10, No. 1 (1987).

FOLDING MODEL ANALYSIS OF ^{12}C - ^{12}C AND ^{16}O - ^{12}C ELASTIC SCATTERING AT INTERMEDIATE ENERGIES USING A DENSITY-DEPENDENT INTERACTION

M. E. Brandan¹ G. R. Satchler

An analysis has been made of 11 sets of elastic scattering measurements on the systems ^{12}C - ^{12}C , ^{13}C - ^{12}C , and ^{16}O - ^{12}C at laboratory energies between 9 and 120 MeV/nucleon (center-of-mass energies between 60 and 725 MeV), using optical potentials whose real parts were obtained from a folding model based upon an energy- and density-dependent effective nucleon-nucleon interaction.² The goals of this study have been, firstly, to determine the usefulness of this particular, so-called DDM3Y, interaction for light heavy-ion systems at various energies, and, secondly, to look for a simple and coherent description of the elastic scattering over a broad range of energies. We were encouraged by the initial successes of the application³ of this model to ^{16}O scattering from a number of targets from ^{12}C to ^{208}Pb at $E/A = 94$ MeV.

Our choice of a density dependence based upon certain G-matrix calculations⁴ is not determined unambiguously at the highest energies included in this study. However, the model was found to be successful if we used the smoothly interpolated parameter values that were adopted previously.² Then these real potentials, accompanied by imaginary potentials of Woods-Saxon shape, can give a good overall description of the data currently available in this energy range.

The optimum imaginary potentials are quite shallow (of order 20 MeV) and result in a certain amount of transparency in the central region and for the low partial waves. Further study of this enables us to conclude that the folding model with the DDM3Y interaction² gives

an adequate account of the potentials for separations of the centers of mass of the two nuclei that are greater than about 4 fm.

However, this apparent success of the DDM3Y interaction should be viewed with caution in light of some of the assumptions made during its derivation and the failure of the same model for heavier systems at the lower energies.² Further, a detailed examination ("Further Optical Model Studies of ^{16}O Scattering at $E/A = 94$ MeV" by Kobos, Brandan, and Satchler in this report) of the $^{16}\text{O} + ^{12}\text{C}$ scattering at $E/A = 94$ MeV suggests that some corrections to this folding model potential are needed for the very best fit to this particular data set.

1. Universidad Nacional Autonoma de Mexico, 01000 Mexico DF, Mexico.

2. M. El-Azab Farid and G. R. Satchler, Nucl. Phys. A438, 525 (1985).

3. P. Roussel et al., Phys. Rev. Lett. 54, 1779 (1985); Phys. Lett. 185B, 29 (1987).

4. J. P. Jeukenne, A. Lejeune, and C. Mahaux, Phys. Rev. C 16, 80 (1977).

ENHANCED DISSIPATION IN NEW MEAN FIELD STUDIES OF STRONGLY DAMPED COLLISIONS¹

S. J. Lee² K.T.R. Davies
A. S. Umar³ M. R. Strayer
P. G. Reinhard⁴

Time-dependent Hartree-Fock (TDHF) calculations have been performed for the $^{86}\text{Kr} + ^{139}\text{La}$ system at a laboratory energy of 610 MeV. The effective interaction includes a spin-orbit force. The results are compared with experiment and with previous TDHF studies in which spin currents were not included. The new results show an overall increase in the amount of dissipation found for strongly damped trajectories including fusion for head-on collisions, a region of negative angle scattering in the deflection function, and enhanced particle transfer for $b \approx 110\text{fm}$.

1. Abstract of paper to be published in Physics Letters.

2. McGill University, Montreal, Quebec H3A 2T8 Canada.

3. Consultant from Vanderbilt University, Nashville, TN 37235.

4. Consultant from Universität Erlangen, D-8520 Erlangen, West Germany.

NUCLEAR STRUCTURE

TAILS OF THE ROTATIONAL STRENGTH FUNCTION IN THE NUCLEAR QUASICONTINUUM¹

G. A. Leander² P. Arve³
B. Lauritzen⁴

The strength function for collective rotational transitions at high level density manifests itself in quasicontinuum gamma-ray spectra following heavy-ion fusion reactions (see Fig. 5.4). The tails of the strength distribution

Fig. 5.4. Schematic illustration of the role that the tails of the rotational E2 strength function would play in a strong residual interaction scenario. The tail at high excitation energy could contain a significant fraction of the rotational strength, which would thus be unavailable for γ decay. The low-energy tail would enhance the "statistical" component of the E2 strength function.

are considered here on the basis of results from a schematic model. In a weak interaction regime, the tails drop off rapidly. In a strong interaction regime, the tails of the standard Breit-Wigner shape are modulated by the level

density and by the few-body nature of the residual interaction. This could reduce the $B(E2)$ strength available for rotational decay.

1. Abstract of paper to be published in Physical Review C.

2. UNISOR, Oak Ridge Associated Universities.

3. Daresbury Laboratory, Daresbury, Warrington WA4 4AD, England.

4. Niels Bohr Institute, DK-2100 Copenhagen, Denmark.

SIMULATION OF NUCLEAR QUASICONTINUUM GAMMA-RAY SPECTRA¹

G. A. Leander²

A code has been made available for Monte Carlo simulation of gamma-ray spectra from evaporation residues of heavy-ion reactions. Its main feature is flexibility in modeling the nuclear structure at high spin and finite temperature. New items include a formula for the energy dependence of the entry distribution and implementation of improved line shapes for the giant E1 and rotational E2 distributions in the quasicontinuum.

1. Abstract of paper to be published in Computer Physics Communications.

2. UNISOR, Oak Ridge Associated Universities.

STATISTICAL E1 AND γ 1 GAMMA STRENGTH FUNCTIONS FROM HEAVY-ION, γ 1 DATA¹

G. A. Leander²

A statistical model analysis of heavy-ion, γ 1 data puts constraints on the electromagnetic dipole strength functions at low energies, $E_\gamma \sim 0.5 - 4$ MeV. The M1 strength is inferred to be up to an order of magnitude smaller than at the higher energies of neutron capture gamma rays. The analysis supports the Kadomensky-Markushev-Furman shape of the E1 strength function (see Fig. 5.5), with a low-energy tail of the giant resonance that is suppressed relative to the shape based on a Lorentzian. The data considered include the yrast feeding pattern in the

Fig. 5.5. The conventional Lorentzian shape (dotted curve) of the giant E1 strength function is compared with the Kadomensky-Markushev-Furman shape (solid curves). The latter is found to be compatible with (HI,xny) data. It depends on the intrinsic excitation energy U_f of the final state, and for "cool" final states the low-energy tail is quenched by an order of magnitude compared to the Lorentzian.

N=92 isotones ^{160}Er , ^{162}Yb , and ^{164}Hf , and in ^{152}Dy up to spin 60h.

1. Abstract of paper to be published in Physical Review C.
2. UNISOR, Oak Ridge Associated Universities.

CRANKED SHELL MODEL AT FINITE TEMPERATURE

T. Bengtsson¹ G. A. Leander³
Y. S. Chen² J. Y. Zhang⁴

Free energy of deformation surfaces at finite rotational frequency and temperature are a standard tool of nuclear theory in predicting nuclear properties at high spin and excitation energy. The cranked modified oscillator codes

have been extended to include temperature and were applied to the interpretation of H,K gated spin spectrometer data. A novel development in progress is a formalism within the finite temperature cranked shell model framework for spectral calculations that relate more directly to the spin spectrometer data.

1. Lund University, Lund, Sweden.
2. Institute of Atomic Energy, Beijing, China.
3. UNISOR, Oak Ridge Associated Universities.
4. Guest Assignee from Institute of Modern Physics, Lanzhou, China.

OCTUPOLE SHAPES AND SHAPE CHANGES AT HIGH SPINS IN Ra AND Th NUCLEI¹

W. Nazarewicz² G. A. Leander³
J. Dudek⁴

The shapes of rotating Ra and Th nuclei ($130 < N < 138$) are calculated using the cranking model. The lightest isotopes have spherical ground states, but develop octupole and quadrupole deformations under rotation which remain up to very high spins. The ground states of the heavier isotopes have octupole and quadrupole deformations which persist up to intermediately high spins ($I = 14-24 \hbar$). At higher spins, a transition is predicted to take place along the yrast line to shapes with similar quadrupole but no octupole deformation component.

1. Abstract of paper: Nucl. Phys. A467, 437 (1987).
2. Technical University, PL-00-662 Warsaw, Poland.
3. UNISOR, Oak Ridge Associated Universities.
4. Guest Assignee from Centre de Recherches Nucléaires and Université Louis Pasteur, F-67037 Strasbourg Cedex, France.

ABUNDANCE AND SYSTEMATICS OF NUCLEAR SUPERDEFORMED STATES; RELATION TO THE PSEUDO-SPIN AND PSEUDO-SU(3) SYMMETRIES¹

J. Dudek² Z. Szymanski⁴
W. Nazarewicz³ G. A. Leander⁵

Results of a multidimensional ($\beta_2, \gamma, \beta_4, w, Z$, and N) search for nuclear superdeformed configurations are presented. In contrast to the

harmonic oscillator result according to which the strongest superdeformed shell structures occur at fixed elongation defined by $\hbar\omega_a:\hbar\omega_b = 1:2$, realistic calculations give a relatively strong dependence of the "super" elongation on the particle number. This dependence is shown to be a cyclic function of the particle number. It originates from the pseudo-spin and pseudo-SU(3) symmetries which are obeyed approximately in a realistic average field.

1. Abstract of paper submitted to Physical Review Letters.
2. Guest Assignee from Centre de Recherches Nucléaires and Université Louis Pasteur, F-67037 Strasbourg Cedex, France.
3. Technical University, PL-00-662 Warsaw, Poland.
4. Centre de Recherches Nucléaires, F-67037 Strasbourg Cedex, France and Warsaw University, PL-00-681 Warsaw, Poland.
5. UNISOR, Oak Ridge Associated Universities.

COLLECTIVE OBLATE BAND IN ^{131}La DUE TO THE ROTATIONAL ALIGNMENT OF $h_{11/2}$ NEUTRONS¹

E. S. Paul ²	W. F. Piel, Jr. ²
C. W. Beusang ²	M. Xu ²
D. B. Fossan ²	L. Hildingsson ³
R. Ma ²	G. A. Leander ⁴

Several rotational bands have been populated to high spin in the γ -soft nucleus ^{131}La . We present experimental evidence for a collective oblate rotational band based on a $\pi h_{11/2}(\nu h_{11/2})^2$ three-quasiparticle configuration. It is the rotational alignment of the pair of neutrons from the upper $h_{11/2}$ midshell which drives the nucleus from a prolate ($\gamma = 0^\circ$) shape to a collectively rotating oblate ($\gamma = -60^\circ$) shape. This band coexists with a prolate band that contains a pair of aligned protons from the lower $h_{11/2}$ midshell.

1. Abstract of paper: Phys. Rev. Letts. 58, 984 (1987).
2. State University of New York at Stony Brook, Stony Brook, NY 11794.
3. Research Institute of Physics, S 104 05 Stockholm 50, Sweden.
4. UNISOR, Oak Ridge Associated Universities.

FERMION DYNAMICAL SYMMETRY FOR ODD-MASS NUCLEI¹

H. Wu ²	D. H. Feng ²
Z. P. Li ³	C. L. Wu ³
M. M. Guidry ⁴	

The properties of odd-mass deformed nuclei are often described in terms of a model in which the unpaired particle is coupled to a geometrically deformed core by the Nilsson potential. The shell model should be able to describe the same odd-mass nuclei to which the Nilsson model is normally applied if an appropriate residual interaction is diagonalized within the valence space. However, for many particles outside closed shells, the direct solution of the spherical shell model is not a viable problem.

In a recent series of publications, a new algebraic fermion approach to the solution of the many-body problem has been introduced (see, e.g., Refs. 5 and 6 and contributions in this section of this report). This fermion dynamical symmetry model (FDSM) corresponds to a severe truncation of the shell-model space according to principles of dynamical symmetry. This model has been applied to even-even nuclei, and it has been shown that the basic features of collective motion emerge as approximate solutions to the shell-model problem. It was pointed out in Ref. 5 that the same methods can be applied to odd-mass and odd-odd nuclei, thus providing a unification of geometrical and algebraic approaches to collective motion for all heavy nuclei. In this report, we demonstrate that the FDSM quantitatively reproduces the well-known coupling schemes for a single unpaired particle in a unique-parity orbital for a deformed nucleus.

In Fig. 5.6 we present an FDSM calculation of the yrast levels for an odd-mass deformed nucleus with an unpaired particle in the $i_{13/2}$ orbital. The calculation is shown as a function of quadrupole coupling strength and is compared with a corresponding calculation using the particle-rotor model.

The agreement between the shell model and particle-rotor calculations across the whole range of angular momenta and coupling strengths

ORNL DWG 87-19546

ORNL DWG 87-19547

Fig. 5.6. Yrast levels for an odd-mass nucleus as a function of quadrupole coupling strength. FDSM and particle-rotor calculations are shown. The horizontal axis for the FDSM calculation is proportional to the two-particle quadrupole coupling strength, while for the particle-rotor calculation it is proportional to quadrupole deformation. The FDSM horizontal axis has been rescaled to coincide with the particle-rotor deformation parameter. For simplicity, pairing has been omitted in both calculations.

is spectacular. In particular, we see that the odd-mass FDSM is able to quantitatively reproduce the well-known strong-coupling, weak-coupling, and rotation-aligned coupling schemes and their evolution as a function of quadrupole coupling strength. Typical spectra in these coupling regimes are shown in Fig. 5.7.

Finally, in more recent work, we have demonstrated that the small differences between the FDSM and particle-rotor calculations in Figs. 5.6 and 5.7 are finite particle number effects. Therefore, the particle rotor model may be

Fig. 5.7. Yrast spectra from Fig. 5.6 illustrating three basic coupling regimes as a function of quadrupole coupling strength.

viewed as the infinite particle number limit of the FDSM.

1. Summary of paper: Phys. Lett. 1938, 163 (1987).
2. Drexel University, Philadelphia, PA 19104.
3. Guest Assignee from University of Tennessee, Knoxville, TN 37996.
4. Adjunct staff member from University of Tennessee, Knoxville, TN 37996.
5. C. L. Wu, D. H. Feng, X. G. Chen, J. Q. Chen, and M. W. Guidry, Phys. Lett. 168B, 313 (1986).
6. M. W. Guidry, C. L. Wu, D. H. Feng, J. N. Ginocchio, X. G. Chen, and J. Q. Chen, Phys. Lett. 176B, 1 (1986).

AN ALGEBRAIC FERMION DESCRIPTION OF BAND TERMINATION AND LOSS OF COLLECTIVITY IN HEAVY NUCLEI¹

M. W. Guidry² C. L. Wu³
Z. P. Li³ D. H. Feng⁴
J. N. Ginocchio⁵

We have recently introduced a fermion dynamical symmetry model (FDSM), which provides a unified treatment of collective and single-particle modes starting from fermions in the spherical shell model.⁶ In this report the $SU_3 \oplus SU_2$ limit of the FDSM is used to interpret the loss

of E2 collectivity and band termination in rare-earth nuclei. By assuming the symmetry limit, it is possible to obtain analytical formulas for the yrast band reduced transition probabilities $B(E2)$.

In Fig. 5.8 some data and the corresponding FDSM calculations of the trends in E2 matrix elements are shown as a function of angular momentum. The data are displayed as the ratio $B(E2)/B(E2)_{\text{Rot}} = [\langle J+2 || M(E2) || J \rangle / \langle J+2 || M(E2) || J \rangle_{\text{Rot}}]^2$ where "Rot" denotes the value expected for a rigid rotor with an intrinsic moment fixed by one transition in the band. The relevant parameters (four free ones except for the two Yb cases where five were used) were determined by an approximate fit to the yrast energy levels, as in Ref. 7.

In Fig. 5.8(a) and (c)-(e), two curves are shown for each case. The dashed line corresponds to the prescription $N_1 = N_N^1 + N_V^1 < \Omega_1/5$ (where Ω_1 is the pair degeneracy of the normal parity orbitals of the valence shell, and N_1 is the number of normal-parity valence pairs) appropriate for pure SU_3 symmetry for both protons and neutrons. The solid line results from a calculation in which the effective value of N_1 is adjusted to give a better visual fit to the high-spin data. The general trends in the $B(E2)$ ratios are reproduced remarkably well. In particular, the reduced E2 strength for ^{172}W in the two-quasiparticle band (unexpected in the original cranking calculations), and the step structure between high- and low-spin data in Fig. 5.8(c) for ^{166}Yb are naturally reproduced. No attempt is made here to describe the transitions correctly at the band crossings, since heritage-breaking perturbations have been omitted. Therefore, no significance should be attached to discrepancies between data and calculations in the spin 12-16 region.

From these results, we conclude that there is systematic evidence for finite SU_3 core angular momentum content in the $B(E2)$ measurements for rare-earth nuclei. The crucial step in this realization is the consistent separation of the total angular momentum of high-spin states into a part associated with rotation of a core of

Fig. 5.8. The ratio $B(E2)/B(E2)_{\text{Rot}}$ for several rare-earth nuclei. In (a) and (c)-(e) two calculations are shown corresponding to different numbers of normal-parity pairs $N_1 = N_N^1 + N_V^1$. (b) Model calculation of a complete yrast termination.

condensed S and D fermion pairs, and a part generated by breaking coherent pairs and coupling the generalized pseudospin to large values of angular momentum.

Finally, let us clearly relate these ideas to band termination at high spins. Both the Sp_6 and SO_8 global FDSM symmetries have rotation-like and vibration-like subchains. All of the SU_3 bands terminate to single-particle strength when the core angular momentum $R = J - I$ satisfies $R = 2N_1$. For few-quasiparticle configurations, these terminating states will usually be non-yrast, but in some cases they could become yrast for $J = 40$. In Fig. 5.8(b) we show a model calculation of band termination by this mechanism. Each band (light lines) eventually terminates, but only near spin 40 is the terminating band also the yrast band (heavy line).

1. Summary of paper: Phys. Lett. 187B, 210 (1987).
2. Adjunct staff member from University of Tennessee, Knoxville, TN 37996.
3. Guest Assignee from University of Tennessee, Knoxville, TN 37996.
4. Drexel University, Philadelphia, PA 19104.
5. Los Alamos National Laboratory, Los Alamos, NM 87545.
6. C. L. Wu et al., Phys. Lett. 168B, 313 (1986).
7. M. W. Guidry, et al., Phys. Lett. 176B, 1 (1986).

A MICROSCOPIC FORMULA FOR ACTINIDE MASSES³

C. L. Wu² X. L. Han²
Z. P. Li² M. W. Guidry³
D. H. Feng⁴

The fermion dynamical symmetry model (FDSM)⁵ exploits fermion dynamical symmetry to construct a many-body solution of the spherical shell model with residual interaction. Elsewhere in this report, the ability of the FDSM to give a microscopic description of the spectra and transition probabilities for nuclei exhibiting collective motion has been emphasized. In this contribution it is demonstrated that the FDSM also provides a microscopic theory of ground-state masses.

In the FDSM, the N - Z plane in the actinide region may be expected to break into domains corresponding to $SU(2)$ or $SU(3)$ symmetry. In addition, the regions corresponding to $SU(3)$ symmetry are expected to break into sub-domains, corresponding to different $SU(3)$ representations

for the ground state. A systematic fit of the FDSM mass equation to the masses of known nuclei in the actinide region shows clear evidence for discontinuities indicating transition between different domains. A phase diagram for the N - Z plane is given in Fig. 5.9 based on systematic

ORNL DWG 87-19549

Fig. 5.9. Phase diagram in the N - Z plane for even-even actinides. The quantities N_v and N_p denote valence neutron and proton pairs, respectively, and different symbols are used to indicate the various ground-state symmetries.

fits of the mass equation to the ground-state masses. In Figs. 5.10(a,b) we show a comparison of the differences between the experimental and calculated masses of the known even-even actinides for the FDSM and for the Moller-Nix⁶ liquid-drop plus shell-correction method. The FDSM calculation exhibits a root-mean square deviation of 0.30 MeV in a fit to 320 ground-state masses. The FDSM fit uses five free parameters for the $SU(2)$ region, five for the $(2N_1, 0)$ representations in the $SU(3)$ regions, and two additional free parameters in the other $SU(3)$ representations.

Although the FDSM is a microscopic theory, the artificial separation of the mass into liquid drop and fluctuating parts is instructive. In Fig. 5.10(c) we show the "shell correction" for the FDSM, calculated by subtracting

ORNL DWG 87-19550

Fig. 5.10. Discrepancy between calculations and experimental masses and the FDSM "shell correction" for even-even actinide nuclei. The quantities $M(\text{FDS})$, $M(\text{MM})$, and $M(\text{EXP})$ are the masses calculated using the FDSM, Moller-Mix mass formulas, and the experimental masses, respectively.

the liquid-drop energy (Ref. 6) from the total binding energy (relative to the doubly closed shell) determined from our calculation. These shell corrections are in excellent agreement with the experimental shell corrections, with deviations as in Fig. 5.10(a).

1. Summary of paper: Phys. Lett. 1948, 447 (1987).

2. Guest Assignee from University of Tennessee, Knoxville, TN 37996.

3. Adjunct staff member from University of Tennessee, Knoxville, TN 37996.

4. Drexel University, Philadelphia, PA 19104.

5. C. L. Wu et al., Phys. Lett. 1688, 313 (1986).

6. P. Moller and J. R. Nix, Atom. Data and Nucl. Data Tables 26, 165 (1981).

CALCULATION OF TRANSITION PROBABILITIES FOR HIGH-SPIN STATES IN ^{183}Ir AND ^{185}Pt

F. Dönau¹
Y. S. Chen²
P. Semmes³

V. P. Janzen⁴
L. L. Riedinger⁵
M. P. Carpenter⁴

G. A. Leander⁶

As a result of an extensive series of experiments on Au, Pt, and Ir nuclei clustered around $N = 106$ (Refs. 7-10) involving researchers from the University of Tennessee, McMaster University, the University of Montreal, and Oak Ridge National Laboratory, there now exists a considerable amount of data on rotational bands in even and odd systems in this region. Our conclusion that both $i_{13/2}$ neutron and $h_{9/2}$ proton quasiparticles are aligning at fairly low rotational frequencies is thus based on a satisfyingly large body of evidence. However, the recent data on $B(M1; I \rightarrow I-1)/B(E2; I \rightarrow I-2)$ transition probabilities in the odd-neutron ^{185}Pt and odd-proton ^{183}Ir nuclei^{9,10} should give us even more precise clues as to the quasiparticles involved. Therefore, we have undertaken a number of theoretical calculations in an effort to understand these experiments.

The results of a triaxial particle-rotor calculation for the low-spin portion of the $\nu i_{13/2}$ $9/2[624]$ band in ^{185}Pt are shown in Fig. 5.11, along with the experimental $B(M1)/B(E2)$'s extracted from the data of Pilotte et al.⁹ Although this band has a fairly high K of $9/2$, there is some degree of signature dependence possible in the theoretical $B(M1)/B(E2)$ values. Fluctuations in γ , or the equilibrium γ deformation treated in the present calculation will affect that signature oscillation somewhat, but not a great deal for such a high K , as seen in the figure. But overall, the calculated $B(M1)/B(E2)$ ratios at low spin are somewhat lower than the experimental points. At medium spin the agreement becomes better; however, the experimental data do not show the signature dependence of the theory. The calculated $B(E2; I \rightarrow I-1)/B(E2; I \rightarrow I-2)$ ratios show fair agreement with the experimental values, but given the

ORNL DMG 87-19551

Fig. 5.11. Calculated and experimental branching ratios for ^{185}Pt and ^{183}Os $\nu_{13/2}$ bands. The $B(E2)/B(E2)$ ratio has been adjusted by the Clebsch-Gordan factors so that for a symmetric rotor with constant quadrupole moment the plotted ratio should remain equal to one.

experimental uncertainties, it is not possible to obtain a measure of γ by evaluating fits to the data.

The clear upbend seen in alignment plots for this band is accompanied by a large increase in the $B(M1)/B(E2)$ values for ^{185}Pt , as shown more clearly in Fig. 5.12. As Larabee et al. have done¹¹ in the case of ^{159}Tm , we refer to the formalism of Dönau and Frauendorf,¹² Within this model, the ratio of reduced transition probabilities is expressed as:

$$\frac{B(M1; I=1-1)}{B(E2; I=1-2)} = \frac{12}{5Q_0^2 \cos^2(30^\circ + \gamma)} \left[1 - \frac{K^2}{(1 - \frac{1}{2})^2} \right]^{-2} \frac{K^2}{I^2} \times \{ (g_1 - g_R) [(I^2 - K^2)^{1/2} - i_1] - (g_2 - g_R) i_2 \} \quad (1)$$

ORNL DMG 87-19552

Fig. 5.12. Measured and calculated $B(M1)/B(E2)$ values for the $\nu_{13/2}$ $9/2[624]$ band in ^{185}Pt .

where Q_0 is the intrinsic quadrupole moment, g_R is the gyromagnetic ratio for a rotating core (approximated by Z/A), g_1 is the ratio for the single quasiparticle excitation in an odd-A nucleus, and g_2 for the aligning quasiparticle in a band crossing. The quantities i_1 and i_2 refer to the initial quasiparticle alignment and gain in alignment as a result of the crossing, respectively. We use $Q_0 = 5.8$ eb obtained from the measured Q_0 for the core nucleus ^{184}Pb $2^+ \rightarrow 0^+$ transition¹³ and scale Q for higher spins by the (β_2, γ) deformation parameters extracted from our TRS calculations to estimate the $B(E2)$ strength. The MI transition probability between signatures of the one-quasiparticle band is represented by the $(g_1 - g_R)$ term, while the alignment of a pair of quasiparticles contributes via the $(g_2 - g_R)$ component in the equation. Since $(g_K - g_R)$ is positive for a proton and negative for a neutron, it is clear that the MI transition rate will increase if a proton backbend occurs in a neutron band and decrease if a neutron backbend occurs, thus giving us the fingerprint we need to identify the cause of an

alignment. Using standard values for the $(g_K - g_A)$'s, this approach yields the calculated $B(M1)/B(E2)$ curves in Fig. 5.12, resulting from changes in both the M1 and E2 rates. The observed rise in the measured values can be explained only by the alignment of a pair of quasiprotons, with $\nu h_{9/2}$ the obvious choice.

The Dönau-Frauendorf approach also does quite well in reproducing the measured M1/E2 ratios¹⁴ in the $^{183}\text{Ir } \pi d_{5/2}$ band as well. Two clear crossings are observed in this band, with the transition ratios showing a slight decrease through the first crossing. This is consistent with a proton alignment and is certainly far from the strong increase expected for a neutron crossing in this proton band. There may be a small increase in the transition ratios in the upper part of the band, which would be compatible with a subsequent $\nu i_{13/2}$ alignment.

These two examples are important indications that the $\nu h_{9/2}$ crossing occurs at a surprisingly low rotational frequency for neutron number $N = 106$. An improved set of self-consistent Total Routhian Surface (TRS) calculations has been initiated with that question in mind.

EXTENSION OF SELF-CONSISTENT TRS CALCULATIONS TO Te, Xe, AND Nd NUCLEI

V. P. Janzen¹
M. P. Carpenter¹
Y. S. Chen³

G. Zhang¹
L. L. Riedinger²
J.-Y. Zhang⁴

In last year's annual report we discussed the methodology and some results of the series of self-consistent "Total Routhian Surface" (TRS) calculations for $Z = 74-80$ nuclei.⁵ Put briefly, the theoretical treatment consists of a total energy minimization with respect to the deformation parameters β_2 , β_4 , and γ within a Strutinsky-Bogoliubov cranking formalism, using a non-axial Woods-Saxon average field.⁶

The results of those calculations have proved to be quite useful in predicting ground-state deformation in the Pt-Hg transitional region,⁷ as well as understanding some of the unusual quasiparticle alignment features exhibited by these "soft" nuclei as they undergo rotation.⁸ The equivalent transition from spherical to moderately deformed nuclear shapes appears to occur quite differently at the lower end of the $Z = 50-82$ shell, though. The prolate-oblate shape coexistence, nicely demonstrated by both theory and experiment in the Hg ($Z = 80$) isotopes, is not seen in the $Z = 52$ Te nuclei; instead, vibrational-type bands and favored single-particle states dominate the experimental level structures.⁹ The light Xe isotopes ($Z = 54$) exhibit rotational bands corresponding to moderate prolate deformation, yet should retain enough of that γ -softness to allow quasiparticle alignments to change the shape drastically. Finally, in connection with some nuclei in the Nd $Z = 60$ region, there have been reports of marked degrees of ground-state triaxiality,¹⁰ as well as observations of highly deformed rotational bands.¹¹ The purpose of the present set of calculations is to: (1) elucidate the physics behind some of the less well-understood structures in the nuclei mentioned, and (2) where the underlying structures are clear, to test the applicability of these calculations. In keeping with the "universal" (albeit smoothly mass-dependent) nature of the Woods-Saxon parameters used in the present theoretical approach, the only adjustable parameter changed from the

1. Zentralinstitut für Kernforschung, Rossendorf, G.D.R.

2. Institute of Atomic Physics, Beijing, China.

3. Tennessee Technological University, Cookeville, TN 38501.

4. University of Tennessee, Knoxville, TN 37996.

5. Adjunct staff member from University of Tennessee, Knoxville, TN 37996.

6. UNISOR, Oak Ridge Associated Universities.

7. A. J. Larabee et al., Phys. Lett. 169B, 21 (1986).

8. M. P. Carpenter et al., University of Tennessee preprint (1987).

9. S. Pilotte et al., University of Montreal, to be published.

10. V. P. Janzen et al., University of Tennessee Progress Report on Nuclear Physics (1987) 15.

11. A. J. Larabee et al., Phys. Rev. C 29, 1934 (1984).

12. F. Dönau and S. Frauendorf, p. 143 in Proceedings of the Conference on High Angular Momentum Properties of Nuclei, Oak Ridge, TN, 1982, ed. N. R. Johnson, Harwood Academic, New York, 1983.

13. U. Garg et al., Phys. Lett. 180B, 319 (1986).

14. V. P. Janzen et al., to be published.

previous set of calculations was the so-called critical frequency, which affects the rate at which the pairing falls off as a function of rotational frequency. The value of the pairing itself is set by a self-consistent BCS calculation at $\hbar\omega = 0$.

Light Te Isotopes

Ground-state energy surfaces have been calculated for the vibrational $^{110-120}\text{Te}$ nuclei. The minimized shapes are similar to previous results obtained using the Nilsson model, but predict smaller equilibrium deformations ($\beta_2 = 0.16$ vs 0.22) which are more reasonable. The example shown in Fig. 5.13 for ^{116}Te illustrates the shallowness of the total energy surface. Calculated prolate-oblate energy differences increase for the more neutron-deficient isotopes, which is consistent with the observed shift at medium

spins from oblate single-particle structure in the middle of the neutron shell to continued quasivibrational bands in the lighter isotopes.⁹

^{118}Xe

The light Xe nuclei have soft moderately deformed prolate cores which should be susceptible to the shape-driving effects of high-j quasiparticles, in this case from the $\nu h_{11/2}$ and $\pi h_{11/2}$ orbitals. Other calculations pertaining to the nearby light Ba ($Z = 56$) isotopes¹² have pointed out that the alignment of both types of $h_{11/2}$ quasiparticles could, in certain cases, drive a nucleus to a single-particle configuration with $\gamma = 60^\circ$. Xenon-118 should be a good candidate for that kind of shape change, since the neutron Fermi level is within the $h_{11/2}$ j-shell but near the bottom, and the proton Fermi level is just below the lowest $h_{11/2}$ orbital. Figure 5.14 contains TRS maps from the present calculations for $\hbar\omega = 0.4$ and 0.6 MeV, showing the predicted shape after $\nu h_{11/2}$ alignment and after the subsequent $\pi h_{11/2}$ alignment respectively. Previous McMaster University high-spin work on $^{116,118}\text{Xe}$ (Ref. 13) followed the ground-state bands through the alignment only. Data from a recent Holifield Spin Spectrometer experiment using the $^{92}\text{Mo}(^{27}\text{Al}, p2n)^{118}\text{Xe}$ reaction at 118 MeV are being analyzed.

^{136}Nd

This nucleus presents an extremely interesting case of nuclear structure physics. Based on standard Nilsson cranked-shell-model calculations, the ground-state band at low spin has been interpreted by Paul et al.¹⁰ as unusually triaxial ($\gamma = -23^\circ$). They have also reported three 10^+ states having different structures built on top. In addition, this nucleus is one of a number in this region in which highly deformed rotational bands have been observed.¹¹

The calculated TRS maps for $\hbar\omega = 0, 0.2, 0.3$, and 0.4 MeV are shown in Fig. 5.15. The favored triaxial shape is quite clear at low spin, as are, interestingly enough, early hints of a plateau in the energy surface at large prolate deformation. Another intriguing feature is the

ORNL DWG 87-19553

Fig. 5.13. Calculated total energy surface for the ^{116}Te ground state, indicating a minimum at $\beta_2 = 0.16$, $\gamma = 1^\circ$ ($\beta_4 = 0.027$). The contour energies are marked in MeV.

imbalance between the three increasing with faster rotation. At low spins, then, the ground-state band should lie in the $\gamma = -30^\circ$ minimum, as shown in Fig. 5.15(b). The $h_{11/2}$ protons are predicted to drive the nucleus toward more positive γ , and so their alignment predictably leads to the $\gamma = +30^\circ$ minimum being favored momentarily, as in Fig. 5.15(c). A further alignment, this time due to the $h_{11/2}$ neutrons, swings the favored shape back to $\gamma = -30^\circ$ (Fig. 5.15(d)). Interpretation of the three 10^4 states as continuation of the ground band, with $h_{11/2}$ and $h_{11/2}$ configurations¹⁰ is understandable in light of the predicted different shapes. However, the theoretical crossing frequencies for both alignments are in poor agreement with experiment. This is also the case in a number of other transitional nuclei, not only in this region but in the light Ir-Au-Pt nuclei as well.¹⁴ Calculations at JIHIR are under way to determine if some of these discrepancies could be due to inaccurate determination of the pairing, due, for example, to the odd-even mass difference containing contributions from deformation changes in addition to the usual pairing energy.¹⁵ The possibility that single-particle orbital energies are not optimal cannot be excluded.

Looking at Fig. 5.15(d), it can be seen that already at $\hbar\omega = 0.4$ MeV another minimum is developing at much larger prolate deformations than the ground-state and s-bands. At approximately $\hbar\omega = 0.5$ MeV and above, that minimum actually represents the favored shape. Fixed-deformation Woods-Saxon cranked-shell-model calculations suggest a $\nu h_{11/2}^2 \pi h_{11/2}^2 \nu i_{13/2}^2$ configuration at that value of β_2 . The recent first observation of a $\nu i_{13/2}$ band in this region, in ^{135}Sm (Ref. 16), fits in nicely with this interpretation. The band moment of inertia, as a function of frequency extracted from the theory, shows the same decreasing trend but does not agree with the absolute experimental numbers. Nonetheless, it is significant that the observed highly deformed prolate band is predicted by these "standard" TRS calculations using such a universal set of parameters, and

Fig. 5.15. Total Routhian Surfaces for the ^{136}Nd ground-state band at selected values of rotational frequency. (a) The triaxial minimum is quite clear in the ground state. In this case, symmetry requires equivalent minima at $\beta_2 = 0.18$ and $\gamma = +24^\circ$, -24° , and -96° (not shown). For the higher frequencies, the calculated favored deformations are: (b) $\hbar\omega = 0.2$ MeV, $\beta_2 = 0.19$, $\gamma = -26^\circ$ ($I = 3$), (c) $\hbar\omega = 0.3$ MeV, $\beta_2 = 0.20$, $\gamma = 20^\circ$ ($I = 12$), and (d) $\hbar\omega = 0.4$ MeV, $\beta_2 = 0.17$, $\gamma = -19^\circ$ ($I = 21$). In (d) a minimum at $\beta_2 = 0.35$, $\gamma = 2^\circ$ ($I = 25$) is also seen.

without invoking unique circumstances such as favored axis ratios. The inference is that these bands, while certainly special features of the nuclear structure physics in this region, are fundamentally different from the so-called "superdeformed" bands recently found in ^{152}Dy and nearby nuclei.

1. University of Tennessee, Knoxville, TN 37996.

2. Adjunct staff member from University of Tennessee, Knoxville, TN 37996.

3. Joint Institute for Heavy Ion Research. Permanent address: Institute of Atomic Physics, Beijing, China.

4. Joint Institute for Heavy Ion Research. Permanent address: Institute of Modern Physics, Lanzhou, China.

5. W. Nazarewicz et al., Phys. Div. Prog. Rept., Sept. 30, 1986, ORNL-6326, p. 85.

6. W. Nazarewicz et al., to be published.

7. R. Bengtsson et al., Phys. Lett. 183B, 1 (1987).

8. M. P. Carpenter et al., University of Tennessee preprint (1987).

9. V. P. Janzen et al., McMaster Accelerator Laboratory Ann. Rept., 1985, p. 54, and T. Lönroth et al., Phys. Scripta 34, 682 (1986).
10. E. S. Paul et al., Phys. Rev. C 36, 153 (1987).
11. E. M. Beck et al., Lawrence Berkeley Laboratory preprint (1987).
12. A. H. Nelson et al., University of Liverpool Ann. Rept., 1984/85, p. 20.
13. V. P. Janzen et al., McMaster Accelerator Laboratory Ann. Rept., 1985, p. 62.
14. L. L. Riedinger et al., Proceedings of the XXII Zakopane School on Physics, Zakopane, Poland (1987) in press.
15. J.-Y. Zhang (1987) private communication.
16. S. M. Mullins et al., J. Phys. G 13, L201 (1987).

INTERMEDIATE-ENERGY, HEAVY-ION REACTIONS

PERTURBATIVE PRODUCTION OF γ 's AND π^0 's IN HEAVY-ION REACTIONS

D. J. Ernst¹ M. R. Strayer

At bombarding energies per nucleon near the Fermi energy, heavy-ion reactions display an unusually large probability for producing π^0 mesons. These reactions are near the absolute threshold for π^0 production and are particularly interesting, since a sizable fraction of the available energy in the center of mass is carried by the emitted pion. Because of the near threshold conditions, a small change in the initial state is reflected in substantially different properties of the emitted pions, and thus these reactions can be used to study the short-time, high-frequency dynamics of the collision, together with the response of the nucleus to these dynamics. However, a complete and convincing mechanism for the emission process has not yet emerged, in part because different models seem to yield qualitatively similar results, and in part because of complications arising from strong pion absorption and rescattering in the colliding nuclei.

Recent investigations² have attempted to probe the collision using high-energy gamma rays. Photons have several advantages as probes of the collision; their coupling to the electromagnetic current is perturbative and the complex final-state interactions are absent. The most

obvious model for this type of emission is as bremsstrahlung during the initial stage of the collision.

This type of emission can be derived from a field theoretic formalism,³ which results in the coupling of the π^0 's and γ 's to the heavy-ion dynamics via a space-time Wigner function.

A diagrammatic method of solving such problems has been proposed by Baranger and Zahed.³ In this theory, the time evolution is divided into two parts — a nonperturbative, strongly dynamical part which must be solved for exactly, and a part which is coupled weakly and can be treated perturbatively.

In our application, we assume the dynamical evolution of the mean field part of the equations to be solved exactly. The emission of pions and photons and the collisions between nucleons are treated perturbatively. This results in a formal structure for the emission process in which the mean field and the lowest order collision terms can be modeled in terms of a phenomenological, external, one-body, time-dependent field. We identify the Wigner function constructed from the Fourier time transform of the nucleon wave functions as the quantity which plays the role of a classical source function. Although the differences between the coupling of a pion to a nucleon and the coupling of a photon to a nucleon precludes any direct relation between gamma and pion data, the formalism developed here implies that a model for the Wigner function which has been adjusted to produce pion emission cross sections could be used to predict gamma emission cross sections. We test this by using a schematic model for the pion emission and find that it produces good results for gamma emission. We also note that within this model, the emission of very high-energy photons, which is dominated by spin currents, can be directly related to measured pion cross sections, as

$$\frac{d\sigma}{dE_\gamma} = \left[\frac{k_\gamma^3}{k_\pi^3} \frac{(\lambda_P^2 + \lambda_N^2)}{f(f/u)^2} \right] \frac{d\sigma}{dE_\pi}; \quad E_\gamma = E_\pi \quad (1)$$

In Fig. 5.16, we plot gamma cross sections predicted from our schematic model for very

Fig. 5.16. The energy differential spectrum for the inclusive gamma and pion emission in the reaction $^{14}\text{N} + \text{Ni}$ at an energy per nucleon of 35 MeV. The solid curve represents the total emission cross section (the upper curve for pions and the lower curve for gammas), the dashed curve the emission caused by the convective currents, and the dot-dashed curve the emission from the spin currents. Note that at sufficiently high gamma energy, the spin-current term becomes dominant.

high-energy gammas and see that for $E_\gamma > 180$ MeV, the spin-current terms become dominant. In this region, a relation like Eq. (1), adjusted for pion rescattering, should be reasonably quantitative. This is because even though the factorization into momentum-dependent terms times energy-dependent terms is only exact in our model, the exponential fall in data with increasing energy is determined predominantly by the time Fourier transform, while the dominant momentum dependence arises from the threshold k^2 dependence of the matrix element is sufficiently smooth so that Eq. (1) follows.

1. Consultant from Texas A&M University, College Station, TX 77843.

2. P. Braun-Munzinger et al., Phys. Rev. C 33, 1420 (1986).

3. M. Baranger and I. Zahed, Phys. Rev. C 29, 1005 (1984).

MODEL CALCULATIONS FOR PRODUCTS OF ONE-BODY NUCLEON GREEN'S FUNCTIONS

G. D. White¹ K.T.R. Davies

A particular product of two one-body, nucleon Green's functions is being evaluated in a

static, nonrelativistic, mean-field model, in which spherical symmetry is also assumed. The structure of this response function will be analyzed in detail, particularly the contributions from different combinations of negative-energy and continuum wave functions. The formalism is being extended to include Δ particles, as well as nucleons. The occupation probabilities are given by Fermi-Dirac distributions, so that highly excited nuclei may be treated. We have shown that the contributions, exclusively from the plane-wave parts of the continuum wave functions give rise to a sharply peaked energy distribution which, in a certain limit, reduces to a delta function. An accurate method is being developed for evaluating the Woods-Saxon negative-energy and continuum wave functions in momentum space, the representation in which one most naturally derives an overall factor making each continuum state orthonormal. The momentum-space wave functions can then easily be transformed to coordinate space, and the behavior in each representation will be studied. However, it has been shown that, for the calculation of this particular folding integral of two single-particle wave functions, coordinate space is superior to momentum space, with the integral for two continuum states efficiently evaluated by a complex contour integration.

1. Northwestern State University, Natchitoches, LA 71437.

INTEGRAL METHODS FOR CALCULATIONS OF GREEN'S FUNCTIONS IN PION-NUCLEON PROBLEMS I¹

K.T.R. Davies M. R. Strayer
G. D. White²

A general program is being developed for the systematic and careful evaluation of Green's functions in pion-nucleon problems. This paper is the first in a series of projects involving integral methods for the calculation of the pion and nucleon propagators. A method is presented for evaluating efficiently and accurately the integral $\int_0^\infty r^2 j_k(kr) j_k(k'r) j_L(pr) dr$, where $j_k(p)$ is a spherical Bessel function. For large r , the integrand of this integral has a slowly

decreasing oscillatory behavior. Rapid convergence is insured by rotating, in the complex plane, the upper part of the integral, giving an integrand which decreases exponentially. A scaling formula is used to evaluate the integral for very small or very large values of the momenta. It is shown that, if k , k' , and L satisfy triangular inequalities and if $k + k' + L$ is even, then k , k' , and p must also satisfy triangular inequalities, which is the condition required by the vector delta function $\delta(\vec{k} + \vec{k}' - \vec{p})$. The method can also be used for evaluating integrals of the form $\int_R^\infty r^2 x_L(kr) x_L(k'r') x_L(pr) dr$, $R \neq 0$, where x_L can be either a spherical Bessel function or a spherical Neumann function. Finally, we present a sum rule for integrals of three spherical Bessel functions.

1. Abstract of paper submitted for publication in Journal of Mathematical Physics.

2. Northwestern State University, Natchitoches, LA 71437.

PHYSICS OF RELATIVISTIC PROJECTILES

PULSED ELECTROMAGNETIC PRODUCTION OF LEPTONS IN ULTRARELATIVISTIC ION-ION COLLISIONS¹

C. Bottcher M. R. Strayer

The possibility of significant heavy lepton production and emission from the electromagnetic field in relativistic, heavy-ion collisions was suggested several years ago by Gould,² based on estimates of the Weizsäcker-Williams method. In such collisions, the near-zone electromagnetic field becomes very large, transverse, and very sharply pulsed. Restating Gould's point, the time-like part of these pulses contains large Fourier frequency components, and hence μ -pair and τ -pair production becomes likely.

We have addressed the production of heavy lepton pairs out of the vacuum using nonperturbative methods. The formal details of our method have been given elsewhere³ and result in a simple picture, in which the propagation of

the vacuum is obtained by solving the time-dependent Dirac equation in the presence of the electromagnetic fields of the colliding nuclei.

The results of calculations for colliding beams of U + U are shown in Fig. 5.17 for the

Fig. 5.17. Total inclusive singles cross sections vs beam energy in a collider computed for electrons, muons, and taus. Full curves refer to the symmetric collision of uranium, and the dashed curves to the symmetric collisions of krypton. The curve labeled W is the production of electrons from a Weizsäcker-Williams model divided by one hundred.

e^- , μ^- , and τ^- , inclusive singles cross sections. The dot-dashed curve is the e -pair cross section evaluated using the Weizsäcker-Williams method, which we include for comparison purposes. There are several important features in Fig. 5.17. At low energies, the e^- cross section is approximately the same as the Weizsäcker-Williams result. However, near energies per nucleon of about 100 GeV, these differ by about a factor of 100. Although we estimate that the local field approximation may have errors of as much as a factor of two at these energies, this difference is essentially due to the unphysical $\ln^3(\gamma)$ energy dependence of the perturbative method. Note that the μ and τ cross sections, for sufficiently high energies, increase as $\ln(\gamma)$ and thus satisfy the Froissart limit, whereas the perturbative result does not. Also note that the muon and tauon cross sections are large; at energies per nucleon of 100 GeV they are, respectively, 100 and 10 mb.

The differential cross sections, in terms of transverse momentum and rapidity, can be obtained from Eq. (1),

$$\sigma = \int_{-\infty}^{\infty} dY \int_0^{\infty} dP_{\perp} \frac{d\sigma}{dY dP_{\perp}}, \quad (1)$$

where

$$Y = \frac{1}{2} \ln \left(\frac{P_0 + P_1}{P_0 - P_1} \right), \quad (2)$$

and where $P = (P_0, \vec{P})$ is the four vector associated with the positive energy continuum state. The vector $\vec{P}$ is decomposed into parts which are transverse, $\vec{P}_{\perp}$, and longitudinal, P_1 , to the beam direction. The transverse part is averaged over the azimuthal angle in order to simplify the calculations. The resulting e^- differential cross section is shown in Fig. 5.18 for the fixed target collision of Au + Au at an energy per nucleon of 4.2 GeV. These are contours of the cross section as a function of the transverse momentum, $P_{\perp}$, in units of $m_e c$, and of the rapidity. The cross section is given in units of $mb/m_e c$, and the contours are labeled by the exponent to the base 10. In this collision, the projectile rapidity is approximately 2.4, as indicated in the figure. Note the sharp side

Fig. 5.18. Contours of the inclusive electron singles production cross section for the fixed target collision of Au + Au at an energy per nucleon of 4.2 GeV as a function of the electron transverse momentum and rapidity. The beam rapidity, 2.39, is indicated by the arrow. $\log_{10}$ of the contour values are included as labels.

peaking at the projectile and target rapidity, reflecting the transverse character of the fields producing the pairs. Also, note that the distribution is a maximum for values of $P_{\perp}$ near the Compton momentum, (λ^{-1}) , and has a broad distribution which decreases by three orders of magnitude by $P_{\perp} \sim 20 m_e c$.

These same features are apparent in colliding beams of Au + Au at an energy per nucleon of 100 GeV, as shown in Fig. 5.19. The transverse momentum and rapidity distribution is very broad in rapidity, reflecting the extreme violence of the collision. However, the cross section still has a maximum for $P_{\perp}$ near the Compton momentum and decreases by about three orders of magnitude at about $P \sim 20 m_e c$. In this particular case, the rapidities of the two beams are at -5.4 and $+5.4$, and the total cross section yield is about 1260 b.

We have also studied these distributions for the production of muons and taus:

i) The production of these leptons occurs mainly within the interior of the nuclei and is sensitive to details of the nuclear charge distribution. Because of the relatively small Compton sizes of the μ and τ , it is probably important to give the nuclear charge form factor

Fig. 5.19. Contours of the inclusive electron singles production cross section for the collision of Au + Au at a collider energy per nucleon of 100 GeV as a function of the electron transverse momentum and rapidity. The beam rapidities, ± 5.37 , are indicated by the arrows. $\log_{10}$ of the contour values are included as labels.

in terms of the quark distributions in the nucleus.

ii) The cross section yields for muons and taus are large compared to those predicted by the Weizsäcker-Williams process, due to the coherence developed during the time evolution in the interior of the nucleus. The differential cross sections are strongly peaked at the projectile and target rapidity, and in the transverse momentum variable, about the Compton momentum of the produced lepton.

In conclusion, we should like to emphasize that other particles should readily be produced by this mechanism, including the J/ψ , W^+W^- pairs, and possibly even pairs of magnetic monopoles. There is some evidence that in central collisions, heavy ions in this energy range will undergo tremendous deceleration forces. If this is the case, then the production of leptons, as we have discussed, will be substantially enhanced.

1. Summary of paper to be published in the proceedings of the 6th Adriatic International Conference on Nuclear Physics, Dubrovnik, Yugoslavia, June 15-19, 1987.

2. H. Gould, in Proceedings of the Atomic Theory Workshop on Relativistic and QED Effects in Heavy Atoms, Gaithersburg, Maryland, May 1985, AIP Conf. Proc. No. 136, American Institute of Physics, New York, 1985.

3. C. Bottcher and M. R. Strayer, pp. 629-44 in Physics of Strong Fields (Proceedings, NATO International Advanced Courses on Physics of Strong Fields, Maratea, Italy, June 1986), Plenum Publishing Corp., New York, 1987.

PARTICLE PRODUCTION IN A FINITE CONSTANT FIELD

R. C. Wang¹ C. Y. Wong
C. M. Ko²

The Schwinger mechanism of pair production,³ first put forth to examine the production of electron-positron pairs in a strong and uniform electric field, has been applied to many problems in contemporary physics.⁴⁻⁸ Many different derivations of the Schwinger result have been put forth.⁹⁻¹¹ The Schwinger mechanism was often invoked to study particle production in QCD.^{5-7,10} As applied to nucleon-nucleon or e^+e^- collisions, the field between a quark and

an anti-quark is represented, as an approximation, by an Abelian gauge field, in the same form as the constant electric field between two condenser plates in quantum electrodynamics (QED). Particles are produced when a quark from the negative-energy sea tunnels through a barrier and emerges as particles in positive-energy states. Such an application has met a high degree of success.⁵ Nevertheless, unresolved problems in the Schwinger mechanism remain. The Schwinger mechanism was formulated for a region of space which is infinite in extent. It is of interest to study the pair production mechanism for a system with a finite dimension, as it may provide an understanding of the time delay in particle production observed in nuclear collisions. For this purpose, we examine the influence of the finite size of the spatial separation on the pair production rate by studying Klein-Gordon particles and Dirac particles in a strong electric field. We solve the parallel condenser plate problem exactly and obtain the transmission amplitude for the incoming negative energy states. We relate the transmission to the pair production rate and give numerical results for a few illustrative cases. We found that particles are not produced until the separation between the plates exceeds a minimum and that the rate of particle production shows large fluctuations as the separation between the parallel plates becomes small.

1. Guest Assignee from University of Science and Technology of China, Hefei, Anhui, People's Republic of China.

2. Texas A&M University, College Station, TX 77843.

3. J. Schwinger, Phys. Rev. 82, 664 (1951).

4. T. Damour, p. 459 in Proceedings of the First Marcel Grossmann Meeting on General Relativity, North-Holland, 1977; T. Damour and R. Ruffini, Phys. Rev. D 14, 332 (1976); T. Damour, Helv. Phys. Acta 59, 292 (1986).

5. A. Casher, H. Neuberger, and S. Nussinov, Phys. Rev. 20, 179 (1979).

6. B. Andersson, G. Gustafson, G. Ingelman, and T. Sjöstrand, Phys. Rev. 29, 31 (1983).

7. M. K. Glendenning and T. Matsui, Phys. Rev. D 28, 2890 (1983).

8. Y. Srivastava and A. Widom, Phys. Lett. 176, 199 (1986); A. Widom, M. H. Friedman, and Y. Srivastava, Northeastern University preprint (Dec., 1985).

9. E. Brezin and C. Itzykson, Phys. Rev. D 2, 1191 (1970).

10. H. Neuberger, Phys. Rev. D 20, 2936 (1979).

11. P. H. Cox and A. Yidiz, Phys. Rev. D 32, 819 (1985).

THEORETICAL ASPECTS OF HIGH-ENERGY, HEAVY-ION REACTIONS¹

C. Y. Wong

We present in these lecture notes an elementary introduction to the subject of nucleus-nucleus collisions at high energies. It begins with a discussion on the relevant kinematic variables to establish the language for these collisions. It examines the question of particle production and the characteristics of the loss of baryon energy in an inelastic nucleon-nucleon collision. The geometrical aspect of a nucleus-nucleus collision is then described in terms of the Glauber multiple-collision model. As the theory of relativistic heavy-ion collision has not yet reached a stage whereby the dynamics can be examined from a fundamental theory, various phenomenological models have been proposed. The assumptions used in various models are described. Future use of relativistic heavy-ion collisions to study the quark-gluon plasma is briefly discussed.

1. Abstract of invited paper to be published in Proceedings of the 10th INS-Kikuchi Spring School on Quarks and Nuclei, Shimoda, Japan, April 1987.

NUCLEAR STOPPING POWER IN HIGH-ENERGY COLLISIONS¹

C. Y. Wong

We study the degree of nuclear stopping from the viewpoint of the slowing down of a nucleon as it passes through a nucleus. The analysis of the $p+A \rightarrow p+X$ data of Bailey et al. shows that the degree of nuclear stopping is large and that the stopping power law depends on the number of collisions.

1. Abstract of invited paper to be published in Proceedings of the International Symposium on Medium Energy, Beijing, China, June 23-27, 1987.

ATOMIC PHYSICS

ROLE OF PROJECTILE $\bar{K}$ -ELECTRONS IN SINGLE AND DOUBLE K TO $\bar{K}$ TRANSFER: COMPARISON OF PASSIVE $\bar{K}$ -ELECTRON MODELS AND OF THE IFPM WITH DATA FOR $Cl^{17+}, 16+, 14+ + Ti^1$

R. L. Becker

Electron transfer between a neutral target and a projectile ion is one of the more interesting and difficult processes to calculate. Experimentally, there is no simple, yet clean, way to measure transfer from a given shell to a given shell. For the case of K to $\bar{K}$ transfer (the bar designating the projectile) an indirect method is common. One measures K-vacancy cross sections for projectiles with ionic charges $q = Z, Z-1$, and $<(Z-2)$. Then with the assumption that the initial $\bar{K}$ electrons are inert, one infers the K^1 to $\bar{K}^1$ and K^2 to $\bar{K}^2$ cross sections from linear combinations of the measured cross sections. The postulate that $\bar{K}$ -electrons are inert is brought into doubt by noting that the probability of inverse ($\bar{K}$ to K) transfer is equal by time-reversal invariance to that for K to $\bar{K}$ transfer. An extensive set of such measurements has been reported recently by Hall et al. for the nearly symmetric, strongly interacting systems $_{17}Cl^{9+} + _{22}Ti$. We have performed coupled-channels calculations for these systems and have compared results of various forms of the independent Fermi particle model (IFPM) with and without the assumption that any initially present $\bar{K}$ electron is passive. The passive $\bar{K}$ -electron models provide only a fair approximation to the results of the full IFPM.

1. Abstract of published paper: Nucl. Instrum. & Meth. B27, 506 (1987).

CALCULATIONS OF COINCIDENT IONIZATION PLUS EXCITATION¹

R. L. Becker

For Li- and Be-like ions, K X-ray yields, together with detection that the ionic charge has increased, give the cross section for ionization plus excitation (IE), a process which can exhibit electron-electron correlations.

Measurements of IE for $^{14}\text{Si}^{11+} + \text{He}$ stimulated our coupled-channels calculations in the independent-Fermi-particle model (IFPM), which includes Pauli correlations. We discuss how the IFPM expressions, generalized here to include an open shell, differ from those for distinguishable electrons. The sensitivity of a_{IE} to correlations is shown. Recent additional measurements and future ones giving excitation functions for resolved configurations and complementary Auger data will provide even more sensitive tests of collisional correlation theory.

1. Abstract of published paper: Nucl. Instrum. & Meth. B24/25, 256 (1987).

SEVERAL MANIFESTATIONS OF PAULI CORRELATIONS IN ENERGETIC ION-ATOM COLLISIONS¹

R. L. Becker

The phrase Pauli correlations is used to refer to effects of Pauli exchange terms arising from the antisymmetry of the many-electron wave function, for example, the Fermi hole in the pair correlation function. Collision processes are described in terms of occupancies and vacancies of the spin-orbitals of an independent Fermi particle model. The description of reactions on a scale of inclusiveness is explained. Calculations are done by a coupled channels method. Prefaced by a brief summary of older results on Pauli correlation effects in multiple-vacancy production, new results on target vacancies in coincidence with 0-, 1-, or 2-electron transfers to the projectile are described for the example of $\text{He}^{2+} + \text{He}$ collisions. The calculations are compared with coincidence data in which the change of charge of the projectile is measured together with either a target K_{α} transition or with the final charge on the target (for L-shell vacancy production). The final topic concerns "Pauli blocking," in which an electron is prevented from making a transition to an already occupied spin-orbital. The attempt to infer the direct (single-electron transition) charge transfer from the K-shell of the target to that of the projectile by varying the ionic charge of the projectile is described.

Data for inclusive-single K-vacancy production in $\text{Cl}^{17+} + \text{Ti}$ collisions are compared with IFPM calculations. The experimentalists' inference of the K-to-K cross section is based on the assumption that any projectile K-electron is inert during the collision. The degree to which an initial K-electron on the projectile is passive is studied by comparing the full IFPM calculations with two sets of approximate calculations in which the projectile K-electron is treated as inert.

1. Abstract of invited paper to be published in Proceedings of the Third Workshop on High Energy Ion-Atom Collisions, Debrecen, Hungary, August 1987.

ANALYSIS OF COULOMB EXPLOSIONS OF POLYATOMIC MOLECULES¹

C. Bottcher

Over the past five years, a group at Argonne National Laboratory has developed the "Coulomb explosion" technique for determining the structure of polyatomic molecular ions. Ions are accelerated, stripped in a very thin foil, and detected when the constituent fragments have expanded to a macroscopic size (a few centimeters). The raw data are a set of event snapshots of the Cartesian coordinates of the fragments from one explosion.

To determine a structure from this data, it is necessary to have a method of analysis which does not require the identification of indistinguishable fragments; e.g., in the case of CH_4^+ , the four protons in any one event cannot be aligned with the four protons in another. This has serious consequences, since any bias in the analysis can predict spurious structures. CH_4^+ in its ground electronic state has either a D_{2h} or C_{2v} symmetry; calculations predict a very small energy barrier.

The new approach I have developed is to convert the raw data to histograms of the distributions of all simple geometric invariants (e.g., angles between bonds, volumes of tetrahedrons, etc.). This representation is obviously invariant under all spatial and permutational symmetries. Then a Monte Carlo technique is used

to generate models which reproduce these histograms, e.g., normal vibrations about a D_{2h} configuration of CH_3^+ .

The analysis for CH_3^+ suggests a distribution of uncorrelated D_{2h} vibrations, but with large excursions into the C_{2v} valleys.

1. Report of work done while on leave to the Physics Division, Argonne National Laboratory, 9/86-9/87.

CAUSTICS IN THE COULOMB THREE-BODY PROBLEM¹

C. Bottcher

Studies have continued on the Coulomb three-body problem near the threshold for breakup. The method relies on a numerical semiclassical approximation to the asymptotic wavefunctions. The predicted amplitudes, as functions of the distribution of energy between the ejected and scattered electrons (Fig. 5.20) and the angle between the electrons (Fig. 5.21), contain semiclassical caustics. These are integrable singularities, of which the best known example is the rainbow in potential scattering. The singularity in Fig. 5.20 has the form $\epsilon^{-1/4}$, where ϵ is the energy of the ejected electron, while that in Fig. 5.21 has the form $(\theta - \theta_c)^{-1/4}$.

The singularities have been analyzed at two levels: (1) The semiclassical problem has been

Fig. 5.20. Variation of the differential ionization probability $dP/d\epsilon$ with ϵ for two energies: I, 0.54 eV and II, 0.012 eV. The ejected energy $\epsilon = \sin^2\alpha \times$ the total energy above threshold.

Fig. 5.21. Variation of $d^2P/d\epsilon d\theta$ vs. θ for two energies: I, 0.14 eV and II, 0.54 eV. The available energy is shared equally between the outgoing electrons.

solved analytically near the singularity as a check on the numerical methods. (2) Higher-order approximations have been developed, based on path integrals, in which the singularity is softened to a finite peak.

1. Report of work done, in part, while on leave to the Physics Division, Argonne National Laboratory, 9/86-9/87.

PRODUCTION OF HIGH-ANGULAR MOMENTUM RYDBERG AND CONTINUUM STATES BY STOCHASTIC COLLISIONS¹

J. Burgdörfer² C. Bottcher

Inelastic high-energy ($v \gg 1$ a.u.) ion-atom collisions strongly favor the electronic excitation of low angular momentum (ℓ) states. This universal trend is visible in both direct excitation and electron capture. In either case, the transition from an energetically low-lying state to the highly excited final state (Rydberg state or low-velocity continuum state) is mediated by the overlap of the wave functions near the nucleus which is maximal for states with low ℓ (or, classically speaking, with high eccentricity). By contrast, the excitation of fast highly-charged ions penetrating solids produces a heretofore unexplained abundance of high ℓ Rydberg states³ absent in gas-phase collisions under otherwise identical conditions of velocity and charge state.⁴

We have developed a classical description for the dynamical evolution of electronic excitation in the solid in which multiple scattering in the dense target is treated as a stochastic process with white non-Gaussian noise calculated from microscopic properties of the solid (crystal potential and dielectronic response function). Electronic transitions in the projectile are driven by δ -correlated "kicks"

$$\vec{F}(t) = \sum_i \vec{\Delta p}_i \delta(t-t_i) \quad (1)$$

representing random momentum transfer $\vec{\Delta p}_i$ in two-body collisions with either ionic cores or conduction electrons in the target. The equation of motion of the projectile electron under the influence of both the Coulomb field of the projectile core and the stochastic force can be transformed into a "noisy" map relating the angular momentum vector $\vec{L}$ and the Runge-Lenz vector $\vec{A}$ between subsequent kicks

$$\begin{aligned} \vec{A}_{i+1} &= \vec{F}_1(\vec{\Delta p}_i, \vec{A}_i, \vec{L}_i) \\ \vec{L}_{i+1} &= \vec{F}_2(\vec{\Delta p}_i, \vec{A}_i, \vec{L}_i) \end{aligned} \quad (2)$$

Iteration of Eq. (2) describes the evolution of the phase space correlated motion of the electron and the projectile. The evolution can be visualized as a random walk in Coulomb state space. The phase space distribution can be determined from a Monte Carlo solution of Eq. (2) for several thousand initial correlations resembling the primary single-collision excitation event. The subsequent random walk leads to diffusion in energy and angular momentum space. Figure 5.22 shows a model calculation for the l distribution after 20 kicks corresponding to a propagation of $\approx 60\text{\AA}$ in the solid for an initial distribution $\delta(l-1)$. The drift towards high l accompanied by rapid diffusion is clearly visible.

1. Abstract of published paper: p. 608 in Contributed Papers of the XV International Conference on the Physics of Electron and Atomic Collisions, Brighton, England, July 22-28, 1987.

2. Adjunct staff member from University of Tennessee, Knoxville, TN 37996.

3. H. D. Betz, p. 115 in Forward Electron Ejection in Ion Collisions, Lecture Notes in Physics 213 (Springer, Berlin, 1984) and references therein.

4. S. B. Elston et al., Phys. Rev. Lett. 55, 2281 (1985).

ORNL-DWG 87-17734

Fig. 5.22. Angular momentum distribution after 20 stochastic collisions. Initial distribution: $\delta(l-1)$.

DISTORTED-WAVE CALCULATIONS OF THE ELECTRON-IMPACT IONIZATION OF HIGHLY IONIZED Na-LIKE IONS¹

D. C. Griffin² M. S. Pindzola³
C. Bottcher

We report on distorted-wave calculations of the electron-impact ionization cross sections and rate coefficients for the Na-like ions Ti^{11+} , Cr^{13+} , Fe^{15+} , and Ni^{17+} . The cross sections for direct ionization out of the 3s, 2p, and 2s subshells were determined using the configuration-average, distorted-wave approximation. In addition, excitation-autoionization contributions originating from inner-shell excitations of the type $2s^2 2p^6 3s + 2s^2 2p^5 3sn^k$ ($n = 3, 4, 5$) and $2s^2 2p^6 3s + 2s 2p^6 3sn^k$ ($n = 3, 4$) were calculated by employing the distorted-wave approximation and configuration-interaction, bound-state wavefunctions.

Near threshold, the total ionization cross sections in all four ions are enhanced by approximately a factor of 5 through excitation autoionization. These excitation-autoionization contributions are large, even though they have

been substantially reduced by radiative decay to the bound states of the initial ion. Furthermore, although electron correlation has a minimal effect on the excitation cross sections, the magnitude of the branching ratios for autoionization is quite sensitive to configuration interaction in the autoionizing levels. This is especially true for the $2p \rightarrow 3d$ excitations, where configuration interaction between $2p^5 3s 3d$ and $2p^5 3p^2$ can increase the magnitude of the autoionizing rates for levels within the $2p^5 3s 3d$ configuration by as much as three orders of magnitude. Thus, for example, in the case of the $2p \rightarrow 3d$ excitation in Ni^{17+} , correlation increases the overall branching ratio for autoionization from 0.27 to 0.53.

-
1. Abstract of paper submitted for publication in Physical Review A.
 2. Rollins College, Winter Park, FL 32789.
 3. Auburn University, Auburn, AL 36849.

ELECTRON-IMPACT IONIZATION IN THE IRON ISONUCLEAR SEQUENCE¹

M. S. Pindzola² D. C. Griffin³
C. Bottcher

Excitation-autoionization contributions to the electron-impact ionization of Fe^{5+} , Fe^{6+} , Fe^{9+} , Fe^{11+} , and Fe^{13+} are calculated in the distorted-wave approximation. Calculations for Fe^{5+} which include only excitations from the $3p^6 3d^3$ ground configuration agree well with the experimental crossed beams measurements of Gregory et al.⁴ For Fe^{6+} the agreement between theory and experiment is also good. Calculations for Fe^{9+} are in reasonable agreement with experiment when only excitations from extremely metastable states of the $3p^6 3d$ excited configuration are included. Theoretical predictions for Fe^{11+} and Fe^{13+} are based on ground-configuration excitations and detailed branching-ratio calculations. Excitation-autoionization contributions in Fe^{13+} are found to enhance the total ionization cross section by a factor of 2 near threshold.

-
1. Abstract of published paper: Phys. Rev. A 34, 3668 (1986).

2. Auburn University, Auburn, AL 36849.
3. Rollins College, Winter Park, FL 32789.
4. D. C. Gregory et al., Phys. Rev. A 34, 3657 (1986).

ELECTRON-ION COLLISIONS IN THE AVERAGE-CONFIGURATION DISTORTED-WAVE APPROXIMATION¹

M. S. Pindzola² D. C. Griffin³
C. Bottcher

Explicit expressions for the electron-impact excitation, ionization, and resonant-recombination cross sections are derived in the average-configuration distorted-wave approximation. Calculations using these expressions are applied to several types of phenomena in electron-ion scattering where comparison with other theoretical methods and experimental measurements can be made.

-
1. Abstract of published paper: pp. 75-91 in Atomic Processes in Electron-Ion and Ion-Ion Collisions, ed. F. Brouillard, NATO ASI Series No. B145, Plenum Press, New York (1986).
 2. Auburn University, Auburn, AL 36849.
 3. Rollins College, Winter Park, FL 32789.

IONIZATION IN COLLISIONS BETWEEN ELECTRONS AND COMPLEX IONS¹

C. Bottcher D. C. Griffin²
M. S. Pindzola³

Most models of hot plasmas containing complex ions still rely on simple, semi-empirical formulae for electron-impact ionization rates. These formulae often fail when applied to complex ions, through neglect of two factors: (1) indirect ionization mechanisms involving autoionizing states, and (2) long-lived metastable states of the target ion. Extensive calculations and measurements on the iron isonuclear sequence, carried out by groups at Oak Ridge,⁴ provide an instructive case study. While the distorted-wave approximation is often adequate, some progress has been made toward more precise calculations. Even approximate calculations on complex systems require extensive computer resources.

-
1. Abstract of invited talk presented at the Gaseous Electronics Conference, Atlanta, Georgia, October 15-16, 1987, published in B.A.P.S.

2. Rollins College, Winter Park, FL 32789.
3. Auburn University, Auburn, AL 36849.
4. M. S. Pindzola, D. C. Griffin, and C. Bottcher, Phys. Rev. A 34, 3668 (1986).

DOUBLE-AUGER PROCESSES IN THE ELECTRON-IMPACT IONIZATION OF LITHIUM-LIKE IONS¹

M. S. Pindzola² D. C. Griffin³

Contributions to the electron-impact ionization of Li-like ions due to resonant-recombination followed by double Auger emission are calculated using first- and second-order perturbation theory. The double Auger rate is found to be quite sensitive to the choice of both continuum phase and excited orbital basis sets. In particular, we find that resonant-recombination to the $1s2s^22p\ ^3P$ term of O^{6+} , followed by double Auger emission to the $1s^2\ ^1S$ term of O^{6+} , has a cross section ranging from $6.4 \times 10^{-22}\text{ cm}^2$ to $4.9 \times 10^{-21}\text{ cm}^2$, depending on how the double Auger rate is calculated. The maximum represents 0.65% of the total ionization cross section for O^{6+} at the resonance energy of 436.3 eV. Thus, a noise level of 1.0%, which is probably a lower limit of current crossed-beams experiments, will mask the contribution in O^{6+} . Similar results are found for other Li-like ions in the first row periodic table elements.

1. Abstract of published paper: Phys. Rev. A 36, 2628 (1987).

2. Auburn University, Auburn, AL 36849.

3. Rollins College, Winter Park, FL 32789.

THEORETICAL CALCULATIONS OF INDIRECT PROCESSES IN ELECTRON-IMPACT IONIZATION OF ATOMIC IONS¹

M. S. Pindzola² D. C. Griffin³
C. Bottcher

The application of continuum Hartree-Fock theory to the calculation of indirect processes in the electron-impact ionization of atomic ions is reviewed. Comparison between theory and recent crossed-beams experiments is made for several multiply charged atomic ions.

1. Abstract of paper submitted for publication in Comments on Atomic and Molecular Physics.

2. Auburn University, Auburn, AL 36849.

3. Rollins College, Winter Park, FL 32789.

PHYSICS OF e^+e^- SYSTEMS

NONPERTURBATIVE COVARIANT TREATMENT OF THE TRIPLET e^+e^- SYSTEM USING TWO-BODY DIRAC EQUATIONS FROM CONSTRAINT DYNAMICS¹

H. W. Crater² R. L. Becker
C. Y. Mong P. Van Alstine³

We consider the nonperturbative properties of two-body Dirac equations derived from constraint mechanics and supersymmetry, for the case of electromagnetic interactions. We are motivated in part by a hypothesis that the persistent appearances of the e^+ and the associated e^- peaks in heavy-ion collisions may be accounted for by purely quantum electrodynamic, highly relativistic, resonances in the e^+e^- system, and in part by the need to confirm that the equations reproduce the known results for ortho-positronium. The system of relativistic wave equations we use is exactly covariant and contains potentials generated by perturbative Q.E.D. These equations have given exact solutions for singlet positronium with a spectrum that matches that of perturbative Q.E.D. (through order α^3) and have been successful when used with Q.C.D. potentials in accounting for quark-anti-quark bound states in highly relativistic configurations. For the e^+e^- system, the relativistic potentials that appear in them are generated by the one-photon exchange diagram and lead to the results of the standard Fermi-Breit equation in the semirelativistic (weak potential, slow motion) limit. Unlike such $O(1/c^2)$ truncations of the Bethe-Salpeter equation, our equations have a built-in smoothing mechanism so that potentials which are too singular in the semirelativistic treatment become less singular and, hence, can be treated nonperturbatively for most angular momentum states. In our approach, the nonperturbative calculation of the $^3S_1 - ^1S_0$ hyperfine splitting is sensitive to the form of the effective potential at short distance. We demonstrate the validity of our equations down to $r \sim a/m$ by numerically calculating this splitting for the ground state of positronium and showing that it is consistent with the perturbative value, $m\alpha^3/3$, due to the exchange diagram. In our examination of the (e^+e^-) system

at short distance, we also find that only the 3P_0 states (which include the hypothesized Q.E.D. resonant state) have an effective potential with a small r behavior just barely too singular to be acceptable as a quantum effective potential, namely $(-1/4 - \alpha^2)/r^2$. Consequently, no prediction of a 3P_0 resonance can be made without a cutoff of some sort. We discuss possible Q.E.D. sources of a cutoff.

1. Abstract of paper submitted for publication in Physical Review D. Preliminary results of this paper were reported in C. Y. Wong et al., pp. 814-815 in Abstract Book of XI International Conference on Particles & Nuclei, Kyoto, Japan, April 1987, and in R. L. Becker et al., p. 390 in Contributed Papers of the XV International Conference on the Physics of Electron and Atomic Collisions, Brighton, England, July 1987.

2. Consultant from University of Tennessee Space Institute, Tullahoma, TN 37388.

3. Pacific Sierra Research Corporation (Eaton), Los Angeles, CA 90025.

VARIATIONAL THEORY OF MULTICOMPONENT QUANTUM FLUIDS: AN APPLICATION TO POSITRON-ELECTRON PLASMA AT $T = 0^1$

L. J. Lantto²

Variational many-body theory is employed to study ground-state properties of a hypothetical

positron-electron plasma. We make use of multicomponent Fermi hypernetted chain methods to calculate the energy and pair-correlation functions of this system. Optimization of the trial wave function is performed through solving a set of approximate Euler-Lagrange equations for the pair distribution functions. Electron densities are chosen to be in the metallic range, and several concentrations of positrons are considered. At fifty-fifty concentration, this system represents an idealized model of electron-hole liquid and at the limit of zero concentration we have a single positron impurity in electron gas. Results of this work support earlier theoretical predictions for the model electron-hole liquid and are in good agreement with available experimental evidence for both electron-hole liquid and single positron impurities.

1. Abstract of paper to be published in Physical Review B.

2. Guest Assignee, Joint Institute for Heavy Ion Research, from University of Oulu, SF-90570 Oulu, Finland.

6. FUSION PLASMA DIAGNOSTICS DEVELOPMENT

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 lasers to the diagnostics of the next generation of ignited multicomponent fusion reactors. Small-angle Thomson scattering of pulsed CO₂-laser radiation is being developed as a diagnostic of energetic alpha particles produced by the D-T fusion reaction. A multichannel interferometer far-infrared interferometer system is being developed for measurement of electron density profiles in the Advanced Toroidal Facility (ATF) being placed into operation in the ORNL Fusion Energy Division. An infrared laser interferometer/polarimeter system has also been proposed for the Compact Ignition Tokamak, whose construction has been proposed at Princeton Plasma Physics Laboratory. Other LEOL activities include measurements of damage to optical materials produced by intense laser or neutron irradiation. This work formed part of the ORNL program in support of the Strategic Defense Initiative.

DEVELOPMENT OF A DIAGNOSTIC FOR FUSION-PRODUCT ALPHA PARTICLES BASED ON PULSED CO₂-LASER THOMSON SCATTERING

R. K. Richards¹ H. T. Hunter
D. P. Hutchinson K. L. Vander Sluis
C. A. Bennett²

In a D-T fusion reactor the kinetic energy of the 3.5-MeV fusion-product alpha particles will be required to heat cold D-T fuel in order to sustain the fusion reaction. The study of the physics of this alpha-particle heating is a primary goal of the next generation of fusion experiments, and the development of diagnostic techniques to measure alpha particle behavior is an important part of the fusion program. To produce such a diagnostic system, we have been investigating a CO₂-laser Thomson-scattering technique for the measurement of the alpha-particle density and velocity distribution in a D-T burning plasma.³

During the past year we have made progress in three areas of investigation: a high-power, long-pulse CO₂ laser, an absorption cell, and a full system test. A necessary component of this diagnostic is a long-pulse, high-power CO₂

laser. The long pulses are achieved by the addition of a low-pressure cell within the cavity of a commercial TEA CO₂ laser. By firing the low-pressure cell slightly before the main discharge, the laser pulse is lengthened from 0.1 to 1 or 2 μ s, with the pulse length controlled by varying low-pressure cell conditions.

It is important to minimize the laser beam divergence because the Thomson scattered radiation related to the alpha particles has only a small angular displacement from the laser beam direction. By using unstable resonator optics the divergence of the laser beam could be minimized. Laser beam profiles were measured at 30 and 50 meters from the laser to estimate the divergence; these were in good agreement with the theory for unstable resonator cavities.⁴

To reduce unscattered laser radiation which could be collected by the detector optics and may interfere with measurement of scattered radiation, an absorption cell was constructed and tested. The absorption cell consists of a tube of heated CO₂ gas which resonantly absorbs unscattered CO₂ laser radiation but not the Thomson scattered radiation which is shifted in

wavelength. Tests with the cell placed in front of the heterodyne detector demonstrated this reduction of laser radiation without reducing black body continuum radiation between the CO_2 lines. These tests were part of a full system test for this diagnostic and included subsystems of the heterodyne receiver, absorption cell, optics, and high-power pulsed CO_2 laser. The full system test demonstrated the compatibility of the subsystems and established a threshold for signal detection.

In further investigations we plan to measure the free electron velocity distribution in the Advanced Toroidal Facility (ATF), which has been assembled by the ORNL Fusion Energy Division and is currently being prepared for plasma operation. Since the free-electron scattering in ATF is expected to be smaller than the alpha-particle scattering in a burning plasma device, this test will establish the feasibility of detecting alpha particles and will also establish the level of background signal from the free electrons.

-
1. Fusion Energy Division.
 2. University of North Carolina, Asheville.
 3. D. P. Hutchinson et al., Rev. Sci. Instrum. 56, 1075 (1985).
 4. W. F. Krupke and W. R. Sooy, IEEE J. Quantum Electron. QE-5, 575 (1969).

MULTICHANNEL INTERFEROMETER SYSTEM DEVELOPMENT FOR ATF

C. H. Ma W. H. Casson¹
D. P. Hutchinson K. L. Vander Sluis
 J. Lee²

The first phase of the interferometer system being developed for the Advanced Toroidal Facility (ATF) at ORNL is nearing completion. The interferometer system consists of two laser systems, each with a 119- μm wavelength CH_3OH optically pumped laser and a 9.6- μm CO_2 laser. The CO_2 laser developed for the ATF interferometer produces more than 150 W in a single mode on the 9.6- μm pump line required by the CH_3OH far-infrared (FIR) laser. This pump power level has allowed us to operate the FIR lasers at a

power level of more than 1.1 W. A feedback control system to lock the frequency of the pump lasers to the absorption peak of the CH_3OH molecule has been developed to enhance the frequency and amplitude stability of the FIR lasers. The control system utilizes a resonant opto-acoustic cell containing 0.5 to 2 torr of CH_3OH vapor. By comparing the output of the acoustic cell microphone with the voltage produced by a pyroelectric detector proportional to the output of the CO_2 laser, a feedback signal may be derived to lock the pump laser on the absorption peak of the FIR lasing molecule.

The support column for the ATF interferometer optical system has been fabricated and will be placed on the ATF device during the first quarter of FY 1988. The support structure consists of three legs and cross members made of 12 x 12-in. fiberglass H-beam. The FIR laser beams will be enclosed in fiberglass tubing filled with dry air to minimize transmission losses due to atmospheric water vapor. The structure was assembled from fiberglass to eliminate the possibility of vibration produced by eddy currents during ATF operation. Such vibration could result in substantial errors in the density measurements due to the short wavelength of the interferometer.

During the initial experimental phase of ATF, the interferometer will be operated on a single channel. A 15-channel segmented detector array is under development along with a beam expansion optical system which will provide density measurements over the entire plasma cross section.

-
1. ORAU Postdoctoral Research Associate.
 2. Graduate student, University of Tennessee, Knoxville.

FEASIBILITY STUDY OF AN INFRARED INTERFEROMETER/POLARIMETER SYSTEM FOR THE COMPACT IGNITION TOKAMAK

C. H. Ma D. P. Hutchinson
 K. L. Vander Sluis

During the past year, the feasibility of a two-dimensional infrared interferometer/

polarimeter system for measurements of electron density and plasma current profiles in the Compact Ignition Tokamak (CIT) has been investigated both theoretically and experimentally. The system utilizes c-w CO₂ lasers at a wavelength of 10.6 μm. The choice of this wavelength results mainly from a trade-off, being sufficiently short to limit both the angle of beam refraction by plasma density gradients and the ellipticity of the polarized wave to an acceptable value, yet sufficiently long to obtain adequate sensitivity for the measurements. A schematic diagram of the proposed system is shown in Fig. 6.1. A Bragg cell diffracts approximately 50% of the laser power into a reference beam. The acousto-optic cell also introduces a frequency shift, Δf, of 40 MHz in the diffracted beam. The probing beam is passed through a polarization modulator, a plasma simulator, and is mixed with the reference beam. The detector is a liquid-nitrogen cooled HgCdTe photovoltaic diode. The output of the detector, V_S, can be expressed by the following relation:

$$\begin{aligned}
 V_S = & \{ \sqrt{P_P} \cos[\theta_p + \theta_m \sin(\omega_m t)] \sin(\omega t + \phi) \\
 & + \sqrt{P_R} \sin[(\omega + \Delta\omega)t] \}^2 \\
 = & R \sqrt{P_P P_R} \cos[\theta_p + \theta_m \sin(\omega_m t)] \cos(\Delta\omega t + \phi) \\
 & + \text{terms of dc and other frequencies}
 \end{aligned}$$

where R is the responsivity of the detector, θ_m is the amplitude of the modulation angle, ω_m is the modulation frequency, φ is the phase shift due to plasma density, θ_p is the poloidal field-induced Faraday rotation in plasma, and P_p and P_r are the power of probing and reference beam at the detector, respectively. The signal is synchronously detected by two lock-in amplifiers at 40 MHz and ω_m, yielding an output voltage

$$V = V_0 \sin(\theta_p) \quad (1)$$

where V₀ = 2 RA √(P_pP_r) J₁(θ_m), A is the total voltage gain of the amplifiers, and J₁(θ_m) is the Bessel function of the first kind with order one. For CIT plasma parameters, the maximum value of θ_p is approximately 1.5°. Therefore,

Fig. 6.1. Schematic of the proposed infrared interferometer/polarimeter system for CIT.

V can be considered as a direct measure of θ_p and Eq. (1) becomes

$$\theta_p = V/V_0 \quad (2)$$

The calibration constant V₀ is obtained by setting the rotation angle of the plasma simulator at few degrees (<4°) and measuring the value of V.

Both magneto-optic and electro-optic polarization-modulation techniques have been investigated to determine the sensitivity and time response of the polarimetry. Cadmium telluride (CdTe) crystal polarization rotators

are used as the modulators and the plasma simulator. The magneto-optic modulator consists of a 210:1 rf current transformer, a 4:1 bifilar-wound matching transformer, and a CdTe crystal. The primary of the current transformer is connected in series with a 0.01- μ f capacitor to achieve a resonant frequency of approximately 80 kHz. The secondary is a three-turn copper coil which acts as the load of the transformer. The CdTe crystal of 12.5 $\times$ 12.5 $\times$ 50.8 mm is mounted in the center of the secondary coil. The electro-optic modulator consists of a

ZnSe fresnel $\lambda/4$ rhomb, and a CdTe crystal of 4 $\times$ 4 $\times$ 50 mm with a half-wave voltage of 4.24 kV. An indium doped CdTe crystal of 12.5 $\times$ 12.5 $\times$ 50.8 mm is used in the plasma simulator. A solenoid of 7.6-mm ID, 94-mm OD, and 65 mm long produces a magnetic flux density approximately 2.7 KG at a dc current of 3.5 A. A test stand of the system has been designed and constructed, and experiments are under way.

1. C. H. Ma and D. P. Hutchinson, Bull. Am. Phys. Soc. 31, 1541 (1986).

7. HIGH ENERGY PHYSICS

H. O. Cohn

The high energy physics program at ORNL is carried out jointly with the University of Tennessee's DOE supported high energy effort. In turn, the ORNL-UT group is collaborating with a large number of institutions in the United States and from abroad. The large effort required to execute a high-energy physics experiment has made such collaborations a necessity. Following are brief reports of projects that have yielded significant physics results and for which papers have been prepared or published by the collaborators during this reporting period. These derive from three separate experiments and collaborations. The leading particle distributions in 200-GeV/c proton nuclei interactions¹ were studied in data obtained with the Fermilab 30-inch hydrogen bubble chamber fitted with thin plates of magnesium, silver, and gold. p and ω production in π^+ proton interactions at 15.7 GeV/c were the subjects of analysis of data obtained with the SLAC rapid-cycling 40-inch bubble chamber.² The unique feature of this experiment was a lead glass wall in the downstream spectrometer which enabled π^0 measurements not otherwise possible. The next two reports derived from the SLAC hybrid facility, which is a much improved version of the setup just mentioned. The original experiment was devised to study charm photoproduction. Since a large amount of data had to be amassed to fulfill this objective, the experiment yielded a plethora of data on photoproduced particles. The two results described here concern the forward charge asymmetry in 20-GeV γ proton reactions³ and production and decay properties of the $\omega\pi^0$ state at 1250 MeV/c² in 20-GeV polarized photoproduction.⁴

In the hybrid-spectrometer experiment at Fermilab, the 30-inch hydrogen-bubble chamber was fitted with plates of Mg, Ag, and Au, and was exposed to a 200-GeV/c proton beam. The momenta of all charged particles were measured and particle identification was obtained for those with momentum less than 1.5 GeV/c. Distributions of the leading positive particles were studied. Estimates of the rapidity loss of the projectile were obtained as a function of target mass, the multiplicity of negative particles and the number of recoil protons. We obtained the rapidity loss of 2.0 ± 0.3 for central $p + Au$ collisions. The impact parameter dependence of the momenta of the first few leading particles was also investigated. The results suggest that, even in central collisions, a significant amount of the energy is possessed by the three leading charged particles. This energy is not likely to be available for producing local regions of high energy density and may, in fact, represent the fragments of the incident proton. The data is consistent with a picture in which the incident proton suffers a rapidity loss of about two units in central $p + A$ collisions. The results also suggest that it may be more difficult to estimate energy densities directly from the rapidity loss of the beam.

The SLAC-hybrid bubble chamber was used to study π^+ proton interactions at 15.7 GeV/c. Three tantalum plates inside the chamber and a large array of lead glass downstream of the chamber provided photon detection over a large solid angle. Final states with two neutral particles were isolated with kinematic fits in which neutral pions were reconstructed from data

obtained with the lead glass and plates. We measured ρ and ω production cross sections for several exclusive final states, and the relative ρ and ω production rates were obtained. The ratio of nondiffractive ω to ρ production was found to be 0.44 ± 0.07 . The inclusive ω cross section was measured to be 1.9 ± 0.34 mb.

The forward-going charge balance was studied in inclusive photon proton interactions at 20 GeV in the SLAC hybrid spectrometer. We observed a positive excess. This effect increases with increasing Feynman x and transverse momentum, suggesting that the outgoing target fragments are not responsible for the observed charge asymmetry. We have searched for possible charge dependent biases in our trigger, scanning, measuring, and reconstruction systems. The diffractive ρ^0 events provided a sample of forward particles which are well understood and were used to search for possible biases. We observe that the average charge for these events is consistent with the Monte Carlo calculation predictions. Subsets of data with various counter triggers, and untriggered data were analyzed to check on trigger and experimental biases. Strange particle production was also considered as the source of the charge asymmetry. Strangeness production was not sufficient to explain the effect. A mechanism involving the preferential annihilation of quark-antiquark pairs has been shown to be qualitatively consistent with the observed imbalance.

The radial recurrences of vector mesons are states important to the understanding of the structure of quark-antiquark interactions. The ρ' (1600) is the only reliably detected recurrence of the ρ . The question of whether there may be another at lower mass is crucial to the understanding of this system. The $\omega\pi^0$ state observed in photoproduction at about 1250 MeV/c² has been suggested to be that recurrence but, alternatively, it could be the B^0 (1235). We obtained new results regarding this question in a study of the production and decay properties of the $\omega\pi^0$ state at 1250 MeV/c² in a photoproduction experiment. The SLAC hybrid facility photoproduction experiment yielded over 300,000 usable hadronic events for which excellent γ -ray detection was provided. Angular distributions of the 274 events fitting the reaction $\gamma p \rightarrow p\omega\pi^0$ were studied. The angular distribution of the production plane relative to the polarization vector is consistent with s-channel helicity nonconserving process. We conclude that the reaction is dominated by the production of the $J^P = 1^+ B$ (1235).

-
1. K. Abe et al., to be published in Physics Letters B.
 2. M. Ferguson et al., Phys. Rev. D 36, 1961 (1987).
 3. V. R. O'Dell et al., Phys. Rev. D 36, 1 (1987).
 4. K. Abe et al., submitted to Physical Review.

8. COMPILATIONS AND EVALUATIONS

CONTROLLED-FUSION ATOMIC DATA CENTER

C. F. Barnett ¹	M. I. Kirkpatrick
H. B. Gilbody ²	E. W. McDaniel ⁵
D. C. Gregory	F. W. Meyer
C. C. Havener	T. J. Morgan ⁶
H. T. Hunter	R. A. Phaneuf
M. S. Huq ³	M. S. Pindzola ⁷
R. K. Janev ⁴	J. K. Swenson ³
E. W. Thomas ⁵	

The primary task of the Controlled-Fusion Atomic Data Center (CFADC) is to collect, review, evaluate, and recommend numerical atomic collision data of interest in controlled thermonuclear fusion research. The CFADC operates with an equivalent of 1.5 full-time staff members, as well as a number of expert consultants from the research community, upon which it depends heavily.

Participants in the ORNL program in experimental atomic physics for fusion also each contribute a small fraction of their time to literature searches and categorization of relevant publications. The major activities of the data center are threefold:

- the maintenance of up-to-date bibliographies of fusion-related publications on atomic collision processes in computer files for on-line searching and publication.
- the preparation and publication of compilations of recommended atomic collision data for fusion research.
- the handling of user requests for specific data or information about relevant atomic processes.

The data center actively participates in cooperative agreements with the Atomic Data Center for Fusion at the Institute for Plasma Physics (IPP) of Nagoya University, Japan, the Atomic and Nuclear Data Center of the Japan

Atomic Energy Research Institute (JAERI), and the Atomic and Molecular Data Unit of the International Atomic Energy Agency (IAEA) in Vienna. Our staff continues to participate in the IAEA International Atomic and Molecular Data Center Network and to advise the IAEA data center on their activities. Our bibliographic updates are sent to these centers every six months and form the basis for the semiannual IAEA International Bulletin on Atomic and Molecular Data for Fusion.

Our data center also maintains a close cooperation with the Atomic and Molecular Processes Information Center at the Joint Institute for Laboratory Astrophysics in Boulder, Colorado, and with the NBS Data Center on Atomic Spectral Lines and Transition Probabilities in Gaithersburg, Maryland.

During this reporting period, a major effort continued to be directed toward the preparation of an updated and expanded version of the 1977 two-volume compilation of recommended tabular and graphical data, entitled Atomic Data for Controlled Fusion Research, and published as ORNL-5206 and -5207 (commonly referred to as the "Redbooks"). The new multiple-volume series is entitled Atomic Data for Fusion, and will consist of five volumes (ORNL-6086 through ORNL-6090). These volumes, with their (expected) publication dates, are as follows:

- Volume 1: Collisions of H, H₂, He and Li Atoms and Ions with Atoms and Molecules (publication expected in early 1988).
- Volume 2: Collisions of Electrons with Atoms and Molecules (publication expected in 1989).
- Volume 3: Particle Interactions with Surfaces (published 2/85).

- Volume 4: Spectroscopic Data for Iron (published 2/85).
- Volume 5: Collisions of Carbon and Oxygen Ions with Electrons, H, H₂ and He (published 2/87).

All tabular and graphical data for the new "Redbook" series are computer-generated in publication-ready format. A computer code calculates Maxwellian rate coefficients from the cross sections, and produces Chebyshev polynomial fits to both the cross sections and rate coefficients. This will facilitate our plans to eventually place these recommended collision data in internationally accessible files on the National Magnetic Fusion Energy Computer Center (NMFECC) network.

A subset of Volume 5 of the new "Redbook" series, entitled "Recommended Cross Sections for Electron Capture and Ionization in Collisions of C^{q+} and O^{q+} with H, He, and H₂" has been accepted for publication in Atomic Data and Nuclear Data Tables.

In addition, two data base assessments have been prepared for collision processes involving iron ions, in coordination with the IAEA Data Center. These are currently in press and will form part of a supplementary issue of Nuclear Fusion. These articles contain recommended and parametrized data, and their titles are as follows:

- "Electron-Impact Ionization Data for the Fe-Isonuclear Sequence," M. S. Pindzola, D. C. Griffin, C. Bottcher, and H. T. Hunter.
- "Charge Exchange Processes Involving Iron Ions," R. A. Phaneuf, R. K. Janev and H. T. Hunter.

A similar data base assessment for heavy-particle processes specific to the edge plasma of magnetic-confinement devices is also in preparation.

Another major accomplishment of this reporting period has been the development of a new data base management system for the CFADC's bibliographic files, and the transfer of approximately 20,000 existing records to this advanced personal-computer system. These current files are now available for instant on-line retrieval

according to collision process, reactants or authors.

-
1. Consultant, ORNL.
 2. Consultant, Queen's University, Belfast, Northern Ireland.
 3. ORAU Postdoctoral Research Associate.
 4. Consultant, Institute of Physics, Belgrade, Yugoslavia.
 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. Ellis-Akovali	M. J. Martin
M. R. Lay	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 8 mass chains. These evaluations have been published 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 ENDSF and MSR 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

During this reporting period, work has concentrated on the proposed Heavy Ion Storage Ring for Atomic Physics (HISTRAP) facility which was described in detail in last year's progress report. HISTRAP is a synchrotron/cooler/storage ring that will allow many new research opportunities in both atomic and nuclear physics. In particular, the ring will be able to accelerate, decelerate, store, and cool ions injected from either the HIRF tandem accelerator or a dedicated ECR source and RFQ pre-accelerator. In-ring experiments with circulating ions interacting with merged photon, electron, and ion beams will be possible. HISTRAP will have a bending power of 2.67 Tm, which corresponds to a mass-energy product $k \cdot AE/Q^2 = 344$. With tandem injection, this will provide energies for $Q/A = 1/2$ ions of 82 MeV/nucleon and an energy of 11 MeV/nucleon for uranium. This increase over ORIC, which has $k = 100$, will allow work in an expanded energy and mass regime. A conceptual design document has been prepared and the project proposed to DOE through the Atomic Physics Program. This year, accelerator physics studies of instabilities and corrections have been completed; prototype hardware studies, supported by the Laboratory Director's Research and Development Fund, have been initiated; and ECR and negative ion pulsed source development has continued.

HISTRAP ACCELERATOR PHYSICS DESIGN STUDIES

I. Y. Lee J. B. McGroory
J. A. Martin D. K. Olsen
G. R. Young

Correction of the $u_x - u_y = 0$ Coupling Resonance

HISTRAP, like many other rings, will operate with nearly equal tunes to take advantage of the large resonance-free region near the tune space diagonal. Consequently, the excitation and compensation of the $u_x = u_y$ resonance which couples the two transverse motions is important. Without compensation, beam would be lost through coherent transverse emittance oscillations between the two transverse planes and the design tunes, $u_x = 2.309$ $u_y = 2.274$, may not be achievable. For HISTRAP, this would be particularly severe since the aperture is designed for $\epsilon_x = 200 \mu\text{m-mrad}$ and $\epsilon_y = 40 \mu\text{m-mrad}$. Because of this, the strengths of the coupling contributions have been estimated, positions for correction skew quadrupoles have been identified, and skew quadrupole strengths for compensation have been calculated.

Solenoid magnet fields, solenoid end fields, quadrupole tilts, dipole tilts, and beam-linking currents all contribute to coupling; however, in HISTRAP, the 1.0-m-long solenoid of the electron

beam cooler dominates all other sources of coupling when operated at 0.2 T for maximum rigidity beams. Following the formalism of Guiguard,¹ this coupling can be compensated to zero by a pair of skew quadrupoles positioned symmetrically about the electron beam cooling straight in either pair of the short straight sections between the dipoles and F quadrupoles as shown in Fig. 9.1. These empty positions have horizontal and vertical betatron phase-advance differences of $\pm 37.3^\circ$ and $\pm 40.4^\circ$. In either pair of positions, integrated and normalized skew quadrupole strengths, $k_B'/B\rho$, of about 0.01 m^{-1} are required for compensation. This is about 1% of the main quadrupole strength. Coupling correction should not be a problem in HISTRAP.

I. G. Guiguard, "A General Treatment of Resonances in Accelerators," CERN 78-11/C1 (1978).

Preliminary Analysis of Correctors in the HISTRAP Lattice

Preliminary investigations of the possible orbit displacements and tracking instabilities due to magnet imperfections in the proposed HISTRAP lattice have been carried out. The low-order errors considered to date include edge

Fig. 9.1. HISTRAP lattice showing the quadrupole families, QF1 QD1 QF2 QD2, required for operation in a twofold symmetric mode with four nondispersed straights. Also shown are the symmetric positions about the cooler straight section for skew quadrupole placement. These positions have horizontal and vertical phase-advance differences of $\pm 37.3^\circ$ and $\pm 40.4^\circ$.

angle distortions of the dipole magnetic fields, dipole tilt errors, quadrupole displacement errors, first order errors of the dipole and quadrupole field gradients, and finally, a systematic sextupole error in the dipoles.

Of these, the most significant arise from possible systematic errors in the edge angles of the dipole magnets. In the design lattice, the rectangular dipole ends make an angle of 22.5° with the central trajectory. Differential saturation and other effects could, under extreme conditions, reduce this angle to 21.0° which is equivalent to introducing effective quadrupole magnets at the dipole ends, giving tune shifts in the order of 0.2. More importantly, about 0.2 m of dispersion is introduced to the non-dispersed straights, which is unacceptably large for some of the proposed experiments involving multiple charge states. It is possible to re-tune the lattice to the original tunes and dispersions by introducing a quadrupole at either the entrance or exit of each dipole and adjusting appropriately the strengths of the

main focusing (QF) and defocusing (QD) quadrupoles and the new trim quadrupole (QT). Also, the chromaticity of the lattice is changed, so the sextupole strengths must change.

Listed below are the original normalized and integrated quadrupole and sextupole strengths and the new strengths which reproduce the original lattice properties with 21.5° dipole angles. The possibility of producing this trim quadrupole strength with dipole pole face windings is being investigated.

	Original Lattice	Re-tuned Lattice
QF	0.925 m^{-1}	0.932 m^{-1}
QD	-1.044 m^{-1}	-1.061 m^{-1}
QT	0.0	0.042 m^{-1}
SF	0.482 m^{-2}	0.541 m^{-2}
SD	-1.760 m^{-2}	-2.132 m^{-2}

The stability of particles in the above re-tuned lattice was studied. Also, a systematic sextupole error in the dipole magnets with a normalized strength of -0.55 m^{-3} was included. A 17-cm horizontal by 5-cm vertical rectangular quadrupole aperture and a 9.4-cm by 5.0-cm dipole aperture were assumed. We further assumed a horizontal emittance of $200 \mu\text{m-mrad}$, and a vertical emittance of $80 \mu\text{m-mrad}$. Particles were "injected," equally displaced in the vertical and horizontal directions, and tracked for 400 turns, using the LIE3 option in MAD.¹

In all cases where DP/P exceeded 0.05 in absolute value, the particles were lost on the "edge" of the dipole aperture. For all particles studied in the $\pm 5\%$ momentum range, the orbit trajectories were dynamically stable until they hit the dipole "edge." Listed below are the maximum displacements for which particles remained within the magnet apertures as a function of momentum error, in units of normalized displacements, where σ_x , horizontal, is 4.58 cm, and σ_y , vertical, is 1.68 cm.

DP/P	$\sigma_x = \sigma_y$
-0.05	0.3
-0.04	0.6
-0.03	0.7
-0.02	0.7
-0.01	0.8
+0.01	0.8
+0.02	0.7
+0.03	0.6
+0.04	0.5
+0.05	0.3

Thus, the aperture limitation is the restrictive feature of the lattice, as opposed to the dynamic stability of the orbits for the momentum range of $\pm 5\%$. In all cases, the limiting factor is the horizontal aperture of the dipoles.

Finally, we have made a preliminary study of the dipole corrector strengths needed for closed orbit correction. Our RMS error assumptions are:

Dipoles:	
Tilt angle	0.0002 rad
Relative strength error	0.0005
Relative quadrupole gradient	0.001

Quadrupoles:	
Transverse displacement errors	0.15 mm
Relative gradient errors	0.001

All the above errors were assumed to be randomly distributed over the lattice magnets using the option TGAUSS(1) in MAD.¹ Twenty runs were made with different random error distributions to study the magnitude of the closed-orbit distortions, and for each run the MICADO option in MAD was used to select dipole corrector strengths which minimized the closed-orbit distortions. Eight horizontal and eight vertical correctors were used. The horizontal correctors were placed at the dipole entrances to model the dipole backlog winding correction capability. The vertical correctors were placed in the F sextupoles located between the dipoles and F quadrupoles. Beam position monitors were placed in all twelve quadrupoles.

For the 20 runs, the average RMS horizontal displacement in the beam position monitors was 5.5 mm, and in the vertical direction, the average RMS displacement runs was 1.0 mm. For the 20 runs, the RMS horizontal corrector strength ranged in values between 0.21 and 0.68 mrad. The maximum individual corrector strength was 1.61 mrad. In the vertical direction, the RMS corrector strengths ranged between 0.18 and 0.58 mrad with maximum strength for a single corrector of 0.97 mrad. In all cases, the dipole correctors reduced the closed-orbit errors to less than 0.1 mm.

1. C. Iselin, "The MAD Program," CERN-LEP/TH-85/15 (1985).

Lattice Operating Modes

The HISTRAP lattice shown in Fig. 9.1 was chosen for multiple-charge-state operation and consists of four 4-m-long straight sections connected by 90° achromatic bends. The achromates consist of two 45° dipoles separated by an FDF quadrupole triplet. The achromatic condition and the design tunes of $\nu_x = 2.309$ and $\nu_y = 2.274$ were met by adjusting the focusing and defocusing quadrupole strengths and the dipole-quadrupole distance separation. This reference design mode is fourfold symmetric, has four dispersionless straights, and two quadrupole families.

Other, more flexible, modes of operating this lattice have been and are being investigated. These modes can be obtained by connecting the quadrupoles in up to six families. Twofold or fourfold symmetric lattice solutions exist with dispersion in zero, two, or four of the straight sections. As an example, Fig. 9.2 shows the

Fig. 9.2. Tune space for HISTRAP lattice operated in a mode with all four straight sections dispersionless. The numbers in the figure are the normalized and integrated strength of the strongest quadrupole in the lattice.

tune space for all operating modes, including the reference design mode of the HISTRAP lattice, with four dispersionless straight sections. Third, fourth, and fifth order sum resonances and the second order difference resonance are shown. The numbers in Fig. 9.2 are the integrated and normalized strengths of the strongest quadrupole required in the lattice which is always defocusing.

Fourfold symmetric solutions with four non-dispersed straights require $QF1 = QF2 = QF$ and $QD1 = QD2 = QD$. These solutions are shown as the heavy line in Fig. 9.2. The strength of QD varies from 0.95 m^{-1} to 1.20 m^{-1} . The HISTRAP reference design operating point, with QD strength = 1.05 m^{-1} and the QF strength = 0.93 m^{-1} , is shown as the heavy solid point. The tune space above this line is also available for stable operation with twofold symmetry simply by setting $QD1 \neq QD2$ and $QF1 \neq QF2$. This region of tune space is indicated by the heavy dashed lines. A maximum quadrupole strength of 1.45 m^{-1} would be desirable. These studies show that HISTRAP can provide a variety of beam conditions for in-ring experiments and contains considerable flexibility in the choice of the tune operating point.

HISTRAP PROTOTYPE HARDWARE STUDIES

M. H. Atkins ¹	R. S. Lord
D. T. Dowling	J. A. Martin
P. F. Dittner	J. W. McConnell
J. W. Johnson	S. W. Mosko
R. C. Juras ²	D. K. Olsen
P. L. Pepmiller	

Ultrahigh Vacuum Test Stand

A vacuum test stand has been designed, engineered, and is being constructed to assess the problems of obtaining the ultralow pressure of 10^{-12} torr which is required in the HISTRAP synchrotron-cooler-storage ring. This vacuum test stand is shown in Fig. 9.3 and models approximately 1/16 of the circumference ring. The vacuum chamber components and sublimation pump housings will be fabricated from 316L and 316LN stainless steel and will be prebaked at 950°C in a vacuum oven after fabrication and before assembly. Pumping will be accomplished by two 1000- ℓ/s titanium sublimation pumps and one 60- ℓ/s magnetic sputter ion pump. Heating blankets will be used for in situ baking at temperatures up to 350°C . Pressures will be read with two extraction gauges, one Bayard-Alpert gauge and a residual gas analyzer.

This vacuum system will be rough-pumped with a cryopump and liquid-nitrogen-cooled sorption

Fig. 9.3. Ultrahigh vacuum test stand to achieve pressures in the order of 10^{-12} torr. The chamber, pumps, and valves will be wrapped with heating blankets to allow in situ bakes at 350°C .

pumps. The roughing system has been assembled and operated to check out the ionization gauges, residual gas analyzer, and magnetic sputter ion pump operation. Pressures of 3×10^{-11} torr have been achieved with the roughing system.

Ionization gauges, residual gas analyzer, power supplies, temperature sensors, and heating jackets will be interfaced with a VAX/VME prototype control system to study bakeout, control, and operation problems for the HISTRAP vacuum system. All apparatus for the vacuum test stand has been received except for the special 316LN Conflat flanges required for the bakeout cycles.

1. Computing and Telecommunications Division.
2. Instrumentation and Controls Division.

Prototype rf Acceleration/Deceleration Cavity

Based on the HISTRAP acceleration and deceleration requirements, an rf cavity has been designed, a prototype cavity has been constructed, and an rf test program has been initiated. Characteristics for the prototype are listed in Table 9.1. The final cavity has a single gap configuration and the ferrite rings are water-cooled.

A single-gap configuration minimizes complexity and maximizes the space available for ferrite. The ferrite bias circuit requires conductors which are insulated from the cavity surface and wound in a "figure eight." The bias winding will be arranged with three turns in order to accommodate a power supply with a maximum current rating of 1000 amperes. Space is available for additional turns in case higher bias excitation is required. An external view of the cavity is shown in Fig. 9.4.

The newly adopted water-cooling configuration follows that used in the BNL AGS cavities in which the ferrite rings are separated by annular copper disks. Water-cooled tubing on the peripheral surfaces of the copper provides cooling. The stacked array of alternated copper and ferrite rings is held in compression by fiber-

Table 9.1. RF cavity characteristics

Tuning range	0.17 to 2.5 MHz
Overall length	1.2 m
Beam tube I.D.	0.2 m
Ferrite rings	
Material	NiZn
I.D.	0.3 m
O.D.	0.5 m
thickness	0.025 m
quantity	28
Cooling for ferrite	water
Peak rf voltage	2500 V
Peak ferrite power density	65 mW/cc
Peak rf drive power	5800 W
Ferrite permeability range	2500 to 12
Peak ferrite bias current	3000 ampere-turns
Shunt capacitance	5000 pF

glass end plates joined by long lead screws. The cavity center conductors are mechanically separate from the high-vacuum beam line which contains a ceramic-insulated accelerating gap. Spring-loaded contact fingers will electrically connect the cavity to the accelerating gap.

Cavity fabrication has been completed. Ferrite was specified and ordered, but the successful domestic bidder was unable to produce a satisfactory ferrite composition within the delivery period and consequently defaulted. The vendor originally planned to use a MnZn ferrite which is noted for its high permeability, but the resultant rings have unacceptably high dielectric losses. The vendor is planning to offer alternative NiZn rings; however, early indications suggest that the permeability will be low. An acceptable NiZn ferrite is available from a foreign source.

An array of test instrumentation has been assembled, including a sweep-frequency synthesizer, a 400-watt rf power amplifier, rf voltmeters, and rf power meters. A 1000-ampere, 60-volt dc power supply was moved to the test area to provide ferrite bias current. This power supply includes a series transistor regulator which will permit bias modulation. The rf amplifier is not sufficient for driving the

Fig. 9.4. The prototype rf cavity and its support frame. The rectangular ports at the middle of the peripheral surface are used for connecting rf power and ferrite bias leads. Extra ports will permit the operation of up to five turns of bias winding in either series or parallel connections. The circular ports on the ends are provided for access to internal connections. The entire upper half of the outer conductor is removable.

cavity to full voltage with a full ferrite load; however, it will be possible to measure the tuning range of the system, and ferrite loss characteristics on a partial ferrite load.

Design of HISTRAP Prototype Dipole

The critical path for HISTRAP construction involves the design, engineering, prototyping, measuring, modifying, production, and installation of a laminated pulsed magnet system consisting of dipole, quadrupole, sextupole, and corrector elements. The dipoles are the most important magnetic elements and present some special problems. These dipoles are short with a large sagitta, producing a complicated 3D geometry and integrated fields profiles which depend heavily on end effects. In addition, the dipoles have a large gap to contain vacuum bake-out insulation, have a "C" design for merged laser beam studies, require a maximum field of 1.6 T, and need good field quality at both high and low excitation. Because of these uncertainties, a prototype dipole will be designed, fabricated, and measured.

The dipole yoke is 123-cm long, has a 12.8-cm sagitta, and has parallel ends giving 22.5° beam

entrance and exit angles. A 7-cm gap and 12-cm horizontal good field width are required. The 110-cm-high x 101-cm-wide lamination cross-section is standard and is scaled from the FNAL-designed and measured Loma Linda medical synchrotron dipole.¹ The initial Rogowsky end cuts also follow standard FNAL practice. Figure 9.5 shows deviation from a pure dipole field as a function of horizontal distance from the central trajectory as calculated by the 3D magnet code TOSCA² for excitation at 0.8 T and 1.6 T. The upper lines are the central field profiles one would get from a standard 2D calculation. The lower lines are 3D results, including end effects, which show field deviations integrated along an ion trajectory through the dipole. The 3D effects produce appreciable quadrupole and sextupole components. In this particular calculation, the 3D quadrupole component at both high and low excitation has been adjusted almost to zero by angling the end of the coil at 3° with respect to the end of the yoke. The average of the 0.8-T and 1.6-T sextupole component can be adjusted to zero by increasing the shims, making a horizontally curved Rogowsky end cut, or curving the coil ends.

Fig. 9.5. Preliminary TOSCA calculations of the field profile for the HISTRAP prototype dipole magnet. Results for both low, 0.8T solid lines, and high, 1.6T dashed lines, are shown. The 2D profiles show the field in the center of the magnet, whereas the 3D profiles show the field, with end effects, integrated along an ion trajectory through the complete magnet.

Upon completion of the design, the dipole will be fabricated by the FNAL magnet factory and shipped to ORNL for testing, measurement, and possible end cut modifications.

1. Fermi National Accelerator Laboratory, "Loma Linda University Medical Center Proton Therapy Facility Engineering Design Report," (1987).
2. Vector Fields Limited, Oxford, England.

Prototype Control System

The conceptual design for the HISTRAP control system is shown in Fig. 9.6. A MicroVAX II/GPX workstation¹ will provide all operator interaction with HISTRAP and will maintain the complete HISTRAP data base. A major advantage of the MicroVAX is that it provides a software environment which is acceptable to accelerator physicists who must access the HISTRAP data base and provides an operating system for which several accelerator physics codes exist. However,

Fig. 9.6. Conceptual design for the HISTRAP control system. A prototype control system consisting of the MicroVAX and VME crate has been assembled and will be used initially to control the vacuum test stand.

many hardware and software features of the MicroVAX are not ideally suited for real-time control systems. Consequently, all real-time functions will be relegated to approximately eight VMEbus² processors. The MicroVAX and the VMEbus processors will communicate over a private local area network.

The hardware for a HISTRAP prototype control system has been purchased and is a subset of the Fig. 9.6 control system. This subset consists of the MicroVAX connected directly to one VMEbus crate. All control hardware will be in the VMEbus crate. Initially, all control functions will be provided by the MicroVAX since real-time response is not critical. However, the hardware interface between the VMEbus crate and the MicroVAX will allow operation of a VMEbus processor in conjunction with the MicroVAX. Therefore, this system will also be used to investigate software development problems associated with a distributed processor control system. The prototype control system will

initially be used to control the vacuum test stand and then the rf test stand.

1. Digital Equipment Corporation, Maynard, Massachusetts.
2. VME International Trade Association, "VME Specification Manual," Revision C1 (1985).

ECR BEAM DEVELOPMENT FOR SYNCHROTRON INJECTION

F. W. Meyer

Motivated by the need for high charge state, heavy ions for the ECR/RFQ injection mode of HISTRAP, new beams were developed on the ORNL ECR source¹ this year in the region of atomic

mass number 127 to 197. Beam development for such heavy ionic species will permit more realistic estimates of ECR/RFQ injector performance for the proposed Au³³⁺ design ion.

Listed in Table 9.2 is a summary of beam currents obtained using the ORNL ECR source for some representative elements, including the I, Xe, Ta, and Au beams developed this year. Ions of the metallic elements were produced using a solid feed technique by inserting a small sample directly into the ECR plasma. The resultant heating of the sample by electron impact is adjusted to raise the vapor pressure of the sample sufficiently to yield usable ion beam

Table 9.2. Representative ORNL ECR source beam currents (electrical μ A); 10-12 kV source voltage

	160	⁴⁰ Ar	⁵⁶ Fe	⁵⁸ Ni	⁸⁴ Kr	127I	¹²⁹ Xe ^a	¹⁸¹ Ta	¹⁹⁷ Au
+1	400	110	10						
+2	300	120	*						
+3	170	90	20						
+4	100	75	*						
+5	83	*	23	3	20				
+6	50	65	25	5	25				
+7	2.5	73	*	7	26				
+8	0.1	105	*	12	27				
+9		45	20	20	33		5.0		
+10		*	20	17	31	8	4.5	12	25
+11		3.0	5	*	33	10	3.5	*	27
+12		0.7	*	5	40	14	3.5	12	21
+13			2	3	23	18	3.2	12	18
+14			*	1	21	20	2.5	12	*
+15			1.5	0.5	15	18	1.5	12	18
+16				0.15	5	*	1.2	12	15
+17				0.03	1	10	1.0	11	12
+18					*	*	0.6	8	10
+19					0.25	3	0.6	5	7
+20						2	0.5	3.5	5
+21						*	0.25	2	5
+22						0.5	0.12	1.8	4
+23								*	3
+24								1.5	2.5
+25							0.08	1.0	*
+26							0.05	*	0.9
+27								0.4	0.4
+28								0.1	*
+29								0.5	0.1
+30									0.15 ^b
+31									0.005 ^b

*Indicates m/q degeneracy with contaminant beam.

^a5 mm x 5 mm slits.

^b2 mm x 2 mm slits.

currents. The rate of vaporization is determined by the local electron power density seen by the sample, and can thus be varied by changing the sample position, tuning the source magnetic field, or adjusting the microwave power.

Ta ions could be produced either from a 0.025-mm-thick foil or from the Ta liner protecting the vacuum wall of the ECR source. The latter method required lowering the solenoidal magnetic field in the source, thereby expanding the ECR plasma toward the Ta liner until sufficient interaction took place for wall material recycling. The Au sample consisted of 0.5-mm-diameter wire wound around a matrix of two 0.8-mm-diameter W rods, the free ends of which were then clamped to the sample positioning mechanism. In the case of the Au ions, a large variation in sample position was required in order to optimize different charge states, low charge states requiring the sample to be inserted significantly farther into the plasma to generate sufficient Au vapor density than the highest charge states. Figure 9.7 shows sample charge state distributions obtained for Au ions under different source conditions.

1. F. W. Meyer, Nucl. Instr. and Meth. **89**, p. 532 (1985).

NEGATIVE ION PULSING STUDIES FOR SYNCHROTRON INJECTION

G. D. Alton

Continued efforts were made toward development and evaluation of pulsed negative ion sources suitable for use for tandem accelerator synchrotron injection. The addition of the new Negative Ion Source Preparation Facility¹ and modifications to the emittance measurement electronics permitted studies to be made of the properties of momentum analyzed, pulsed $^{12}\text{C}^-$, $^{58}\text{Ni}^-$, and $^{197}\text{Au}^-$ negative ion beams extracted from sources equipped with cylindrical² and ellipsoidal³ geometry ionizers and from the

Fig. 9.7. Charge state distributions of Au ions from ORNL ECR source optimized for maximum current for the 27^+ charge state and the 31^+ charge state.

Model 860 negative ion source.⁴ With momentum analysis, the intensity levels were found typically to be about half of those measured previously without momentum analysis for Ni^- and Au^- negative ion beams.⁵ The maximum pulse intensity levels for all three sources were found to be approximately the same. For example, the maximum peak pulse intensities for $^{58}\text{Ni}^-$ were typically found to range between 50 and 80 μA , while those for $^{197}\text{Au}^-$ ranged from 40–70 μA , and those for $^{12}\text{C}^-$ ranged between 70 and 120 μA . These results are to be contrasted with those reported previously for total negative ion beams generated from Ni and Au samples measured prior to momentum analysis of 250 μA and 100 μA , respectively.⁵

The pulse shape and amplitude of negative ion beams were found to be independent of repetition rate over a range of frequencies between 1 and 56 Hz. The range over which this effect could be studied was dictated by power limitations of the supply. Pulsed beam intensity levels were also found to be independent of pulse width over a range of widths between 10 and 230 μs . The

upper width was again limited by the pulsed power supply.

During earlier injection studies,⁵ the percentage transmissions of pulsed beams were found to be ~20% lower than those observed for dc beams. Beam transport lens potentials were also found to be slightly higher for the pulsed mode ion beams. These findings prompted concern that the emittances of pulsed ion beams may be considerably higher than those for dc beams. Consequently, the emittances of pulsed $^{12}\text{C}^-$, $^{58}\text{Ni}^-$, and $^{197}\text{Au}^-$ negative ion beams extracted from the cylindrical geometry ionizer, ellipsoidal geometry ionizer, and Model 860 negative ion sources were measured for the first time. Pulsed emittance contours, particularly in the x-direction, exhibit considerably more structure than do their dc counterparts and are considerably higher. Emittances versus percentage pulsed $^{197}\text{Au}^-$ negative ion beam extracted from the cylindrical geometry ion source are shown in Fig. 9.8. The magnitude of the emittances for the 80% contour levels for maximum ion beam intensities was found to be $14\sqrt{\text{mm-mrad}}$ (MeV)^{1/2} regardless of species and type of source utilized in the measurements. The data in Fig. 9.8 clearly suggest an intensity-dependent effect. These emittances of pulsed negative ion beams are found to be factors of 1.6 for the cylindrical geometry ionizer source, 1.75 for the ellipsoidal geometry ionizer source, and ~1.0 for the Model 860 negative ion

Fig. 9.8. Normalized emittance versus percentage pulsed negative ion beam intensity for various peak $^{197}\text{Au}^-$ negative ion currents extracted from the cylindrical geometry ionizer source.

source larger than those measured previously for dc ion beams extracted from these sources.^{6,7}

1. Phys. Div. Prog. Rep. Sept. 30, 1986, ORNL-6326, p. 7.
2. G. D. Alton, Nucl. Instrum. and Meth. in Phys. Res., A244 (1986) 133.
3. Phys. Div. Prog. Rep. Sept. 30, 1986, ORNL-6326, p. 8.
4. General Ionex Corporation, Newburyport, MA.
5. G. D. Alton and C. M. Jones, Nucl. Instrum. and Meth. in Phys. Res., A244 (1986) 170.
6. G. D. Alton, J. W. McConnell, S. Tajima, and G. J. Nelson, Nucl. Instrum. and Meth. in Phys. Res., B 24/25 (1987) 826.
7. G. D. Alton, Proc. of the Eleventh Symp. on Ion Sources and Ion Assisted Technology, Tokyo, Japan, 1987, p. 157.

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 1986 through September 1987. Articles pending publication as of September 30, 1987, are listed immediately following this section.

BOOK, JOURNAL, AND PROCEEDINGS ARTICLES

- Alton, G. D.
 "Semi-empirical Mathematical Relationships for Electropositive Adsorbate-Induced Work Function Changes," *Surf. Sci.* 175, 226-40 (1986)
- Alton, G. D. (Invited Paper)
 "The Emittance and Brightness Characteristics of Negative Ion Sources Suitable for MeV Ion Implantation," pp. 157-70 in *Proceedings, Eleventh Symposium on Ion Sources and Ion-Assisted Technology (ISIAT '87)*, Tokyo, Japan, June 1-3, 1987, Kyoto University, Japan, 1987
- Alton, G. D., J. W. McConnell, S. Tajima, and G. J. Nelson (Invited Paper)
 "Emittance Studies of High Intensity Negative Ion Sources Equipped with Continuous Surface Cylindrical and Spherical Geometry Tungsten Ionizers," *Proceedings, Ninth Conference on the Application of Accelerators in Research and Industry*, Denton, Texas, November 10-12, 1986, *Nucl. Instrum. Methods Phys. Res.* B24/25, 826-33 (1987)
- Appleton, B. R., R. A. Zuhr, T. S. Noggle, M. Herbots, S. J. Pennycook, and G. D. Alton
 "Ion Beam Deposition," *MRS Bulletin XII*, 52-58 (Feb. 16/Mar. 16, 1987)
- Auble, R. L.
 "Holifield Heavy Ion Research Facility Newsletter," Issue No. 32 (1986)
- Auble, R. L., Editor
 "Holifield Heavy Ion Research Facility Users Handbook," (January 1987)
- Auble, R. L.
 "Holifield Heavy Ion Research Facility Newsletter," Issue No. 33 (1987)
- Auble, R. L.
 "Holifield Heavy Ion Research Facility Newsletter," Issue No. 34 (1987)
- Ayik, S.
 "Nucleon Transport Induced by Two-Body Collisions," *Phys. Rev. C* 35, 2086-89 (1987)
- Ayik, S., B. Shivakumar, and D. Shapira
 "A Transport Description of Intermediate Processes in Heavy Ion Collisions," pp. 407-12 in *Proceedings, Symposium on the Many Facets of Heavy Ion Fusion Reactions*, Argonne, Illinois, March 24-26, 1986, Argonne National Laboratory Report ANL-PHY-86-1 (1986)
- Bai, J. J., R. Y. Cusson, J. Wu, P.-G. Reinhard, H. Stoecker, W. Greiner, and M. R. Strayer
 "Mean Field Model for Relativistic Heavy Ion Collisions," *Z. Phys.* A326, 269-77 (1987)
- Balantekin, A. B. (Invited Paper)
 "Interacting Boson Model: Selected Recent Developments," pp. 732-37 in *Intersections Between Particle and Nuclear Physics (Proceedings, Conference, Lake Louise, Canada, May 26-30, 1986)*, AIP Conf. Proc. 150, American Institute of Physics, New York, 1986
- Balantekin, A. B. (Invited Paper)
 "Dynamical Symmetries for Odd-Odd Nuclei," pp. 223-30 in *Proceedings, International Conference on Nuclear Structure, Reactions, and Symmetries*, Dubrovnik, Yugoslavia, June 5-14, 1986, World Scientific Publishing, Singapore, 1986

Balantekin, A. B. (Invited Paper)

"On the Possibility of New Particle Production in Heavy-Ion Collisions," pp. 349-57 in Physics of Strong Fields (Proceedings, NATO International Advanced Course on Physics of Strong Fields, Maratea, Italy, June 1-14, 1986), Plenum Publishing, New York, 1987

Balantekin, A. B., T. Hubsch, and V. Paar (Invited Paper)

"Boson Fermion Symmetries and Dynamical Supersymmetries for Odd-Odd Nuclei," pp. 14-19 in Proceedings, ACS Symposium on Recent Advances in the Study of Nuclei Off the Line of Stability, Chicago, Illinois, September 8-13, 1985, ACS Symposium Series 324, American Chemical Society, Washington, D.C., 1986

Balantekin, A. B., and V. Paar

"Bose-Fermi Symmetry Chain for the Description of Odd-Odd Nuclei," *Phys. Rev. C* 34, 1917-19 (1986)

Baranger, M., K.T.R. Davies, M.A.M. de Aguiar, C. P. Malta, and E.J.V. de Passos

"Periodic Trajectories for Non-integrable Two-Dimensional Hamiltonians," *Z. Phys. A* 325, 491-92 (1986)

Becker, R. L. (Invited Paper)

"Calculations of Coincident Ionization Plus Excitation," Proceedings, Ninth Conference on the Application of Accelerators in Research and Industry, Denton, Texas, November 10-12, 1986, *Nucl. Instrum. Methods Phys. Res.* B24/25, 256-60 (1987)

Becker, R. L. (Invited Paper)

"Role of Projectile $\bar{K}$ -Electrons in Single and Double K-to- $\bar{K}$ Transfer: Comparison of Passive K-Electron Models and of the IFPM with Data for $Cl^{17+}, 16+, 14+ + Ti$," Proceedings, Third International Workshop on Cross Sections for Fusion and Other Applications, College Station, Texas, November 6-8, 1986, *Nucl. Instrum. Methods Phys. Res.* B27, 506-11 (1987)

Beckerman, M. (Invited Paper)

"Experimental Overview of Subbarrier Fusion," pp. 1-25 in Proceedings, Symposium on the Many Facets of Heavy Ion Fusion Reactions, Argonne, Illinois, March 24-26, 1986, Argonne National Laboratory Report ANL-PHY-86-1 (1986)

Beckerman, M., R. L. Auble, F. E. Bertrand, J. L. Blankenship, B. L. Burks, C. W. Glover, R. O. Sayer, G. R. Satchler, D. Shapira, and R. L. Varner

"Quasielastic Transfer of a Neutron Between ^{58}Ni and ^{208}Pb at Bombarding Energies of 598 and 1011 MeV," *Phys. Rev. Lett.* 58, 455-58 (1987)

Beckerman, M., R. L. Auble, F. E. Bertrand, J. L. Blankenship, B. L. Burks, M.A.G. Fernandes, C. W. Glover, E. E. Gross, D. J. Horen, R. O. Sayer, G. R. Satchler, D. Shapira, K. Sugiyama, and R. L. Varner

"Elastic and Inelastic Scattering of $^{58}Ni + ^{208}Pb$ at Bombarding Energies from 598 to 1011 MeV," *Phys. Rev. C* 36, 657-66 (1987)

Bengtsson, R., T. Bengtsson, J. Dudek, G. Leander, W. Nazarewicz, and J. Y. Zhang

"Shape Coexistence and Shape Transitions in Even-Even Pt and Hg Isotopes," *Phys. Lett.* 183B, 1-6 (1987)

Bertrand, F. E., J. R. Beene, and M. L. Halbert (Invited Paper)

"Photon Decay of Giant Resonances," pp. 132-41 in Weak and Electromagnetic Interactions in Nuclei (Proceedings, International Symposium, Heidelberg, West Germany, July 1-5, 1986), Springer-Verlag, Berlin, 1986

Bertrand, F. E., R. O. Sayer, R. L. Auble, M. Beckerman, J. L. Blankenship, B. L. Burks, M.A.G.

Fernandes, C. W. Glover, E. E. Gross, D. J. Horen, J. Gomez del Campo, D. Shapira, and H. P. Morsch

"Excitation of the High Energy Nuclear Continuum in ^{208}Pb by 22 MeV/Nucleon ^{17}O and ^{32}S ," *Phys. Rev. C* 35, 111-16 (1987)

Bingham, C. R., J. A. Bounds, H. K. Carter, R. L. Mlekodaj, J. C. Griffin, and W. M. Fairbank, Jr.

"Application of Collinear Laser Spectroscopy on Fast Atom Beams to Measure Nuclear Properties," Proceedings, Eleventh International Conference on Electromagnetic Isotope Separators and Techniques Related to Their Applications, Los Alamos, New Mexico, August 18-22, 1986, *Nucl. Instrum. Methods Phys. Res.* B26, 426-30 (1987)

Bock, R., G. Claesson, K.G.R. Doss, R. L. Ferguson, A. Gavron, H.-A. Gustafsson, H. M. Gutbrod, J. W.

Harris, B. V. Jacak, K.-H. Kampert, B. Kolb, P. Kristiansson, F. Lefebvres, A. M. Poskanzer, H. G.

Ritter, H. R. Schmidt, T. Siemiarz, L. Teitelbaum, M. Tincknell, S. Weiss, H. Wieman, and J. Wilhelmy

"Collectivity in Composite Fragment Emission from Relativistic Heavy Ion Collisions," *Mod. Phys. Lett. A* 2, 721-26 (1987)

- Bortignon, P. F., R. A. Broglia, G. F. Bertsch, and J. Pacheco
 "Damping of Nuclear Excitations at Finite Temperature," Nucl. Phys. A460, 149-63 (1986)
- Bottcher, C., and M. R. Strayer
 "Relativistic Theory of Fermions and Classical Fields on a Collocation Lattice," Ann. Phys. (N.Y.) 175, 64-111 (1987)
- Bottcher, C., and M. R. Strayer (Invited Paper)
 " μ - and τ -Pair Production from Relativistic Heavy-Ion Collisions," pp. 629-44 in Physics of Strong Fields (Proceedings, NATO International Advanced Course on Physics of Strong Fields, Maratea, Italy, June 1-14, 1986), Plenum Publishing, New York, 1987
- Braga, R. A., P. B. Semmes, W. R. Western, and R. W. Fink
 "Decay of Mass-Separated ^{201}mPo and ^{201}Po ," Nucl. Phys. A459, 359-73 (1986)
- Bruch, R., M. Stoltterfoht, S. Datz, P. D. Miller, P. L. Pepmiller, Y. Yamazaki, H. F. Krause, J. K. Swenson, K. T. Chung, and B. F. Davis
 "High-Resolution KLL Auger Spectra of Multiply Ionized Oxygen Projectiles Studied by Zero-Degree Electron Spectroscopy," Phys. Rev. A 35, 4114-21 (1987)
- Bruch, R., S. Datz, P. D. Miller, P. L. Pepmiller, H. F. Krause, J. K. Swenson, and M. Stoltterfoht
 "Partial Autoionization Rates of O^{9+} ($1s2s^22p$) $^3\text{p}^0$ and 1p^0 : A Crucial Test of Electron Correlation in Be-Like Systems," Phys. Rev. A 36, 394-96 (1987)
- Burgdorfer, J. (Invited Paper)
 "Dynamical Image Charge Effects on Convoy Electron Emission from Solid Surfaces," Proceedings, Ninth Conference on the Application of Accelerators in Research and Industry, Denton, Texas, November 10-12, 1986, Nucl. Instrum. Methods Phys. Res. B24/25, 139-42 (1987)
- Burgdorfer, J., and E. Kupfer
 "Distance of Excited-State Formation in Ion-Surface Collisions," Phys. Rev. Lett. 57, 2649-52 (1986)
- Burgdorfer, J., E. Kupfer, and H. Gabriel
 "Theory of Resonant Charge Transfer in Ion-Surface Collisions at Grazing Incidence at Intermediate Velocities," Phys. Rev. A 35, 4963-76 (1987)
- Burks, B. L., R. L. Varner, and E. J. Ludwig
 "Q-Value Determination for the $^{80}\text{Kr}(d,p)^{81}\text{Kr}$ Reaction," Phys. Rev. C 34, 2316-18 (1986)
- Butler, P. A., C. Baktash, C. R. Bingham, M. Carpenter, D. Cline, B. Cox, M. M. Guidry, S. Juutinen, A. E. Kavka, W. J. Kernan, R. W. Kincaid, A. Larabee, I. Y. Lee, X. T. Liu, S. P. Sorensen, E. Vogt, and C. Y. Wu
 "Observation of Intrinsic Excitation in ^{160}Dy Following Heavy-Ion Transfer Reactions," Phys. Lett. 191B, 333-38 (1987)
- Carlton, R. F., J. A. Harvey, R. L. Macklin, C. H. Johnson, and B. Castel
 "Nuclear Structure of ^{49}Ca above 5 MeV Excitation from $n + ^{48}\text{Ca}$ and Astrophysics for 30-keV Neutrons," Nucl. Phys. A465, 274-90 (1987)
- Carter, H. K., G. A. Leander, J. A. Bounds, and C. R. Bingham (Invited Paper)
 "UNISOR Collinear Laser Facility: First Results," pp. 364-69 in Proceedings, ACS Symposium on Recent Advances in the Study of Nuclei Off the Line of Stability, Chicago, Illinois, September 8-13, 1985, ACS Symposium Series 324, American Chemical Society, Washington, D.C., 1986
- Chen, Y. S., P. B. Semmes, and G. A. Leander
 "Calculation of M1 Transition Rates at High Spin in Axial Nuclei," Phys. Rev. C 34, 1935-41 (1986)
- Church, D. A., S. D. Kravis, I. A. Sellin, C. S. O, J. C. Levin, R. T. Short, M. Meron, B. M. Johnson, and K. W. Jones
 "Confined Thermal Multicharged Ions Produced by Synchrotron Radiation," Phys. Rev. A 36, 2487-90 (1987)
- Datta, S., R. Caplar, N. Cindro, R. L. Auble, J. B. Ball, and R. L. Robinson
 "Coalescence-Model Analysis of Alpha-Particle and Deuteron Spectra from Energetic Heavy-Ion Collisions," Phys. Lett. 192B, 302-06 (1987)
- Datz, S. (Invited Paper)
 "Atomic Physics Experiments with Stored Cooled Heavy Ion Beams," Proceedings, Ninth Conference on the Application of Accelerators in Research and Industry, Denton, Texas, November 10-12, 1986, Nucl. Instrum. Methods Phys. Res. B24/25, 3-10 (1987)

- Datz, S., P. F. Dittner, C. M. Fou, P. D. Miller, and P. L. Pepmiller (Invited Paper)
 "Dielectronic Recombination of Multiply Charged Ions," Proceedings, Conference on the Physics of Multiply Charged Ions, Groningen, The Netherlands, September 16-20, 1986, Nucl. Instrum. Methods Phys. Res. B23, 248-53 (1987)
- Dickens, J. K., J. W. McConnell, K. M. Chase, H. W. Hendel, E. B. Nieschmidt, and F. Y. Tsang
 "Measurements of the Neutron and Gamma-Ray Fluences in the TFTR Test Cell Due to a Point Source Simulating D-T Fusion Plasma Neutron Production," Fusion Technology 12, 270-80 (1987)
- Dittner, P. F., S. Datz, H. F. Krause, P. D. Miller, P. L. Pepmiller, C. Bottcher, C. M. Fou, D. C. Griffin, and M. S. Pindzola
 "Dielectronic Recombination of the Be-Like Ions: C^{2+} , N^{3+} , O^{4+} , and F^{5+} ," Phys. Rev. A 36, 33-39 (1987)
- Dittner, P. F., S. Datz, P. D. Miller, P. L. Pepmiller, and C. M. Fou
 "Dielectronic Recombination Measurements of Li-Like Ions: B^{2+} , C^{3+} , N^{4+} , and O^{5+} ," Phys. Rev. A 35, 3668-73 (1987)
- Donau, F.
 "Electromagnetic Radiation of Rotating Nuclei," Nucl. Phys. A471, 469 (1987)
- D'Onofrio, A., B. Delaunay, J. Delaunay, H. Dumont, J. Gomez del Campo, F. Andreozzi, A. Brondi, R. Moro, M. Romano, F. Terrasi, and J. F. Bruandet
 "Heavy Residue Masses as Possible Indicators of the Impact Parameter in the Reaction $^{20}Ne + ^{60}Ni$ at 742 MeV," Phys. Rev. C 35, 1167-69 (1987)
- D'Onofrio, A., B. Delaunay, J. Delaunay, H. Dumont, J. Gomez del Campo, A. Brondi, R. Moro, M. Romano, F. Terrasi, and J. F. Bruandet
 "Evidence for Equilibration of Hot Nuclei," Z. Phys. A326, 335-36 (1987)
- Dudek, J., W. Nazarewicz, Z. Szymanski, and G. A. Leander
 "Abundance and Systematics of Superdeformed States; Relation to the Pseudospin and Pseudo-SU(3) Symmetries," Phys. Rev. Lett. 59, 1405-08 (1987)
- Ellis-Akovali, Y. A.
 "Nuclear Data Sheets for A = 226," Nucl. Data Sheets 50, 229-54 (1987)
- Ellis-Akovali, Y. A.
 "Nuclear Data Sheets for A = 222," Nucl. Data Sheets 51, 765-82 (1987)
- Elston, S. B. (Invited Paper)
 "Measured Multipole Moments of Continuum Electron Transfer Angular Distributions," Proceedings, Ninth Conference on the Application of Accelerators in Research and Industry, Denton, Texas, November 10-12, 1986, Nucl. Instrum. Methods Phys. Res. B24/25, 214-18 (1987)
- Erb, K. A., I. Y. Lee, and W. T. Milner
 "Evidence for Peak Structure in $e^+ + Th$ Interactions," Phys. Lett. 181B, 52-56 (1986)
- Erb, K. A., and D. Shapira (Invited Paper)
 "Nuclear Orbiting," pp. 316-19 in 1987 McGraw-Hill Yearbook of Science and Technology, McGraw-Hill, New York, 1986
- Fairbank, W. M., Jr., and H. K. Carter
 "A Completely Cold Laser Ion Source for Separators," Proceedings, Eleventh International Conference on Electromagnetic Isotope Separators and Techniques Related to Their Applications, Los Alamos, New Mexico, August 18-22, 1987, Nucl. Instrum. Methods Phys. Res. B26, 357-61 (1987)
- Fernandes, M.A.G., F. E. Bertrand, R. L. Auble, R. O. Sayer, B. L. Burks, D. J. Mores, E. E. Gross, J. L. Blankenship, D. Shapira, and M. Beckerman
 "Single-Nucleon Transfer Reactions Induced by 376-MeV ^{17}O on ^{208}Pb ," Phys. Rev. C 36, 108-14 (1987)
- Gaukler, G., G. Nolte, and R. Schuch (Invited Paper)
 "Nucleus-Nucleus Bremsstrahlung from Scattering Angle Selected Cl-Sn Collisions," Proceedings, Third International Workshop on Cross Sections for Fusion and Other Applications, College Station, Texas, November 6-8, 1986, Nucl. Instrum. Methods Phys. Res. B27, 532-35 (1987)
- Gavron, A., A. Gayer, J. Boissevain, H. C. Britt, T. C. Awes, J. R. Beene, B. Cheynis, D. Drain, R. L. Ferguson, F. E. Obenshain, F. Plasil, G. R. Young, G. A. Pettit, and C. Butler
 "Neutron Emission in the Fissioning ^{158}Er Composite System," Phys. Rev. C 35, 579-90 (1987)

Gomez del Campo, J. (Invited Paper)

"Crystal Blocking in Heavy-Ion Reactions," Proceedings, Ninth Conference on the Application of Accelerators in Research and Industry, Denton, Texas, November 10-12, 1986, Nucl. Instrum. Methods Phys. Res. B24/25, 447-53 (1987)

Gomez del Campo, J., D. E. DiGregorio, J. A. Biggerstaff, Y. D. Chan, D. C. Hensley, P. H. Stelson, D. Shapira, and M. E. Grtiz

"Correlations Between α Particles and Evaporation Residues for the $^{14}\text{N} + ^{12}\text{C}$ Reaction at $E(^{14}\text{N}) = 180$ MeV," Phys. Rev. C 35, 137-40 (1987)

Gonzalez Lepera, C. E., M. Breinig, J. Burgdorfer, R. DeSerio, S. B. Elston, J. P. Gibbons, H.-P. Mulskotter, L. Liljeby, R. T. Short, and C. R. Vane (Invited Paper)

"Angular Distributions of Very Low Energy Recoil Ions," Proceedings, Ninth Conference on the Application of Accelerators in Research and Industry, Denton, Texas, November 10-12, 1986, Nucl. Instrum. Methods Phys. Res. B24/25, 316-20 (1987)

Gregory, D. C., F. W. Meyer, A. Muller, and P. DeFrance

"Experimental Cross Sections for Electron-Impact Ionization of Iron Ions: Fe^{5+} , Fe^{6+} , and Fe^{9+} ," Phys. Rev. A 34, 3657-67 (1986)

Gregory, D. C., L. J. Wang, F. W. Meyer, and K. Rinn

"Electron-Impact Ionization of Iron Ions: Fe^{11+} , Fe^{13+} , and Fe^{15+} ," Phys. Rev. A 35, 3256-64 (1987)

Guidry, M. W. (Invited Paper)

"Population of High Spin States in Very Heavy Ion Transfer Reactions — The Experimental Evidence," pp. 99-103 in Proceedings, Conference on Nuclear Structure with Heavy Ions, Legnaro, Italy, May 27-31, 1985, Italian Physical Society, 1985

Guidry, M. W., R. Donangelo, O. Rasmussen, and M. S. Hussein

"Zero-Point Fluctuations and the Diffuseness of the Nuclear Surface," Phys. Rev. C 36, 609-11 (1987)

Guidry, M. W., C. L. Wu, Z. P. Li, D. H. Feng, and J. N. Ginocchio

"An Algebraic Fermion Description of Band Termination and Loss of Collectivity in Heavy Nuclei," Phys. Lett. 187B, 210-14 (1987)

Guthbrod, H. H., R. Albrecht, T. C. Aves, C. Baktash, P. Beckmann, F. Berger, R. Bock, G. Claesson, L. Dragon, R. L. Ferguson, A. Franz, S. Garpman, R. Glasow, H. A. Gustafsson, J. W. Johnson, K. H. Kampert, B. W. Kolb, P. Kristiansson, I. Y. Lee, H. Lohner, I. Lund, F. E. Obenshain, A. Oskarsson, I. Otterlund, T. Peitzmann, S. Persson, F. Plasil, A. M. Poskanzer, M. Purschke, H. G. Ritter, R. Santo, H. R. Schmidt, T. Siemiarczuk, K. Soderstrom, S. P. Sorensen, E. Stenlund, and G. R. Young (Invited Paper)

"Preliminary Results from Collisions Between 3.2-TeV ^{16}O and Target Nuclei of C, Cu, and Au," pp. 42-52 in Proceedings, International Workshop on Gross Properties of Nuclei and Nuclear Excitations XV, Hirschegg, Austria, January 12-17, 1987, GSI and Institut für Kernphysik, Darmstadt, F.R.G., 1987

Halbert, M. L., J. R. Beene, D. C. Hensley, K. Honkanen, T. Semkow, V. Abenante, and D. G. Sarantites

"Entry States in Subbarrier Fusion," pp. 511-18 in Proceedings, Symposium on the Many Facets of Heavy Ion Fusion Reactions, Argonne, Illinois, March 24-26, 1986, Argonne National Laboratory Report ANL-PHY-86-1 (1986)

Harmon, B. A., D. Shapira, P. H. Stelson, B. L. Burks, K. A. Erb, B. Shivakumar, K. Teh, and S. T. Thornton

"Entrance Channel Limitations in the High-Energy Fusion of Light-Heavy Systems Leading to ^{40}Ca and ^{42}Ca ," pp. 519-24 in Proceedings, Symposium on the Many Facets of Heavy Ion Fusion Reactions, Argonne, Illinois, March 24-26, 1986, Argonne National Laboratory Report ANL-PHY-86-1 (1986)

Hausser, O., K. Hicks, C. W. Glover, R. Abegg, W. P. Alford, A. Celler, C. Gunther, R. L. Helmer, R. Henderson, D. J. Horen, C. J. Horowitz, K. P. Jackson, J. Lisantti, D. K. McDaniels, C. A. Miller, R. Sawafte, and L. W. Swenson

"Spin Observables for $^{208}\text{Pb}(\beta, \beta)$ Elastic Scattering at 290 MeV," Phys. Lett. 184B, 316-19 (1987)

Hawryluk, R. J., V. Arunasalam, M. G. Bell, M. Bitter, W. R. Blanchard, N. L. Bretz, R. Budny, C. E. Bush, J. D. Callen, S. Cohen, S. K. Combs, S. L. Davis, D. L. Dimock, H. F. Dylla, P. C. Efthimion, L. C. Emerson, A. C. England, M. P. Eubank, R. J. Fonck, E. Fredrickson, H. P. Furth, G. Gammel, R. J. Goldston, B. Grek, L. R. Grisham, G. Hammett, W. W. Heidbrink, H. W. Hendel, K. W. Hill, E. Hinnov, S. Hiroe, H. Hsuan, R. A. Hulse, K. P. Jaehnig, D. Jassby, F. C. Jobs, D. W. Johnson, L. C. Johnson, R. Kaita, R. Kamperschroer, S. M. Kaye, S. J. Kilpatrick, R. J. Knize, H. Kugel, P. H. LaMarche, B. LeBlanc, R. Little, C. H. Ma, O. M. Manos, D. K. Mansfield, R. T. McCann, M. P. McCarthy, D. C. McCune, K. McGuire, D. H. McNeill, D. M. Meade, S. S. Medley, D. R. Mikkelsen, S. L. Milora, W. Morris,

D. Mueller, V. Mukhovatov, E. B. Mieschmidt, J. O'Rourke, D. K. Owens, H. Park, M. Pomphrey, B. Prichard, A. T. Ramsey, M. H. Redi, A. L. Roquemore, P. H. Rutherford, M. R. Sauthoff, G. Schilling, J. Schivell, G. L. Schmidt, S. D. Scott, S. Sesnic, J. C. Sinnis, F. J. Stauffer, B. C. Stratton, G. D. Tait, G. Taylor, J. R. Timberlake, H. H. Touner, M. Ulrickson, V. Vershkov, S. Von Goeller, F. Wagner, R. Weiland, J. B. Wilgen, M. Williams, K. L. Wong, S. Yoshikawa, R. Yoshino, K. M. Young, M. C. Zarnstorff, V. S. Zaveryaev, and S. J. Zueben

"TFTR Plasma Regimes," pp. 51-64 in Plasma Physics and Controlled Nuclear Fusion Research 1986, Vol. 1 (Proceedings, Eleventh International Conference on Plasma Physics and Controlled Nuclear Fusion Research, Kyoto, Japan, November 13-20, 1986), International Atomic Energy Agency, Vienna, 1987

Harryluk, R. J., V. Arunasalam, J. D. Bell, M. G. Bell, M. Bitter, W. R. Blanchard, F. Boody, M. Bretz, R. Budny, C. E. Bush, J. D. Callen, J. L. Cecchi, S. Cohen, R. J. Colchin, S. K. Combs, J. Coonrod, S. L. Davis, D. Dimock, M. F. Dylla, P. C. Efthimion, L. C. Emerson, A. C. England, M. P. Eubank, R. Fonck, E. Fredrickson, R. J. Goldston, L. R. Grisham, B. Grek, R. Groebner, H. Hendel, K. W. Hill, D. L. Hillis, E. Hinnov, S. Hiroe, R. Hulse, M. Hsuan, D. Johnson, L.-C. Johnson, R. Kaita, R. Kamperschroer, S. M. Kaye, S. Kilpatrick, H. Kugel, P. H. LaMarche, R. Little, C. H. Ma, D. M. Manos, D. Mansfield, R. T. McCann, M. McCarthy, D. C. McCune, K. McGuire, D. M. Meade, S. S. Medley, S. L. Milora, D. R. Mikkelsen, W. Morris, D. Mueller, M. Murakami, E. Mieschmidt, D. K. Owens, V. K. Pare, H. Park, B. Prichard, A. Ramsey, D. A. Rasmussen, M. H. Redi, A. L. Roquemore, M. R. Sauthoff, J. Schivell, G. L. Schmidt, S. D. Scott, S. Sesnic, M. Shimada, J. E. Simpkins, J. Sinnis, F. Stauffer, B. Stratton, G. D. Tait, G. Taylor, C. E. Thomas, H. H. Touner, M. Ulrickson, S. Von Goeller, R. Weiland, J. B. Wilgen, M. Williams, K. L. Wong, S. Yoshikawa, K. M. Young, M. C. Zarnstorff, and S. Zueben

"Experimental Results from the TFTR Tokamak," *Philos. Trans. R. Soc. London A322*, 147-162 (1987)

Herath-Banda, M. A., A. V. Ramayya, L. Cleemann, J. Eberth, J. Roth, T. Heck, M. Schmal, T. Mylaeus, W. Koenig, B. Martin, K. Bethge, and G. A. Leander

"Signature Splitting of Electromagnetic Transitions in ^{75}Kr ," *J. Phys. G13*, 43-55 (1987)

Hippler, R.

"Atomic Effects of Electrons and Protons at Low Energies," *Proceedings, Third International Symposium on Radiation Physics, Ferrara, Italy, September 30-October 4, 1985*, *Nucl. Instrum. Methods Phys. Res. A255*, 17-27 (1987)

Hippler, R., S. Datz, P. D. Miller, P. L. Pepmiller, and P. F. Dittner

"Double- and Single-Electron Capture and Loss in Collisions of 1-2 MeV/u Boron, Oxygen and Silicon Projectiles with Helium Atoms," *Phys. Rev. A 35*, 585-90 (1987)

Honkanen, K., M. C. Griffin, D. G. Sarantites, V. Abenante, L. A. Adler, C. Baktash, Y. S. Chen, O. Dietzsch, M. L. Halbert, D. C. Hensley, M. R. Johnson, A. Larabee, I. Lee, L. L. Riedinger, J. X. Saladin, T. Semkow, and Y. Schutz (Invited Paper)

"High-Spin Structure of ^{163}Lu ," pp. 317-22 in *Proceedings, ACS Symposium on Recent Advances in the Study of Nuclei Off the Line of Stability*, Chicago, Illinois, September 8-13, 1985, ACS Symposium Series 324, American Chemical Society, Washington, D.C., 1986

Horen, D. J.

"Isotopes," pp. 433-36 in Vol. 9, *McGraw-Hill Encyclopedia of Science and Technology*, Sixth Edition, McGraw-Hill, New York, 1987

Horen, D. J., B. L. Burks, M.A.G. Fernandes, R. L. Auble, F. E. Bertrand, J. L. Blankenship, J.L.C. Ford, Jr., E. E. Gross, D. C. Hensley, R. O. Sayer, G. R. Satchler, D. Shapira, T. P. Sjoreen, and F. Petrovich

"Investigation of the One-Step Direct Contribution to the $^{28}\text{Si}(^{18}\text{O},^{18}\text{F})^{28}\text{Al}$ Reaction at 19.6 MeV/Nucleon," *Phys. Lett. 181B*, 38-42 (1986)

Hulskotter, H. P., J. Burgdorfer, and I. A. Sellin (Invited Paper)

"Exit Charge-State Dependence of Convoy Electron Production in Heavy-Ion-Solid Collisions," *Proceedings, Ninth Conference on the Application of Accelerators in Research and Industry*, Denton, Texas, November 10-12, 1986, *Nucl. Instrum. Methods Phys. Res. B24/25*, 147-52 (1987)

Jacak, B. V., M. C. Britt, G. Claesson, K.G.R. Doss, R. L. Ferguson, A. I. Gavron, H.-A. Gustafsson, H. H. Gutbrod, J. W. Harris, K.-H. Kampert, B. Kolb, A. M. Poskanzer, H.-G. Ritter, H. R. Schmidt, L. Teitelbaum, M. Tincknell, S. Weiss, H. Wieman, and J. Wilhelmy

"Multifragmentation in Intermediate Energy Heavy Ion Collisions," pp. 267-76 in *Hadronic Matter in Collision* (Proceedings, Second International Workshop on Local Equilibrium in Strong Interaction Physics, Santa Fe, New Mexico, April 9-12, 1986), World Scientific Publishing, 1986

- Johnson, M. R. (Invited Paper)
 "Evolution of Nuclear Shapes at High Spins," pp. 298-304 in Proceedings, ACS Symposium on Recent Advances in the Study of Nuclei Off the Line of Stability, Chicago, Illinois, September 8-13, 1985, ACS Symposium Series 324, American Chemical Society, Washington, D.C., 1986
- Johnson, M. R. (Invited Paper)
 "Evolution of Nuclear Shapes at High Spins as Determined by Lifetime Measurements," pp. 44-50 in Proceedings, Nuclear Structure Workshop, Copenhagen, Denmark, May 12-17, 1986, Niels Bohr Institute, Copenhagen, 1986
- Juutinen, S., X. T. Liu, S. Sorensen, B. Cox, R. W. Kincaid, C. R. Bingham, M. W. Guidry, W. J. Kernan, C. Y. Wu, E. Vogt, T. Czosnyka, D. Cline, M. L. Halbert, I. Y. Lee, and C. Baktash
 "Anomalous Two-Neutron Transfer Cross Sections at Large Separation in Heavy Ion Reactions," Phys. Lett. 192B, 307-11 (1987)
- Kahane, S., J. E. Lynn, and S. Raman
 "Analysis of Primary Electric Dipole Gamma Rays from Slow-Neutron Capture by Ca Isotopes," Phys. Rev. C 36, 533-42 (1987)
- Kim, H. J., and R. K. Janev
 "Electron-Loss Cross Sections in Symmetric Multicharged-Ion Collisions," Phys. Rev. Lett. 58, 1837-40 (1987)
- Kohler, R., J. A. Martena, H. Weigmann, L. Merissen, F. Poortmans, J. P. Theobald, and S. Raman
 "Nuclear Structure of ^{208}Pb from $^{207}\text{Pb} + n$ Resonances," Phys. Rev. C 35, 1646-60 (May 1987)
- Korolija, M., M. Cindro, R. Caplar, R. L. Auble, J. B. Ball, and R. L. Robinson
 "Multiple-Source Analysis of Inclusive Proton Spectra from $^{58}\text{Ni} + ^{60}\text{Ni}$ Collisions at 876.5 MeV," Z. Phys. A327, 237-38 (1987)
- Kortelahti, M., E. F. Zganjar, R. L. Mlekodaj, B. D. Kern, R. A. Braga, R. W. Fink, and C. P. Perez
 "Beta Decay of Light Rare-Earth $^{130,132}\text{Pr}$ and $^{132,134}\text{Pm}$ Nuclei," Z. Phys. A327, 231-32 (1987)
- Konacki, J., and C. Baktash (Invited Paper)
 "A Semiempirical Shell Model Calculation in the $N = 82$, $Z = 64$ Region," pp. 290-96 in Proceedings, International Symposium on Symmetries and Nuclear Structure, Dubrovnik, Yugoslavia, June 1986, Harwood Academic, New York, 1986
- Krofcheck, O., E. Sugarbaker, A. J. Wagner, J. Rapaport, D. Wang, J. W. Bahcall, R. C. Byrd, C. C. Foster, C. D. Goodman, C. Gaarde, D. J. Molen, T. Carey, and T. M. Taddeucci
 "Gamow-Teller Strength Distribution in ^{81}Kr and the Consequences for a ^{81}Br Solar Neutrino Detector," Phys. Lett. 189B, 299-303 (1987)
- Kvale, T. J., G. D. Alton, R. M. Compton, J. S. Thompson, and D. J. Pegg (Invited Paper)
 "Autodetachment Spectroscopy of Metastable Negative Ions," Proceedings, Ninth Conference on the Application of Accelerators in Research and Industry, Denton, Texas, November 10-12, 1986, Nucl. Instrum. Methods Phys. Res. B24/25, 325-28 (1987)
- Leander, G. A. (Invited Paper)
 "Electromagnetic Properties of Nuclei at High Spins," pp. 79-87 in Weak and Electromagnetic Interactions in Nuclei (Proceedings, International Symposium, Heidelberg, West Germany, July 1-5, 1986), Springer-Verlag, Berlin, 1986
- Leander, G. A., and Y. S. Chen
 "Rigid Reflection-Asymmetric Rotor Description of the Nucleus ^{227}Ac ," Phys. Rev. C 35, 1145-47 (1987)
- Lee, I. Y. (Invited Paper)
 "High Spin Nuclear Structure Studies Using the Spin Spectrometer," pp. 461-68 in Proceedings, Beijing International Symposium on Physics at Tandem, Beijing, People's Republic of China, May 26-30, 1986, World Scientific Publishing, Singapore, 1987
- Lee, I. Y., C. Baktash, J. R. Beene, M. P. Fewell, M. L. Halbert, M. R. Johnson, F. K. McGowan, W. T. Milner, H. J. Kim, R. O. Sayer, and D. G. Sarantites
 "Distributions of the Total Energy and Multiplicity of Gamma Rays Feeding the Discrete Yrast States in Heavy-Ion-Induced Fusion Reactions," Phys. Rev. C 35, 605-13 (1987)
- Lee, S. J., J. Fink, A. B. Balantekin, M. R. Strayer, A. S. Umar, P.-G. Reinhard, J. A. Maruhn, and W. Greiner
 "Relativistic Hartree Calculations for Axially Deformed Nuclei," Phys. Rev. Lett. 57, 2916-19 (1986)

- Levin, J. C., R. T. Short, C.-S. O, M. Cederquist, S. B. Elston, J. P. Gibbons, I. A. Sellin, and M. Schmidt-Böcking
 "Steep Dependence of Recoil-Ion Energy on Coincident Projectile and Target Ionization in Swift Ion-Atom Collisions," *Phys. Rev. A* **36**, 1649-52 (1987)
- Lopac, V., S. Brant, V. Paar, O.W.B. Schult, H. Seyfarth, and A. B. Balantekin
 "Odd-Odd Nucleus ^{198}Au as First Test of IBFFM (OTQM)," *Z. Phys. A* **323**, 491-93 (1986)
- Lynn, J. E., S. Kahane, and S. Raman
 "Analysis of Slow Neutron Capture by ^9Be , ^{12}C , and ^{13}C ," *Phys. Rev. C* **35**, 26-36 (1987)
- Majka, Z., D. G. Sarantites, L. G. Sobotka, K. Honkanen, E. L. Dines, L. A. Adler, Li Ze, M. L. Halbert, J. R. Beene, D. C. Hensley, R. P. Schmitt, and G. Mebbia
 "Nuclear Shapes from Alpha-Gamma Ray Angular Correlations," *Phys. Rev. Lett.* **58**, 322-25 (1987)
- McDaniels, D. K., J. Lisantti, I. Bergqvist, L. W. Swenson, X. Y. Chen, D. J. Horen, F. E. Bertrand, E. E. Gross, C. Glover, R. Sayer, B. L. Burks, O. Hausser, and K. Hicks
 "Validity of Collective Model DWBA Analysis for Intermediate Energy Proton Scattering to Low-Lying States of ^{208}Pb ," *Nucl. Phys. A* **467**, 557-74 (1987)
- McDaniels, D. K., J. Lisantti, L. W. Swenson, X. Y. Chen, F. E. Bertrand, E. E. Gross, D. J. Horen, C. Glover, R. Sayer, B. L. Burks, O. Hausser, and K. Hicks
 "Multipole Matrix Elements for ^{208}Pb ," pp. 727-28 in Intersections Between Particle and Nuclear Physics (Proceedings, Conference, Lake Louise, Canada, May 26-31, 1986), AIP Conf. Proc. **150**, American Institute of Physics, New York, 1986
- McGowan, F. K., M. R. Johnson, I. Y. Lee, W. T. Milner, C. Roulet, R. M. Diamond, F. S. Stephens, and M. W. Guidry
 "Test of the Triaxial Rotor Model and the Interacting Boson-Fermion Approximation Model Description of Collective States in ^{193}Ir ," *Phys. Rev. C* **35**, 968-76 (1987)
- Meyer, F. W.
 "Operation of the ORNL ECR Source," pp. 10-24 in Proceedings, 7th International ECR Source Workshop, Contributed Papers, Julich, West Germany, May 22-23, 1986, Kernforschungsanlage Julich, West Germany, July 1986
- Meyer, F. W., C. C. Havener, S. H. Overbury, K. J. Snowden, D. M. Zehner, W. Heiland, and H. Hemme
 "Charge Exchange Processes Between Highly Charged Ions and Metal Surfaces," Proceedings, Conference on the Physics of Multiply Charged Ions, Groningen, The Netherlands, September 17-19, 1986, *Nucl. Instrum. Methods Phys. Res. B* **23**, 234-38 (1987)
- Meyer, F. W., C. C. Havener, R. A. Phaneuf, J. K. Swenson, S. M. Shafroth, and N. Stolterfoht (Invited Paper)
 "Evidence for Correlated Double-Electron Capture in Slow Collisions of Multicharged Ions with He and H_2 ," Proceedings, Ninth Conference on the Application of Accelerators in Research and Industry, Denton, Texas, November 10-12, 1986, *Nucl. Instrum. Methods Phys. Res. B* **24/25**, 106-10 (1987)
- Meyer, F. W., C. C. Havener, K. J. Snowden, S. H. Overbury, D. M. Zehner, and W. Heiland
 "Observation of the Neutralization of Highly Charged Ions Interacting with a Metal Surface," *Phys. Rev. A* **35**, 3176-79 (1987)
- Milner, W. T., W. H. Atkins, J. A. Biggerstaff, and R. O. Sayer
 "Holifield Heavy Ion Research Facility Computer Handbook," 1987
- Mioduszewski, P. K., R. C. Isler, J. E. Simpkins, F. H. Edmonds, E. A. Lazarus, C. H. Ma, and M. Murakami
 "Improvement of Plasma Performance with Chromium Gettering in ISX-B," *Nucl. Fusion* **27**, 195-203 (1987)
- Mlekosdaj, R. L., R. A. Braga, B. D. Kern, G. A. Leander, K. S. Toth, and B. E. Gnade (Invited Paper)
 "Decay of ^{138}Eu and ^{136}Eu and Deformation in the Light Sm Region," pp. 502-07 in Proceedings, ACS Symposium on Recent Advances in the Study of Nuclei Off the Line of Stability, Chicago, Illinois, September 8-13, 1985, ACS Symposium Series 324, American Chemical Society, Washington, D.C., 1986
- Moltz, D. M., A. C. Betker, J. P. Sullivan, R. H. Burch, C. A. Gagliardi, R. E. Tribble, K. S. Toth, and F. T. Avignone, III
 "Masses of ^{77}Kr and ^{75}Kr ," *Phys. Rev. C* **35**, 1275-79 (1987)
- Nazarewicz, W., G. A. Leander, and J. Dudek
 "Octupole Shapes and Shape Changes at High Spins in Ra and Th Nuclei," *Nucl. Phys. A* **467**, 437-60 (1987)

- Olsen, D. K.
 "Resolved Resonance Parameters for ^{238}U from 1 to 10 keV," Nucl. Sci. Eng. 94, 102-06 (1986)
- Olsen, D. K., G. D. Alton, S. Datz, P. F. Dittner, D. T. Dowling, D. L. Haynes, E. D. Hudson, J. W. Jonsson, I. Y. Lee, R. S. Lord, C. A. Ludemann, J. A. Martin, J. B. McGroarty, F. W. Meyer, P. D. Miller, W. T. Milner, S. W. Mosko, P. L. Pepmiller, and G. R. Young (Invited Paper)
 "The HISTRAP Proposal: Heavy Ion Storage Ring for Atomic Physics," Proceedings, Ninth Conference on the Application of Accelerators in Research and Industry, Denton, Texas, November 10-12, 1986, Nucl. Instrum. Methods Phys. Res. B24/25, 26-37 (1987)
- Olsen, D. K., K. A. Erb, C. M. Jones, W. T. Milner, D. C. Weiser, and M. F. Ziegler
 "Calibration of the NHIRF Tandem Accelerator Energy-Analyzing Magnet," Nucl. Instrum. Methods Phys. Res. A254, 1-6 (1987)
- Park, H., J. O. Kephart, R. K. Klein, R. H. Pantell, B. L. Berman, and S. Datz
 "Channeling Radiation from GaAs," Phys. Rev. B 36, 1259-61 (1987)
- Park, H., J. O. Kephart, R. K. Klein, R. H. Pantell, M. V. Hynes, B. L. Berman, B. A. Dahling, S. Datz, R. L. Swent, and M. J. Alguard
 "Temperature Dependence of Planar Channeling Radiation," Phys. Rev. B 35, 13-17 (1987)
- Paul, E. S., C. W. Beausang, D. B. Fossan, R. Ma, M. F. Piel, Jr., M. Xu, L. Hildingsson, and G. A. Leander
 "Collective Oblate Band in ^{131}La Due to the Rotational Alignment of $h_{11/2}$ Neutrons," Phys. Rev. Lett. 58, 984-87 (1987)
- Phaneuf, R. A.
 "Experiments on Electron-Impact Excitation and Ionization of Ions," pp. 117-56 in Atomic Processes in Electron-Ion and Ion-Ion Collisions (Proceedings, NATO Advanced Study Institute on Physics of Electron-Ion and Ion-Ion Collisions, Han sur Lesse, Belgium, September 30-October 12, 1985), Plenum Publishing, New York, 1986
- Phaneuf, R. A., D. C. Gregory, C. C. Havener, and F. W. Meyer (Invited Paper)
 "Collision Experiments with Highly Ionized Atoms," pp. 265-81 in Atomic Physics 10 (Proceedings, Tenth International Conference on Atomic Physics, Tokyo, Japan, August 25-29, 1986), North-Holland, Amsterdam, 1987
- Physics Division and Joint Institute for Heavy Ion Research, ORNL, Sponsors
 Mini-Proceedings of the Workshop on Heavy Ion Physics and Instrumentation for a 15-Tm Booster and Storage Ring, Oak Ridge, Tennessee, CONF-8610150 (November 1986)
- Pindzola, M. S., and D. C. Griffin
 "Double Auger Processes in the Electron-Impact Ionization of Lithiumlike Ions," Phys. Rev. A 36, 2628-32 (1987)
- Pindzola, M. S., D. C. Griffin, and C. Bottcher
 "Electron-Impact Ionization in the Iron Isotopic Sequence," Phys. Rev. A 34, 3668-75 (1986)
- Pindzola, M. S., D. C. Griffin, and C. Bottcher
 "Electron-Ion Collisions in the Average-Configuration Distorted-Wave Approximation," pp. 75-91 in Atomic Processes in Electron-Ion and Ion-Ion Collisions (Proceedings, NATO Advanced Study Institute on Physics of Electron-Ion and Ion-Ion Collisions, Han-sur-Lesse, Belgium, September 30-October 12, 1985), Plenum Publishing, New York, 1986
- Pindzola, M. S., C. Bottcher, and D. C. Griffin
 "Indirect Processes in the Electron Impact Ionisation of Ca^+ Using an LS-Term-Dependent Close-Coupling Method," J. Phys. B20, 3535-46 (1987)
- 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, J. W. Johnson, K. H. Kampert, B. W. Kolb, P. Kristiansson, I. Y. Lee, M. Lohner, J. Lund, F. E. Obenshain, A. Oskarsson, I. Otterlund, T. Peltzmann, S. Persson, A. M. Poskanzer, M. Purschke, H. G. Ritter, R. Santo, H. R. Schmidt, T. Siemiarczuk, K. Soderstrom, S. P. Sorensen, E. Stenlund, and G. R. Young (Invited Paper)
 "Preliminary Results from Collisions Between 3.2-TeV ^{16}O and Target Nuclei of C, Cu, and Au," pp. 34-45 in Proceedings, XXV International Winter Meeting on Nuclear Physics, Bormio, Italy, January 19-24, 1987, Ricerca Scientifica ed Educazione Permanente, Supplement 56, University of Milano, Italy, 1987

- Raman, S., Editor
 "Actinide Newsletter," Issue 10 (March 1987)
- Raman, S., and J. E. Lynn (Invited Paper)
 "Applications and Misapplications of the Channel-Capture Formalism of Direct Neutron Capture," pp. 253-74 in Proceedings, Fourth International Symposium on Neutron-Induced Reactions, Smolenice, Czechoslovakia, June 17-21, 1985, Veda, Bratislava, Czechoslovakia, 1986
- Raman, S., C. H. Malarkey, W. T. Milner, C. W. Nestor, Jr., and P. H. Stelson
 "Transition Probability, $B(E2)_{\uparrow}$, from the Ground to the First-Excited 2^+ State of Even-Even Nuclides," At. Data Nucl. Data Tables 36, 1-96 (1987)
- Raman, S., and C. W. Nestor (Invited Paper)
 " $B(E2)_{\uparrow}$ for the 2^+ States of Collective Nuclei Off the Line of Stability," p. 512 in Proceedings, ACS Symposium on Recent Advances in the Study of Nuclei Off the Line of Stability, Chicago, Illinois, September 8-13, 1985, ACS Symposium Series 324, American Chemical Society, Washington, D.C., 1986, and pp. S28-S31 in Supplement to Nuclei Off the Line of Stability, Clark University, Worcester, Mass. (November 1986)
- Raman, S. and C. W. Nestor, Jr. (Invited Paper)
 "Global Set of Quadrupole Deformation Parameters for Even-Even Nuclei," pp. 25-30 in Weak and Electromagnetic Interactions in Nuclei (Proceedings, International Symposium, Heidelberg, Germany, July 1-5, 1986), Springer-Verlag, Berlin, 1986
- Rapaport, J., D. Wang, J. A. Carr, F. Petrovich, C. C. Foster, C. D. Goodman, C. Gaarde, J. Larsen, C. A. Goulding, T. M. Taddeucci, D. Horen, and E. Sugarbaker
 " (p,n) Reaction on Carbon Isotopes at $E_p = 160$ MeV," Phys. Rev. C 36, 500-12 (1987)
- Read, P. M., J. A. Cookson, and G. D. Alton (Invited Paper)
 "Beam Developments for the Harwell Microprobe System," Proceedings, Ninth Conference on the Application of Accelerators in Research and Industry, Denton, Texas, November 10-12, 1986, Nucl. Instrum. Methods Phys. Res. B24/25, 627-34 (1987)
- Richards, R. K., and D. C. Griffin
 "Producing a Steady-State Population Inversion," pp. 343-45 in Proceedings, Third Topical Meeting on Short Wavelength Coherent Radiation: Generation and Applications, Monterey, California, March 24-26, 1986, AIP Conf. Proc. 147 (Optical Science and Engineering Series 7), American Institute of Physics, New York, 1986
- Rinn, K., D. C. Gregory, L. J. Wang, R. A. Phaneuf, and A. Muller
 "Electron-Impact Ionization of U^{6+} : Improved Measurements," Phys. Rev. A 36, 595-98 (1987)
- Satchler, G. R.
 "Isospin and Macroscopic Models for the Excitation of Giant Resonances and Other Collective States," Nucl. Phys. A472, 215-36 (1987)
- Satchler, G. R.
 "The Threshold Anomaly and the Effective Interaction for Nuclear Nonelastic Scattering," Nucl. Phys. A472, 591-604 (1987)
- Satchler, G. R., M. A. Nagarajan, J. S. Lilley, and I. J. Thompson
 "Heavy-Ion Fusion: Channel-Coupling Effects, the Barrier Penetration Model, and the Threshold Anomaly for Heavy-Ion Potentials," Ann. Phys. (N.Y.) 178, 110-42 (1987)
- Schmorak, M. R.
 "Nuclear Data Sheets for $A = 201$," Nucl. Data Sheets 49, 733-84 (1986)
- Schmorak, M. R.
 "Nuclear Data Sheets for $A = 202$," Nucl. Data Sheets 50, 669-717 (1987)
- Schmorak, M. R.
 "Nuclear Data Sheets for $A = 204$," Nucl. Data Sheets 50, 719-779 (1987)
- Schmorak, M. R.
 "Nuclear Data Sheets for $A = 200$," Nucl. Data Sheets 51, 689-764 (1987)
- Scholten, O., R. M. Ronningen, A. Y. Ahmed, G. O. Bomar, H. L. Crowell, J. H. Hamilton, H. Kawakami, C. J. Maguire, W. G. Nettles, R. B. Piercey, A. V. Ramayya, S. Soundranayagam, and P. H. Stelson
 "Mass Dependence of Effective Charges in the Interacting-Boson Model," Phys. Rev. C 34, 1962-64 (1986)

- Schuch, R. (Invited Paper)
 "Atomic Physics at the Heidelberg Test Storage Ring (TSR)," Proceedings, Ninth Conference on the Application of Accelerators in Research and Industry, Denton, Texas, November 10-12, 1986, Nucl. Instrum. Methods Phys. Res. B24/25, 11-17 (1987)
- Schutz, Y., C. Baktash, I. Y. Lee, M. L. Halbert, D. C. Mensley, M. R. Johnson, M. Oshima, R. Ribas, J. C. Lisle, L. Adler, K. Honkanen, D. G. Sarantites, A. J. Larabee, and J. X. Saladin
 "Search for Superdeformed Shapes in ^{144}Gd ," Phys. Rev. C 35, 348-51 (1987)
- Semkow, T. M., D. G. Sarantites, K. Honkanen, V. Abenante, C. Baktash, M. R. Johnson, I. Y. Lee, M. Oshima, Y. Schutz, C. Y. Chen, O. Dietzsch, J. X. Saladin, A. J. Larabee, and O. C. Kistner (Invited Paper)
 "Signature Splitting in ^{135}Pr ," pp. 305-10 in Proceedings, ACS Symposium on Recent Advances in the Study of Nuclei Off the Line of Stability, Chicago, Illinois, September 8-13, 1985, ACS Symposium Series 324, American Chemical Society, Washington, D.C., 1986
- Semmes, P. B., R. A. Braga, R. W. Fink, J. L. Wood, and J. D. Cole
 "Decay of Mass-Separated 7.4-min ^{203}At ," Nucl. Phys. A464, 381-94 (1987)
- Shapira, D., B. Shivakumar, S. Ayik, and B. A. Harmon
 "Formation of a Dinuclear Complex in Collisions Between Light Nuclei and Entrance Channel Limitations to Their Fusion," pp. 597-604 in Proceedings, Symposium on the Many Facets of Heavy Ion Fusion Reactions, Argonne, Illinois, March 24-26, 1986, Argonne National Laboratory Report ANL-PHY-86-1 (1986)
- Shivakumar, B., S. Ayik, B. A. Harmon, and D. Shapira
 "Equilibrium Model for Fusion and Orbiting," Phys. Rev. C 35, 1730-33 (1987)
- Shivakumar, B., D. Shapira, P. H. Stelson, M. Beckerman, B. A. Harmon, K. Teh, and S. Ayik
 "Destination Fusion," pp. 605-12 in Proceedings, Symposium on the Many Facets of Heavy Ion Fusion Reactions, Argonne, Illinois, March 24-26, 1986, Argonne National Laboratory Report ANL-PHY-86-1 (1986)
- Short, R. T., C.-S. O, J. C. Levin, I. A. Sellin, B. M. Johnson, M. Meron, K. W. Jones, and D. A. Church
 "Synchrotron Radiation Inner-Shell Photoionization of Atomic and Molecular Gases," Proceedings, Ninth Conference on the Application of Accelerators in Research and Industry, Denton, Texas, November 10-12, 1986, Nucl. Instrum. Methods Phys. Res. B24/25, 417-19 (1987)
- Sorensen, S. P.
 "Event Simulation for the WABO Experiment," Proceedings, Fifth International Conference on Ultrarelativistic Nucleus-Nucleus Collisions, Asilomar, California, April 13-17, 1986, Nucl. Phys. 461, 487c-99c (1987)
- Stolterfoht, N., C. C. Havener, R. A. Phaneuf, J. K. Swenson, S. M. Shafroth, and F. W. Meyer
 "Reply to the Comment on 'Evidence for Correlated Double Electron Capture in Low-Energy Collisions of O^{6+} with He'," Phys. Rev. Lett. 58, 958 (1987)
- Stolterfoht, N., C. C. Havener, R. A. Phaneuf, J. K. Swenson, S. M. Shafroth, and F. W. Meyer
 "Correlated Double Electron Capture in Slow, Highly Charged Ion-Atom Collisions," Proceedings, Third International Workshop on Cross Sections for Fusion and Other Applications, College Station, Texas, November 6-8, 1987, Nucl. Instrum. Methods Phys. Res. B27, 584-89 (1987)
- Stolterfoht, N., P. D. Miller, H. F. Krause, Y. Yamazaki, J. K. Swenson, R. Bruch, P. F. Dittner, P. L. Pepmiller, and S. Datz (Invited Paper)
 "Surgery of Fast, Highly Charged Ions Studied by Zero-Degree Auger Spectroscopy," Proceedings, Ninth Conference on the Application of Accelerators in Research and Industry, Denton, Texas, November 10-12, 1986, Nucl. Instrum. Methods Phys. Res. B24/25, 168-72 (1987)
- Swenson, J. K., Y. Yamazaki, P. D. Miller, H. F. Krause, P. F. Dittner, P. L. Pepmiller, S. Datz, and N. Stolterfoht
 "Observation of Resonant Transfer and Excitation to Specific L,S-Coupled States in $\text{O}^{5+} + \text{He}$ Collisions By High Resolution O^+ Auger Electron Spectroscopy," Phys. Rev. Lett. 57, 3042-45 (1986)
- Taddeucci, T. M., C. A. Goulding, T. A. Carey, R. C. Byrd, C. D. Goodman, C. Gaarde, J. Larsen, D. Horen, J. Rapaport, and E. Sugarbaker
 "The (p,n) Reaction as a Probe of Beta Decay Strength," Nucl. Phys. A469, 125-72 (1987)
- Teh, K. M., D. Shapira, B. L. Burks, R. L. Varner, J. L. Blankenship, E. J. Ludwig, R. E. Fauber, and C. F. Maguire
 "Some Properties of Slow Plastic Scintillators," Nucl. Instrum. Methods Phys. Res. A254, 600-03 (1987)

- Toth, K. S. (Invited Paper)
 "Particle Decay Studies at or near Closed Shells," p. 514 in Proceedings, ACS Symposium on Recent Advances in the Study of Nuclei Off the Line of Stability, Chicago, Illinois, September 8-13, 1985, ACS Symposium Series 324, American Chemical Society, Washington, D.C., 1986, and pp. S45-S50 in Supplement to Nuclei Off the Line of Stability, Clark University, Worcester, Mass. (November 1986)
- Toth, K. S., Y. A. Ellis-Akova, J. M. Nitschke, P. A. Wilmarth, P. K. Lemmertz, D. M. Moltz, and F. T. Avignone, III
 "Structure in β -Delayed Proton Spectra of $N = 81$ Precursors," Phys. Lett. 178B, 150-54 (1986)
- Toth, K. S., J. Gilat, J. M. Nitschke, P. A. Wilmarth, K. Vierinen, and F. T. Avignone, III
 "Observation of ^{149}Tm Decay to ^{149}Er Levels and β -Delayed Proton Emission," Phys. Rev. C 36, 826-29 (1987)
- Toth, K. S., D. M. Moltz, F. Blonningen, and F. T. Avignone, III
 "Identification of ^{182}Pb in ^{40}Ca Irradiations of ^{147}Sm ," Phys. Rev. C 35, 2330-32 (1987)
- Toth, K. S., D. C. Sousa, J. M. Nitschke, and P. A. Wilmarth
 "Investigation of $A = 152$ Radioactivities with Mass-Separated Sources: Identification of ^{152}Lu ," Phys. Rev. C 35, 310-14 (1987)
- Toth, K. S., D. C. Sousa, J. M. Nitschke, and P. A. Wilmarth
 "Decay Properties of ^{150}Tm and ^{150}Er ," Phys. Rev. C 35, 620-24 (1987)
- Vane, C. R., M. Smith, S. Raman, J. Heard, and T. Walkiewicz (Invited Paper)
 "Ion-Induced X-Ray Studies with a High Luminosity von Hamos Crystal Spectrometer," Proceedings, Ninth Conference on the Application of Accelerators in Research and Industry, Denton, Texas, November 10-12, 1986, Nucl. Instrum. Methods Phys. Res. B24/25, 59-63 (1987)
- Wells, J. C., M. R. Johnson, C. Baktash, I. Y. Lee, F. K. McGowan, M. M. Rao, L. L. Riedinger, V. Janzen, W. C. Ma, S. Wen, Z. M. Chen, P. B. Semmes, G. A. Leander, and Y. S. Chen
 "Low-Frequency Anomaly in ^{172}Os Moment of Inertia," Phys. Rev. C 36, 431-34 (1987)
- Wong, C. Y.
 "Reply to Comments by H. J. Lipkin," Phys. Rev. Lett. 58, 426 (1987)
- Wong, C. Y., and R. L. Becker
 "Scalar Magnetic (e^+e^-) Resonance as Possible Source of an Anomalous e^+ Peak in Heavy-Ion Collisions," Phys. Lett. 102B, 251-55 (1986)
- Wu, C. L., D. H. Feng, X. G. Chen, J. Q. Chen, and M. W. Guidry
 "Fermion Dynamical Symmetry Model of Nuclei: (I) Basis, Hamiltonian, and Symmetries," Phys. Rev. C 36, 1157-80 (1987)
- Wu, C. Y., X. T. Liu, S. P. Sorensen, R. W. Kincaid, M. W. Guidry, D. Cline, W. J. Kernan, E. Vogt, T. Czornyka, A. E. Kavka, M. A. Stoyer, J. O. Rasmussen, and M. L. Halbert
 "Population of High-Spin States in the Actinide Region by Heavy-Ion Transfer Reactions," Phys. Lett. 100B, 25-28 (1987)
- Wuosmaa, A. H., R. W. Zurmuhle, P. H. Kutt, S. F. Pate, S. Saini, M. L. Halbert, and D. C. Hensley
 "Single and Correlated Spin Alignments for Resonances in $^{24}\text{Mg} + ^{24}\text{Mg}$ Inelastic Scattering," Phys. Rev. Lett. 58, 1312-15 (1987)
- Xu, H. M., D. J. Fields, W. G. Lynch, M. B. Tsang, C. K. Gelbke, M. R. Maier, D. J. Morrissey, J. Pochodzalla, D. G. Sarantites, L. G. Sobotka, M. L. Halbert, D. C. Hensley, D. Hahn, and H. Stocker
 "Nuclear Temperature Measurements and Feeding from Particle Unbound States," Phys. Lett. 102B, 155-58 (1986)
- Yamazaki, Y., H.-P. Hulskotter, M. Breinig, R. DeSerio, J. Burgdorfer, T. Underwood, J. Gibbons, I. A. Sellin, and P. Popmiller
 "Target-Thickness Dependence of the Convoy-Electron Yield Measured in Coincidence with Exit Charge State in Fast-Ion-Solid Collisions," Phys. Rev. A 34, 4493-96 (1986)
- Young, G. R. (Invited Paper)
 "Storage Rings for Heavy-Ion Atomic and Nuclear Physics," pp. 357-65 in Intersections Between Particle and Nuclear Physics (Proceedings, Conference, Lake Louise, Canada, May 26-30, 1986), AIP Conf. Proc. 150, American Institute of Physics, New York, 1986

Zehner, D. M., S. H. Overbury, C. C. Havener, F. W. Meyer, and W. Heiland
 "Electron Emission from the Interaction of Multiply Charged Ions with a Au (110) Surface,"
 Proceedings, Eighth European Conference on Surface Science, Julich, West Germany, April 14-17, 1986,
 Surf. Sci. 178, 359-66 (1986)

Zganjar, E. F., C. D. Papanicopoloulos, J. L. Wood, R. A. Braga, R. W. Fink, A. J. Larabee,
 M. Carpenter, D. Love, C. R. Bingham, L. L. Riedinger, J. C. Maddington (Invited Paper)
 "Shape Coexistence in ^{185}Au ," pp. 245-51 in Proceedings, ACS Symposium on Recent Advances in the
 Study of Nuclei Off the Line of Stability, Chicago, Illinois, September 8-13, 1985, ACS Symposium
 Series 324, American Chemical Society, Washington, D.C., 1986

PROGRESS REPORT

Ball, J. B., F. E. Bertrand, S. Datz, C. M. Jones, J. B. McGrory, F. Plasil, and R. L. Robinson
 Physics Division Progress Report for Period Ending September 30, 1986, ORNL-6326 (March 1987)

TOPICAL REPORTS

Phaneuf, R. A., R. K. Janev, and M. S. Pindzola
 Atomic Data for Controlled Fusion Research. Volume V. Collisions of Carbon and Oxygen Ions with
 Electrons, H, H_2 , and He, ORNL-6090/V5 (February 1987)

Richards, R. K., K. L. Vander Sluis, and D. P. Hutchinson
 Feasibility of Alpha Particle Measurement in a Magnetically Confined Plasma by CO_2 Laser Thomson
 Scattering, ORNL/TM-10363 (August 1987)

ARTICLES PENDING PUBLICATION AS OF SEPTEMBER 30, 1987

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. M. Gutbrod, J. W. Johnson, K. H.
 Kampert, B. W. Kolb, P. Kristiansson, I. Y. Lee, H. Lohner, 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
 "Forward and Transverse Energy Flow in Oxygen-Induced Reactions at 60 A GeV and 200 A GeV," Physics
 Letters B

Alton, G. D.
 "I. Characterization of a Cesium Surface Ionization Source with a Porous Tungsten Ionizer," Review of
 Scientific Instruments

Alton, G. D.
 "II. Aspects of Negative Ion Generation and Extraction from a Refocus Geometry Cesium Sputter
 Negative Ion Source," Review of Scientific Instruments

Alton, G. D., and J. W. McConnell (Invited Paper)
 "The Emittances and Brightnesses of High-Intensity Negative Ion Sources," Proceedings, Seventh Tandem
 Conference, Berlin, West Germany, April 6-10, 1987, Nuclear Instruments and Methods in Physics
 Research

Alton, G. D., and P. M. Read
 "The Emittances and Brightnesses of $^{69}\text{Ga}^+$ Ion Beams Extracted from Needle-Type, Liquid-Metal Ion
 Sources," Journal of Applied Physics

Andrews, M. C., F. D. McDaniel, J. L. Duggan, P. D. Miller, P. L. Pepmiller, H. F. Krause, T. M.
 Rosseel, L. A. Rayburn, R. Mehta, and G. Lapicki
 "L- and M-Shell X-Ray Production Cross Sections of Nd, Gd, Ho, Yb, Au, and Pb by 25-MeV Carbon and
 32-MeV Oxygen Ions," Physical Review A

Aryaeinejad, R., D. J. Morrissey, R. A. Blue, R. M. Ronningen, J. X. Saladin, M. Kaplan, C. M. Knott,
 H. Takai, D. Winchel, and I. Y. Lee
 "Spin Alignment of Two Products from the Reaction $^{22}\text{Ne} + ^{170}\text{Er}$," Physical Review C

Auble, R. L., J. B. Ball, F. E. Bertrand, R. L. Ferguson, I. Y. Lee, R. L. Robinson, and G. R. Young
 "Target/Projectile Mass Dependence of Light Ion Yields from Heavy Ion Collisions," Physical Review C

- Baktash, C. (Invited Paper)
 "Energetic M1 Transitions as a Probe of Nuclear Collectivity at High Temperatures," Proceedings, International Conference on Nuclear Shapes, Crete, Greece, June 28-July 4, 1987
- Baranger, M., and K.T.R. Davies
 "Periodic Trajectories for a Two-Dimensional Nonintegrable Hamiltonian," *Annals of Physics* (New York)
- Becker, R. L. (Invited Paper)
 "Several Manifestations of Pauli Correlations in Energetic Ion-Atom Collisions," Proceedings, Third Workshop on High-Energy Ion-Atom Collision Processes, Debrecen, Hungary, August 3-5, 1987
- Beckerman, M.
 "Subbarrier Fusion of Two Nuclei," *Reports on Progress in Physics*
- Beene, J. R., F. E. Bertrand, M. L. Halbert, R. L. Auble, D. C. Hensley, D. J. Horen, R. L. Robinson, R. O. Sayer, and T. P. Sjoreen
 "Electromagnetic Decay of Giant Resonances in ^{208}Pb ," *Physical Review Letters*
- Beene, J. R., R. L. Varner, and F. E. Bertrand (Invited Paper)
 "Gamma Decay of Isoscalar and Isovector Giant Resonances Following Heavy-Ion Inelastic Scattering," Proceedings, First Topical Meeting on Giant Resonance Excitation in Heavy-Ion Collisions, Legnaro, Italy, September 21-25, 1987, *Nuclear Physics A*
- Bertrand, F. E., J. R. Beene, and D. J. Horen (Invited Paper)
 "Heavy Ion Excitation of Giant Resonances - The Next Generation," Proceedings, First Topical Meeting on Giant Resonance Excitation in Heavy-Ion Collisions, Legnaro, Italy, September 21-25, 1987, *Nuclear Physics A*
- Bottcher, C., and M. R. Strayer
 "Lepton Pair Production in Relativistic Heavy-Ion Collisions," *Physical Review Letters*
- Bottcher, C., and M. R. Strayer (Invited Paper)
 "Lepton Production in Ultra-Relativistic Ion-Ion Collisions," Proceedings, 6th Adriatic International Conference on Nuclear Physics, "Frontiers of Heavy-Ion Physics," Dubrovnik, Yugoslavia, June 15-19, 1987
- Bottcher, C., and M. R. Strayer (Invited Paper)
 "Probing the Vacuum with Highly Charged Ions," Proceedings, International Conference on Spectroscopy and Structure of Highly Ionized Atoms, Lisle, Illinois, August 17-21, 1987, *Nuclear Instruments and Methods in Physics Research*
- Bottcher, C., and M. R. Strayer (Invited Paper)
 "Pulsed Electromagnetic Production of Leptons," Proceedings, Second Workshop on Experiments and Detectors for RHIC, Berkeley, California, May 25-29, 1987
- Bounds, J. A., C. R. Bingham, H. K. Carter, G. A. Leander, R. L. Mlekodaj, E. H. Spejewski, and W. M. Fairbank, Jr.
 "Nuclear Structure of Light Thallium Isotopes as Deduced from Laser Spectroscopy on a Fast Atom Beam," *Physical Review C*
- Bracco, A., J. R. Beene, F. E. Bertrand, M. L. Halbert, R. L. Auble, D. C. Hensley, D. J. Horen, R. L. Robinson, and R. O. Sayer
 "Neutron Decay of Giant Resonances in ^{208}Pb ," *The Response of Nuclei under Extreme Conditions* (Proceedings, International School on Heavy-Ion Physics, Second Course, Erice, Sicily, October 12-22, 1986)
- Bracco, A., J. R. Beene, F. E. Bertrand, M. L. Halbert, D. C. Hensley, R. L. Auble, D. J. Horen, R. L. Robinson, and R. O. Sayer
 "Neutron Decay of Giant Resonances in ^{208}Pb ," *Physics Letters B*
- Brogia, R. A., and B. Lauritzen (Invited Paper)
 "Relaxation Processes in Rotational Motion," Proceedings, International Conference on Unified Concepts of Many-Body Problems, Stony Brook, New York, September 4-6, 1986
- Chen, X. Y., L. W. Swenson, F. Farzanpay, D. K. McDaniels, Z. Tang, Z. Xu, D. M. Drake, I. Bergqvist, A. Brockstedt, F. E. Bertrand, D. J. Horen, J. Lisantti, K. Hicks, M. Vetterli, and M. J. Iqbal
 "Nuclear Response Mechanism and Medium Effects for $^{208}\text{Pb}(\bar{p}, p')$ at Intermediate Energies," *Physics Letters B*

- Crater, H. W., C. Y. Wong, R. L. Becker, and P. Van Alstine
 "Nonperturbative Covariant Treatment of the Triplet e^+e^- System Using Two-Body Dirac Equations from Constraint Dynamics," *Physical Review D*
- Datz, S., Chairman, Committee for the International Survey on Atomic and Molecular Science
 "International Survey of Atomic and Molecular Science, 1984-1985," report, to be published by National Academy Press
- Datz, S., L. H. Andersen, J.-P. Briand, and D. Liesen (Invited Paper)
 "Experimental Atomic Physics in Heavy-Ion Storage Rings," *Proceedings, Workshop and Symposium on the Physics of Stored and Trapped Particles, Stockholm, Sweden, June 15-19, 1987, Physica Scripta*
- Datz, S., B. L. Berman, R. H. Pantell, and J. O. Kephart (Invited Paper)
 "Radiation from Channeled Electrons and Positrons," *Proceedings, XIII International Symposium on Physics in Ionized Gases (SPIG), Sibenik, Yugoslavia, September 1-5, 1986*
- Datz, S., P. F. Dittner, C. M. Fou, P. D. Miller, and P. L. Pepmiller (Invited Paper)
 "Dielectronic Recombination of Multiply Charged Ions," *Proceedings, XIII International Symposium on Physics in Ionized Gases (SPIG), Sibenik, Yugoslavia, September 1-5, 1986*
- Datz, S., R. Hippler, L. H. Andersen, P. F. Dittner, H. Knudsen, H. F. Krause, P. D. Miller, P. L. Pepmiller, T. Rosseel, M. Stolterfoht, and Y. Yamazaki (Invited Paper)
 "Electron Transfer Processes in Collisions of Highly Charged Energetic (0.1 to 1.0 MeV/Nucleon Ions with Helium Atoms," *Proceedings, U.S.-Japan Cooperative Science Programme, Joint Seminar on Interactions of Highly Ionized Atoms Produced in Heavy Ion Collisions, Kobe, Japan, March 16-20, 1987, Nuclear Instruments and Methods in Physics Research*
- Davies, K.T.R.
 "Complex-Plane Methods for Evaluating Integrals with Highly Oscillatory Integrands," *Annals of Physics (New York)*
- Davies, K.T.R., and R. W. Davies
 "Evaluation of a Class of Integrals Occurring in Mathematical Physics via a Higher Order Generalization of the Principal Value," *American Journal of Physics*
- Davies, K.T.R., M. R. Strayer, and G. D. White
 "Integral Methods for Calculations of Green's Functions in Pion-Nucleon Problems," *Physical Review C*
- De Aguiar, M.A.M., C. P. Malta, M. Baranger, and K.T.R. Davies
 "Bifurcations of Periodic Trajectories in Nonintegrable Hamiltonian Systems with Two Degrees of Freedom: Numerical and Analytical Results," *Annals of Physics (New York)*
- De Aguiar, M.A.M., C. P. Malta, E.J.V. de Passos, M. Baranger, and K.T.R. Davies
 "The Genealogy of Periodic Trajectories," *Proceedings, First International Conference on the Physics of Phase Space, College Park, Maryland, May 20-23, 1986*
- Defrance, P., S. Rachafi, J. Jureta, F. Meyer, and S. Chantrenne
 "Electron Impact Ionization of Ar^{2+} ," *Proceedings, Conference on the Physics of Multiply Charged Ions, Groningen, The Netherlands, September 16-20, 1986*
- DeSerio, R., C. Gonzalez-Lepera, J. P. Gibbons, J. Burgdorfer, and I. A. Sellin
 "Measurements of the Hydrogen 2s-2p Coherence Using the Quantum Beat Technique," *Physical Review A*
- Dittner, P. F. (Invited Paper)
 "Dielectronic Recombination Measurements of Multicharged Ions," *Proceedings, Workshop and Symposium on the Physics of Low Energy, Stored and Trapped Particles, Stockholm, Sweden, June 14-18, 1987*
- Dudek, J. (Invited Paper)
 "Superdeformed Nuclei. Shells-vs.-Liquid Drop, Pairing-vs.-Thermal Excitations, Triaxial-vs.-Octupole Shapes, Super-Superdeformation," *Proceedings, International Conference on Nuclear Shapes, Crete, Greece, June 28-July 4, 1987*
- Ellis-Akovall, Y. A., K. S. Toth, H. K. Carter, C. R. Bingham, I. C. Girit, and M. O. Kortelahti
 "The α -Decay Reduced Width of ^{194}Pb and Low-Spin Levels in ^{194}Tl Populated in ^{194}Pb β Decay," *Physical Review C*
- Fewell, M. P., M. R. Johnson, F. K. McGowan, J. S. Mattiia, I. Y. Lee, C. Baktash, Y. Schutz, J. C. Wells, L. L. Riedinger, M. W. Guidry, and S. C. Panchoil
 "Lifetimes of Yrast and Near-Yrast States of $^{159,160,161}\text{Yb}$," *Physical Review C*

- Girit, I. C., G. D. Alton, C. R. Bingham, H. K. Carter, M. L. Simpson, J. D. Cole, J. H. Hamilton, B. D. Kern, K. S. Krane, and E. F. Zganjar
 "UNISOR On-Line Nuclear Orientation Facility," Proceedings, Fifth International Conference on Nuclei Far from Stability, Rousseau Lake, Ontario, Canada, September 14-19, 1987
- Griffin, D. C., R. D. Cowan, and M. S. Pindzola
 "Mayer-Fermi Theory and the Long Sequences in the Periodic Table," Proceedings, NATO Advanced Study Institute on Giant Resonances in Atoms, Molecules, and Solids, Les Houches, France, June 16-26, 1986
- Griffin, D. C., M. S. Pindzola, and C. Bottcher
 "Distorted-Wave Calculations of the Electron-Impact Ionization of Highly Ionized Na-Like Ions," Physical Review A
- Hahn, R. L., K. S. Toth, Y. LeBeyec, B. Lagarde, and M. W. Guidry
 "Reactions with ^{40}Ar and ^{84}Kr Leading to the Same Compound Nucleus, ^{200}Po ," Physical Review C
- Halbert, M. L., J. R. Beene, D. C. Hensley, K. Honkanen, T. M. Semkow, V. Abenante, D. G. Sarantites, and Z. Li (Invited Paper)
 "Angular Momentum Effects in Subbarrier Fusion," Proceedings, 6th Adriatic International Conference on Nuclear Physics, "Frontiers of Heavy-Ion Physics," Dubrovnik, Yugoslavia, June 15-19, 1987
- Hamilton, J. H., A. V. Ramayya, X. Zhao, C. F. Maguire, W.-C. Ma, J. Kormicki, S. Men, L. Chaturvedi, Z.-M. Chen, T. M. Cormier, M. Satteson, J. D. Cole, R. B. Piercey, M. A. Herath-Banda, E. F. Zganjar, M. O. Kortelahti, G. A. Leander, J. Eberth, M. Schmal, T. Heck, L. Cleemann, T. Mylaeus, W. Neumann, M. Molte, and M. Wosna
 "Oblate-Prolate Shape Competition in $Z = 34-38$ Nuclei," Proceedings, Fifth International Conference on Nuclei Far from Stability, Rousseau Lake, Canada, September 14-19, 1987
- Hippler, R., S. Datz, H. F. Krause, P. D. Miller, P. L. Pepmiller, and P. F. Dittner
 "Partial Cross Sections for Electron Capture into Specific n-States for 0.1 and 0.25 MeV/Nucleon $19^+ - \text{H}_2$ Collisions ($q = 12-18$)," Physical Review A
- Hofmann, H. J., J. Beer, E. Bonani, H. R. von Gunten, S. Raman, M. Suter, R. L. Walker, W. Wolfli, and D. Zimmerman
 "Beryllium-10: Half-Life and AMS Standards," Proceedings, Fourth International Symposium on Accelerator Mass Spectrometry, Niagara-on-the-Lake, Ontario, Canada, April 27-30, 1987, Nuclear Instruments and Methods in Physics Research
- Horen, D. J., J. R. Beene, and F. E. Bertrand
 "Comment on the Characterization of the Giant Quadrupole Resonance in ^{208}Pb as Reported from π^+/π^- Scattering," Physical Review C
- Horen, D. J., M.A.G. Fernandes, B. L. Burks, G. R. Satchler, R. L. Auble, F. E. Bertrand, E. E. Gross, D. C. Hensley, R. O. Sayer, and D. Shapira
 "Transfer Reactions at High Energy Can Resolve Ambiguities in Heavy-Ion Potentials," Physics Letters B
- Horen, D. J., J. Lisantti, R. L. Auble, F. E. Bertrand, 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
 "First Quantitative Study of $T = 1$, Spin-Dipole Strength in ^{40}Ca ," Physical Review Letters
- Inn, K.G.W., J. D. Fassett, B. M. Coursey, R. L. Walker, and S. Raman (Invited Paper)
 "Development of the NBS Beryllium Isotopic Standard Reference Material," Proceeding, Workshop on Advanced Laser Technology for Chemical Measurements, Gaithersburg, Maryland, November 4-6, 1987
- Inn, K.G.W., S. Raman, B. M. Coursey, J. D. Fassett, and R. L. Walker
 "Development of the $^{10}\text{Be}/^9\text{Be}$ Isotopic NBS Standard Reference Material," Proceedings, Fourth International Symposium on Accelerator Mass Spectrometry, Niagara-on-the-Lake, Ontario, Canada, April 27-30, 1987, Nuclear Instruments and Methods in Physics Research
- Janev, R. K., R. A. Phaneuf, and H. T. Hunter
 "Recommended Cross Sections for Electron Capture and Ionization in Collisions of C^{9+} and O^{9+} Ions with H, He, and H_2 ," Atomic Data and Nuclear Data Tables
- Johnson, C. H., D. J. Horen, and C. Mahaux
 "Unified Description of the Neutron- ^{208}Pb Mean Field Between -20 and +165 MeV from the Dispersion Relation Constraint," Physical Review C
- Johnson, C. H., and R. R. Winters
 "Evidence for Parity Dependence of the Imaginary Part of the Neutron Optical Model Potential," Physical Review C

- Johnson, M. (Invited Paper)
 "Nuclear Collectivity at High Spins Determined from Lifetime Measurements," Proceedings, International Conference on Nuclear Structure Through Static and Dynamic Moments, Melbourne, Australia, August 25-28, 1987
- Jones, C. M., G. D. Alton, J. B. Ball, J. A. Biggerstaff, D. T. Dowling, K. A. Erb, D. L. Haynes, D. E. Hoglund, E. D. Hudson, R. C. Juras, S. M. Lane, C. A. Ludemann, J. A. Martin, M. J. Meigs, S. M. Mosko, D. K. Olsen, and M. F. Ziegler
 "The Holifield Heavy Ion Research Facility," Proceedings, Seventh Tandem Conference, Berlin, West Germany, April 6-10, 1987, Nuclear Instruments and Methods in Physics Research
- Jones, C. M., K. A. Erb, D. L. Haynes, J. T. Mitchell, M. F. Ziegler, J. E. Raatz, and R. D. Rathmell
 "Initial Tests of Compressed Geometry Acceleration Tubes in the ORNL 25URC Tandem Accelerator," Proceedings, Twentieth Symposium of Northeastern Accelerator Personnel, SNEAP XX, Notre Dame, Indiana, November 3-6, 1986
- Jones, C. M., K. A. Erb, D. L. Haynes, J. T. Mitchell, M. F. Ziegler, J. E. Raatz, and R. D. Rathmell
 "Tests of Compressed Geometry Acceleration Tubes in the Oak Ridge 25 URC Tandem Accelerator," Proceedings, Seventh Tandem Conference, Berlin, West Germany, April 6-10, 1987, Nuclear Instruments and Methods in Physics Research
- Juras, R. C., M. F. Ziegler, M. J. Meigs, R. L. McPherson, D. E. Hoglund, and J. A. Biggerstaff (Invited Talk)
 "Evolution and Development of the Oak Ridge 25 URC Tandem Accelerator Control System," Proceedings, Seventh Tandem Conference, Berlin, West Germany, April 6-10, 1987, Nuclear Instruments and Methods in Physics Research
- Jury, J. W., P. C.-K. Kuo, K. G. McNeill, C. K. Ross, H. R. Weller, and S. Raman
 "Ground-State Photoneutron Reactions in ^{180}O ," *Physical Review C*
- Kemmler, J., O. Heil, C. Biedermann, P. Koschar, H. Rothard, K. Kroneberger, K. O. Groeneveld, and I. A. Sellin
 "Convoy Electrons in Coincidence with Outgoing Charge States of Ni (920 MeV)," Proceedings, 14th International Conference on X-Ray and Inner-Shell Processes, Paris, France, September 14-18, 1987, *Journal of Physics (Paris)*
- Kern, B. D., G. A. Leander, R. L. Mlekodaj, M. K. Carter, M. O. Kortelahti, E. F. Zganjar, R. A. Braga, R. W. Fink, C. P. Perez, P. B. Semmes, and W. Nazarewicz
 "Energy Levels and Structure of Light Rare-Earth Nuclei, $^{136,138,140}\text{Sm}$ and $^{132,134,136}\text{Nd}$, via Beta Decay," Proceedings, Fifth International Conference on Nuclei Far from Stability, Rousseau Lake, Ontario, Canada, September 14-19, 1987
- Kern, B. D., R. L. Mlekodaj, M. O. Kortelahti, E. F. Zganjar, R. A. Braga, R. W. Fink, and C. P. Perez
 "Beta Decay of ^{136}Sm and ^{136}Pm ," *Zeitschrift für Physik*
- Kern, B. D., R. L. Mlekodaj, G. A. Leander, M. O. Kortelahti, E. F. Zganjar, R. A. Braga, R. W. Fink, C. P. Perez, W. Nazarewicz, and P. B. Semmes
 "Transition Through Triaxial Shapes of the Light Samarium Isotopes and the Beta Decay of $^{136,138,140}\text{Eu}$," *Physical Review C*
- Kobos, A. M., and G. R. Satchler (Invited Paper)
 "An Optical Model Analysis of $^{16}\text{O} + ^{12}\text{C}$ Elastic Scattering at $E/A = 94$ MeV," Proceedings, Supercomputing Symposium '87, Calgary, Alberta, Canada, June 15-16, 1987
- Kortelahti, M., E. F. Zganjar, H. K. Carter, C. D. Papanicolaopoulos, M. A. Grimm, and J. L. Wood
 "Nuclear Systematics Far from the Line of Beta Stability: The Low-Lying Excited States of $^{185,187,189}\text{Au}$," *Journal of Physics G*
- Krause, H. F. (Invited Paper)
 "A Novel High-Resolution Experimental Approach for Studying Laser Photodetachment in a Magnetic Field," Proceedings, Fourth International Symposium on the Production and Neutralization of Negative Ion Beams, Upton, New York, October 27-31, 1986
- Leander, G. A.
 "Statistical E1 and M1 Gamma Strength Functions from Heavy-Ion, xn_γ Data," *Physical Review C*
- Leander, G. A.
 "Simulation of Nuclear Quasicontinuum Gamma-Ray Spectra," *Computer Physics Communications*
- Leander, G. A., P. Arve, and B. Lauritzen
 "Tails of the Rotational Strength Function in the Nuclear Quasicontinuum," *Physical Review C*

- Lee, I. Y., J. A. Martin, J. B. McGrory, W. T. Milner, D. K. Olsen, and G. R. Young
 "Lattice Design of HISTRAP: Heavy Ion Storage Ring for Atomic Physics," Proceedings, 1987 IEEE Particle Accelerator Conference, Washington, D.C., March 16-19, 1987
- Lee, S.-J., A. S. Umar, K.T.R. Davies, M. R. Strayer, and P.-G. Reinhard
 "Enhanced Dissipation in New Mean Field Studies of Strongly Damped Collisions," Physics Letters B
- Levin, J. C., H. Cederquist, C.-S. O, R. T. Short, I. A. Sellin, L. Liljeby, S. Huldt, S.-E. Johansson, E. Nilsson, and D. A. Church
 "Production of Very Cold, Highly Charged Ions by Synchrotron Radiation: Comparisons of the 'Scalpel' and 'Hammer' Methods," Proceedings, U.S.-Japan Cooperative Science Programme, Joint Seminar on Interactions of Highly Ionized Atoms Produced in Heavy Ion Collisions, Kobe, Japan, March 16-20, 1987
- Liu, B., and C. Y. Wong
 "Multiplicity Distribution and Energy Loss in Nucleon-Nucleus Collisions," Physical Review D
- Ma, C. H., and D. P. Hutchinson (Invited Paper)
 "Feasibility Study of an Infrared Interferometer/Polarimeter System for CIT," Proceedings, Third International Symposium on Laser-Aided Plasma Diagnostics, Los Angeles, California, October 28-30, 1987
- Mallory, M. L., P. S. Miller, J. Kuchar, and E. D. Hudson (Invited Paper)
 "Vacuum Measurements of the K500 Cyclotron Accelerator Chamber," Proceedings, Eleventh International Conference on Cyclotrons and Their Applications, Tokyo, Japan, October 13-17, 1986
- Mansfield, D. K., H. K. Park, L. C. Johnson, H. M. Anderson, R. Chouinard, V. S. Foote, and C. H. Ma
 "MIRI: A Multichannel Far-Infrared Laser Interferometer for Electron Density Measurements on TFTR," Applied Optics
- Martin, J. A., D. T. Dowling, D. L. Haynes, E. D. Hudson, C. M. Jones, R. C. Juras, S. M. Lane, C. A. Ludemann, M. J. Meigs, W. T. Milner, S. W. Mosko, D. K. Olsen, and M. F. Ziegler (Invited Paper)
 "Operational Experience for Coupled Operation of the Holifield Tandem Electrostatic Accelerator and Isochronous Cyclotron," Proceedings, Eleventh International Conference on Cyclotrons and Their Applications, Tokyo, Japan, October 13-17, 1986
- Meyer, F. W., D. C. Griffin, C. C. Havener, M. S. Huq, R. A. Phaneuf, J. K. Swenson, and N. Stolterfoht (Invited Paper)
 "Correlation Effects on Double Electron Capture in Highly-Charged, Low-Energy Ion-Atom Collisions," Proceedings, XVth International Conference on the Physics of Electronic and Atomic Collisions, Brighton, England, July 22-28, 1987
- Meyer, F. W., and J. W. Hale
 "Operation of the ORNL ECR Source," Proceedings, 1987 Particle Accelerator Conference, Washington, D.C., March 16-19, 1987
- Nazarewicz, W., G. A. Leander, and S. Tabor (Invited Paper)
 "Octupole Instability in the Heavy Barium Region," Proceedings, XXV Winter School on Nuclear Structure, Zakopane, Poland, 1987
- Nitschke, J. M., P. A. Wilmarth, J. Gilat, P. Moller, and K. S. Toth (Invited Paper)
 "Beta-Delayed Proton Decay in the Lanthanide Region," Proceedings, Fifth International Conference on Nuclei Far from Stability, Rousseau Lake, Ontario, Canada, September 14-19, 1987
- Nitschke, J. M., P. A. Wilmarth, J. Gilat, K. S. Toth, and F. T. Avignone, III
 "Delayed Proton Emission of $N = 81$ Odd-Odd Precursors: ^{148}Ho , ^{150}Tm , and ^{152}Lu ," Physical Review C
- Olsen, D. K., G. D. Alton, S. Datz, P. F. Dittner, D. T. Dowling, D. L. Haynes, E. D. Hudson, J. W. Johnson, I. Y. Lee, R. S. Lord, C. A. Ludemann, J. A. Martin, J. B. McGrory, F. W. Meyer, P. D. Miller, W. T. Milner, S. W. Mosko, P. L. Pepmiller, and G. R. Young
 "The HISTRAP Proposal: Heavy Ion Storage Ring for Atomic Physics," Proceedings, Eleventh Conference on Cyclotrons and Their Applications, Tokyo, Japan, October 13-17, 1986
- Olsen, D. K., K. A. Erb, C. M. Jones, W. T. Milner, and M. F. Ziegler
 "A Novel Method for Measuring Beam Energies by Time-of-Flight," Proceedings, Twentieth Symposium of Northeastern Accelerator Personnel, SNEAP XX, Notre Dame, Indiana, November 3-6, 1986
- Pantell, R. H., J. O. Kephart, R. K. Klein, H. Park, B. L. Berman, and S. Datz
 "The Study of Material Properties Using Channeling Radiation," Proceedings, NATO Advanced Research Workshop on Relativistic Channeling, March 31-April 4, 1986, Maratea, Italy

- Papanicolopoulos, C. D., M. A. Grimm, J. L. Wood, E. F. Zganjar, M. Kortelahti, J. D. Cole, and H. K. Carter
 "Very Converted Transitions and Particle-Core Coupling in Neutron-Deficient Odd-Mass Au Isotopes,"
 Journal of Physics 6
- Pegg, D. J., J. S. Thompson, R. M. Compton, and G. D. Alton
 "Evidence for a Stable Negative Ion of Calcium," Physical Review Letters
- Phaneuf, R. A.
 "Charge Exchange Processes Involving Iron Ions," Proceedings, IAEA Advisory Group Meeting on Atomic
 Data for Fusion Plasma Modelling, Vienna, Austria, September 18-20, 1985
- Pindzola, M. S., D. C. Griffin, and C. Bottcher
 "Theoretical Calculations of Indirect Processes in Electron-Impact Ionization of Atomic Ions,"
 Comments on Atomic and Molecular Physics
- Pindzola, M. S., D. C. Griffin, C. Bottcher, S. M. Younger, and H. T. Hunter
 "Electron-Impact Ionization Data for the Fe Isonuclear Sequence," Proceedings, IAEA Advisory Group
 Meeting on Atomic Data for Fusion Plasma Modelling, Vienna, Austria, September 18-20, 1986
- Plasil, F., R. Albrecht, T. C. Aves, C. Baktash, P. Beckmann, F. Berger, R. Bock, G. Claesson,
 L. Dragon, R. L. Ferguson, A. Franz, S. Garpman, R. Glasow, H. A. Gustafsson, H. H. Gutbrod, J. W.
 Johnson, K. H. Kampert, B. W. Kolb, P. Kristiansson, I. Y. Lee, H. Lohner, 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 Paper)
 "Nucleus-Nucleus Collisions at Relativistic Energies: The CERN NA80 Experiment," Proceedings, 6th
 Adriatic International Conference on Nuclear Physics, "Frontiers of Heavy-Ion Physics," Dubrovnik,
 Yugoslavia, June 15-19, 1987
- Raman, S. (Invited Paper)
 "Selected Topics in Nuclear and Atomic Physics," Proceedings, VIII International School on Nuclear
 Physics, Neutron Physics, and Nuclear Energy, Varna, Bulgaria, October 19-28, 1987
- Raman, S., S. Kahane, and J. E. Lynn (Invited Paper)
 "Direct Thermal Neutron Capture," Proceedings, Sixth International Symposium on Capture Gamma-Ray
 Spectroscopy, Leuven, Belgium, August 31-September 4, 1987
- Raman, S., C. W. Nestor, Jr., and K. H. Bhatt
 "Systematics of $B(E2; 0_1^+ \rightarrow 2_2^+)$ Values for Even-Even Nuclei," Physical Review C
- Raman, S., T. A. Walkiewicz, L. G. Multhaupt, K. G. Tirsell, G. Bonsignori, and K. Allaart
 "Decays of ^{118}In , ^{120}In , and ^{122}In Isomers," Physical Review C
- Reinhard, P. G., M. Rufa, J. Fink, J. Maruhn, H. Stocker, W. Greiner, S. Y. Lee, S. Umar, M. R. Strayer,
 and R. Y. Cusson
 "Relativistic Mean-Field Theories and Nuclear Properties," Proceedings, 18th Mikolajki Summer School
 on Nuclear Physics, Mikolajki, Poland, September
 1-13, 1986
- Reinhard, P. G., A. S. Umar, K.T.R. Davies, M. R. Strayer, and S. J. Lee
 "Dissipation and Forces in TDHF," Physical Review C
- Schuch, R. (Invited Paper)
 "Storage Rings for Investigation of Ion-Atom Collisions," Proceedings, Third Workshop on High Energy
 Ion-Atom Collisions, Debrecen, Hungary, August 3-5, 1987
- Schuch, R. (Invited Paper)
 "Electron Ion Collisions with a Heavy Ion Cooler Ring," Proceedings, Second U.S.-Mexico Atomic
 Physics Symposium on Two-Electron Phenomena, Mexico City, Mexico, January 8-11, 1986
- Schuch, R. (Invited Paper)
 "Heavy Ion Storage Rings," Proceedings, Workshop on Opportunities for Atomic Physics Using Slow,
 Highly-Charged Ions, Argonne, Illinois, January 12-13, 1987, Argonne National Laboratory Report
- Schuch, R., S. Datz, P. F. Dittner, H. F. Krause, and P. D. Miller (Invited Paper)
 "Measurement of Inelasticities for Charge Correlated Multiple Ionization of Ne by Fast C^{6+} Ions,"
 Proceedings, U.S.-Japan Cooperative Science Programme, Joint Seminar on Interactions of Highly
 Ionized Atoms Produced in Heavy Ion Collisions, Kobe, Japan, March 16-20, 1987, Nuclear Instruments
 and Methods in Physics Research

- Schuch, R., H. Schone, P. D. Miller, H. F. Krause, P. F. Dittner, S. Datz, and R. E. Olson
 "Charge and Angular Correlated Inelasticities in Collisions of Bare Fast Carbon Ions with Neon,"
 Physical Review Letters
- Sellin, I. A. (Invited Paper)
 "What Is New in Convoy Electron Physics?," Proceedings, International Seminar on Dynamic Processes of
 Highly Charged Ions, Susono, Japan, August 21-24, 1986
- Sellin, I. A., J. C. Levin, C.-S. O, H. Cederquist, S. B. Elston, R. T. Short, and H. Schmidt-Bocking
 (Invited Paper)
 "Cold Highly Ionized Ions: Comparison of Energies of Recoil Ions Produced by Heavy Ions and by
 Synchrotron Radiation X Rays," Proceedings, Workshop and Symposium on the Physics of Low Energy,
 Stored and Trapped Particles, Stockholm, Sweden, June 14-18, 1987, Physica Scripta
- Semkow, T. M., D. G. Sarantites, K. Honkanen, Z. Li, M. Ross, J. R. Beene, M. L. Halbert, and D. C.
 Hensley
 "Excitation Energy Division in the Quasi-Elastic Region from Reactions of 12 MeV/Nucleon ^{48}Ti with
 ^{150}Nd ," Physical Review C
- Shapira, D., B. Shivakumar, B. A. Harmon, and S. Ayik (Invited Paper)
 "Close Collisions Between Light Nuclei — Orbiting and Fusion," Proceedings, 6th Adriatic
 International Conference on Nuclear Physics, "Frontiers of Heavy-Ion Physics," Dubrovnik, Yugoslavia,
 June 15-19, 1987
- Silk, J. D., H. D. Holmgren, D. L. Hendrie, T.J.M. Symons, G. D. Westfall, P. H. Stelson, S. Raman,
 R. L. Auble, J. R. Wu, and K. Van Bibber
 "Fragmentation of ^{16}O Projectiles at 100 MeV Per Nucleon," Physical Review C
- Snowdon, K. J.
 "Charge Transfer Mechanisms and Predicted Characteristics of the Electron Emission in the Slow
 ($v < v_0$) Multicharged Ion Surface Interaction," Physical Review A
- Snowdon, K. J., C. C. Havener, F. W. Meyer, S. H. Overbury, D. M. Zehner, and W. Heiland
 "Charge Exchange at Molecular Orbital Pseudocrossings as an Important Mechanism for Non-kinetic
 Electron Emission in Slow ($v < v_0$) Multicharged Ion Metal Surface Scattering," Physical Review A
- Snowdon, K. J., C. C. Havener, F. W. Meyer, S. Overbury, D. M. Zehner, and W. Heiland
 "Technique for Determination of the Metastable Fraction of Multicharged Ion Beams," Review of
 Scientific Instruments
- Sobotka, L. G., D. G. Sarantites, Z. Li, E. L. Dines, M. L. Halbert, D. C. Hensley, R. P. Schmitt,
 Z. Majka, G. Nebbia, H. C. Griffin, and A. J. Sierk (Invited Paper)
 "The Angular Momentum Dependence of Complex Fragment Emission," Proceedings, American Chemical
 Society Meeting, Denver, Colorado, April 5-10, 1987, Nuclear Physics A
- Soffield, C. J., L. B. Bridwell, C. D. Moak, P. D. Miller, D. C. Gregory, C. M. Jones, G. D. Alton, P. L.
 Pepmiller, and J. Hall
 "Charge-Exchange Cross Sections for 445 MeV Cl Ions in Solid C Targets," Physical Review A
- Stelson, P. H.
 "Neutron Flow Between Nuclei as the Principal Enhancement Mechanism in Heavy-Ion Subbarrier Fusion,"
 Physics Letters B
- Stolterfoht, M., P. D. Miller, H. F. Krause, Y. Yamazaki, P. F. Dittner, P. L. Pepmiller, I. A. Sellin,
 and S. Datz
 "Production of Autoionizing Rydberg States by Transfer Excitation in High-Energy Ion-Atom
 Collisions," Proceedings, Second United States-Mexico Cooperative Joint Symposium on Atomic and
 Molecular Physics, Mexico City, Mexico, January 5-7, 1986
- Strayer, M. R. (Invited Paper)
 "What Lies Beyond the Mean-Field?," Proceedings, Workshop on Heavy-Ion Reaction Dynamics Studies with
 Large Counter Arrays, Toronto, Canada, March 27, 1987
- Strayer, M. R. (Invited Paper)
 "The Time-Dependent Hartree-Fock Method and Chaos in Nuclear Dynamics," Proceedings, Symposia of the
 American Physical Society Topical Group on Few-Body Systems and Multiparticle Dynamics, Crystal City,
 Virginia, April 20-23, 1987

- Swenson, J. K., N. Stolterfoht, Y. Yamasaki, P. D. Miller, H. Krause, P. F. Dittner, P. L. Pepmiller, and S. Datz
 "Observation of Resonant Transfer and Excitation in $O^{5+} + He$ Collisions through High Resolution O^+ Auger Electron Spectroscopy," Proceedings, Second United States-Mexico Cooperative Joint Symposium on Atomic and Molecular Physics, Mexico City, Mexico, January 5-7, 1986
- Swenson, L. W., X. Y. Chen, J. Lisantti, D. K. McDaniels, I. Bergqvist, F. E. Bertrand, D. J. Horen, E. E. Gross, C. Glover, R. O. Sayer, B. L. Burks, O. Hausser, K. Hicks, and M. J. Iqbal
 "New Continuum Approaches in the Study of Giant Resonances in ^{208}Pb with 400-MeV Protons," Physical Review C
- Teh, K. M., D. Shapira, J. W. McConnell, H. Kim, and R. Novotny
 "Data Acquisition for the HILI Detector," Proceedings, 1987 IEEE Nuclear Science Symposium, San Francisco, California, October 19-23, 1987
- Toth, K. S., Y. A. Ellis-Akovi, H. J. Kim, J. W. McConnell, H. K. Carter, and D. M. Moltz (Invited Paper)
 "Nuclear Structure Effects on α Reduced Widths," Proceedings, Fifth International Conference on Nuclei Far from Stability, Rousseau Lake, Ontario, Canada, September 14-19, 1987
- Toth, K. S., J. M. Nitschke, P. A. Wilmarth, Y. A. Ellis-Akovi, D. C. Sousa, K. Vierinen, D. M. Moltz, J. Gilat, and M. N. Rao
 "Radioactivities with $146 < A < 152$ Investigated at the OASIS Facility: Evidence for ^{147}Tm β -Decay," Proceedings, Fifth International Conference on Nuclei Far from Stability, Rousseau Lake, Ontario, Canada, September 14-19, 1987
- Toth, K. S., D. C. Sousa, J. M. Nitschke, and P. A. Wilmarth
 "Beta Decay Properties of ^{148}Er and ^{148}Ho ," Physical Review C
- Vandenbosch, R., R. C. Connolly, S. Gil, D. D. Leach, T. C. Awes, S. Sorensen, and C. L. Wu
 "Light-Particle Multiplicity Accompanying Projectile Breakup at 20 MeV/A," Physical Review C
- Vourvopoulos, G., D. L. Humphrey, T. Vancleve, D. C. Hensley, and E. E. Gross (Invited Paper)
 "Nuclear Shapes from Heavy Ion Inelastic Scattering," Proceedings, International Conference on Nuclear Shapes, Crete, Greece, June 28-July 4, 1987
- Waggoner, W., C. L. Cocke, L. M. Tunnell, C. C. Havener, F. W. Meyer, and R. A. Phaneuf
 "Angular Distributions for Electron Capture from He by Multiply Charged C, N, O, F, and Ne Ions," Physical Review A
- Weigmann, H., R. Kohler, F. Poortmans, S. Raman, and J. A. Wartena
 "Ground State Partial Radiative Widths of $^{207}Pb + n$ Resonances and M1 and E2 Strengths in ^{208}Pb ," Proceedings, Sixth International Symposium on Capture Gamma-Ray Spectroscopy, Leuven, Belgium, August 31-September 4, 1987
- Wong, C. Y. (Invited Paper)
 "On the Possibility of QED (e^+e^-) Resonances at 1.6-1.8 MeV," Proceedings, International Conference and Symposium on Unified Concepts of Many-Body Problems, Stony Brook, New York, September 4-6, 1986
- Wong, C. Y. (Invited Paper)
 "Theoretical Aspects of High-Energy Heavy-Ion Reactions," Proceedings, 10th INS-Kikuchi Spring School on Quarks and Nuclei, Shimoda, Japan, April 15-18, 1987
- Wong, C. Y. (Invited Paper)
 "Nuclear Stopping Power in High-Energy Collisions," Proceedings, International Symposium on Medium Energy Physics, Beijing, P.R.C., June 23-27, 1987
- Young, G. R. (Invited Paper)
 "A π^0 Spectrometer for Low-Energy Heavy-Ion Reactions," Proceedings, Workshop on Photon and Neutral Meson Physics at Intermediate Energies, Los Alamos, New Mexico, January 8-10, 1987
- Zganjar, E. F., M. O. Kortelahti, J. L. Wood, and C. D. Papanicolaopolous (Invited Paper)
 "Low-Energy E0 Transitions in Odd-Mass Nuclei of the Neutron-Deficient $180 < A < 200$ Region," Proceedings, Fifth International Conference on Nuclei Far from Stability, Rousseau Lake, Ontario, Canada, September 14-19, 1987
- Ziegler, M. F., and R. L. McPherson
 "Charging and Corona Modifications to the ORNL 25 URC Accelerator," Proceedings, Twentieth Symposium of Northeastern Accelerator Personnel, SNEAP XX, Notre Dame, Indiana, November 3-6, 1986

Ziegler, M. F., W. T. Milner, G. D. Mills, M. J. Meigs, R. L. McPherson, R. C. Juras, C. M. Jones, D. E. Hoglund, D. L. Haynes, J. A. Biggerstaff, and G. D. Alton (Invited Paper)
"Status of the ORNL 25 URC Accelerator," Proceedings, Symposium of Northeastern Accelerator Personnel, Notre Dame, Indiana, November 3-6, 1986

Ziegler, M. F., G. K. Schulze, J. W. Rochelle, W. T. Milner, M. J. Meigs, R. L. McPherson, and R. C. Juras
"Recent Electronic Improvements to the Oak Ridge 25 URC Accelerator," Proceedings, Seventh Tandem Conference, Berlin, West Germany, April 6-10, 1987, Nuclear Instruments and Methods in Physics Research

11. PAPERS PRESENTED AT SCIENTIFIC AND TECHNICAL MEETINGS

October 1986 Through September 1987

List Prepared by Shirley J. Ball

1986

Annual Meeting of Interchange Computer User Group, San Diego, California, October 2-11, 1986

W. H. Atkins (Invited Talk)
"Interchange 1986 Advanced OS/32 Tutorial"

American Physical Society Meeting, Vancouver, Canada, October 9-11, 1986

C. Baktash (Invited Talk)
"Evolution of Nuclear Collectivity at High Spins and Temperatures," Bull. Am. Phys. Soc. 31, 1224 (1986)

A. B. Balantekin and B. R. Barrett
"The U(5) Classical Limit of the Neutron-Proton Interacting Boson Model," Bull. Am. Phys. Soc. 31, 1222 (1986)

C. R. Bingham, H. V. Carmichael, V. Janzen, L. L. Riedinger, W. Schmitz, R. A. Braga, R. W. Fink, J. L. Wood, M. Kortelahti, E. F. Zganjar, C. Girit, H. K. Carter, and R. L. Mlekodaj
"Decay of the Low-Spin Isomer of ^{195}Pb ," Bull. Am. Phys. Soc. 31, 1236 (1986)

X. Y. Chen, L. W. Swenson, D. K. McDaniels, J. Lisantti, F. E. Bertrand, D. J. Horen, E. E. Gross, C. Glover, R. Sayer, B. Burks, K. Hicks, and O. Hausser
"Continuum Models for 400-MeV Protons Inelastically Scattered by ^{208}Pb ," Bull. Am. Phys. Soc. 31, 1207 (1986)

Y. A. Ellis-Akova, K. S. Toth, H. K. Carter, R. L. Mlekodaj, I. C. Girit, M. O. Kortelahti, and C. R. Bingham
"Low-Spin States in ^{194}Tl ," Bull. Am. Phys. Soc. 31, 1236 (1986)

M.A.G. Fernandes, B. Shivakumar, D. Shapira, B. A. Harmon, P. H. Stelson, K. Teh, and R. L. Varner
"Orbiting in the $^{30}\text{Si} + ^{12}\text{C}$ Reaction," Bull. Am. Phys. Soc. 31, 1205 (1986)

P. A. Harmon, D. Shapira, P. H. Stelson, B. L. Burks, K. A. Erb, B. Shivakumar, K. Teh, and S. T. Thornton
"Entrance Channel Limitation to the Fusion of Light Nuclei Leading to ^{40}Ca and ^{42}Ca ," Bull. Am. Phys. Soc. 31, 1205 (1986)

D. J. Horen, C. H. Johnson, M. L. Roberts, C. R. Howell, W. Tornow, R. L. Walter, Z. Chen, K. Murphy, H. G. Pfitzner, and P. D. Felsher
"Comparison Between Predictions and Preliminary Data of 7-MeV Analyzing Power for ^{208}Pb ," Bull. Am. Phys. Soc. 31, 1237 (1986)

C. H. Johnson and D. J. Horen
"Dispersion Optical Model Analysis of $^{208}\text{Pb} + n$," Bull. Am. Phys. Soc. 31, 1237 (1986)

D. Krofcheck, E. Sugarbaker, A. Wagner, J. Rapaport, D. Wang, J. N. Bahcall, R. C. Byrd, C. C. Foster, C. D. Goodman, I. J. Van Heerden, W. Huang, C. Gaarde, J. S. Larsen, D. J. Horen, T. Carey, and T. M. Taddeucci
"Measurement of the Gamow-Teller Strength Distribution in ^{81}Kr ," Bull. Am. Phys. Soc. 31, 1214 (1986)

- L. Liljeby, C.-S. O, J. C. Levin, R. T. Short, and I. A. Sellin
"Reduction of Saturation Distortion in Mass Measurements of Light Neutron-Rich Nuclei," *Bull. Am. Phys. Soc.* 31, 1233 (1986)
- J. Lisantti, D. K. McDaniels, L. W. Swenson, X. Y. Chen, F. E. Bertrand, D. J. Horen, E. E. Gross, C. Glover, R. Sayer, B. Burks, O. Hausser, and K. Hicks
"Excitation of Low Lying Collective States in ^{28}Si ," *Bull. Am. Phys. Soc.* 31, 1207 (1986)
- D. K. McDaniels, J. Lisantti, L. W. Swenson, X. Y. Chen, D. J. Horen, F. E. Bertrand, E. E. Gross, C. Glover, R. Sayer, B. L. Burks, O. Hausser, and K. Hicks
"Collective DWBA Analysis for Medium Energy Proton Scattering to Low-Lying States of ^{208}Pb ," *Bull. Am. Phys. Soc.* 31, 1207 (1986)
- J. X. Saladin, O. Dietzsch, C. Y. Chen, I. Y. Lee, C. Baktash, N. Johnson, M. Halbert, and G. Sarantites
"Multipolarity of Continuum Transitions in ^{130}Ce ," *Bull. Am. Phys. Soc.* 31, 1212 (1986)
- G. R. Satchler, M. A. Nagarajan, and I. J. Thompson
"A Barrier-Penetration Model (BPM) for Heavy-Ion Fusion, and the Threshold Anomaly," *Bull. Am. Phys. Soc.* 31, 1216 (1986)
- L. W. Swenson, S. Y. Chen, D. K. McDaniels, J. Lisantti, F. E. Bertrand, E. E. Gross, D. J. Horen, C. Glover, R. Sayer, B. L. Burks, K. Hicks, and O. Hausser
"High Multipole Giant Resonance Strength," *Bull. Am. Phys. Soc.* 31, 1207 (1986)
- K. S. Toth, Y. A. Ellis-Akovi, M. N. Rao, J. M. Nitschke, and P. A. Wilmarth
"Investigation of ^{146}Ho , ^{146}Dy , and ^{146}Tb Decay Properties with Mass-Separated Sources," *Bull. Am. Phys. Soc.* 31, 1213 (1986)
- A. J. Wagner, E. Sugarbaker, D. Krofcheck, L. J. Rybarczyk, C. D. Goodman, R. Byrd, W. Huang, T. N. Taddeucci, T. Carey, J. McClelland, J. Rapaport, D. Horen, H. Sakai, and D. Cisnowski
"Measurement of the $B(\text{GT})/B(\text{F})$ for the Anomalous $^{35}\text{Ar}^+$ Decay Via the (p, n) Reaction," *Bull. Am. Phys. Soc.* 31, 1213 (1986)
- J. L. Wood, C. D. Papanicolaopolos, E. F. Zganjar, and M. Kortelahti
"Coexisting Collective Structure in the Neutron-Deficient Au Isotopes," *Bull. Am. Phys. Soc.* 31, 1236 (1986)

International School of Heavy-Ion Physics, Second Course, Erice, Sicily, October 12-22, 1986

- A. Bracco, J. R. Beene, F. E. Bertrand, M. L. Halbert, R. L. Auble, D. C. Hensley, D. J. Horen, R. L. Robinson, and R. O. Sayer
"Neutron Decay of Giant Resonances in ^{208}Pb "

Eleventh International Conference on Cyclotrons and Their Applications, Tokyo, Japan, October 13-17, 1986

- M. L. Mallory, P. S. Miller, J. Kuchar, and E. D. Hudson (Invited Talk)
"Vacuum Measurements of the K500 Cyclotron Accelerator Chamber"
- J. A. Martin, D. T. Dowling, D. L. Haynes, E. D. Hudson, C. M. Jones, R. C. Juras, S. N. Lane, C. A. Ludemann, M. J. Meigs, W. T. Milner, S. W. Mosko, D. K. Olsen, and N. F. Ziegler (Invited Talk)
"Operational Experience for Coupled Operation of the Holifield Tandem Electrostatic Accelerator and Isochronous Cyclotron"
- D. K. Olsen, G. D. Alton, J. A. Biggerstaff, S. Datz, P. F. Dittner, D. T. Dowling, D. L. Haynes, E. D. Hudson, J. W. Johnson, I. Y. Lee, R. S. Lord, C. A. Ludemann, J. A. Martin, J. B. McGrory, F. W. Meyer, P. D. Miller, W. T. Milner, S. W. Mosko, P. L. Pepmiller, and G. R. Young
"The HISTRAP Proposal: Heavy Ion Storage Ring for Atomic Physics"

13th Annual Stanford Synchrotron Radiation Laboratory (SSRL) Users Group Meeting, Stanford, California, October 23-24, 1986

- R. T. Short, C.-S. O, J. C. Levin, I. A. Sellin, S. Hultdt, L. Liljeby, S.-E. Johansson, E. Nilsson, and D. A. Church
"Measurement of Recoil Energies of Highly Charged Ions Produced by Synchrotron Radiation"

Fourth International Symposium on the Production and Neutralization of Negative Ion Beams, Upton, New York, October 27-31, 1986

- H. F. Krause (Invited Talk)
 "A Novel High-Resolution Experimental Approach for Studying Laser Photodetachment in a Magnetic Field"

Twentieth Symposium of Northeastern Accelerator Personnel, SNEAP XX, Notre Dame, Indiana, November 3-6, 1986

- C. M. Jones, K. A. Erb, D. L. Haynes, J. T. Mitchell, M. F. Ziegler, J. E. Raatz, and R. D. Rathwell
 "Initial Tests of Compressed Geometry Acceleration Tubes in the ORNL 25URC Tandem Accelerator"
- D. K. Olsen, K. A. Erb, C. M. Jones, W. T. Milner, and M. F. Ziegler
 "A Novel Method for Measuring Beam Energies by Time-of-Flight"
- M. F. Ziegler and R. L. McPherson
 "Charging and Corona Modifications to the ORNL 25 URC Accelerator"
- M. F. Ziegler, W. T. Milner, G. D. Mills, M. J. Meigs, R. L. McPherson, R. C. Juras, C. M. Jones, D. E. Hoglund, D. L. Haynes, J. A. Biggerstaff, and G. D. Alton (Invited Talk)
 "Status of the ORNL 25 URC Accelerator"

American Physical Society, Twenty-Eighth Annual Meeting of the Division of Plasma Physics, Baltimore, Maryland, November 3-7, 1986

- C. A. Bennett, D. P. Hutchinson, and R. K. Richards
 "Performance Characteristics of a Heterodyne Infrared Receiver for Alpha-Particle Thomson Scattering," Bull. Am. Phys. Soc. 31, 542 (1986)
- D. P. Hutchinson, R. K. Richards, and K. L. Vander Sluis
 "Alpha Particle Measurement by CO₂ Laser Thomson Scattering," Bull. Am. Phys. Soc. 31, 1541 (1986)
- C. H. Ma and D. P. Hutchinson
 "Feasibility Study of an Infrared System for Plasma Diagnostics on CIT," Bull. Am. Phys. Soc. 31, 1541 (1986)
- H. K. Park, D. K. Mansfield, L. C. Johnson, and C. H. Ma
 "Density Profile Evolution and Faraday Rotation Measurements on TFTR," Bull. Am. Phys. Soc. 31, 1451 (1986)

Third International Workshop on Cross Sections for Fusion and Other Applications, College Station, Texas, November 6-8, 1986

- R. L. Becker (Invited Talk)
 "Role of Projectile $\bar{K}$ -Electrons in Single and Double K -to- $\bar{K}$ Transfer: Comparison of Passive $\bar{K}$ -Electron Models and of the IFPM with Data for $Cl^{17+}, 16+, 14+ + Ti$ "
- G. Gaukler, G. Nolte, and R. Schuch (Invited Talk)
 "Nucleus-nucleus Bremsstrahlung from Scattering Angle Selected $Cl-Sn$ Collisions"
- N. Stolterfoht, C. C. Havener, R. A. Phaneuf, J. K. Swenson, S. M. Shafroth, and F. W. Meyer
 "Correlated Double Electron Capture in Slow, Highly Charged Ion-Atom Collisions"

Ninth Conference on the Application of Accelerators in Research and Industry, Denton, Texas, November 10-12, 1986

- G. D. Alton and J. W. McConnell (Invited Talk)
 "Emittance Studies of Negative Ion Sources Recently Developed at the Oak Ridge National Laboratory," Bull. Am. Phys. Soc. 31, 1277 (1986)
- A. B. Balantekin (Invited Talk)
 "Survey of Theoretical Explanations of Anomalous Positron Peaks Observed in Heavy-Ion Collisions," Bull. Am. Phys. Soc. 31, 1251 (1986)

- R. L. Becker (Invited Talk)
"Calculations of Coincident Ionization Plus Excitation," Bull. Am. Phys. Soc. 31, 1259 (1986)
- J. Burgdorfer (Invited Talk)
"Theory of Electron Capture and Electron Loss to the Continuum," Bull. Am. Phys. Soc. 31, 1334 (1986)
- S. Datz (Invited Talk)
"Atomic Physics Experiments with Stored Cooled Heavy Ion Beams," Bull. Am. Phys. Soc. 31, 1321 (1986)
- S. B. Elston (Invited Talk)
"Measured Multipole Moments of Continuum Electron Transfer Angular Distributions"
- J. Gomez del Campo (Invited Talk)
"Crystal Blocking in Heavy-Ion Reactions," Bull. Am. Phys. Soc. 31, 1275 (1986)
- C. E. Gonzalez Lepera, M. Breinig, J. Burgdorfer, R. DeSerio, S. B. Elston, J. P. Gibbons, H. P. Hulskotter, L. Liljeby, C. R. Vane, and I. A. Sellin (Invited Talk)
"Angular Distributions of Very Low Energy Recoil Ions"
- H. P. Hulskotter (Invited Talk)
"Exit Charge-State Dependence of Convoy Electron Production in Heavy-Ion-Solid Collisions," Bull. Am. Phys. Soc. 31, 1262 (1986)
- T. J. Kvale (Invited Talk)
"Autodetachment Spectroscopy of Metastable Negative Ions," Bull. Am. Phys. Soc. 31, 1316 (1986)
- F. W. Meyer (Invited Talk)
"Evidence for Correlated Double-Electron Capture in Slow Collisions of Multicharged Ions with He," Bull. Am. Phys. Soc. 31, 1252 (1986)
- C.-S. O, L. Liljeby, J. C. Levin, R. T. Short, I. A. Sellin, and A. Dalgarno
"Atmospheric Contaminant Filtering in Time of Flight Analyzers," Bull. Am. Phys. Soc. 31, 1286 (1986)
- D. K. Olsen (Invited Talk)
"HISTRAP: Heavy Ion Storage Ring for Atomic Physics at ORNL," Bull. Am. Phys. Soc. 31, 1322 (1986)
- R. Schuch (Invited Talk)
"Atomic Physics at the Heidelberg Test Storage Ring (TSR)"
- R. T. Short, C.-S. O, J. C. Levin, I. A. Sellin, B. M. Johnson, M. Meron, K. W. Jones, and D. A. Church
"Configuration of Free Molecules and Orientation of Surface Adsorbed Molecules Studied by Synchrotron Radiation Inner Shell Photoionization," Bull. Am. Phys. Soc. 31, 1307 (1986)
- N. Stolterfoht (Invited Talk)
"Surgery of Fast, Highly Charged Ions Studied by Zero-Degree Auger Spectroscopy," Bull. Am. Phys. Soc. 31, 1253 (1986)
- C. R. Vane, M. Smith, S. Raman, J. Heard, and T. A. Walkiewicz (Invited Talk)
"Ion-Induced X-Ray Studies with a High Luminosity von Hamos Crystal Spectrometer"

Alpha Particle Diagnostic Workshop, JET Joint Undertaking, Abingdon, England, December 9-10, 1986

- R. K. Richards, D. P. Hutchinson, and C. A. Bennett (Invited Talk)
"Alpha Particle Measurement by CO₂ Laser Thomson Scattering"

1987

Workshop on Photon and Neutral Meson Physics at Intermediate Energies, Los Alamos, New Mexico, January 8-10, 1987

- G. R. Young (Invited Talk)
"A π^0 Spectrometer for Low-Energy Heavy-Ion Reactions"

Workshop on Opportunities for Atomic Physics Using Slow, Highly-Charged Ions, Argonne, Illinois, January 12-13, 1987

R. Schuch (Invited Talk)
"Heavy Ion Storage Rings"

XV International Workshop on Gross Properties of Nuclei and Nuclear Excitations, Hirschegg, Austria, January 12-17, 1987

H. H. Gutbrod, R. Albrecht, T. C. Aves, C. Baktash, P. Beckmann, F. Berger, R. Bock, G. Claesson, L. Dragon, R. L. Ferguson, A. Franz, S. Garman, R. Glasow, H. A. Gustafsson, J. W. Johnson, K. H. Kampert, B. W. Kolb, P. Kristiansson, I. Y. Lee, H. Lohner, I. Lund, F. E. Obenshain, A. Oskarsson, I. Otterlund, T. Peitzmann, S. Persson, F. Plasil, A. M. Poskanzer, M. Purschke, H. G. Ritter, R. Santo, H. R. Schmidt, T. Siemiarczuk, K. Soderstrom, S. P. Sorensen, E. Stenlund, and G. R. Young (Invited Talk)

"Preliminary Results from Collisions Between 3.2-TeV ^{16}O and Target Nuclei of C, Cu, and Au"

XXV International Winter Meeting on Nuclear Physics, Bormio, Italy, January 19-24, 1987

F. Plasil, R. Albrecht, T. C. Aves, C. Baktash, P. Beckmann, F. Berger, R. Bock, G. Claesson, L. Dragon, R. L. Ferguson, A. Franz, S. Garman, R. Glasow, H. A. Gustafsson, H. H. Gutbrod, J. W. Johnson, K. H. Kampert, B. W. Kolb, P. Kristiansson, I. Y. Lee, H. Lohner, 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, K. Soderstrom, S. P. Sorensen, E. Stenlund, and G. R. Young (Invited Talk)

"Preliminary Results from Collisions Between 3.2-TeV ^{16}O and Target Nuclei of C, Cu, and Au"

XXV Winter School on Nuclear Structure, Zakopane, Poland, 1987

W. Nazarewicz, G. A. Leander, and S. Tabor (Invited Talk)
"Octupole Stability in the Heavy Barium Region"

1987 IEEE Particle Accelerator Conference, Gaithersburg, Maryland, March 16-19, 1987

I. Y. Lee, J. B. McGrory, and G. R. Young
"Lattice Design of HISTRAP," Bull. Am. Phys. Soc. 32, 165 (1987)

F. W. Meyer and J. Hale
"Operation of the ORNL ECR Source," Bull. Am. Phys. Soc. 32, 165 (1987)

U.S.-Japan Cooperative Science Programme, Joint Seminar on Interactions of Highly Ionized Atoms Produced in Heavy Ion Collisions, Kobe, Japan, March 16-20, 1987

S. Datz, R. Hippler, L. H. Andersen, P. F. Dittner, H. Knudsen, H. F. Krause, P. D. Miller, P. L. Pepmiller, N. Stolterfont, and Y. Yamazaki (Invited Talk)
"Electron Pair Transfer and Ionization in Multicharged Ion Collisions with Helium"

J. C. Levin, H. Cederquist, C.-S. O, R. T. Short, I. A. Sellin, L. Liljeby, S. Hultdt, S.-E. Johansson, E. Nilsson, and D. A. Church
"Production of Very Cold, Highly Charged Ions by Synchrotron Radiation: Comparisons of the 'Scalpel' and 'Hammer' Methods"

R. Schuch, S. Datz, P. F. Dittner, H. F. Krause, and P. D. Miller (Invited Talk)
"Measurement of Inelasticities for Charge Correlated Multiple Ionization of Ne by Fast C^{6+} Ions"

Workshop on the Collective Properties of Mid-Mass Nuclei, Tallahassee, Florida, March 19-20, 1987

S. Raman (Invited Talk)
"Global Set of β_2 Values for Even-Even Nuclei"

Workshop on Heavy-Ion Reaction Dynamics Studies with Large Counter Arrays, Toronto, Canada, March 27, 1987

M. R. Strayer (Invited Talk)
"What Lies Beyond the Mean-Field?"

American Chemical Society Symposium on Nuclear Detectors for Nuclear and Radiochemistry, Denver, Colorado, April 5-10, 1987

D. Shapira, H. J. Kim, B. Burks, J. Blankenship, R. Varner, K. Teh, and R. Novotny (Invited Talk)
"HILI - A Heavy Ion-Light Ion Detection System"

L. G. Sobotka, D. G. Sarantites, Z. Li, E. L. Dines, M. L. Halbert, D. C. Hensley, R. P. Schmitt, Z. Majka, G. Nebbia, H. C. Griffin, and A. J. Sierk (Invited Talk)
"The Angular Momentum Dependence of Complex Fragment Emission"

Seventh Tandem Conference, Berlin, West Germany, April 6-10, 1987

G. D. Alton and J. W. McConnell
"The Emittance of High-Intensity Negative-Ion Sources Operated in the Pulsed Mode"

C. M. Jones, G. D. Alton, J. B. Ball, J. A. Biggerstaff, D. T. Dowling, K. A. Erb, D. L. Haynes, D. E. Hoglund, E. D. Hudson, R. C. Juras, S. M. Lane, C. A. Ludemann, J. A. Martin, M. J. Meigs, S. W. Mosko, D. K. Olsen, and M. F. Ziegler
"The Holifield Heavy Ion Research Facility"

C. M. Jones, K. A. Erb, D. L. Haynes, J. T. Mitchell, M. F. Ziegler, J. E. Raatz, and R. D. Rathmell
"Tests of Compressed Geometry Acceleration Tubes in the Oak Ridge 25 URC Tandem Accelerator"

R. C. Juras, M. F. Ziegler, M. J. Meigs, R. L. McPherson, D. E. Hoglund, J. A. Biggerstaff
"Evolution and Development of the Oak Ridge 25 URC Tandem Accelerator Control System"

M. F. Ziegler, M. J. Meigs, and R. C. Juras
"Recent Electronic Improvements to the Oak Ridge 25 URC Accelerator"

10th INS-Kikuchi Spring School on Quarks and Nuclei, Shimoda, Japan, April 15-18, 1987

C. Y. Wong (Invited Talk)
"Theoretical Aspects of High-Energy Heavy-Ion Reactions"

American Physical Society Meeting, Crystal City, Virginia, April 20-23, 1987

T. C. Awes, C. Baktash, R. P. Cumby, R. L. Ferguson, A. Franz, E. E. Gross, H.-A. Gustafsson, J. W. Johnson, P. Kristiansson, I. Y. Lee, F. E. Obenshain, A. Oskarsson, I. Otterlund, F. Plasil, S. Persson, A. M. Poskanzer, H.-G. Ritter, S. P. Sorensen, and G. R. Young
"Performance of the Pb/Fe/Scintillator Sampling Calorimeters for the CERN WA80 Experiment," Bull. Am. Phys. Soc. 32, 1031 (1987)

T. C. Awes, R. L. Ferguson, F. E. Obenshain, F. Plasil, G. R. Young, Z. Chen, C. K. Gelbke, W. G. Lynch, J. Pochodzalla, and H. M. Xu
"Light-Particle Correlations in ^{32}S -Induced Reactions at 22 MeV/Nucleon," Bull. Am. Phys. Soc. 32, 1078 (1987)

C. W. Beausang, D. B. Fossan, R. Ma, E. S. Paul, W. F. Piel, Jr., M. Xu, L. Hildingsson, and G. A. Leander
"Collective Bands in γ -Soft ^{131}La ," Bull. Am. Phys. Soc. 32, 1095 (1987)

Y. A. Ellis-Akovali, M. N. Rao, K. S. Toth, A. L. Goodman, J. M. Nitschke, and P. A. Wilmarth
"Beta Decays of ^{151}Yb , ^{151}Tm , and ^{149}Ho ; Systematics of Neutron States in $N = 83$ Nuclei," Bull. Am. Phys. Soc. 32, 1018 (1987)

C. H. Johnson, D. J. Moren, and C. Mahaux
"Predictions of Neutron Single-Particle Energies for ^{208}Pb from Dispersion Relation Analyses $^{208}\text{Pb} + n$ Scattering," Bull. Am. Phys. Soc. 32, 1111 (1987)

C. M. Knott, H. Takai, D. F. Winchell, J. X. Saladin, M. S. Kaplan, L. B. de Faro, I. Y. Lee, R. Aryaeinejad, R. Blue, D. J. Morrissey, and R. Ronningen
"High Spin Spectroscopy of Decay Products from the Reaction $^{27}\text{Ne} + ^{170}\text{Er}$ at 220 MeV," Bull. Am. Phys. Soc. 32, 1111 (1987)

V. E. Oberacker, A. S. Umar, M. R. Strayer, and C. E. Bottcher
"Theory of Lepton Production in Relativistic Heavy-Ion Collisions," Bull. Am. Phys. Soc. 32, 1015 (1987)

- G. R. Satchler (Invited Talk)
 "Heavy-Ion Fusion and the Threshold Anomaly for Heavy-Ion Elastic Scattering," Bull. Am. Phys. Soc. 32, 1054 (1987)
- T. M. Semkow, D. G. Sarantites, K. Honkanen, Z. Li, M. Ross, J. R. Beene, M. L. Halbert, and D. C. Hensley
 Excitation Energy Division in the Quasielastic Region from Reactions of 12 MeV/Nucleon ^{48}Ti with ^{150}Nd ," Bull. Am. Phys. Soc. 32, 1108 (1987)
- M. R. Strayer (Invited Talk)
 "The Time-Dependent Hartree-Fock Method and Chaos in Nuclear Dynamics," Bull. Am. Phys. Soc. 32, 1026 (1987)
- H. Takai, D. F. Winchell, C. N. Knott, J. X. Saladin, M. S. Kaplan, L. B. de Faro, I. Y. Lee, R. Aryaeinejad, R. Blue, D. J. Morrissey, and R. Ronningen
 "Population of High Spin States by Quasi-Elastic and Deep-Inelastic Collisions," Bull. Am. Phys. Soc. 32, 1108 (1987)
- F. Videbaek, S. B. Kaufman, B. K. Dichter, H. C. Britt, A. Gavron, B. Jacak, J. Wilhelmy, J. Boissevain, M. Fowler, O. Hansen, M. J. Levine, C. E. Thorn, R. Ferguson, G. Westfall, W. Trautman, G. Mamane, and Z. Fraenkel
 "Heavy Fragment Emission in 100 MeV/Nucleon $^{56}\text{Fe} + ^{197}\text{Au}$," Bull. Am. Phys. Soc. 32, 1108 (1987)
- G. R. Young, T. C. Awes, C. Baktash, R. P. Cumby, R. L. Ferguson, E. E. Gross, J. W. Johnson, I. Y. Lee, F. E. Obenshain, F. Plasil, and S. P. Sorensen
 "Performance of a Uranium/Scintillator Sampling Calorimeter for the CERN WA80 Experiment," Bull. Am. Phys. Soc. 32, 1033 (1987)
- G. R. Young, T. C. Awes, R. L. Ferguson, F. E. Obenshain, F. Plasil, K. Smith, N. Alamanos, P. Braun-Munzinger, J. Stachel, and L. Waters
 "Emission of Photons with $E_\gamma > 45$ MeV in Heavy-Ion Collisions of $E/A < 25$ MeV," Bull. Am. Phys. Soc. 32, 1109 (1987)
- XI International Conference on Particles and Nuclei, Kyoto, Japan, April 20-24, 1987
- C. Y. Wong, H. Crater, R. L. Becker, and P. van Alstine
 "Study of QED (e^+e^-) Resonance with Relativistic Constraint Dynamics"
- Fourth International Symposium on Accelerator Mass Spectrometry, Niagara-on-the-Lake, Ontario, Canada, April 27-30, 1987
- H. J. Hofmann, J. Beer, G. Bonani, H. R. von Gunten, S. Raman, M. Suter, R. L. Walker, W. Wolfli, and D. Zimmerman
 "Beryllium-10: Half-Life and AMS Standards"
- K.G.W. Inn, S. Raman, B. M. Coursey, J. D. Fassett, and R. L. Walker
 "Development of the $^{10}\text{Be}/^9\text{Be}$ Isotopic NBS Standards Reference Material"
- American Physical Society, Annual Meeting of the Division of Atomic, Molecular, and Optical Physics, Cambridge, Massachusetts, May 18-20, 1987
- R. L. Becker
 "Role of Projectile $\bar{\kappa}$ -Electrons in K-to- $\bar{\kappa}$ Transfer: Comparison of Passive and Active $\bar{\kappa}$ Models with Data for $\text{Cl}^{19+} + \text{Ti}$," Bull. Am. Phys. Soc. 32, 1225 (1987)
- C. Bottcher and M. R. Strayer
 "Lepton Pair Production in Relativistic Heavy Ion Colliders," Bull. Am. Phys. Soc. 32, 1240 (1987)
- M. Breinig, R. DeSerio, H. P. Hulskotter, and Y. Yamazaki
 "Coincidence Experiments Concerning the Convoy-Electron Yield as a Function of Target Thickness," Bull. Am. Phys. Soc. 32, 1243 (1987)
- J. Burgdorfer and C. Bottcher
 "Stochastic Perturbations of Coulomb Orbits," Bull. Am. Phys. Soc. 32, 1262 (1987)

- S. Datz (Invited Talk)
 "Electron Capture, Ionization, and Transfer Ionization in Fast (0.1-1.0 E/A MeV) Highly Charged Ion Collisions with Helium," Bull. Am. Phys. Soc. 32, 1260 (1987)
- J. B. Elston, C. E. Gonzalez Lepera, J. P. Gibbons, M. Breinig, R. DeSerio, O. Heil, H. P. Hulskotter, I. A. Sellin, and C. R. Vane
 "Target Thickness Dependence of Doubly Differential Convoy Electron Emission Velocity Distributions," Bull. Am. Phys. Soc. 32, 1243 (1987)
- C. E. Gonzalez Lepera, M. Breinig, H. Cederquist, R. DeSerio, S. B. Elston, J. P. Gibbons, H. P. Hulskotter, L. Liljeby, C. R. Vane, and I. A. Sellin
 "Backward Scattering of Recoil Ions Produced in Swift Ion-Atom Collisions," Bull. Am. Phys. Soc. 32, 1250 (1987)
- H. Gould, M. Claytor, B. Feinberg, C. E. Bemis, Jr., J. Gomez del Campo, C. A. Ludeman, and C. R. Vane
 "Channeling of Relativistic Uranium," Bull. Am. Phys. Soc. 32, 1244 (1987)
- C. C. Havener, M. S. Huq, and R. A. Phaneuf
 "Low-Energy Electron Capture Cross Sections for $O^{5+} + H$ and $N^{5+} + H$ Using Merged Beams," Bull. Am. Phys. Soc. 32, 1226 (1987)
- L. D. Hendrick, D. M. Peterson, J. M. Anthony, J. K. Swenson, M. Benhenni, S. M. Shafroth, and T. Zorou
 "Projectile Electron Spectra Arising from Decay of 3 and 4 Electron States in C^{2+} and C^{3+} at 9.6, 20, 30, 40° for 5 MeV C^{2+} on Ne," Bull. Am. Phys. Soc. 32, 1250 (1987)
- J. C. Levin, C.-S. O, R. T. Short, H. Cederquist, S. B. Elston, J. P. Gibbons, I. A. Sellin, and H. Schmidt-Bocking
 "Recoil Ion Energy Dependence on Coincident Projectile Electron Transfer in Fast Ion-Atom Collisions," Bull. Am. Phys. Soc. 32, 1250 (1987)
- F. W. Meyer, C. C. Havener, R. A. Phaneuf, J. K. Swenson, M. Stolterfoht, and S. M. Shafroth
 "Electron Correlation Effects in Slow, Double-Electron Capture Collisions Involving Multicharged Ions," Bull. Am. Phys. Soc. 32, 1222 (1987)
- P. D. Miller, R. Hippler, S. Datz, P. F. Dittner, H. F. Krause, and P. L. Pepmiller
 "Partial Cross Sections for Capture to Specific n States in Collisions of 0.1 and 0.25 MeV/Nucleon 19^+ Ions with H_2 ," Bull. Am. Phys. Soc. 32, 1243 (1987)
- R. Schuch, S. Datz, P. F. Dittner, H. F. Krause, P. D. Miller, and H. Schone
 "Measurements of Q Values and Angular Distributions for Multiply Ionizing Collisions of 10-MeV C on Ne, Ar," Bull. Am. Phys. Soc. 32, 1222 (1987)
- S. M. Shafroth, M. Benhenni, J. M. Anthony, D. M. Peterson, L. D. Hendrick, and J. K. Swenson
 "K-Auger Decay of Double Excited He-Like C^{4+} Arising from 5 MeV C^{5+} on He and Ne," Bull. Am. Phys. Soc. 32, 1242 (1987)
- J. K. Swenson, C. C. Havener, M. S. Huq, F. W. Meyer, R. A. Phaneuf, and M. Stolterfoht
 "Electron Correlation Effects in Slow, Double-Electron Capture Collisions Involving Multicharged Ions"
- L. J. Wang, K. Rinn, and D. C. Gregory
 "Electron-Impact Ionization Cross Section Measurements for Ni^{5+} , Ni^{6+} , and Ni^{7+} ," Bull. Am. Phys. Soc. 32, 1273 (1987)

Second Workshop on Experiments and Detectors for RHIC, Berkeley, California, May 25-29, 1987

- C. Bottcher and M. R. Strayer (Invited Talk)
 "Pulsed Electromagnetic Production of Leptons"

Eleventh Symposium on Ion Sources and Ion-Assisted Technology, Tokyo, Japan, June 1-3, 1987

- G. D. Alton (Invited Talk)
 "The Emittance and Brightness Characteristics of Negative Ion Sources Suitable for MeV Ion Implantation"

Workshop and Symposium on the Physics of Low Energy, Stored and Trapped Particles, Stockholm, Sweden, June 14-18, 1987

P. F. Dittner (Invited Talk)

"Dielectronic Recombination Measurements of Multicharged Ions"

I. A. Sellin, J. C. Levin, C.-S. O, H. Cederquist, S. B. Elston, R. T. Short, and H. Schmidt-Bocking (Invited Talk)

"Cold Highly Ionized Ions: Comparison of Energies of Recoil Ions Produced by Heavy Ions and by Synchrotron Radiation X Rays"

Supercomputing Symposium '87, Calgary, Alberta, Canada, June 15-16, 1987

A. M. Kobos and G. R. Satchler (Invited Talk)

"An Optical Model Analysis of $^{16}\text{O} + ^{12}\text{C}$ Elastic Scattering at $E/A = 94$ MeV"

6th Adriatic International Conference on Nuclear Physics, "Frontiers of Heavy-Ion Physics," Dubrovnik, Yugoslavia, June 15-19, 1987

C. Bottcher and M. R. Strayer (Invited Talk)

"Lepton Production in Ultra-Relativistic Ion-Ion Collisions"

M. L. Halbert, J. R. Beene, D. C. Hensley, K. Honkanen, T. M. Semkow, V. Abenante, D. G. Sarantites, and Z. Li (Invited Talk)

"Angular Momentum Effects in Subbarrier Fusion"

F. Plasil, R. Albrecht, T. C. Aves, C. Baktash, P. Beckmann, F. Berger, R. Bock, G. Claesson, L. Dragon, R. L. Ferguson, A. Franz, S. Garpman, R. Glasow, H. A. Gustafsson, H. H. Gutbrod, J. W. Johnson, K. H. Kampert, B. W. Kolb, P. Kristiansson, I. Y. Lee, H. Lohner, 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 (Invited Talk)

"Nucleus-Nucleus Collisions at Relativistic Energies: The CERN WA80 Experiment"

D. Shapira, B. Shivakumar, B. A. Harmon, and S. Ayik (Invited Talk)

"Close Collisions Between Light Nuclei — Orbiting and Fusion"

International Symposium on Medium Energy Physics, Beijing, P.R.C., June 23-27, 1987

C. Y. Wong (Invited Talk)

"Nuclear Stopping Power in High-Energy Collisions"

International Conference on Nuclear Shapes, Crete, Greece, June 28-July 4, 1987

C. Baktash, Y. Schutz, I. Y. Lee, F. K. McGowan, M. R. Johnson, M. L. Halbert, D. C. Hensley, L. Courtney, A. J. Larabee, L. L. Riedinger, Y. S. Chen, and D. G. Sarantites

"Energetic M1 Transitions as a Probe of Nuclear Shape at High Temperatures"

J. Dudek (Invited Talk)

"Superdeformed Nuclei. Shells-vs.-Liquid Drop, Pairing-vs.-Thermal Excitations, Triaxial-vs.-Octupole Shapes, Super-Superdeformation"

L. Hildingsson, E. S. Paul, C. W. Beausang, D. B. Fossan, R. Ma, W. F. Piel, M. Xu, and G. A. Leander

"Collective Oblate Band in ^{131}La "

G. Vourvopoulos, D. L. Humphrey, T. VanCleve, D. C. Hensley, and E. E. Gross (Invited Talk)

"Nuclear Shapes from Heavy Ion Inelastic Scattering"

IAEA Specialists' Meeting on Atomic and Molecular Data for Plasma Edge Studies, Vienna, Austria, July 8-10, 1987

R. A. Phaneuf, M. T. Hunter, and C. F. Barnett

"Heavy-Particle Collisions in the Plasma Edge"

XVth International Conference on the Physics of Electronic and Atomic Collisions, Brighton, England, July 22-28, 1987

- R. L. Becker, C. Y. Wong, H. W. Crater, and P. Van Aistine
"Study of the Possibility of e^+e^- Magnetic Resonances with Two-Body Dirac Equations from Constraint Dynamics"
- M. Breinig, H.-P. Hulskotter, and T. Underwood
"Coincident Detection of Two Highly Excited/Ionized Electrons in Fast Ion Atom/Solid Collisions"
- J. Burgdorfer and C. Bottcher
"Production of High-Angular Momentum Rydberg and Continuum States by Stochastic Collisions"
- S. Datz, R. Hippler, L. H. Andersen, P. F. Dittner, H. Knudsen, H. F. Krause, P. D. Miller, P. L. Pepmiller, T. Rosseel, and M. Stolterfoht
"Electron Capture, Ionization, and Transfer Ionization in Rapid (0.1-1.0 MeV/Nucleon) Highly Charged Ion Collisions with Helium"
- S. B. Elston, C. E. Gonzalez Lepera, J. P. Gibbons, M. Breinig, R. DeSerio, O. Heil, H. P. Hulskotter, I. A. Sellin, and C. R. Vane
"Doubly Differential Convoy Electron Emission Distributions in High Velocity Ion-Solid Collisions: Target Thickness Dependence"
- C. E. Gonzalez Lepera, M. Breinig, H. Cederquist, R. DeSerio, S. B. Elston, J. P. Gibbons, H. P. Hulskotter, L. Liljeby, C. R. Vane, and I. A. Sellin
"Forward and Backward Scattering of Recoil Ions Produced in Swift Ion-Atom Collisions"
- C. C. Havener, M. S. Huq, and R. A. Phaneuf
"Merged-Beams Measurements of Electron-Capture Cross Sections for $O^{5+} + H$ and $N^{5+} + H$ Collisions at eV Energies"
- F. W. Meyer, D. C. Griffin, C. C. Havener, M. S. Huq, R. A. Phaneuf, J. K. Swenson, and M. Stolterfoht (Invited Talk)
"Correlation Effects on Double Electron Capture in Highly-Charged, Low-Energy Ion-Atom Collisions"
- F. W. Meyer, C. C. Havener, W. Heiland, S. H. Overbury, K. J. Snowden, and D. M. Zehner
"Electron Emission in Collisions of Highly Charged Ions with Au and Cu Surfaces"
- P. D. Miller, R. Hippler, S. Datz, P. F. Dittner, H. F. Krause, and P. L. Pepmiller
"Partial Cross Sections for Capture to Specific n States in Collisions of 0.1 and 0.25 MeV/Nucleon $19F^+$ Ions with H_2 "
- C. S. O, J. C. Levin, R. T. Short, H. Cederquist, S. B. Elston, J. P. Gibbons, I. A. Sellin, H. Schmidt-Bocking
"Observation of Steep Variation of Recoil-Ion Energy on Scattered Ion Charge State in Coincident Multielectron Projectile and Target Ionization Events"
- D. J. Pegg, J. S. Thompson, T. J. Kvale, G. D. Alton, R. N. Compton, and T. G. Heil
"Autodetachment of He_2^- and the He-He Ground State Potential"
- R. Schuch, S. Datz, P. F. Dittner, H. F. Krause, P. D. Miller, and H. Schone
"Inelasticity and Angular Distributions for Charge Correlated Multiple Ionization of Ne and Ar by C Ions"
- C. J. Sofield, P. M. Read, L. B. Bridwell, P. L. Pepmiller, G. D. Alton, D. C. Gregory, and P. D. Miller
"Ionization of H, He, and Li-Like 1 GeV Ni Ions in Solid C Targets"
- M. Waggoner, C. L. Cocke, L. M. Tunnell, C. C. Havener, F. W. Meyer, R. A. Phaneuf
"Angular Distributions for Electron Capture from He by Multiply Charged C, N, O, F, and Ne Ions"
- L. J. Wang, K. Rinn, and D. C. Gregory
"Cross Section Measurements for Electron-Impact Ionization of Ni^{5+} , Ni^{6+} , Ni^{7+} , and Ni^{8+} "

Xth International Symposium on Ion-Atom Collisions, Bad Soden, West Germany, July 30-31, 1987

- R. L. Becker (Invited Talk)
"Pauli Correlations in Energetic Ion-Atom Collisions"

F. D. McDaniel, M. C. Andrews, J. L. Duggan, P. D. Miller, P. L. Pepmiller, H. F. Krause, T. M. Rosseel, L. A. Rayburn, R. Mehta, and G. Lapicki

"L- and M-Shell Direct Ionization and Electron Capture for Highly Charged Carbon and Oxygen Ions"

F. W. Meyer, D. C. Griffin, C. C. Havener, M. S. Huq, R. A. Phaneuf, J. K. Swenson, and M. Sto'terfoht
"Electron Correlation Effects in Slow, Double-Electron Capture Collisions Involving Multicharged Ions"

Atomic Collisions in Fusion, Oxford, England, July 30-August 1, 1987

C. C. Havener, M. S. Huq, and R. A. Phaneuf

"Electron Capture Cross Sections for $O^{6+} + H$ and $N^{5+} + H$ at eV Energies Using Merged Beams"

Third Workshop on High-Energy Ion-Atom Collision Processes, Debrecen, Hungary, August 3-5, 1987

R. L. Becker (Invited Talk)

"Several Manifestations of Pauli Correlations in Energetic Ion-Atom Collisions"

R. Schuch (Invited Talk)

"Storage Rings for Investigation of Ion-Atom Collisions"

International Conference on Spectroscopy and Structure of Highly Ionized Atoms, Lisle, Illinois, August 17-21, 1987

C. Bottcher and M. R. Strayer (Invited Talk)

"Probing the Vacuum with Highly Charged Ions"

International Conference on Nuclear Structure Through Static and Dynamic Moments, Melbourne, Australia, August 25-28, 1987

M. Johnson (Invited Talk)

"Nuclear Collectivity at High Spins Determined from Lifetime Measurements"

K. S. Krane, H. K. Carter, M. L. Simpson, J. H. Hamilton, and C. Girit

"The UNISOR On-Line Nuclear Orientation Facility"

K. S. Toth, Y. A. Ellis-Akovi, H. J. Kim, J. W. McConnell, and H. K. Carter

"Alpha-Decay Rates and Nuclear Shapes"

Sixth International Symposium on Capture Gamma-Ray Spectroscopy, Leuven, Belgium, August 31-September 4, 1987

S. Raman, S. Kahane, and J. E. Lynn (Invited Talk)

"Direct Thermal Neutron Capture"

H. Weigmann, R. Kohler, F. Poortmans, S. Raman, and J. A. Wartena

"Ground State Partial Radiative Widths of $^{207}Pb + n$ Resonances and M1 and E2 Strengths in ^{208}Pb "

Conference on Interactions and Structures of Nuclei, Brighton, England, September 7-9, 1987

Y. A. Ellis-Akovi, K. S. Toth, J. M. Nitschke, and P. A. Wilmarth

"Particle Decay Studies at or near Closed Shells"

14th International Conference on X-Ray and Inner-Shell Processes, Paris, France, September 14-18, 1987

J. Kemmler, O. Heil, C. Biedermann, P. Koschar, H. Rothard, K. Kroneberger, K. O. Groeneveld, and I. A. Sellin

"Convoy Electrons in Coincidence with Outgoing Charge States of Ni (920 MeV)"

Fifth International Conference on Nuclei Far from Stability, Rousseau Lake, Ontario, Canada, September 14-19, 1987

I. C. Girit, K. S. Krane, J. H. Hamilton, D. Olive, E. F. Zganjar, J. D. Cole, B. D. Kern, H. K. Carter, M. L. Simpson, C. R. Bingham, G. D. Alton, D. Dowling, C. A. Reed, and W. B. Newbolt
 "On-Line Nuclear Orientation Facility at UNISOR"

B. D. Kern, G. A. Leander, R. L. Mlekodaj, H. K. Carter, M. O. Kortelahti, E. F. Zganjar, R. A. Braga, R. W. Fink, C. P. Perez, P. B. Semmes, and W. Nazarewicz
 "Energy Levels and Structure of Light Rare-Earth Nuclei, $^{136,138,140}\text{Sm}$ and $^{132,134,136}\text{Nd}$, via Beta Decay"

R. L. Mlekodaj, G. A. Leander, H. K. Carter, M. O. Kortelahti, E. F. Zganjar, B. D. Kern, R. A. Braga, R. W. Fink, C. P. Perez, P. B. Semmes, and W. Nazarewicz
 "Energy Levels and Structure of Light Rare-Earth Nuclei via Beta Decay: $^{136,138,140}\text{Sm}$ and $^{132,134,136}\text{Nd}$ "

J. M. Nitschke, P. A. Wilmarth, J. Gilat, P. Moller, and K. S. Toth (Invited Talk)
 "Beta-Delayed Proton Decay in the Lanthanide Region"

C. D. Papanicolopoulos, J. L. Wood, M. Kortelahti, E. F. Zganjar, and H. K. Carter
 "Odd-Mass Core Shape Isomerism: A Strongly-Coupled Positive Parity Band in ^{185}Au "

K. S. Toth, Y. A. Ellis-Akovali, H. J. Kim, J. W. McConnell, H. K. Carter, and D. M. Moltz (Invited Talk)
 "Nuclear Structure Effects on α Reduced Widths"

K. S. Toth, J. M. Nitschke, P. A. Wilmarth, Y. A. Ellis-Akovali, J. Gilat, D. M. Moltz, M. N. Rao, D. C. Sousa, and K. Vierinen
 "Radioactivities with $146 < A < 152$ Investigated at the OASIS Facility"

K. S. Toth, J. M. Nitschke, P. A. Wilmarth, Y. A. Ellis-Akovali, and K. Vierinen
 "Decomposition of the ^{147}Er β -Delayed-Proton Spectrum"

E. F. Zganjar, M. Kortelahti, J. L. Wood, and C. D. Papanicolopoulos (Invited Talk)
 "Low-Energy E0 Transitions in Odd-Mass Nuclei of the Neutron-Deficient $180 < A < 200$ Region"

X. Zhao, A. V. Ramayya, J. H. Hamilton, C. F. Maguire, W.-C. Ma, J. Kormicki, S. Wen, L. Chaturvedi, Z.-M. Chen, T. M. Cormier, J. D. Cole, R. B. Piercey, M. A. Herath-Banda, E. F. Zganjar, M. O. Kortelahti, G. Leander, J. Eberth, M. Schmal, T. Heck, L. Cleeman, T. Mylaeus, W. Neumann, M. Tölle, and M. Włosna
 "Oblate and Prolate Bands in ^{71}Se "

XXI Symposium of Northeastern Accelerator Personnel, Tallahassee, Florida, September 28-October 1, 1987

P. L. Pepmiller
 "The ORNL EN Tandem"

6th APS Topical Conference on Atomic Processes in High-Temperature Plasmas, Santa Fe, New Mexico, September 28-October 2, 1987

D. C. Gregory (Invited Talk)
 "Electron-Impact Ionization Cross Section Measurements for Highly Charged Fe and Ni Ions"

R. A. Phaneuf, H. T. Hunter, M. I. Kirkpatrick, and C. F. Barnett
 "Atomic Collision Data Compilations for High-Temperature Plasmas"

12. GENERAL INFORMATION

PERSONNEL CHANGES

New Staff Members

A. Administrative and Technical Staff

O. J. McBride, Secretary (transferred from Fuel Recycle Division)

Staff Transfers and Terminations

A. Scientific Staff

B. L. Burks (transferred to Engineering Physics and Mathematics Division)

K. A. Erb (present address: National Science Foundation, Washington, D.C.)

B. A. Harmon (completion of temporary, part-time assignment)

E. D. Hudson (retirement)

B. Administrative and Technical Staff

S. L. Birch, Accelerator Operations (transferred to Engineering Technology Division)

R. P. Cumby, Engineering Technologist (retirement)

TEMPORARY ASSIGNMENTS

Short-Term Assignments

Scientific Staff

Z. Lu, Institute of Atomic Energy, Beijing, People's Republic of China

R. Wang, University of Science and Technology of China, Hefei, Anhui, People's Republic of China

Guest Assignments

A. Joint Institute for Heavy Ion Research

M. Beckerman, Joint Institute for Heavy Ion Research, Oak Ridge, Tennessee

J.-L. Charvet, Centre d'Etudes de Bruyeres-le-Chatel, Bruyeres-le-Chatel, France

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

M. Cindro, Ruder Boskovic Institute, Croatia, Yugoslavia

R. Donangelo, Institute de Fisica-UFRJ, Rio de Janeiro-RJ, Brazil

F. E. Donau, Zentralinstitut fur Kernforschung, Dresden, East Germany

A. D'Onofrio, National Institute of Nuclear Physics, Naples, Italy

J. Dudek, Centre de Recherches Nucleaires, Strasbourg, France

A. Faessler, Institut fur Theoretische Physik, University of Tübingen, Tübingen, West Germany

J. S. Forster, Atomic Energy of Canada Ltd., Chalk River, Ontario, Canada

I. C. Girit, Hacettepe University, Beytepe - Ankara, Turkey

J. J. Griffin, University of Maryland, College Park, Maryland

X.-L. Han, University of Tennessee, Knoxville, Tennessee

M. M. Hindi, Tennessee Technological University, Cookeville, Tennessee

J. M. Irvine, University of Manchester, Manchester, England

H. Jin, University of Tennessee, Knoxville, Tennessee

A. Joint Institute for Heavy Ion Research (continued)

S. Kahane, Nuclear Research Center-Negev, Beer Sheva, Israel
 M. Korolija, Ruder Boskovic Institute, Croatia, Yugoslavia
 S. Landowne, Argonne National Laboratory, Argonne, Illinois
 L. J. Lantto, University of Oulu, Oulu, Finland
 Z-P. Li, University of Tennessee, Knoxville, Tennessee
 J. E. Lisantti, TRIUMF, University of British Columbia, Vancouver, Canada
 C. Magnago, Centre d'Etudes de Bruyeres-le-Chatel, Bruyeres-le-Chatel, France
 J. Mitchell, Yale University, New Haven, Connecticut
 B. Mueller, University of Frankfurt, Frankfurt, West Germany
 A. Mourreddine, Universite Louis Pasteur, Strasbourg, France
 J. C. Parikh, Physical Research Laboratory, Navrangpura, Ahmedabad, India
 P. G. Quentin, Laboratoire de Physique Theorique, Gradignan, France
 M. A. Riley, Niels Bohr Institute, Roskilde, Denmark
 S. Saini, University of Pennsylvania, Philadelphia, Pennsylvania
 W. J. Schmitz, University of Tennessee, Knoxville, Tennessee
 M. Schulz, Heidelberg University, Heidelberg, West Germany
 Y. R. Schutz, GANIL, Caen, France
 P. Semmes, Tennessee Technological University, Cookeville, Tennessee
 D. C. Sousa, Eastern Kentucky University, Richmond, Kentucky
 K. M. Teh, Vanderbilt University, Nashville, Tennessee
 A. J. A. Virtanen, University of Jyväskylä, Jyväskylä, Finland
 J. Wang, University of Tennessee, Knoxville, Tennessee
 C-L. Wu, University of Tennessee, Knoxville, Tennessee
 X. Yang, Institute of Atomic Energy, Beijing, People's Republic of China
 J. Y. Zhang, University of Tennessee, Knoxville, Tennessee
 L. Zhou, Institute of Atomic Energy, Beijing, People's Republic of China

B. Graduate Students

G. A. Barrera, Colorado State University, Fort Collins, Colorado
 L. M. Baume, Yale University, New Haven, Connecticut
 V. Carmichael, University of Tennessee, Knoxville, Tennessee
 M. P. Carpenter, University of Tennessee, Knoxville, Tennessee
 L. H. Courtney, University of Tennessee, Knoxville, Tennessee
 J. E. Freyou, University of Tennessee, Knoxville, Tennessee
 C. C. Gaither, University of Tennessee, Knoxville, Tennessee
 J. P. Gibbons, University of Tennessee, Knoxville, Tennessee
 J. C. Griffin, Georgia Institute of Technology, Atlanta, Georgia
 E. C. Jones, University of Tennessee, Knoxville, Tennessee
 J. N. Juang, Tennessee Technological University, Cookeville, Tennessee
 R. W. Kincaid, University of Tennessee, Knoxville, Tennessee
 S. E. Lasley, University of Tennessee, Knoxville, Tennessee
 B-a. Li, Institute of Modern Physics, Lanzhou, People's Republic of China
 X. T. Liu, University of Tennessee, Knoxville, Tennessee
 P. F. Mantica, Jr., University of Maryland, College Park, Maryland
 W. J. Schmitz, University of Tennessee, Knoxville, Tennessee
 H. Schone, University of Heidelberg, Heidelberg, West Germany
 R. T. Short, University of Tennessee, Knoxville, Tennessee
 W. Spang, KFA Julich, Institut fur Kernphysik, Julich, West Germany
 J. S. Thompson, University of Tennessee, Knoxville, Tennessee
 T. A. Underwood, University of Tennessee, Knoxville, Tennessee
 J. Ye, Vanderbilt University, Nashville, Tennessee

C. Postdoctoral Research Associate

J. C. Levin, University of Tennessee, Knoxville, Tennessee

D. Co-op Students

D. E. Hoglund, Virginia Polytechnic Institute and State University, Blacksburg, Virginia
 C. E. Jones, Tennessee Technological University, Cookeville, Tennessee

E. ORAU Graduate Research Participant

S. M. Fischer, Colorado State University, Fort Collins, Colorado

F. ORAU Postgraduate Research Training Program

M. H. Casson, University of Tennessee, Knoxville, Tennessee
 M. S. Huq, College of William and Mary, Williamsburg, Virginia
 J. K. Swenson, University of North Carolina, Chapel Hill, North Carolina

G. ORAU Faculty Research Participants

C. A. Bennett, Jr., University of North Carolina, Asheville, North Carolina
 W. M. Fairbank, Jr., Colorado State University, Fort Collins, Colorado
 W. B. Newbolt, on sabbatical from Washington and Lee University, Lexington, Virginia
 T. A. Walkiewicz, Edinboro University of Pennsylvania, Edinboro, Pennsylvania

H. ORAU Student Research Participants

D. G. Baize, Western Kentucky University, Bowling Green, Kentucky
 A. D. Murphy, Western Kentucky University, Bowling Green, Kentucky
 R. W. Sayer, University of North Carolina, Chapel Hill, North Carolina
 S. D. Stewart, Western Kentucky University, Bowling Green, Kentucky

I. Great Lakes College Association Science Program

T. J. Allen, Ripon College, Ripon, Wisconsin
 A. M. Calabrese, Depauw University, Greencastle, Indiana
 S. T. Churchwell, Earlham College, Richmond, Indiana
 B. J. Vartanian, Albion College, Albion, Michigan

J. Great Lakes College Association Faculty Participant

R. R. Winters, Denison University, Granville, Ohio

Summer Assignments

A. ORAU STRIVE Participant

J. R. Wilson, Bearden High School, Knoxville, Tennessee

B. ORAU Professional Internship

D. H. Olive, Jr., Vanderbilt University, Nashville, Tennessee

C. DOE Magnetic Fusion Science Fellow

M. E. Bannister, Princeton University, Princeton, New Jersey

D. University of Tennessee/ORNL Science Alliance Undergraduate Program

S. Ginther, Hillsdale College, Hillsdale, Michigan
 C. Graney, University of Dayton, Dayton, Ohio
 K. Hart, Transylvania University, Lexington, Kentucky
 R. Hunt, Western Carolina State University, Cullowhee, North Carolina
 A. Kast, University of Chicago, Chicago, Illinois
 J. G. Kreke, Duquesne University, Pittsburgh, Pennsylvania
 J. Lewis, King College, Bristol, Tennessee
 D. Monchilovich, Gustavus Adolphus College, Saint Peter, Minnesota
 D. Thompson, Indiana/Purdue Universities, Indianapolis, Indiana
 B. Wood, Central Washington University, Ellensburg, Washington

PHYSICS DIVISION SEMINARS: OCTOBER 1986-SEPTEMBER 1987

Seminars arranged by the Physics Division and announced in the ORNL Technical Calendar are listed below. During the period of this report, Terry C. Aves served as Seminar Chairman.

<u>Date</u>	<u>Speaker</u>	<u>Title</u>
1986		
Oct. 6	H. H. Bultin University of Melbourne Melbourne, Australia	"Recent Transient Field g-Factor Measurements-Tests of IBM and CNFB Calculations"
Oct. 7	A. Faessler Universität Tübingen Institut für Theoretische Physik Tübingen, F.R.G.	"Heavy-Ion Physics from the Coulomb Barrier to the Quark-Gluon Plasma"
Oct. 20	Thomas Lindblad Research Institute of Physics Stockholm, Sweden	"Ultrahigh Vacuum System for CRYRING Accelerator in Stockholm"
Oct. 21	George D. Dracoulis Australian National University Canberra, Australia	"High-Spin States and Octupole Coupling in the Radon Isotopes"
Oct. 22	S. Åberg University of Lund Lund, Sweden	"Giant Monopole and Quadrupole Resonances in Rotating Nuclei"
Oct. 23	Alain Poncet CERN Geneva, Switzerland	"UHV (10^{-12} torr) Techniques and Technology as Applied to LEAR"
Nov. 4	Bernhard Franzke GSI Darmstadt, F.R.G.	"The Physics Program for the Darmstadt ESR Ring"
Nov. 14	H. Schröder Freie Universität Berlin Berlin, F.R.G.	"Optical Polarization by Capture and Excitation in Beam Foil Interaction"
	Paul M. Read Harwell Laboratory Harwell, England	"Ion Beam Analysis at the Harwell Laboratory"
Nov. 17	Nico Stolterfoht Hahn-Meitner Institute Berlin, F.R.G.	"Multicharged-Ion Surgery Studied by Zero-Degree Auger-Electron Spectroscopy"
	Béla Sulik Institute of Nuclear Research Hungarian Academy of Science Debrecen, Hungary	"Electron Spectroscopy in Ion-Atom Collision Experiments at INR"
Nov. 21	Philippe Quentin University of Bordeaux, France	"A Consistent Description of Particle and Collective Low-Energy Excitations"
Dec. 2	H. P. Morsch Institut für Kernphysik Jülich, F.R.G.	"Study of Giant Resonances in Hot Nuclei"
Dec. 3	Richard Wigmans Dutch Institute of High-Energy Physics, Amsterdam	"Compensation Mechanism in Hadron Calorimetry"

<u>Date</u>	<u>Speaker</u>	<u>Title</u>
1987		
Jan. 12	P. Clout Los Alamos National Laboratory Los Alamos, New Mexico	"Experiences in Designing the Control System for the Proton Storage Ring at LANL"
Jan. 15	Hong Yuan Zhu Chinese Academy of Sciences and Institute of High-Energy Physics Beijing, P.R.C.	"Beijing Electron-Positron Collider and Lanzhou Heavy-Ion Research Facility (HIRFL)"
Jan. 20	D. L. Friesel Indiana Univ. Cyclotron Facility Bloomington, Indiana	"Status Report of the IUCF Ring Project and Electron Cooling System"
Jan. 20	J. Markey Yale University New Haven, Connecticut K. Okada and T. Shibata Laboratory for Nuclear Studies Osaka University, Japan	"Minisymposium on Double Beta Decay"
Feb. 10	Gerald E. Brown State University of New York Stony Brook, New York	"Equation of State of Dense Matter from Heavy-Ion Reactions"
Feb. 11	Madeleine Soyeur Service de Physique Théorique Saclay, France	"Excitation of Spin-Isospin Modes in Heavy-Ion Charge-Exchange Reactions at 900 MeV/Nucleon"
Feb. 20	Chris Bottcher Division Staff Member	"Numerical Studies of Electron-Impact Ionization near Threshold"
Mar. 12	Carl Herrlander Institute of Physics Stockholm, Sweden	"The CRYRING Project: A Small Heavy-Ion Synchrotron and Storage Ring"
Mar. 24	Akira Noda Institute for Nuclear Studies University of Tokyo, Japan	"The Design and Construction of the TARN II Heavy-Ion Synchrotron Storage-Ring/Cooler"
Apr. 6	Eric van Walle Instituut voor Kern-en Stralingsfysika Leuven, Belgium	"On-Line Nuclear Orientation of n-Deficient Transitional Nuclei Around $Z = 50,82$ "
Apr. 14	Josef Pochodzalla GSI Darmstadt, F.R.G.	"Correlated Heavy-Fragment Emission: A Signature for Multifragmentation?"
Apr. 15	Nick Stone Clarendon Laboratory Oxford, England	"Quadrupole Orientation to 1 Millikelvin: Ground-State Deformations in the Region below $Z = 40$ "
Apr. 16	Johanna Stachel State University of New York Stony Brook, New York Peter Braun-Munzinger State University of New York Stony Brook, New York	"From Central Collisions to Fragmentation: Heavy-Ion Physics Within Experiment 814 at the AGS" "Transverse Energy Production in p-Nucleus and Nucleus-Nucleus Collisions"
May 21	R. L. Mahn Brookhaven National Laboratory Upton, New York	"The GALLEX Collaboration: Searching for Solar Neutrinos"

<u>Date</u>	<u>Speaker</u>	<u>Title</u>
1987		
May 26	H. Knudsen University of Aarhus, Denmark	"Production of Anti-Hydrogen"
May 27	Peter Spädtke GSI Darmstadt, F.R.G.	"Application of the AXCEL and KOBRA3 Codes to the Electron Cooler Project at GSI"
May 29	Volker Metag University of Giessen, F.R.G.	"Does the Compound Nucleus Memorize Its Formation? — The Influence of Reaction Dynamics and Nuclear Structure on Heavy-Ion Fusion"
June 2	Hans-Ake Gustafsson Lund University, Sweden	"Composite Particle and Entropy Production in Relativistic Nuclear Collisions"
June 4	Rainer Schicker State University of New York Stony Brook, New York	"Identifying Evaporation Residues with an Electrostatic Deflector"
June 5	Mark Tincknell Lawrence Berkeley Laboratory Berkeley, California	"The NA35 Ultrarelativistic Nucleus-Nucleus Collision Experiment"
June 22	I. Ragnarsson Lund Institute of Technology Lund, Sweden	"Limits to the Angular Momentum of Rotational Bands at Small and Large Deformations"
July 13	R. Donangelo University of Rio de Janeiro Brazil	"Neck Effects in Subbarrier Fusion Enhancement"
July 23	Howard R. Reiss American University Washington, D.C.	"External Field Effects on Nuclear β Decay"
July 27	J. D. Garrett Niels Bohr Institute Copenhagen, Denmark	"Observable Phase Transitions in Nuclei"
July 28	Wolfgang Wilke II. Physical Institute University of Giessen, F.R.G.	"Development of Position-Sensitive 4π PPAC Arrangement for Photofission Experiments"
Aug. 11	J. J. Gaardhoje Niels Bohr Institute Copenhagen, Denmark	"Giant Resonances Built on Excited States: A Probe of the Structure of Hot Nuclei"
Aug. 12	J. M. Irvine University of Manchester Manchester, England	"Cosmic Neutrinos"
Aug. 17	B. Herskind Niels Bohr Institute Copenhagen, Denmark	"Superdeformed ^{152}Dy : Population and Decay"
Aug. 25	Herbert Uberall Catholic University of America Washington, D.C.	"Channeling Radiation and Coherent Bremsstrahlung"
Sept. 17	J. S. Forster Chalk River Nuclear Laboratories Chalk River, Ontario	"Deflection of GeV Particle Beams by Channeling in Bent Si Single Crystals"
Sept. 24	Alex C. Mueller GANIL Caen, France	"Production and Study of Light Nuclei Very Far from Stability with the LISE Facility at GANIL"

SCIENTIFIC MEETINGS HELD DURING THIS PERIOD

Workshop on Heavy Ion Physics and Instrumentation
for a 15-Tm Booster and Storage Ring

Oak Ridge, Tennessee, October 2-4, 1986

J. L. Wood (Georgia Tech), A. B. Balantekin (U Wisconsin),
M. W. Guidry (U Tennessee), A. C. Mignerey (U Maryland),
and E. F. Zganjar (Louisiana SU), organizersMeeting of the Users Advisory Committee
for the Heavy Ion Storage Ring for Atomic Physics (HISTRAP)

Oak Ridge, Tennessee, March 9, 1987

S. Datz, organizer

Holifield Theory Users Group Meeting

Oak Ridge, Tennessee, September 25-26, 1987

J. B. McGrory, M. R. Strayer, and G. A. Leander, organizers

INFORMATION MEETING

The most recent Physics Division Information Meeting was held on May 4-6, 1987. The members of the Advisory Committee were:

D. Cline, University of Rochester
R. Henry, Louisiana State University
J. R. Huizenga, University of Rochester
M. Macfarlane, Indiana University
S. Nagamiya, Columbia University
L. C. Teng, Fermi National Accelerator Laboratory

DEPARTMENT 100

INTERNAL DISTRIBUTION

1.	E. D. Aebischer	239.	A. B. Livingston
2.	G. D. Alton	240.	C. A. Ludemann
3.	T. D. Anderson	241.	C. H. Ma
4.	B. R. Appleton	242.	F. Maienschein
5.	R. L. Auble	243.	J. A. Martin
6.	T. C. Awes	244.	M. J. Martin
7.	C. Baktash	245.	O. J. McBride
8-178.	J. B. Ball	246.	J. W. McConnell
179.	S. J. Ball	247.	F. K. McGowan
180.	C. F. Barnett	248.	J. B. McGrory
181-185.	V. B. Baylor	249.	G. S. McNeilly
186.	R. L. Becker	250.	F. W. Meyer
187.	M. Beckerman	251.	R. W. Miles
188.	J. R. Beene	252.	P. D. Miller
189.	C. E. Bemis, Jr.	253.	W. T. Milner
190.	F. E. Bertrand	254.	S. W. Mosko
191.	J. A. Biggerstaff	255.	F. R. Mynatt
192.	C. R. Bingham	256.	F. E. Obenshain
193.	Biology Library	257.	D. K. Olsen
194.	C. Bottcher	258.	ORNL - Y-12 Technical Library
195.	H. K. Carter		Document Reference Section
196-197.	Central Research Library	259.	F. K. Ombby
198.	H. O. Cohn	260.	D. C. Parzyck
199.	S. Datz	261.	R. W. Peelle
200.	K. T. R. Davies	262.	D. J. Pegg
201.	P. F. Dittner	263.	F. G. Perey
202.	D. T. Dowling	264.	R. A. Phaneuf
203.	B. G. Eads	265.	Physics Division Library
204.	Y. A. Ellis-Akovali	266.	F. Plasil
205.	S. B. Elston	267.	H. Postma
206.	F. P. Ervin	268.	M. L. Poutsma
207.	R. L. Ferguson	269.	S. Raman
208.	I. C. Girit	270.	D. E. Reichle
209.	J. Gomez del Campo	271.	C. R. Richmond
210.	J. H. Greene	272.	L. L. Riedinger
211.	D. C. Gregory	273.	R. L. Robinson
212.	E. E. Gross	274.	T. M. Rosseel
213.	M. W. Guidry	275.	T. M. Row
214.	M. L. Halbert	276.	M. J. Saltmarsh
215.	J. A. Harvey	277.	G. R. Satchler
216.	L. J. Hawkins-Saddiq	278.	M. R. Schmorak
217.	D. L. Haynes	279.	I. A. Sellin
218.	J. R. Heath	280.	P. B. Semmes
219.	J. M. Helton	281.	D. Shapira
220.	D. C. Mensley	282.	J. Sheffield
221.	J. R. Hightower	283.	P. J. Siemens
222.	O. J. Horen	284.	M. Simpson
223.	H. T. Hunter	285.	T. P. Sjoreen
224.	D. P. Hutchinson	286.	A. H. Snell
225.	C. H. Johnson	287.	S. P. Sorensen
226.	J. W. Johnson	288.	P. H. Stelson
227.	M. R. Johnson	289.	M. R. Strayer
228.	C. M. Jones	290.	A. S. Tate
229.	S. V. Kaye	291.	B. A. Tatum
230.	H. J. Kim	292.	J. K. Thacker
231.	C. H. Krause	293.	K. S. Toth
232.	H. F. Krause	294.	K. L. Vander Sluis
233.	E. H. Krieg, Jr.	295.	C. R. Vane
234-235.	Laboratory Records Department	296.	R. L. Varner
236.	Laboratory Records, ORNL R.C.	297.	C. R. Wallace
237.	G. A. Leander	298.	K. M. Wallace
238.	I. Y. Lee	299.	P. J. Walsh

300. J. C. Wells, Jr.
 301. M. Whitley
 302. C-Y. Wong

303. G. R. Young
 304. M. F. Ziegler
 305. A. Zucker

EXTERNAL DISTRIBUTION

306. J. M. Alexander, Department of Physics, SUNY at Stony Brook, Stony Brook NY 11794
 307. B. J. Allen, Physics Division, Australian Atomic Energy Commission, Sutherland, N.S.W., Australia
 308. J. U. Andersen, Institute of Physics, Aarhus University, DK-8000, Aarhus C, Denmark
 309. Sakir Ayik, Tennessee Technological University, Physics Department, Cookeville, TN 38505
 310. A. B. Balantekin, Department of Physics, University of Wisconsin, 1150 University Avenue, Madison, WI 53706.
 311. Charles A. Barnes, Division of Physics and Astronomy, California Institute of Technology, Pasadena, CA 91125
 312. G. A. Bastin, Centre de Spectrometrie Nucleaire et de Spectrometrie de Masse, B. P. 104, 91406 Orsay, France
 313. Bates Linear Accelerator, P. O. Box 95, Middleton, MA 01949
 314. H. Behrens, Zentralstelle fur Atomkernenergie-Dokumentation, Kernforschungszentrum Karlsruhe 7514, Eggenstein-Leopoldshafen-2, Federal Republic of Germany
 315. Ingmar Bergstrom, Nobel Institute of Physics, Stockholm 50, Sweden
 316. B. L. Berman, Department of Physics, The George Washington University, Washington, DC 20052
 317. Biblioteca do Depto. de Fisica Nuclear, Instituto de Fisica da USP, Caixa Postal 20516, 0100 - Sao Paulo, SP, Brasil
 318. Bibliotheque - Madame Belle, Universite de Grenoble, Institut des Sciences Nucleaires, 53, rue des Martyrs, B. P. 38 Grenoble, France
 319. J. P. Blaser, Swiss Institute for Nuclear Research (SIN), CH-5234 Villigen, Switzerland
 320. P. Blasi, Universita di Fierenza, Largo E. Fermi 2, 50125 Fierenza, Italy
 321. S. D. Bloom, University of California, Lawrence Livermore National Laboratory, P. O. Box 808, Livermore, CA 94550
 322. H. G. Blosser, Cyclotron Laboratory, Michigan State University, East Lansing, MI 48824
 323. R. Bock, Gesellschaft für Schwerionenforschung, Postfach 11 05 41, 6100 Darmstadt, West Germany
 324. H. Bohn, Physik-Department E12, Technische Universitat, 8046 Garching bei Munchen, Federal Republic of Germany
 325. A. Bohr, Copenhagen University, Niels Bohr Institute, Blegdamsvej 17, Copenhagen, Denmark
 326. Peter Braun-Munzinger, Department of Physics, SUNY at Stony Brook, Stony Brook, NY 11794
 327. L. B. Bridwell, Office of the President, S.W. Missouri State University, 901 South National, Springfield, MO 65804
 328. J. S. Briggs, Theoretical Physics Division, Atomic Energy Research Establishment, Harwell, Didcot, Oxfordshire OX 11 0RA, England
 329. J. A. Brink, Library Division, The Merensky Institute of Physics, University of Stellenbosch, Stellenbosch, Republic of South Africa
 330. H. C. Britt, Lawrence Livermore Laboratory, P. O. Box 808, Livermore, CA 94550
 331. Ricardo Americo Broglia, Niels Bohr Institute, Blegdamsvej 17, 2100 Copenhagen O, Denmark
 332. D. A. Bromley, Nuclear Structure Laboratory, Yale University, New Haven, CT 06520
 333. Peter Anthony Butler, University of Liverpool, P. O. Box 147, Liverpool L69 3X, United Kingdom
 334. T. A. Cahill, Director, Crocker Nuclear Laboratory, University of California, Davis, CA 95616
 335. R. Caplar, Ruder Boskovic Institute, Bijenicka 54, 41001 Zagreb, Croatia, Yugoslavia
 336. Jose L. S. Carvalho, Instituto de Radioprotecao e Dosimetria, C.N.E.N., Av. das Americas km 11,5 Barra de Tijuca - R. J., 22700 - Rio de Janeiro, R. J. Brazil
 337. Yong Shou Chen, Institute of Atomic Energy, Academia Sinica, P. O. Box 275, Beijing, China
 338. F. E. Chukreev, Kurchatov Institute of Atomic Energy, Kurchatov Square, 123 182 Moscow, USSR
 339. M. Cindro, Ruder Boskovic Institute, Bijenicka 54, 41001 Zagreb, Yugoslavia
 340. David Clark, Lawrence Berkeley Laboratory, University of California, Berkeley, CA 94720
 341. Douglas Cline, Nuclear Structure Research Laboratory, University of Rochester, Rochester, NY 14627
 342. J. D. Cole, EG&G Idaho, Inc., TRA 652, Idaho Falls, ID 83415
 343. University of Colorado, Department of Physics, Boulder, CO 80309
 344. D. H. Crandall, Branch Chief for Experimental Research, Applied Plasma Physics Division, Office of Fusion Energy, ER 542, G-226, GTN, U.S. Department of Energy, Washington, DC 20545
 345. F. L. Culler, Office of the President, Electric Power Research Institute, P. O. Box 20412, 3412 Hillview Avenue, Palo Alto, CA 94303
 346. R. E. Culp, Martin Marietta Denver Aerospace, P.O. Box 179, M/S # P0540, Denver, CO 80201
 347. T. J. Curtin, Director, Office of Research and Grants Administration, Texas Women's University, Box 22939, TWU Station, Denton, TX 76204

348. R. Y. Cusson, Physics Department, Duke University, Durham, NC 27706
349. Cyclotron Library, Indiana University Cyclotron Facility, 2401 Milo B. Sampson Lane, Bloomington, IN 47405
350. B. A. Dahling, Lawrence Livermore National Laboratory, University of California, Livermore, CA 94550
351. Solange de Barros, Head, Department of Nuclear Physics, Universidade Federal do Rio de Janeiro, Instituto de Fisica - Department Fisica Nuclear, Centro de Tecnologia - Bloco A, Ilha do Fundao - Rio de Janeiro, Brasil
352. Adriano de Lima, Physics Laboratory, University of Coimbra, Coimbra, Portugal
353. Claude Détraz, Director, GANIL, B.P. 5027, 14021 Caen Cedex, France
354. R. M. Diamond, Chemistry Division, Lawrence Berkeley Laboratory, Berkeley, CA 94720
355. Olafio Dietzsch, Depto. de Fisica Experimental, Instituto de Fisica, Universidade de Sao Paulo, Cr. Postal 20516, Sao Paulo, S.P., Brazil
356. J. L. Duggan, Department of Physics, North Texas State University, Denton, TX 76203
357. K. A. Erb, National Science Foundation, Rm. 341, 1800 G Street NW, Washington, DC 20550
358. John R. Erskine, U.S. Department of Energy, Division of Nuclear Physics, ER-23, GTN, Washington, DC 20545
359. U. Facchini, Physics Department, University of Milan, Via Salidini 50, Milan, Italy
360. Amand Faessler, Institut fur Theoretische Physik, Universitat Tubingen, Auf der Morgenstelle 14, D-7400 Tubingen, West Germany
361. D. H. Feng, Department of Physics, Drexel University, Philadelphia, PA 19104
362. M. P. Fewell, Australian National University, Canberra, 2600 Australia
363. R. W. Fink, School of Chemistry, Georgia Institute of Technology, Atlanta, GA 30332
364. G. N. Flerov, Laboratory for Nuclear Reactions, Dubna Joint Institute for Nuclear Research, Dubna, Moscow Oblast, U.S.S.R.
365. J. S. Forster, Nuclear Physics Branch, Atomic Energy of Canada Limited, Chalk River Nuclear Laboratories, Chalk River, Ontario, Canada K0J 1J0
366. J. O. Fox, Department of Physics, Florida State University, Tallahassee, FL 32306
367. I. M. Frank, Laboratory for Nuclear Reactions, Dubna Joint Institute for Nuclear Research, Dubna, Moscow Oblast, U.S.S.R.
368. Claus-Konrad Gelbke, National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, MI 48824
- 369-378. GLCA-ORS, Attention: R. R. Winters, Denison University, Granville, OH 43023
379. Alan Goodman, Department of Physics, Tulane University, New Orleans, LA 70118
380. Harvey A. Gould, Lawrence Berkeley Laboratory, 1 Cyclotron Blvd., Berkeley, CA 94720
381. H. E. Gove, Nuclear Structure Laboratory, University of Rochester, Bldg. 510A, Rochester, NY 14627
382. Walter Greiner, Institut fur Theoretische Physik der Universitat Frankfurt Main, Robert Mayer-Strasse 8-10, West Germany
383. H. Gruner, Continuous Electron Beam Accelerator Facility (CEBAF), 12070 Jefferson Avenue, Newport News, VA 23606
384. M. Grypeos, University of Thessaloniki, Department of Theoretical Physics, Thessaloniki, Greece
385. H. H. Gutbrod, Gesellschaft für Schwerionenforschung, Postfach 11 05 41, 6100 Darmstadt 1, West Germany
386. J. H. Hamilton, Department of Physics, Vanderbilt University, Nashville, TN 37203
387. Ole Hansen, Brookhaven National Laboratory, Bldg. 901A, Upton, NY 11973
388. J. S. Hattula, Department of Physics, University of Jyväskylä, Seminaarinkatu 15, SF-40100 Jyväskylä 10, Finland
389. R. L. Heath, Idaho National Engineering Laboratory, EG&G Idaho, Inc., P. O. Box 1625, Idaho Falls, ID 83401
390. David L. Hendrie, Director, Division of Nuclear Physics, ER 23, Mail Station J-309, U.S. Department of Energy, Washington, DC 20545
391. Ronald Henry, Department of Physics and Astronomy, Louisiana State University, 202 Nicholson Hall, Baton Rouge, LA 70803-4001
392. Bent Herskind, Niels Bohr Institute, Riso, DK-4000 Roskilde, Denmark
393. Rainer Hippler, Universitat Bielefeld, Fakultat fur Physik, University of Bielefeld, Postfach 8640, 4800 Bielefeld 1, West Germany
394. Harry D. Holmgren, Department of Physics, University of Maryland, College Park, MD 20742.
395. J. R. Huizenga, Department of Physics and Astronomy, University of Rochester, Rochester, NY 14627
396. P. Hvelplund, Institute of Physics, Aarhus University, DK-8000, Aarhus C, Denmark
397. H. R. McK. Hyder, Nuclear Physics Laboratory, Oxford University, Keble Road, Oxford OX1 3RH, England
398. M. V. Hynes, Department of Physics, Los Alamos National Laboratory, University of California, Los Alamos, NM 97545
399. Francesco Iachello, Yale University, Department of Physics, New Haven, CT 06520
400. University of Illinois at Urbana-Champaign, Department of Physics, Urbana, IL 61801
401. Institute for Energy Analysis, P. O. Box 117, Oak Ridge, TN 37830

402. Institute of Physics, High Energy and Nuclear Physics Library, C. Postal 20.516,0100 - Sao Paulo, S.P., Brasil
403. I. Iori, Istituto di Scienze Fisiche, Aldo Pontromoli, Via Celoria 16, 20133 Milano, Italy
404. Iowa State University, Department of Physics, Ames, IA 50011
405. J. M. Irvine, Department of Physics, University of Manchester, Oxford Rd., GB-Manchester M13 9 PL, United Kingdom
406. Beth Jinkerson, ORAU/UPD, Oak Ridge, TN 37831-0117
407. R. C. Johnson, University of Surrey, Guildford, Surrey GU2 5XH, United Kingdom
408. R. Kamerling, Fysisch Laboratorium, Rijksuniversiteit Utrecht, P. O. Box 80.000, 3508 TA UTRECHT, The Netherlands
409. H. Kamitsubo, Head, Cyclotron Laboratory, Institute of Physical and Chemical Research, Wako-shi, Saitama, 351 Japan
410. D. G. Kamke, Ruhr-Universität Bochum, Dynamitron Tandem Laboratory, Universitätsstr., 150 Gibaunde NT, Postfach 1021 48, 4360 Bochum 1, Federal Republic of Germany
411. University of Kansas, Department of Physics, Lawrence, KS 66045
412. Norihisa Kato, Department of Physics, Kyushu University, 33 Fukuoka, 812, Japan
413. H. Kawakami, Institute for Nuclear Study, University of Tokyo, Midori-cho, Tokyo, Japan
414. J. O. Kephart, Department of Electrical Engineering, Stanford University, Stanford, CA 94305
415. B. D. Kern, Department of Physics & Astronomy, University of Kentucky, Lexington, KY 40506
416. Uwe Keyser, Institut F. Metallphysik und Nukleare, Festkörperphysik Techn.-Universität, D3300 Braunschweig, Mendelssohnstr. 3, Federal Republic of Germany
417. R. K. Klein, Department of Electrical Engineering, Stanford University, Stanford, CA 94305
418. P. K. Kloeppe, Continuous Electron Beam Accelerator Facility, 12070 Jefferson Avenue, Newport News, VA 23606
419. H. Knudsen, Institute of Physics, Aarhus University, DK-8000, Aarhus C, Denmark
420. Steven E. Koonin, Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, CA 91125
421. M. O. Kortelahti, Physics Department, University of Jyväskylä, Seminaarink 15, 40100 Jyväskylä, Finland
422. K. S. Krane, Department of Physics, Oregon State University, Corvallis, OR 97331-6507
423. B. Krishnarajulu, Department of Physics, Gulbarga University, Gulbarga 585106, India
424. Thomas J. Kvale, Department of Physics & Astronomy, University of Toledo, Toledo, OH 43606
425. Michel LeTourneil, Centre de Recherches Nucleaires, Service des Accelérateurs, B. P. 20 CRO, 67037 Strasbourg Cedex, France
426. Librarian, Atomic Energy Centre, P. O. Box No. 164, Ramna, Dacca, Bangladesh
427. Librarian, Chen Kin-hai, Institute of Modern Physics, Academia Sinica, P. G. Box 31, Lanzhou, People's Republic of China
428. Librarian, Cyclotron Laboratory, Michigan State University, East Lansing, MI 48824
429. Librarian, Cyclotron Laboratory, RIKEN (The Institute of Physical and Chemical Research), Wako-shi, Saitama 351, Japan
430. Librarian, Department of Physics, Georgia State University, Atlanta, GA 30303
431. Librarian, Fermi National Accelerator Lab., P.O. Box 500, Batavia, IL 60510
432. Librarian, GANIL, B. P. No. 5027, 14004 Caen Cedex, France
433. Librarian, GSI, Postfach 11 05 41, 6100 Darmstadt, Federal Republic of Germany
434. Librarian, Institut des Sciences Nucleaires, B. P. No. 257 - Centre de Tri, 38044 Grenoble Cedex, France
435. Librarian, MERT Division Library, Oak Ridge Associated Universities, P. O. Box 117, Oak Ridge, TN 37831-0117
436. Librarian, Nuclear Physics Group, Department of Physics, Schuster Laboratory, The University, Manchester, M13 9PL, United Kingdom
437. Librarian, Nuclear Physics Group, Institute of Physics, Academia Sinica, Taipei, Taiwan 11529, Republic of China
438. Librarian, Nuclear Physics Lab, University of Oxford, 1 Keble Rd., Oxford OX1 3PH, United Kingdom
439. Librarian, Physics Department, 374 Bausch and Lomb Building, University of Rochester, Rochester, NY 14627
440. Library of the Institute of Atomic Energy, Beijing, People's Republic of China
441. Rainer M. Lieder, Institut für Kernphysik, Postfach 1913, 5170 Jülich, West Germany
442. J. S. Lilley, Daresbury Laboratory, GB-Warrington WA4 4AD Cheshire, England
443. J. C. Lisle, Dept. of Physics, Schuster Laboratory, Manchester University, Manchester M13 9 M13 9 PL, United Kingdom
444. H. Lizurej, Jagellonian University, Institute of Physics, Reymonta 4, 30-059 Krakow 16, Poland
445. Tom Lonnroth, Department of Physics, Abo Akademi, Porthansgatan 3, SF-20500 Turku, Finland
446. Malcolm Macfarlane, Department of Physics, Indiana University, Bloomington, IN 47405
447. A. O. MacKellar, Department of Physics and Astronomy, University of Kentucky, Lexington, KY 40506-0055
448. G. Madurga, Departamento de Física Atomica y Nuclear, Facultad de Ciencias, Universidad de Sevilla, Sevilla, Spain

449. Claude Charles Mahaux, Institut de Physique BS Universite de Liege, Sait Tilman, B-4000 Liege 1, Belgium
450. Robert S. Marianelli, Division of Chemical Sciences, Office of Basic Energy Sciences, U.S. Department of Energy, Mail Station G-334, GTN, Washington, DC 20545
451. Mario Mariscotti, Comision Nacional de Energia Atomica, Departamento de Fisica, Avenida del Libertador 8250, 1429 Buenos Aires, Argentina
452. Niels Marquardt, Universität Dortmund Lehrstuhl für Beschleunigerphysik, P.O. Box 500 500, D-4600 Dortmund 50, West Germany
453. J. V. Martinez, Division of Chemical Sciences, Mail Stop J309 GTN, U.S. Department of Energy, Washington, DC 20545
454. Floyd D. McDaniel, Department of Physics, North Texas State University, Denton, TX 76203
455. W. R. McMurray, Deputy Chief Scientist, Kerninstituut Van Die Suidelike Universiteite, Southern Universities Nuclear Institute, Republic of South Africa
456. G. K. Mehta, Professor of Physics, Van de Graaff Laboratory, Indian Institute of Technology Kanpur, Kanpur 208 016, India
457. Eugen Merzbacher, University of North Carolina, Department of Physics and Astronomy, Chapel Hill, NC 27514
458. R. J. Meyer, Nuclear Physics Department, Fysisch Laboratorium Rijksuniversiteit, P. O. Box 80 000, 3508 TA Utrecht, The Netherlands
459. R. Middleton, Department of Physics, University of Pennsylvania, Philadelphia, PA 19104
460. E. Migneco, INFN Laboratorio Nazionale del Sud, Corso Italia 57, 95127 Catania, Italy
461. Alice C. Mignerey, Department of Chemistry, University of Maryland, College Park, MD 20742
462. J. C. D. Milton, Physics Division, Atomic Energy of Canada Ltd., Chalk River, Canada K0J 1J0
463. University of Minnesota, Physics Department, 116 Church Street SW, Minneapolis, MN 55455
464. C. D. Moak, 332 Louisiana Avenue, Oak Ridge, TN 37830
465. G. C. Morrison, Department of Physics, University of Birmingham, Birmingham B15 2TT, England
466. U. Mosel, Institut für Theoretische Physik, Universität Giessen, 6300 Giessen, West Germany
467. Brian W. Moudry, c/o Ms. Helene Perry, Department of Physics, Loyola College, Baltimore, MD 21210
468. S. C. Mukherjee, Librarian, Saha Institute of Nuclear Physics, 92, Acharya Prafulla Chandra Road, Calcutta - 9, India
469. Shoji Nagamiya, Department of Physics, Columbia University, New York, NY 10027
470. M. A. Nagarajan, Daresbury Laboratory, GB-Warrington WA4 4AD Cheshire, England
471. Y. Nakamura, JPL, Systems Analysis Section, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91103
472. Wittek Nazarewicz, Institute of Physics, Politechnika Warszawska ul. Koszykowa 75, PL-00662 Warszawa, Poland
473. John H. Neiler, 853 West Outer Drive, Oak Ridge, TN 37830
474. Nebojsa Neskovic, Boris Kidric Institute of Nuclear Science - Vinca, Institute for Research in Physics, P.O. Box 522, 11001 Beograd - Yugoslavia
475. John Newton, Dept. of Nuclear Physics, The Australian National University, P. O. Box 4, Canberra ACT 2600, Australia
476. Ray Nix, Nuclear Theory, T-9, MS B279, Los Alamos National Laboratory, Los Alamos, NM 87545
477. Ranier W. Novotny, II. Physikalisches Institut, Justus-Liebig Universität, Heinrich-Buff-Ring 16, 6300 Giessen, West Germany
478. Office of Assistant Manager for Energy Research and Development, Department of Energy, Oak Ridge Operations Office, Oak Ridge, TN 37830
479. Yuko Okamoto, Particle Theory Group, Department of Physics, Nara Women's University, Nara-shi 630, Japan
480. Masumi Oshima, Japan Atomic Energy Research Institute, Tokai Establishment, Tokai-mura, Naka-gun, Ibaraki-ken 319-11, Japan
481. Ingvar Otterlund, Division of Cosmic and Subatomic Physics, University of Lund, Sölvegatan 14, S-233 62 Lund, Sweden
482. R. H. Pantell, Department of Electrical Engineering, Stanford University, Stanford, CA 94305
483. H. Park, Department of Electrical Engineering, Stanford University, Stanford, CA 94305
484. Peter Paul, Department of Physics, S.U.N.Y. at Stony Brook, Stony Brook, NY 11794
485. Max Peisach, Southern Universities Nuclear Institute, P. O. Box 17, Faure, 7131, Republic of South Africa
486. A. A. Pitt, Tandem Accelerator Laboratory, McMaster University, Hamilton, Ontario, Canada L8S 4K1
487. University of Pittsburgh, Department of Physics, Pittsburgh, PA 15260
488. J. G. Pochodzalla, Gesellschaft für Schwerionenforschung, Postfach 11 05 41, Darmstadt 1, West Germany
489. R. E. Pollock, Department of Physics, Indiana University, Bloomington, IN 47405
490. A. M. Poskanzer, Nuclear Science Division, Lawrence Berkeley Laboratory, Berkeley, CA 94720
491. Helmut Poth, C.E.R.N., European Laboratory for Particle Physics, CH-1211, Geneva 23, Switzerland
492. F. Pougheon, Institut de Physique Nucleaire, B.P. No. 1, 91406 Orsay, France

493. B. Povh, Max Planck Institut für Kernphysik, 69 Heidelberg, Saupfercheckweg, Postfach 1248, Federal Republic of Germany
494. James Purcell, Department of Physics, Georgia State University, Atlanta, GA 30303
495. A. V. Ramayya, Department of Physics, Vanderbilt University, Nashville, TN 37203
496. Jacobo Rapaport, Department of Physics, Ohio University, Athens, OH 45701-0640
497. John Rasmussen, Lawrence Berkeley Laboratory, Building 70A, Berkeley, CA 94720
498. Patrick Richard, Physics Department, Kansas State University, Manhattan, KS 66506
499. Sheila Robinson, Department of Physics & Astronomy, Western Kentucky University, Bowling Green, KY 42101
500. L. Rosen, Los Alamos National Laboratory, P. O. Box 1663, Los Alamos, NM 87544
501. Rainer Santo, Sektion Physik der Universität München, 8046 Garching, Beschleunigerlaboratorium (Forschungsgelände), Federal Republic of Germany
502. D. G. Sarantites, Department of Chemistry, Washington University, St. Louis, MO 63130
503. V. Sarantseva, Head, Publishing Department, Joint Institute for Nuclear Research, Head Post Office, P. O. Box 79, Moscow, U.S.S.R.
504. J. P. Schiffer, Physics Division, Argonne National Laboratory, 9700 South Cass Avenue, Argonne, IL 60439
505. K. D. Schilling, Zentralinstitut für Kernforschung, Rossendorf, Bereich 2, DDR-8051 Dresden, Democratic Republic of Germany
506. Hermann Schweickert, Cyclotron Laboratory, Kernforschungszentrum Karlsruhe, Institut für Applied Physik, P. O. Box 3640, D-7500 Karlsruhe 1, Federal Republic of Germany
507. David K. Scott, National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, MI 48824
508. S. Seki, Tandem Accelerator Center, University of Tsukuba, Ibaraki 305, Japan
509. J.P.F. Sellschop, Department of Physics, University of Witwatersrand, Johannesburg, South Africa
510. M. H. Sergolle, Director, Institut de Physique Nucleaire - Orsay, B.P. N° 1, 91406 Orsay Cedex, France
511. J. C. C. Sharp, Information Officer, Daresbury Laboratory, Science Research Council, Daresbury, Warrington WAA 4AD, England
512. J. F. Sharpey-Schafer, Oliver Lodge Laboratory, The University, P. O. Box 147, Liverpool, L69 3BX, United Kingdom
513. M. Shikazono, Division of Physics, Japan Atomic Energy Research Institute, Tokai Research Institute, Postal Area Number 319-11, Tokai-mura, Naka-gun, Ibaraki-ken, Japan
514. R. H. Siemssen, Kernfysisch Versneller Instituut der Rijksuniversiteit Zernikelaan 25, 9747 AA Groningen, The Netherlands
515. C. Signorini, INFN Laboratorio Nazionale di Legnaro, Via Roma 4, 35020 Legnaro-Padova, Italy
516. S. J. Skorka, Tandem Accelerator Laboratory, University of Munich, Munich, Federal Republic of Germany
517. Carl Sofield, Nuclear Physics Division, Bldg. 477, AERE Harwell, Oxfordshire OX 11 0RA, England
518. Hsu Loke Soo, Department of Physics, Nanyang University, Singapore 22, Republic of Singapore
519. C. Speth, Institut für Kernphysik, KFA, Jülich, Postfach 1913, D-5170 Jülich, Federal Republic of Germany
520. T. Springer, Institut Max von Laue - Paul Langevin, 156 X Centre de Tri, 38402 Grenoble Cedex, France
521. Stanford University, Department of Physics, Stanford, CA 94305
522. Stephen G. Steadman, Massachusetts Institute of Technology, Room 26-411, Cambridge, MA 02139
523. Alberto Stefanini, Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali di Legnaro, 35020 Legnaro (Padova), Italy
524. Donald K. Stevens, Office of Basic Energy Sciences, U.S. Department of Energy, Mail Station J-304, GTN, Washington, DC 20545
525. R. G. Stokstad, Lawrence Berkeley Laboratory, Bldg. 88, Berkeley, CA 94720
526. N. Stolterfoht, Hahn-Meitner-Institut für Kernforschung Berlin GmbH, Bereich Kern- und Strahlenphysik, D-1000 Berlin 39, West Germany
527. Kazusuke Sugiyama, Department of Nuclear Engineering, Faculty of Engineering, Tohoku University, Sendai, Japan
528. J. K. Swenson, Department of Physics, University of North Carolina, Chapel Hill, NC 27514
529. T. J. Symons, Nuclear Science Division, Lawrence Berkeley Laboratory, 1 Cyclotron Road, Berkeley, CA 94720
530. Shigeya Tanaka, Japan Atomic Energy Research Institute, Tokai-mura, Ibaraki-ken, Japan
531. Hiroyuki Tawara, Institute of Plasma Physics, Nagoya University, Chikusa-ku Nagoya 464, Japan
532. Lee C. Teng, Fermi National Accelerator Laboratory, Accelerator Division, P. O. Box 500, Batavia, IL 60510
533. The High Energy Group, Institute of Physics, Academia Sinica, Nankang, Taipei, Taiwan, ROC
534. Mauro Donizette Tonasse, Faculdade Integrada de Uberaba, Avenida Afranio de Azevedo no. 115, UBERABA - MG - Brazil

535. P. J. Twin, Daresbury Nuclear Physics Laboratory, Daresbury, Nr. Warrington, Lancashire, England
536. J. P. Unik, Argonne National Laboratory, Building 200, Argonne, IL 60439
537. Robert Vandenbosch, Department of Chemistry, University of Washington, Seattle, WA 98195
538. A. van der Woude, Kernfysisch Versneller Instituut der Rijksuniversiteit, Universiteitscomplex Paddepoel, Groningen, The Netherlands
539. H. Verheul, Natuurkundig Laboratorium der Vrije Universiteit de Boelelaan 1081, Amsterdam, The Netherlands
540. VICKSI, Sekretariat, Hahn-Meitner Institut für Kernforschung Berlin GmbH, Postfach 39 01 28, D-1000 Berlin 39, Federal Republic of Germany
541. Virginia Polytechnic Institute and State University, Department of Physics, Blacksburg, VA 24061
542. A. J. A. Virtanen, Department of Physics, University of Jyväskylä, Seminaarinkatu 15, SF-40100 Jyväskylä, Finland
543. W. von Oertzen, Hahn-Meitner Institut für Kernforschung, Berlin GmbH, Federal Republic of Germany
544. George Yourvopoulos, Department of Physics, Western Kentucky University, Bowling Green, KY 42101
545. A. H. Wapstra, Institute voor Kernfysisch Onderzoek, Ooster Ringdijk 18, Amsterdam, The Netherlands
546. David Ward, Nuclear Physics Branch, Chalk River Nuclear Laboratories, Ontario, Canada K0J 1J0
547. Harlan L. Watson, Deputy Staff Director, Subcommittee on Energy Development and Applications, Committee on Science and Technology, U.S. House of Representatives, B374 Rayburn House Office Building, Washington, DC 20515
548. H. E. Wegner, Department of Physics, 901A, Brookhaven National Laboratory, Upton, NY 11973
549. D. C. Weisser, Department of Nuclear Physics, Institute of Advanced Studies, The Australian National University, P. O. Box 4, Canberra ACT 2600, Australia
550. W. G. Weitkamp, Nuclear Physics Laboratory, G-10, University of Washington, Seattle, WA 98195
551. Robert A. Weller, Jr., Department of Physics, Yale University, New Haven, CT 06511
552. Joseph Weneser, Department of Physics, Bldg. 510, Brookhaven National Laboratory, Upton, NY 11973
553. E. P. Wigner, Department of Physics, Princeton University, Princeton, NJ 08540
554. B. H. Wildenthal, Department of Physics & Astronomy, University of New Mexico, 800 Yale NE, Albuquerque, NM 87131
555. University of Wisconsin, Department of Physics, Madison, WI 53706
556. J. L. Wood, School of Chemistry, Georgia Institute of Technology, Atlanta, GA 30332
557. Alexander Xenoulis, Van de Graaff Laboratory, Nuclear Research Center, Demokritos, Aghia Paraskevi Attikis, Athens, Greece
558. Takashi Yamazaki, Research Center for Nuclear Physics, Osaka University (Suita Campus), Ibaraki, Osaka, 567 Japan
559. Yasunori Yamazaki, Research Laboratory for Nuclear Reactors, Tokyo Institute of Technology, Tokyo, Japan
560. Fujia Yang, Director, Institute of Modern Physics, Fudan University, Shanghai, People's Republic of China
561. D. Youngblood, Cyclotron Institute, Texas A&M University, College Station, TX 77940
562. E. F. Zganjar, Department of Physics and Astronomy, Louisiana State University, Baton Rouge, LA 70803
563. K. Ziegler, Hahn-Meitner Institut für Kernforschung Berlin GmbH, Postfach 39 01 28, D-1000 Berlin 39, Federal Republic of Germany
- 564-617. Given distribution as shown in TID-4500 under Physics category (25 copies - NTIS)