118/11-1-73

ANL-8035

Dr. 400

ANL-8035

MASTER

PHYSICS DIVISION ANNUAL REVIEW

1 April 1972—31 March 1973

U of C-AUA-USAEC

ARGONNE NATIONAL LABORATORY, ARGONNE, ILLINOIS

**Prepared for the U.S. ATOMIC ENERGY COMMISSION
under Contract W-31-109-Eng-38**

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

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.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

The facilities of Argonne National Laboratory are owned by the United States Government. Under the terms of a contract (W-31-109-Eng-38) between the U. S. Atomic Energy Commission, Argonne Universities Association and The University of Chicago, the University employs the staff and operates the Laboratory in accordance with policies and programs formulated, approved and reviewed by the Association.

MEMBERS OF ARGONNE UNIVERSITIES ASSOCIATION

The University of Arizona	Kansas State University	The Ohio State University
Carnegie-Mellon University	The University of Kansas	Ohio University
Case Western Reserve University	Loyola University	The Pennsylvania State University
The University of Chicago	Marquette University	Purdue University
University of Cincinnati	Michigan State University	Saint Louis University
Illinois Institute of Technology	The University of Michigan	Southern Illinois University
University of Illinois	University of Minnesota	The University of Texas at Austin
Indiana University	University of Missouri	Washington University
Iowa State University	Northwestern University	Wayne State University
The University of Iowa	University of Notre Dame	The University of Wisconsin

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, subcontractors, or 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.

Printed in the United States of America

Available from

National Technical Information Service

U.S. Department of Commerce

5285 Port Royal Road

Springfield, Virginia 22151

Price: Printed Copy \$7.60; Microfiche \$0.95

ARGONNE NATIONAL LABORATORY
9700 South Cass Avenue
Argonne, Illinois 64039

PHYSICS DIVISION ANNUAL REVIEW
1 APRIL 1972-31 MARCH 1973

Murray Peshkin, Acting Division Director

Preceding Annual Reviews:

ANL-7728, Annual Review 1969-1970
ANL-7848, Annual Review 1970-1971
ANL-7971, Annual Review 1971-1972

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, subcontractors, or 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.

FOREWORD

The Physics Division Annual Review presents a comprehensive picture of the work of the Division in the year ending in the spring of 1973. In addition, the papers published in the 1-year period from 1 April 1972 through 31 March 1973 are listed immediately after the reports on the research.

Another picture of the relative emphases on the different programs of the Division is supplied by the roster of personnel, in which the staff members are grouped by program. (It must be understood, however, that staff members frequently do part of their work in another program.) This roster forms the last section of the report.

TABLE OF CONTENTS

	<u>Page</u>
I. EXPERIMENTAL LOW-ENERGY NUCLEAR PHYSICS	1
<u>Introduction</u>	1
A. <u>Research at the Reactor CP-5</u>	2
1. <u>Fundamental Experiments</u>	2
a. <u>Nuclear Raman Scattering of Photons by Nuclei</u> (H. E. Jackson and K. J. Wetzel)	2
b. <u>Measurements of Spatial Asymmetries in the Decay</u> <u>of Polarized Neutrons</u> (V. E. Krohn and G. R. Ringo)	3
2. <u>Neutron-Capture γ Rays</u>	4
a. <u>Experimental Systems</u>	5
(i) High-Sensitivity Internal-Target Facility (G. E. Thomas and J. R. Specht)	5
(ii) The 7.7-m Bent-Crystal Spectrometer (R. K. Smither)	5
(iii) Internal-Conversion Electron Spectrometer (S. B. Burson and C. H. Batson)	6
b. <u>γ-Ray Intensity Standards</u>	6
(i) High-Energy Standards: The Reactions $^{14}\text{N}(n,\gamma)^{15}\text{N}$, $^{35}\text{Cl}(n,\gamma)^{36}\text{Cl}$, and $^{53}\text{Cr}(n,\gamma)^{54}\text{Cr}$ (G. D. Loper and G. E. Thomas)	6
(ii) Targets with Prominent Low-Energy Resonances (G. E. Thomas and L. M. Bollinger)	8
(iii) Absolute Intensities for $^{113}\text{Cd}(n,\gamma)^{114}\text{Cd}$ (R. K. Smither and G. E. Thomas)	9
c. <u>Giant-Resonance-Like Structure for M1 Radiation</u> (L. M. Bollinger and G. E. Thomas)	9
d. <u>Radiative Capture of Thermal Neutrons in ^3He</u> (L. M. Bollinger, J. R. Specht, and G. E. Thomas)	11

e. <u>Average Resonance Neutron Capture Leading to Levels in ^{112}Cd and ^{114}Cd (R. K. Smither, G. E. Thomas, and L. M. Bollinger)</u>	13
f. <u>Level Structure of the Odd-A Isotopes of Sm (R. K. Smither and G. E. Thomas)</u>	13
g. <u>Level Structure of ^{148}Sm and ^{150}Sm (R. K. Smither, G. E. Thomas, and D. J. Buss)</u>	17
h. <u>Excited States in $^{160}_{65}\text{Tb}$, $^{150}_{62}\text{Sm}$, and $^{182}_{73}\text{Ta}$ (S. B. Burson, F. J. Zehr, and C. H. Batson)</u>	17
(i) $^{159}\text{Tb}(n,\gamma)^{160}\text{Tb}$	17
(ii) $^{181}\text{Ta}(n,\gamma)^{182}\text{Ta}$ and $^{149}\text{Sm}(n,\gamma)^{150}\text{Sm}$	18
i. <u>Level Schemes of ^{178}Hf and ^{180}Hf</u>	18
j. <u>Nuclear States in $^{182}_{75}\text{Re}$ Populated in the Decay of ^{182}Os (22 h) (S. B. Burson, P. J. Daly, P. F. A. Goudsmit, and A. A. C. Klaasse)</u>	20
k. <u>Excited States of ^{184}W (A. R. Adams, N. Smith, D. Bushnell, R. K. Smither, G. E. Thomas, and J. R. Specht)</u>	22
l. <u>The $^{195}\text{Pt}(n,\gamma)^{196}\text{Pt}$ and $^{196}\text{Pt}(n,\gamma)^{197}\text{Pt}$ Spectra and the γ-Ray Spectrum Following β Decay from ^{197}Pt to ^{197}Au (R. K. Smither)</u>	23
m. <u>Modification and Improvements of the Bent-Crystal Spectrometer (R. K. Smither)</u>	24
 B. <u>Threshold Photoneutron Experiments</u>	25
a. <u>Photoneutron Resonances from $^{29}\text{Si}(\gamma,n)^{28}\text{Si}$ (H. E. Jackson and R. E. Toohey)</u>	25
b. <u>Valence Component in the Threshold Photoneutron Spectrum of ^{91}Zr (R. E. Toohey and H. E. Jackson)</u>	26
c. <u>Ground-State M1 Radiation Widths in ^{117}Sn and ^{119}Sn (H. E. Jackson and E. N. Strait)</u>	28
d. <u>Giant M1 Resonance and E1 Doorway States in ^{207}Pb (L. R. Medsker, H. E. Jackson, and R. E. Toohey)</u>	29

	<u>Page</u>
<u>C. Research at the Dynamitron</u>	33
<u>1. Dynamitron Operation, Use, and Equipment</u>	34
<u>a. Operational Experience and Continuing Development</u> <u>at the Dynamitron (R. L. Amrein, A. Langsdorf, Jr.,</u> <u>F. P. Mooring, and J. R. Wallace)</u>	34
<u>b. Ion-Source Systems (R. L. Amrein, F. P. Mooring,</u> <u>and W. J. Ray, Jr.)</u>	36
<u>c. Generating Voltmeter (F. P. Mooring)</u>	37
<u>d. Post-Acceleration Beam Chopper (F. J. Lynch)</u>	38
<u>e. High-Current Beam-Line System (F. P. Mooring)</u>	38
<u>2. Experiments at the Dynamitron</u>	39
<u>a. Fission Isomers in Neutron-Induced Reactions</u> <u>(A. J. Elwyn, F. J. Lynch, F. P. Mooring, and</u> <u>M. Fluss)</u>	39
<u>b. Analysis of the $^{18}\text{O}(\text{p},\text{n})^{18}\text{F}$ Reaction (J. F. Lemming,</u> <u>A. J. Elwyn, F. T. Kuchnir, F. P. Mooring, J. E.</u> <u>Monahan, and R. Finlay)</u>	40
<u>c. Polarization and Differential Cross Sections in</u> <u>Analog-Resonant (p,n) Reactions (A. J. Elwyn and</u> <u>J. E. Monahan)</u>	40
<u>d. Possible Resonance Structure in the Elastic Scattering</u> <u>of ~ 1-MeV Neutrons by Y (A. J. Elwyn, J. E.</u> <u>Monahan, S. A. Cox, J. Adams, and C. Chen)</u>	41
<u>e. Neutrons from Thick Be Targets Bombarded by</u> <u>Charged Particles (F. T. Kuchnir, L. S. Skaggs,</u> <u>A. J. Elwyn, and F. P. Mooring)</u>	43
<u>f. Lifetimes of Carbon Foils Used As Strippers for</u> <u>Heavy Ions (J. L. Yntema)</u>	43
<u>g. Inhibition of Radiation Blistering in Tin Bombarded by</u> <u>Protons and Alpha Particles (R. C. Mikkelsen, J. W.</u> <u>Miller, R. E. Holland, and D. S. Gemmell)</u>	44
<u>h. Equilibrium Positions of Au Atoms in Sn As Determined</u> <u>by a Channeling Technique (D. S. Gemmell, R. E.</u> <u>Holland, J. W. Miller, and J. -C. Poizat)</u>	44

	<u>Page</u>
i. <u>Dechanneling Due to Radiation-Induced Defect Clusters in Au (D. S. Gemmell, R. C. Mikkelson, K. L. Merkle, P. P. Pronko, and J. R. Wrobel)</u>	45
D. <u>Research at the Tandem Van de Graaff Accelerator</u>	47
1. <u>Operation and Development at the Tandem</u>	48
a. <u>Operational Experience and Changes in the Equipment (P. Billquist, W. F. Evans, F. P. Mooring, and J. R. Wallace)</u>	48
b. <u>Instrumentation at the Tandem</u>	48
(i) Charging System for the Tandem Van de Graaff Accelerator (P. J. Billquist, F. P. Mooring, and J. R. Wallace)	48
(ii) Ion-Source Development at the Tandem (W. F. Evans, F. P. Mooring, and J. L. Yntema)	49
(iii) A Voltage-Distribution System for the Tandem (P. J. Billquist, F. P. Mooring, and J. R. Wallace)	49
(iv) Beam-Profile Monitors (P. J. Billquist, F. P. Mooring, and J. R. Wallace)	51
(v) Modifications of the Magnetic-Spectrograph System for Study of Heavy-Ion-Induced Reactions (J. R. Erskine, T. H. Braid, L. R. Greenwood, and E. A. Sutter)	51
(vi) Position-Sensitive Proportional Counters (L. R. Greenwood, J. C. Stoltzfus, and T. H. Braid)	52
(vii) Physics Division On-Line Computer System (D. S. Gemmell)	52
c. <u>University Use of the 8.5-MV Tandem (F. P. Mooring)</u>	53
2. <u>Heavy-Ion Reactions</u>	56
a. <u>A Detailed Study of the $^{12}\text{C}(^{12}\text{C}, \alpha)^{20}\text{Ne}$ Reaction (L. R. Greenwood, R. E. Segel, J. R. Erskine, and H. T. Fortune)</u>	56

	<u>Page</u>
b. <u>Persistence of the $^{12}\text{C} + ^{16}\text{O} \rightarrow ^{28}\text{Si}$ Resonance in the $^{13}\text{C}(^{16}\text{O}, ^{17}\text{O})^{12}\text{C}$ Reaction (P. T. Debevec, H. J. Körner, and J. P. Schiffer)</u>	56
c. <u>Highly Excited States in ^{28}Si (P. T. Debevec, J. P. Schiffer, and W. R. Wharton)</u>	58
d. <u>The $^{16}\text{O} + ^{16}\text{O} \rightarrow \alpha + ^{28}\text{Si}^*$ Reaction (P. Debevec, W. Wharton, and J. P. Schiffer)</u>	58
e. <u>The $(^{12}\text{C}, \alpha)$ Reaction on Targets of ^{40}Ca and ^{11}B (J. R. Erskine, G. C. Morrison, and J. P. Schiffer)</u>	59
f. <u>Reactions and Inelastic Scattering with ^{18}O Ions (K. Katori, C. L. Fink, G. C. Morrison, and J. L. Yntema)</u>	59
g. <u>Gamma Spectra from $^{16}\text{O} + ^{45}\text{Sc}$ and $^{16}\text{O} + ^{40}\text{Ca}$ Reactions (W. R. Wharton, L. Meyer-Schützmeister, T. Sjoreen, and G. Hardie)</u>	60
h. <u>Transfer Reactions Induced on ^{88}Sr by ^{16}O (N. Anantaraman, K. Katori, and H. J. Körner)</u>	60
i. <u>^{16}O-Induced Reactions on ^{124}Sn (K. Katori, C. L. Fink, and J. L. Yntema)</u>	62
j. <u>^{16}O-Induced Transfer Reactions on ^{172}Yb (H. J. Körner, K. W. Jones, R. H. Siemssen, J. P. Schiffer, and A. Schwarzschild)</u>	62
k. <u>Optimum Q Values in $(^{16}\text{O}, \text{C})$ Reactions Below the Coulomb Barrier (N. Anantaraman, K. Katori, and J. P. Schiffer)</u>	65
l. <u>Use of the Magnetic Spectrograph for Heavy-Ion-Induced Transfer Reactions (J. R. Erskine, C. L. Fink, L. R. Greenwood, W. Henning, G. C. Morrison, and J. P. Schiffer)</u>	65
m. <u>Experimental and Theoretical Study of the $^{48}\text{Ca}(^{16}\text{O}, ^{14}\text{C})^{50}\text{Ti}$ Reaction (Y. Cassagnou, R. M. DeVries, M. C. Lemaire, and G. C. Morrison)</u>	67
n. <u>Comparison of Different Four-Particle Transfer Reactions on ^{54}Fe and ^{90}Zr Targets (Y. Cassagnou, H. Faraggi, G. C. Morrison, and A. Papineau)</u>	68

	<u>Page</u>
o. <u>The $^{58}\text{Ni}(\alpha, \alpha')$ Reaction to the High-Lying States in ^{58}Ni (G. Bruge, A. Chaumeaux, R. DeVries, and G. C. Morrison)</u>	69
p. <u>Study of γ Rays Following the Heavy-Ion-Induced Transfer Reactions (R. Ballini, J. Delaunay, J.-P. Fouan, and G. C. Morrison)</u>	69
<u>3. Li-Induced Reactions</u>	70
a. <u>The $^{12}\text{C}(^6\text{Li}, d)^{16}\text{O}$ Reaction (P. T. Debevec, H. T. Fortune, and R. E. Segel)</u>	70
b. <u>The $^{18}\text{O}(^6\text{Li}, ^6\text{He})^{18}\text{F}$ Reaction (W. R. Wharton and P. Debevec)</u>	71
c. <u>α Transfer in the $(^6\text{Li}, d)^{44}\text{Ti}$ Reaction (U. Strohmusch, C. L. Fink, B. Zeidman, R. N. Horoshko, H. W. Fulbright, and R. Markham)</u>	71
d. <u>^6Li and ^7Li Elastic and Inelastic Scattering in the Calcium Region (C. L. Fink, U. Strohmusch, and B. Zeidman)</u>	73
e. <u>The $(^7\text{Li}, ^6\text{Li})$ Reaction on ^{40}Ca and ^{56}Fe (C. L. Fink, K. Katori, and B. Zeidman)</u>	75
f. <u>Interference Between Coulomb and Nuclear Potentials in ^7Li Inelastic Scattering on ^{56}Fe (C. L. Fink, K. Katori, G. C. Morrison, and B. Zeidman)</u>	75
g. <u>An Attempt to Study the $^{90}\text{Zr}(^6\text{Li}, d)^{94}\text{Mo}$ Reaction (U. Strohmusch and J. P. Schiffer)</u>	77
<u>4. Charged-Particle Spectroscopy with Light Ions</u>	79
a. <u>No New States in ^{16}N (P. T. Debevec)</u>	79
b. <u>Levels in ^{29}Si by Means of the $^{28}\text{Si}(d, p)$ Reaction (L. R. Medsker and J. L. Yntema)</u>	79
c. <u>Study of the $(d_{3/2} f_{7/2})$ Interaction by Means of the $^{37}\text{Cl}(d, p)^{38}\text{Cl}$ and $^{39}\text{K}(d, p)^{40}\text{K}$ Reactions (C. L. Fink and J. P. Schiffer)</u>	79
d. <u>The $(d_{5/2} g_{9/2})$ Interaction from $^{91}\text{Zr}(^3\text{He}, \alpha)^{90}\text{Zr}$ Reaction (H. Fann, U. Strohmusch, and J. P. Schiffer)</u>	80

	<u>Page</u>
e. <u>Neutron Pickup on ^{41}K (P. T. Debevec and C. L. Fink)</u>	82
f. <u>The $^{41}\text{K}(^3\text{He}, t)^{41}\text{Ca}$ and $^{89}\text{Y}(^3\text{He}, t)^{89}\text{Zr}$ Reactions (M. Stautberg Greenwood, L. R. Greenwood, N. Anantaraman, and Maria Pluta)</u>	82
g. <u>A Study of ^{47}Ti Levels with the $^{45}\text{Sc}(\alpha, d)^{47}\text{Ti}$ Reaction (L. Meyer-Schützmeister, G. Hardie, and T. H. Braid)</u>	84
h. <u>Levels in ^{97}Nb by Means of the $^{96}\text{Zr}(^3\text{He}, d)$ Reaction (L. R. Medsker and J. P. Schiffer)</u>	86
5. <u>γ-Ray Spectroscopy with Charged-Particle-Induced Reactions</u>	89
a. <u>γ-Ray Decay in ^{36}Cl (A. S. Yousef, E. L. Sprenkel-Segel, and R. E. Segel)</u>	89
b. <u>Spectroscopy of ^{39}Ar (E. L. Sprenkel-Segel, W. C. Corwin, and R. E. Segel)</u>	89
c. <u>γ Decay of High-Spin States in ^{47}Ti (T. Sjoreen, L. Meyer-Schützmeister, and G. Hardie)</u>	91
d. <u>Radiative Capture into ^{55}Co and ^{57}Co (L. Meyer-Schützmeister, R. E. Segel, E. L. Sprenkel-Segel, J. V. Maher, D. von Ehrenstein, G. C. Kiang, R. J. Nemanich, and J. F. Tonn)</u>	93
e. <u>E2 Isomers in Odd-Neutron Nuclei (R. E. Holland, F. J. Lynch, and B. D. Belt)</u>	93
f. <u>Nuclear Data Sheets for $A = 95, 96$, and 97 (L. R. Medsker and J. P. Schiffer)</u>	95
6. <u>Structure of Actinide Nuclei</u>	95
a. <u>Single-Particle States in Actinide Nuclei (J. R. Erskine, A. M. Friedman, R. R. Chasman, and T. H. Braid)</u>	95
b. <u>Two-Quasiparticle States in Actinide Nuclei (K. Katori, A. M. Friedman, R. R. Chasman, and J. R. Erskine)</u>	97

	<u>Page</u>
c. <u>A Study of ^{249}Bk, ^{241}Am, and ^{231}Pa with Proton-Transfer Reactions (J. R. Erskine, G. Kyle, R. R. Chasman, and A. M. Friedman)</u>	99
d. <u>Pair Correlations in Actinide Nuclei (D. Albright, A. Friedman, K. Katori, and J. P. Schiffer)</u>	99
e. <u>Coupled-Channel Calculations for Sub-Coulomb Transfer Reactions on Actinide Nuclei (J. R. Erskine and T. Tamura)</u>	102
 <u>E. Research at the Cyclotron</u>	 105
a. <u>Improvements on the Spectrograph at the Cyclotron (T. H. Braid)</u>	105
b. <u>Double-Focusing Uniform-Field Magnet with Circular Poles (J. J. Livingood)</u>	106
c. <u>The $^{43}\text{Ca}(d, ^3\text{He})^{42}\text{K}$ Reaction (T. H. Braid and J. L. Yntema)</u>	106
d. <u>The $^{44}\text{Ca}(d, ^3\text{He})^{43}\text{K}$ Reaction (J. L. Yntema and T. H. Braid)</u>	106
e. <u>The (d,t) Reaction on Even-A Germanium Isotopes (J. L. Yntema)</u>	108
f. <u>The $^{96}\text{Ru}(^3\text{He}, t)^{96}\text{Rh}$ Reaction (L. R. Medsker, T. H. Braid, and J. L. Yntema)</u>	108
 II. MEDIUM-ENERGY PHYSICS	 111
 <u>1. Medium-Energy Experiments</u>	 113
a. <u>Pion Channeling (D. S. Gemmell, T. H. Braid, R. E. Holland, J. C. Poizat, J. P. Schiffer, T. P. Wangler, and B. Zeidman)</u>	113

	<u>Page</u>
b. <u>K-Mesic and Antiprotonic Atoms in the Interaction Between Hadrons and Nuclei</u> (P. D. Barnes, S. Dytman, M. Eckhause, R. A. Eisenstein, D. A. Jenkins, J. R. Kane, A. R. Kunselman, W. C. Lam, J. Miller, R. J. Powers, R. P. Redwine, B. L. Roberts, J. P. Schiffer, R. E. Segel, R. B. Sutton, and R. E. Welsh)	114
2. <u>Development of LAMPF Facilities; Instrumentation</u>	115
a. <u>System to Analyze Measurements of Fields in EPICS Magnets</u> (Thomas P. Wangler)	115
b. <u>A Monte Carlo Ray-Tracing Routine for the EPICS Channel</u> (Thomas P. Wangler)	118
c. <u>Multi-Wire Proportional Counters</u> (T. H. Braid)	119
 III. THEORETICAL PHYSICS	121
1. <u>Nuclear Scattering and Reactions Involving Heavy Ions</u>	122
a. <u>Studies of Heavy-Ion Transfer Reactions</u> (D. H. Gloeckner, M. H. Macfarlane, and F. J. D. Serduke)	122
b. <u>Semiclassical Treatment of Heavy-Ion Transfer</u> (G. Theodorou and M. H. Macfarlane)	122
c. <u>Structure Amplitudes for Multinucleon Transfer</u> (D. Kurath)	123
d. <u>Dependence of α-Structure Amplitudes on Configuration Space</u> (D. Kurath and I. S. Towner)	123
e. <u>CCBA Analysis of Heavy-Ion Reactions</u> (K. S. Low and T. Tamura)	124
2. <u>Nuclear Structure</u>	127
a. <u>Properties of the Argon Isotopes</u> (D. H. Gloeckner, R. D. Lawson, and F. J. D. Serduke)	

	<u>Page</u>
b. <u>Inhibited Transitions and Isomeric States in the N = 50 Isotones</u> (D. H. Gloeckner, M. H. Macfarlane, R. D. Lawson, and F. J. D. Serduke)	127
c. <u>SU(3) Shell-Model Program for Nuclei with A = 12—20</u> (A. Müller-Arnke)	128
d. <u>Hartree-Fock Studies of Deformed Nuclei by Use of Density-Dependent and Three-Body Effective Interactions</u> (B. D. Chang and M. H. Macfarlane)	128
3. <u>Nuclear Forces, Nuclear Scattering, and Nuclear Matter</u>	129
a. <u>Separable Potentials for the 3S_1 - 3D_1 N-N Interaction</u> (Steven Pieper)	129
b. <u>Perturbative Calculation of Nucleon-Deuteron Scattering</u> (Steven Pieper)	129
c. <u>The Inverse Problem with Constraints</u> (J. E. Monahan, C. M. Shakin, and R. M. Thaler)	131
d. <u>Electric Form Factors of the Deuteron</u> (F. Coester and A. Ostebee)	131
e. <u>Relativistic Effects in Phenomenological Nucleon-Nucleon Potentials</u> (F. Coester, P. Havas, and H. W. Woodcock)	133
f. <u>Relativistic Effects in Nuclear Matter</u> (F. Coester and F. J. D. Serduke)	133
g. <u>Three-Body Correlations in Nuclear Matter</u> (B. Day and F. Coester)	136
h. <u>Boson Expansion Technique Applied to the Description of the Nuclear Collective Motions</u> (D. Braunschweig and T. Tamura)	136
4. <u>Computing Language and Technique for Scientific Research</u>	137
a. <u>The "Speakeasy" User Community</u> (S. Cohen)	137
b. <u>Documentation of "Speakeasy"</u> (S. Cohen, J. K. Fink, R. N. Kimmel, K. Rich, F. J. D. Serduke, and C. M. Vincent)	137
5. <u>Other Theoretical Physics</u>	139

	<u>Page</u>
a. <u>Λ-Particle Binding in Nuclear Matter: the Λ Well Depth (A. R. Bodmer and D. M. Rote)</u>	139
b. <u>Collapsed Nuclei and Nuclear Collapse (A. R. Bodmer)</u>	139
c. <u>Mutually Orthogonal Orthogonalized Plane Waves (G. E. Juras, J. E. Monahan, C. M. Shakin, and R. M. Thaler)</u>	141
d. <u>Presymmetry of Classical Relativistic Fields (Y. Avishai and H. Ekstein)</u>	141
e. <u>An Explicit Physical Interpretation of General Relativity (Y. Avishai and H. Ekstein)</u>	142
f. <u>Production of Coherent Mixtures of Resonances in the Quark Model (Harry J. Lipkin)</u>	143
g. <u>Quark-Model Predictions for Reactions with Hyperon Beams (Harry J. Lipkin)</u>	143
h. <u>New Finite-Energy Sum Rules Based on ρ and ω Exchange (Harry J. Lipkin)</u>	144
i. <u>Experimental Tests for Exotics in the Baryon-Antibaryon System (Harry J. Lipkin)</u>	144
j. <u>Light-Cone Relations for the Strangeness-Changing Structure Functions (Harry J. Lipkin and E. A. Paschos)</u>	145
k. <u>Symmetry Relations for Deep Inelastic Processes (Harry J. Lipkin and E. A. Paschos)</u>	145

IV. EXPERIMENTAL ATOMIC PHYSICS 147

1. <u>Interaction of Vacuum-Ultraviolet Radiation with Gases and Vapors</u>	148
a. <u>Photoionization Studies with the New 3-m Monochromator and Quadrupole Mass Filter</u>	148

	<u>Page</u>
(i) Photoionization Mass Spectrometer with High-Resolution Monochromator (W. T. Jivery and W. A. Chupka)	148
(ii) High-Resolution Photoionization Mass-Spectrometric Study of the O ₂ Molecule (W. A. Chupka, P. M. Dehmer, W. T. Jivery, and J. Berkowitz)	149
(iii) Photoionization Mass Spectrometry of H ₂ O and H ₂ O ₂ (W. A. Chupka, W. T. Jivery, and J. Berkowitz)	152
(iv) High-Resolution Photoabsorption, Photoionization, and Chemi-ionization Studies of the Hydrogen Molecule (W. A. Chupka and W. T. Jivery)	153
(v) Ion-Molecule Reactions in Mixtures of Rare Gas and Hydrogen by High-Resolution Photoionization Mass Spectrometry (W. A. Chupka and W. T. Jivery)	153
(vi) Reactions of Highly Excited Rydberg States of Rare Gases (W. A. Chupka, S. Antos, and W. T. Jivery)	154
<u>b. Photoionization Studies with the 1-m Monochromator</u>	155
(i) Photoionization of HOF with Mass Analysis (J. Berkowitz, E. H. Appelman, and W. A. Chupka)	155
(ii) Photoionization Mass Spectrometry of F ₂ O (J. Berkowitz, P. M. Dehmer, and W. A. Chupka)	156
(iii) Photoionization of Atomic Oxygen (P. M. Dehmer, J. Berkowitz, and W. A. Chupka)	156
(iv) Photoionization of Atomic Nitrogen (P. M. Dehmer, J. Berkowitz, and W. A. Chupka)	157
<u>c. Photoelectron Spectroscopy with the Cylindrical-Mirror Analyzer</u>	158
(i) The High-Temperature Vapors GaX ₃ and InX ₃ (X = Cl, Br, or I) (J. Berkowitz and J. L. Dehmer)	158

	<u>Page</u>
(ii) The High-Temperature Vapors TlF and Tl_2F_2 (J. Berkowitz, J. L. Dehmer, and L. C. Cusachs)	158
(iii) Photoelectron Spectra of Zn and Cd Atoms (J. Berkowitz and J. L. Dehmer)	160
(iv) Photoelectron Spectra of Butyl Naphthalene and Butyl Dinaphthalene (J. Berkowitz, J. L. Dehmer, and M. Szwarc)	161
(v) Photoelectron Spectrum of HOF (J. Berkowitz, J. L. Dehmer, and E. H. Appelman)	162
(vi) Comparison of Photoelectron Spectral Inten- sities and Franck-Condon Factors for H_2 , HD, and D_2 (J. Berkowitz and R. Spohr)	162
(vii) Band Envelopes, Rotational Transitions, and the $^2\Pi_{3/2}$ - $^2\Pi_{1/2}$ Spin-Orbit Splitting of HF^+ (J. Berkowitz, T. E. H. Walker, and P. M. Dehmer)	163
d. <u>Beam-Foil Auger Spectroscopy</u> (J. Berkowitz, J. L. Dehmer, D. S. Gemmell, and J. L. Yntema)	164
<u>2. Interaction of Energetic Particles with Solids</u>	165
a. <u>The Effect of Channeling on the Shape and Density of Radiation Blisters on Monocrystalline Metals</u> (M. Kaminsky and S. K. Das)	165
b. <u>The Effect of Irradiation Temperature on Blister Morphology</u> (M. Kaminsky and S. K. Das)	168
c. <u>Radiation Blistering of Polycrystalline Metals</u>	170
(i) Irradiation of Nb by D^+ Ions (M. Kaminsky and S. K. Das)	170
(ii) Irradiation of Nb by He^+ Ions (S. K. Das and M. Kaminsky)	170
(iii) A Comparative Study of Blistering in Nb, V, and V-20%Ti (S. K. Das and M. Kaminsky)	171
(iv) He Blistering in Nb Damaged by 14-MeV Neutron Irradiation (M. Kaminsky and S. K. Das)	173
d. <u>Sputtering by MeV Neutrons</u> (M. Kaminsky and J. H. Peavey)	174

	<u>Page</u>
e. <u>Development of Techniques for Measuring Surface Contaminations in Very Small Concentrations (10^{-1} — 10^{-4} Monolayers) (M. Kaminsky and P. Dusza)</u>	175
f. <u>Phenomena Induced by Photon Impact (M. Kaminsky, J. Peavey, and S. Das)</u>	175
g. <u>Polarization of Particles by Channeling (M. Kaminsky)</u>	176
h. <u>Polarization of Particles by Small-Angle Scattering (M. Kaminsky)</u>	177
i. <u>Preparation and Characterization of Thin Monocrystalline Foils (M. Kaminsky, T. Campana, and P. Dusza)</u>	178
j. <u>Operation of the 2-MV Van de Graaff Accelerator (R. Amrein, T. Campana, P. Dusza, and J. R. Wallace)</u>	179
k. <u>Microscopic Location of ^{17}O, ^{18}O, and ^{15}N (G. R. Ringo and V. E. Krohn)</u>	179
3. <u>Mössbauer Measurements</u>	180
a. <u>Mössbauer Studies of Ions in Aqueous Glass (S. L. Ruby and B. J. Zabransky)</u>	180
b. <u>^{57}Fe Mössbauer Spectroscopy with ^{57}Mn Sources (R. S. Preston and B. J. Zabransky)</u>	181
c. <u>Mössbauer Experiments with the 93.26-keV Transition in ^{67}Zn (G. J. Perlow, W. Potzel, L. E. Campbell, and L. E. Conroy)</u>	183
d. <u>The Anisotropic Debye-Waller Factor of CsC_8 and the Quadrupole Moment of the First Excited State in ^{133}Cs (L. E. Campbell, G. L. Montet, and G. J. Perlow)</u>	185
e. <u>Lifetime of the ^{197}Au Mössbauer γ Ray (Frank J. Lynch)</u>	185
f. <u>Anomalously Narrow Mössbauer Linewidth in ^{197}Au (W. Potzel and G. J. Perlow)</u>	187

	<u>Page</u>
<u>4. Atomic-Beam Research</u>	189
<u>a. Hyperfine Structure of Stable Isotopes (W. J. Childs and L. S. Goodman)</u>	189
<u>b. Hyperfine-Structure Studies of Radioactive Isotopes (H. Diamond, L. S. Goodman, and H. E. Stanton)</u>	190
<u>c. Atomic and hfs Spectroscopy of ^{221}Fr (H. Diamond, M. S. Fred, L. S. Goodman, B. Greenebaum, and F. S. Tomkins)</u>	190
<u>d. Low-Energy Positron and Positronium Experiments (L. S. Goodman)</u>	191
<u>5. Radio-Frequency Plasmas</u>	192
<u>a. Confinement of Low-Density Plasma in a Microwave Cavity (A. J. Hatch and C. F. Shelby)</u>	192
<u>b. Computer Simulation of RF Confinement of Plasma (A. J. Hatch and J. L. Shohet)</u>	192
<u>c. Bounded Plasmas in Resonant Cavity Fields (A. J. Hatch and J. Hamann)</u>	193
<u>d. Plasmas in Toroidal Resonant Cavities (A. J. Hatch, S. G. Sanders, M. Hasan, and J. Robinson)</u>	193
<u>e. Parametric Study of Tokamak Plasma Systems (A. J. Hatch and J. F. Etzweiler)</u>	195

V. PUBLICATIONS FROM 1 APRIL 1972 THROUGH 31 MARCH 1973	197
--	-----

VI. STAFF MEMBERS OF THE PHYSICS DIVISION	223
---	-----

I. EXPERIMENTAL LOW-ENERGY NUCLEAR PHYSICS

INTRODUCTION

The over-all purpose of the program continues to be to obtain a much more complete understanding of all aspects of the atomic nucleus: its structure, its simple modes of excitation, and its reactions with simple projectiles and with other nuclei. Consequently, the program consists mainly of experimental and theoretical studies of the energies, quantum numbers, and lifetimes of low-lying nuclear states, and of studies of nuclear reactions involving both light projectiles and heavy-ion beams. Experimenters and theorists work closely together so that new results in one area may suggest new approaches in another. An effort is made to stress work that can be done more advantageously at Argonne than elsewhere because of the special facilities available here. In view of the history and tradition of the Laboratory, it is natural that considerable emphasis is placed on studies of interactions between nuclei and neutrons. Even greater effort is devoted to experiments using beams of charged particles, with principal attention to heavy-ion-induced reactions. These activities are balanced by a diversified program of other nuclear-physics investigations and by a proportionate level of development of experimental techniques and apparatus.

With a few exceptions, the program in experimental nuclear physics is most easily outlined by subdividing the work into various categories for which a major piece of equipment or an important experimental technique is the unifying factor. The current categories are:

- (1) Studies of the neutron and of neutron-induced reactions at the reactor CP-5.
- (2) Threshold photoneutron experiments at the electron Linac.
- (3) Neutron and charged-particle reactions at the 4-MV Dynamitron.
- (4) Charged-particle reactions at the tandem Van de Graaff accelerator.
- (5) Charged-particle reactions at the 60-in. cyclotron.
- (6) Various other experiments, including the use of atomic-physics techniques to obtain nuclear information.

Some physicists restrict their efforts to the use of a single machine or technique, whereas others investigate related problems with several systems of apparatus. The group as a whole may be described as being problem oriented rather than technique oriented. In particular, although Medium-Energy Physics is presented here as a separate program (Sec. II) because of its special technological problems, we do not think of it as a separate scientific area. Many of the same persons work in both programs.

A. RESEARCH AT THE REACTOR CP-5

The Physics Division employs CP-5 for two general categories of neutron research: (a) fundamental experiments with thermal neutrons and (b) studies of neutron-capture γ rays. In spite of the relatively low flux of CP-5, it continues to be an excellent reactor for this work. This is because the flux is quite adequate for most of the experiments and especially because of the advanced experimental systems that have been developed over a period of many years.

Research on neutron-capture γ rays is carried out at CP-5 with three major experimental systems, which together constitute one of the world's most refined and varied experimental setups for neutron-capture γ -ray spectroscopy. These systems are (1) an internal-target facility used for the study of high-energy γ rays, (2) a bent-crystal diffraction spectrometer for precision measurements on low-energy γ rays, and (3) an internal-conversion spectrometer. The research carried out with these experimental systems will continue to emphasize the spectroscopy of low-energy nuclear states, but some of the experiments also provide important information about the mechanisms of neutron capture.

During the past year, a team of staff members and students from Northern Illinois University have become increasingly active in the use of the capture- γ -ray facilities at CP-5.

1. FUNDAMENTAL EXPERIMENTS

a. Nuclear Raman Scattering of Photons by Nuclei¹

H. E. Jackson and K. J. Wetzels*

Studies of the elastic and inelastic scattering of 10.8-MeV photons by heavy nuclei have continued during the past year at the

*University of Portland, Portland, Oregon.

¹H. E. Jackson and K. J. Wetzels, Phys. Rev. Letters 28, 513 (1972).

internal-target facility of the CP-5 reactor. In measurements reported earlier, the inelastic scattering by ^{238}U and ^{232}Th was found to be much weaker than predicted by currently accepted models of the giant dipole resonance. This discrepancy was ascribed to the presence of a substantial direct-reaction component which accounts for about 15% of the photon absorption in the region of the giant dipole resonance. The results indicate that this type of measurement can yield information of great value in establishing details of the photonuclear interaction.

In a series of measurements exploring these possibilities, 10.8-MeV photons have been scattered by a range of lanthanide and actinide nuclei from Tb to U. The nuclei were chosen on the basis of the availability of new high-precision data on the parameters of the giant dipole resonance in their photoabsorption cross section. The general trend observed for U and Th persists throughout the lanthanide region—i. e., Raman scattering is weaker than expected. Analysis of the data is continuing.

b. Measurements of Spatial Asymmetries in the Decay of Polarized Neutrons

V. E. Krohn and G. R. Ringo

Knowledge of the asymmetry coefficients in the expression describing the decay of polarized neutrons is important to the theory of the weak interaction. The electron asymmetry coefficient A leads to a value for G_A/G_V , the ratio of the beta-decay coupling constants. The neutrino asymmetry coefficient B helps to establish an upper limit on the coupling constants G_S and G_T . A nonzero result for the third coefficient D would indicate a violation of time-reversal invariance. More precise experimental measurements of any or all of these coefficients will provide more stringent tests of the theory of the weak interaction. This is particularly important because, in the case of neutron decay, the comparison of theory and experiment is free from the complications associated with nuclear structure.

It is believed that the analysis of data already obtained with the apparatus at the reactor CP-5 will lead to improved experimental values for the coefficients A and B.

2. NEUTRON-CAPTURE γ RAYS

The neutron-capture γ -ray program at CP-5 includes (1) measurements of low-energy spectra both with the bent-crystal spectrometer and with Ge(Li) detectors, (2) measurements of the high-energy spectra produced by capture of thermal neutrons, (3) measurements of average-resonance-capture spectra, and (4) measurements of internal-conversion-electron spectra. This diversity of techniques is needed because only rarely is a single kind of measurement able to unravel the complex decay schemes that are involved.

Again because of the complexity of the (n, γ) spectra, the range of problems that can be studied effectively is severely limited by the inadequacies of the existing techniques. Thus, a good research program must devote considerable effort to the development of new or improved techniques. During the past year, our main efforts in this regard have been devoted to (1) the development of an efficient spectrometer for the detection of the very-high-energy γ ray (21.6 MeV) that results from thermal-neutron capture in ^3He , and (2) to the improvement of the resolution of the bent-crystal spectrometer. In spite of the highly-developed state of the latter, it still seems to be feasible to push the diffraction technique much farther than it has been either here or elsewhere.

Most of the CP-5 investigations carried out by means of the (n, γ) technique are concerned with the spectroscopy of low-energy states. However, a few are concerned with the mechanisms of neutron capture and with the behavior of high-energy radiative transitions. In practice, the experimenter often is forced to investigate both of these problems simultaneously because he cannot extract the one kind of information from the data without having a better understanding of the other.

The various individual subjects of investigation in the (n, γ) program are outlined below. Several of the experimental techniques mentioned above are brought to bear on most of the research problems, with the result that some of the investigations are very time consuming and extend over a period of several years.

a. Experimental Systems

The three experimental systems now in use in (n, γ) experiments are described briefly below. The names associated with each instrument are those of the persons who are principally responsible for its continuing development.

(i) High-Sensitivity Internal-Target Facility

G. E. Thomas and J. R. Specht

Both thermal-neutron capture and average resonance capture are studied at the internal-target facility. The sample under investigation is placed at the center of a through tube that passes tangent to the reactor core. The (n, γ) spectrum is measured by a refined annihilation-pair spectrometer consisting of a Ge(Li) detector and a large NaI annulus that efficiently detects the annihilation quanta. A carefully designed collimation system assures that the Ge(Li) spectrometer sees only the sample of interest, and not the walls of the through tube.

The internal-target facility is used primarily to measure the high-energy portion ($E_{\gamma} > 5 \text{ MeV}$) of the capture γ -ray spectrum. A bare sample gives a spectrum that is dominated by thermal-neutron capture whereas a boron-surrounded sample is used to produce an average-resonance-capture spectrum, i. e., a spectrum formed by neutron capture in a band of energies that extends typically from 50 to 2000 eV.

The internal-target facility was used almost continuously during the past year.

(ii) The 7.7-m Bent-Crystal Spectrometer

R. K. Smither

The 7.7-m bent-crystal spectrometer is used to measure the low-energy portion (20 keV—2 MeV) of the γ -ray spectra formed by thermal-neutron capture in separated-isotope samples placed in the high-flux region of the reactor CP-5. These spectra are combined with

the high-energy (n, γ) data taken with a Ge(Li) spectrometer to develop the level schemes of nuclei with medium and high Z. The main value of the bent-crystal spectrometer is its extremely good energy resolution for low-energy γ rays.

The bent-crystal spectrometer was operated approximately 50% of the time during the calendar year 1972. The typical operation schedule was 24 hours a day for 2–4 weeks at a time, followed by a week or two of half-day experiments and 2–3 weeks of complete downtime. This downtime was often used for routine maintenance and general improvements.

(iii) Internal-Conversion Electron Spectrometer

S. B. Burson and C. H. Batson

The internal-conversion electron spectrometer consists of a superconducting magnet to guide the electrons and a solid-state electron detector. In comparison with other kinds of electron spectrometers, the system is unusual because of its high detection efficiency and because it can be used in coincidence with another spectrometer such as a Ge(Li) detector.

b. γ -Ray Intensity Standards

(i) High-Energy Standards: The Reactions $^{14}\text{N}(n, \gamma)^{15}\text{N}$, $^{35}\text{Cl}(n, \gamma)^{36}\text{Cl}$, and $^{53}\text{Cr}(n, \gamma)^{54}\text{Cr}$

G. D. Loper and G. E. Thomas

The relative and absolute intensities of γ rays from thermal-neutron capture in ^{53}Cr , ^{52}Cr , ^{50}Cr , and ^{35}Cl have been determined over the energy range 1.8–11 MeV. The absolute intensities were measured by a method in which transition intensities are compared with the well-known 100% intensity of the 7368-keV transition in ^{208}Pb . Detector-efficiency curves were computed from the previously reported

Fig. 1. Partial thermal-neutron-capture γ -ray spectrum of the sample composed of Cl, Pb, and melamine. Lines are identified by isotope and the γ -ray energy in keV.

relative intensities for transitions in $^{14}\text{N}(n, \gamma)^{15}\text{N}$ and in $^{53}\text{Cr}(n, \gamma)^{54}\text{Cr}$, and the good agreement between their shapes over a wide energy range suggests that both sets of intensities are reliable. The results of this investigation have been published.¹

¹G. D. Loper and G. E. Thomas, Nucl. Instr. Methods 105, 453 (1972).

(ii) Targets with Prominent Low-Energy Resonances

G. E. Thomas and L. M. Bollinger

The internal-target facility at CP-5 has been shown to be excellent for the measurement of absolute intensities of thermal-neutron-capture γ rays. In the measurements reported heretofore, the sample has been placed at the center of the through tube that passes near the core of the reactor. Here the thermal-neutron flux is a maximum, but epi-thermal neutrons are also relatively intense (Cd ratio ≈ 7). These epi-thermal neutrons do not cause significant errors in the measured intensities of the thermal-neutron-capture γ rays for nuclides such as $^{53,52,50}\text{Cr}$ and ^{35}Cl (for which results are reported above), which have no low-energy resonances. For nuclides such as ^{197}Au , however, which has a prominent resonance at 4.9 eV, the presence of the epi-thermal neutrons may be a problem.

The present work has shown that the possible influence of the epi-thermal neutrons can be eliminated by placing the sample where the intensity of the epi-thermal neutrons is negligible—far from the center of the reactor. The drawback is that the absolute magnitude of the thermal-neutron flux is an order of magnitude lower there than at the center. Nevertheless, the over-all sensitivity of the internal-target system is so great that measurements of good quality can be made.

Samples of Au and Ta have been measured with the new technique. For Au, the derived thermal-neutron-capture intensities are $\sim 15\%$ lower than had been obtained with the sample at the position of maximum flux; for Ta, the intensities are $\sim 20\%$ lower.

Now that the question about the possible influence of epithermal neutrons has been answered, the revised result for Au may be used with confidence as a convenient intensity standard.

(iii) Absolute Intensities for $^{113}\text{Cd}(n, \gamma)^{114}\text{Cd}$

R. K. Smither and G. E. Thomas

The $^{113}\text{Cd}(n, \gamma)^{114}\text{Cd}$ spectrum resulting from thermal-neutron capture in a mixed sample of ^{113}Cd and Melamine ($\text{C}_3\text{H}_6\text{N}_6$) was used to measure the absolute cross section for the $^{113}\text{Cd}(n, \gamma)^{114}\text{Cd}$ reaction and the absolute energies and intensities in the γ -ray spectrum. The high cross section of ^{113}Cd has made it difficult to do this in normal experiments because of self-shielding effects in the sample. (The published values vary by a factor of two.) A dilution of 10^{-4} to 1 was needed in the sample to obtain good results. The sample was left in the reactor long enough to obtain a 65% burnup of the ^{113}Cd in the source. This gives an independent determination of the capture rate in the ^{113}Cd part of the sample (a quantity equal to the cross section times the effective neutron flux). This approach avoids uncertainties involved in calculating the resonance integral for the Cd sample—a calculation which can result in an appreciable error if the energy distribution of the neutron flux is not known accurately.

Fig. 2

c. Giant-Resonance-Like Structure for M1 Radiation

L. M. Bollinger and G. E. Thomas

As has been reported previously, average-resonance-capture measurements on the reactions $^{117}\text{Sn}(n, \gamma)^{118}\text{Sn}$ and $^{119}\text{Sn}(n, \gamma)^{120}\text{Sn}$ seemed to show that the widths for M1 primary transitions exhibit a giant-resonance-like structure at about 8.3 MeV. However, the results of the initial measurements were not quite conclusive because of statistical uncertainties caused by the fact that only a few initial states contributed to the measured average-resonance-capture spectrum. In an effort to

Fig. 2. A comparison between the high-energy $^{113}\text{Cd}(n, \gamma)^{114}\text{Cd}$ spectra measured at the start and near the end of the absolute-intensity measurements. The reduction of the $^{113}\text{Cd}(n, \gamma)^{114}\text{Cd}$ γ -ray intensities relative to the $^{14}\text{N}(n, \gamma)^{15}\text{N}$ γ -ray intensities results from the high neutron-capture rate in the ^{113}Cd part of the sample.

reduce the statistical errors, we have increased the neutron-energy range contributing to the capture spectrum by increasing the thickness of the boron filter. The previously observed giant-resonance structure is still present in the new data. However, the interpretation of the observed peak is still inconclusive because the thick boron filter causes two new experimental difficulties: (1) a sizable contribution by unwanted p-wave neutrons and (2) a poor signal-to-background ratio. In view of these difficulties, the experiment has been discontinued.

d. Radiative Capture of Thermal Neutrons in ^3He

L. M. Bollinger, J. R. Specht, and G. E. Thomas

Flowers and Mandl have shown from rather general considerations that the $^3\text{He}(n, \gamma)^4\text{He}$ cross section for electric dipole and quadrupole radiation approaches zero as the neutron energy approaches zero. Thus, the (n, γ) reaction for thermal neutrons is expected to be dominated by magnetic dipole radiation, which is also very weak and involves matrix elements that are masked in other reactions. Previous efforts to measure the (n, γ) cross section for thermal neutrons have not been successful because of its small size and because $\sigma(n, p)$ is very large. We have solved the experimental problem by mounting a ^3He sample in the high-flux region of the CP-5 reactor and detecting the 20.6-MeV thermal-neutron-capture γ ray with a spectrometer consisting of a large array of NaI(Tl) scintillators.

Initially, the 20.6-MeV γ -ray line of interest (which has an intensity of only about 1 count per minute) was completely obscured by cosmic-ray background and by pile-up pulses resulting from several kinds of nuclear radiation. However, by imposing appropriate pulse-height requirements on the various parts of the detector system, it proved possible to observe the 20.6-MeV γ ray with high efficiency and with a good signal-to-background ratio. The preliminary result of the measurement is $\sigma(n, \gamma) = 60 \pm 30 \text{ } \mu\text{b}$, where the error results mainly from uncertainties in the efficiency of the detection system. This capture cross section is

Fig. 3

Fig. 3. Partial thermal-neutron-capture γ -ray spectrum obtained with a sample consisting of 1 atm of ^3He enclosed in a thin-walled aluminum can 1.5 in. in diameter and 12 in. long. The well isolated γ -ray peak at 20.6 MeV is well above the energy range in which the background is high.

some two orders of magnitude smaller than that of any other nucleus for which the capture cross section has been reported.

e. Average Resonance Neutron Capture Leading to Levels in ^{112}Cd and ^{114}Cd

R. K. Smither, G. E. Thomas, and L. M. Bollinger

The average resonance neutron capture has been studied with a natural-abundance sample of Cd and one highly enriched in ^{111}Cd . The remaining reaction, $^{113}\text{Cd}(n, \gamma)^{114}\text{Cd}$ to be done with an enriched sample of ^{113}Cd , awaits the arrival of a new Ge(Li) detector for the CP-5 system. Although Cd ($Z = 48$) is only two protons away from the closed proton shell at $Z = 50$, the level scheme is quite insensitive to the addition of two neutrons in going from ^{112}Cd to ^{114}Cd . These two isotopes with $N = 64$ and 66 , respectively, fall about midway between the closed neutron shells at $N = 50$ and 82 . Their remoteness from a neutron closed shell may explain the insensitivity to neutron number, which is analogous to that found in the rare earth region, where the nuclear deformation is almost independent of neutron number. One of the major objectives of this new work is to better define the negative-parity states. If there is a difference between the two nuclei, it may appear in these states—if not in the energies of the levels then possibly in the γ -ray branching ratios of the E1 transitions between the negative- and positive-parity states.

Fig. 4

f. Level Structure of the Odd-A Isotopes of Sm

R. K. Smither and G. E. Thomas

The object of these experiments is to develop the level schemes of the odd-A isotopes of Sm ($A = 145, 149, 151, 153$, and 155) and to follow the trends and changing patterns of the level energies and γ -ray branching ratios of the low-energy rotational bands, as one moves from the region of stable deformation (isotope ^{155}Sm) to the nearly-closed-shell isotope ^{145}Sm . Three kinds of neutron-capture γ -ray spectra were

Fig. 4. Comparison of the ^{112}Cd and ^{114}Cd level schemes developed from (n, γ) experiments. Spin and parity assignments for positive-parity levels are indicated to the right for positive-parity states and to the left for negative-parity states. A few of the observed low-energy γ -ray transitions are shown to indicate the detailed information that is available in the data from the bent-crystal γ -ray diffraction spectrometer. Some of these γ -ray lines are very weak, with intensities of only a few photons per 10^5 neutron captures.

measured at the internal-target facility: (1) the high-energy region (4–10 MeV) of the thermal-neutron-capture spectrum, (2) the intermediate-energy region (0.5–3 MeV) of the thermal-neutron-capture spectrum, and (3) the average-resonance-capture spectrum. The bent-crystal spectrometer was used for measurements in the low-energy range 20–2000 keV.

The reactions studied are $^{154}\text{Sm}(n, \gamma)^{155}\text{Sm}$, $^{152}\text{Sm}(n, \gamma)^{153}\text{Sm}$, $^{150}\text{Sm}(n, \gamma)^{151}\text{Sm}$, $^{148}\text{Sm}(n, \gamma)^{149}\text{Sm}$, and $^{144}\text{Sm}(n, \gamma)^{145}\text{Sm}$. The relative intensities of the different average-resonance-capture spectra have been analyzed in detail and the weak M1 and E2 transitions can be identified. This makes it possible to assign parities to all low-lying levels with spin $\frac{1}{2}$ and $\frac{3}{2}$ and to identify all $\frac{5}{2}^+$ states uniquely. The Ge(Li) data are combined with the crystal-spectrometer results on the low-energy portion of the (n, γ) spectrum to develop the level schemes and the details of the γ -ray transitions between the low-lying levels.

The level scheme of ^{153}Sm was quite well established in the previously published bent-crystal work. The new data plus some new charged-particle work have eliminated the remaining uncertainties with regard to spins and parities of the known levels below 1 MeV. The proton and neutron configurations responsible for the rotational bands that make up this level scheme are also well defined now.

The combination of our new work with the results of (1) crystal measurements (Argonne), (2) β -decay measurements (Chalk River), and (3) recent charged-particle measurements (McMaster and others) have led to a fairly complete level scheme for ^{151}Sm . The level schemes of ^{153}Sm and ^{151}Sm are quite similar in structure.

We are now trying to extend the Sm studies to ^{155}Sm on the neutron-rich side and to ^{147}Sm and ^{145}Sm on the neutron-deficient side. The ^{149}Sm level scheme is still quite preliminary, but it looks similar to the ^{153}Sm scheme. The ^{145}Sm scheme, however, is quite different. This nucleus is only one neutron away from the closed shell

at $N = 82$, so this is not too surprising. What is interesting is that above 1 MeV it developed a level structure that is quite similar to those of ^{151}Sm and ^{153}Sm . The level structure of ^{155}Sm appears to fall somewhere between ^{151}Sm and ^{147}Sm .

g. Level Structure of ^{148}Sm and ^{150}Sm

R. K. Smither, G. E. Thomas, and D. J. Buss

The main objective of this work is to compare the details of the level structure and of the low-energy γ -ray branching ratios in ^{148}Sm and ^{150}Sm . Previously published (p,t) and (t,p) data suggest that the ground-state configurations of ^{148}Sm and ^{150}Sm are quite different, whereas the previously published (n, γ) work of Buss and Smither indicate that the level structure of the positive-parity states in the two nuclei is almost identical. In order to clarify the matter, we have measured the four kinds of (n, γ) spectra listed in the preceding section. Since the average-resonance-capture measurements were made with highly enriched samples, the quality of the data is greatly improved and the negative-parity states can be identified reliably and with good sensitivity.

h. Excited States in $^{160}_{65}\text{Tb}$, $^{150}_{62}\text{Sm}$, and $^{182}_{73}\text{Ta}$

S. B. Burson, F. J. Zehr, and C. H. Batson

(i) $^{159}\text{Tb}(n,\gamma)^{160}\text{Tb}$

The odd-odd nucleus $^{160}_{65}\text{Tb}$ is formed by neutron capture in ^{159}Tb , which occurs naturally as a 100% isotope. The primary γ -ray spectra from thermal-neutron capture and from average resonance capture were examined by irradiating samples in the internal-target facility at the Argonne CP-5 reactor. The analysis of these data is not yet complete, but a number of significant conclusions have been reached.

To study the low-energy portion of the capture γ -ray spectra, ^{159}Tb targets placed in the Argonne superconducting spectrometer

were irradiated with a flux of 1.0×10^8 neutrons $\text{cm}^{-2} \text{sec}^{-1}$ from the "high quality" external-beam facility at the east thermal column of the CP-5 reactor. The electron and γ -ray spectra were measured both singly and in coincidence. The coincidence data are currently being analyzed.

In its present stage of development, the decay scheme of ^{160}Tb comprises 32 excited states, between which approximately 75 γ -ray transitions have been assigned. Approximately 60 excited states below 1 MeV are populated by decay from the capture states, whose spins and parities are 1^+ and 2^+ . The ground state of ^{160}Tb is characterized by the configuration $p_{3/2}^+ [411] \uparrow + n_{3/2}^- [521] \uparrow$, in which the coupling of Nilsson orbitals results in spin and parity $I^\pi = 3^-$, and corresponds to the $\Sigma = 1$ state predicted by the Gallagher-Moszkowski coupling rule. The expected 1^- state resulting from the configuration $p_{3/2}^+ [411] \uparrow - n_{5/2}^- [523] \downarrow$ is found at 63.80 keV; the data indicate that two and perhaps three members of a rotational band built on this level are also populated. Of particular interest are levels at 78.9, 139.7, 133.1, and 236.2, which can be interpreted as the 0^- , 2^- , 1^- , and 3^- members of a $K = 0$ band resulting from the particle configuration $p_{3/2}^+ [411] \uparrow - n_{3/2}^- [521] \uparrow$, which represents the $\Sigma = 0$ member of the ground-state doublet.

(ii) $^{181}\text{Ta}(n, \gamma)^{182}\text{Ta}$ and $^{149}\text{Sm}(n, \gamma)^{150}\text{Sm}$

Since both the high- and low-energy γ -ray spectra of ^{182}Ta and ^{150}Sm had been studied earlier by others, our work on these nuclides has been restricted to electron-gamma coincidences. These data are now being analyzed.

i. Level Schemes of ^{178}Hf and ^{180}Hf

R. K. Smither, D. L. Bushnell, and D. J. Buss

The object of these investigations is to determine the level structure of ^{178}Hf and ^{180}Hf , seemingly similar nuclides that are

Fig. 6. Low-energy (n, γ) spectrum from the $^{179}\text{Hf}(n, \gamma)^{180}\text{Hf}$ reaction, as measured by the Argonne 7.7-m bent-crystal γ -ray diffraction spectrometer. Some of the weaker lines are not shown. Special labels on the lines indicate the intensities of the very strong lines in the spectrum. Transitions between the levels of the ground-state rotational band are indicated by the labels $(2^+ \rightarrow 0^+)$, $(4^+ \rightarrow 2^+)$, and $(6^+ \rightarrow 4^+)$.

Fig. 7. Intensities of primary γ rays following average resonance neutron capture in ^{179}Hf , plotted as a function of energy. An E^6 energy dependence has been removed from the intensity to obtain an approximate equalization of all transition intensities of a particular multipolarity. The complete separation of the E1 transitions from the M1 transitions on the basis of their relative intensities makes it possible to assign unique parities to the corresponding low-lying levels.

far from closed shells. The internal-target facility and the bent-crystal spectrometer were used to measure four kinds of spectra: the low-, intermediate-, and high-energy regions of the spectrum for thermal-neutron capture, and the spectrum for average resonance capture.

The main problem encountered was the great complexity of the level schemes above 1 MeV. This was particularly true for ^{180}Hf , for which the average level spacing is 30 keV. Previously published information suggested that there are only two or three overlapping rotational bands in this region of excitation, and the greater complexity that usually starts when enough energy is available to break up many different pairs of nucleons was expected to begin at 2 MeV or above. However, the level scheme derived from our data suggests that at least 6 or 7 overlapping rotational bands are present in the region from 1 to 2 MeV. Furthermore, it appears that the levels in each band are thoroughly mixed with the levels of similar spin and parity in the other bands, with the result that the intraband transitions are very little favored over interband transitions. This is in contrast to the ^{178}Hf level scheme, for which the intraband transitions do appear to be favored over the interband transitions. It was this high degree of complexity that made the new measurements with the bent-crystal spectrometer necessary.

j. Nuclear States in $^{182}_{75}\text{Re}$ Populated in the Decay of $^{182}_{76}\text{Os}$ (22 h)
 S. B. Burson, P. J. Daly,* P. F. A. Goudsmit,[†] and A. A. C. Klaasse[†]

Information about the excited states of the doubly-odd nuclide $^{182}_{75}\text{Re}$ has been deduced from studies of the radioactive precursor $^{182}_{76}\text{Os}$ (22 h). The γ -ray spectra were measured with several Ge(Li) detectors. The internal-conversion-electron groups were studied both with the

* Chemistry Division, Purdue University, Lafayette, Indiana.

[†] Instituut voor Kernfysisch Onderzoek, Amsterdam, The Netherlands.

Fig. 8. The decay scheme of ^{182}Os . The intensities following the γ -ray energies are in transitions per hundred β decays.

double-focusing β -ray spectrometer at the Institute for Nuclear Physics Research, Amsterdam, and with the Argonne superconducting electron spectrometer. Both delayed and prompt γ - γ coincidence experiments were performed. In the energy region below 800 keV excitation, 57 transitions were observed and 41 of these have been placed in a level scheme comprising 14 excited states and the ground state. The energies of the excited states were determined by making a least-squares fit to the γ rays assigned between the various pairs of levels. Spin and parity assignments are proposed for most of the levels. Some of these states are interpreted in terms of the Nilsson model and the Gallagher-Moszkowski coupling rules. The half-life of the level at 235.77 keV was measured to be 570 ± 30 nsec, in agreement with the value reported by Akhmadzhanov *et al.* This state is interpreted as the $(p[402]\uparrow - n[521]\downarrow)$, $I^\pi = 2^-$ configuration; decay to the ground-state band is thus threefold Ω forbidden. This forbiddenness has a significant effect on the γ -ray transition probabilities. The study of ^{182}Os is complete and a report has been accepted for publication in Nuclear Physics.

k. Excited States of ^{184}W

A. R. Adams, N. Smith, * D. Bushnell, R. K. Smither, G. E. Thomas, and J. R. Specht

The excited states of ^{184}W are being studied in a collaborative effort involving (n, γ) measurements at CP-5 and β -decay measurements at Northern Illinois University. Primary $^{183}\text{W}(n, \gamma)^{184}\text{W}$ transitions for both thermal-neutron capture and average-resonance capture were measured with the Ge(Li) spectrometer at the internal-target facility. Cascade γ rays were similarly studied. For isotopic identification, spectra from targets containing a natural abundance of tungsten isotopes were compared with spectra obtained with targets enriched to 80% in ^{183}W . Energies and parities for 42 levels from 0 to 2400 keV have been

* Northern Illinois University, DeKalb, Illinois.

deduced. The level scheme that has been constructed incorporates 62 γ rays having energies ranging from 600 to 2400 keV. Coincidence measurements on γ -ray cascades following β -decay excitation have been used in conjunction with the average-resonance neutron-capture data to obtain unique spin assignments for the levels.

l. The $^{195}\text{Pt}(n, \gamma)^{196}\text{Pt}$ and $^{196}\text{Pt}(n, \gamma)^{197}\text{Pt}$ Spectra and the γ -Ray Spectrum Following β Decay from ^{197}Pt to ^{197}Au

R. K. Smither

The primary purpose of this experiment was to look for a close doublet at ~ 77.3 keV in the γ spectrum following β decay of ^{197}Pt . It was possible that a second line at this energy might explain the conflict between the lifetime of the 77.34-keV first excited state in ^{197}Au as measured electronically and the lifetime obtained in the Mössbauer-effect measurements of Potzel and Perlow.¹ No extra lines were observed in the energy range from 60 to 95 keV. The resolution (FWHM) of the spectrometer at 77.3 keV was 33 eV. The 77.3-keV line did not show any trace of broadening. Thus if it is a doublet in which the second member is at least 1/4 as intense as the main transition, then this second component must fall within a few eV of the main line. The line was checked both with the reactor on and with the reactor off. The buildup and decay of the 77-keV line was consistent with the β -decay lifetime of ^{197}Pt to within 6%, the error of the experiment. The only sizable lines in the γ -ray spectrum observed with the pile off were the K x rays of Pt. The Au and Hg x rays were very weak—less than 1/20 as intense as the 77-keV line. If a new line were present in the data, then it must lie under one of the x rays of Pt. The experiment will be repeated at a favorable time (overlapping a long period during which the pile is shut down) with a natural-abundance sample cut from one of Perlow's Pt foils.

¹ W. Potzel and G. J. Perlow, Phys. Rev. Letters 29, 910 (1972).

m. Modification and Improvements of the Bent-Crystal Spectrometer

R. K. Smither

A New Crystal-Bending Technique

We have bought a new quartz diffraction crystal whose main faces measure 28×30.5 cm and which is only 1 mm thick. If it can be bent with sufficient accuracy, the new crystal is expected to double the resolving power of the spectrometer; for example, the energy resolution width would be reduced to 23 eV for 100-keV γ rays. In order to achieve the required accuracy, a method for making and checking bending blocks has been developed.

The construction of the new crystal-bending system is about 70% complete. The results of tests on the partially completed system encourage us to believe that the required accuracy will be achieved.

Data-Storage System

A new data-recording system has been designed and is under construction. The data will be recorded on magnetic tape that is compatible with the Laboratory's main computer. Thus, it will be feasible, in a single pass through the computer, to correct the data for the large number of instrumental imperfections that limit the energy resolution and precision of the data. The new approach is expected to eliminate about 90% of the time and effort now required for the preliminary processing of experimental data—a major gain in the over-all efficiency of research.

B. THRESHOLD PHOTONEUTRON EXPERIMENTS

The use of the threshold-photoneutron technique to study the ground-state radiative transitions of highly excited nuclear states is carried out at the high-current 20-MeV electron linac operated by the Chemistry Division. Data obtained in the past two years demonstrate the extreme power of these high-resolution measurements as a probe for studying the details of nuclear interactions and nuclear structure.

The high intensity and good energy resolution of the Argonne photoneutron facility make it unique for studying phenomena that previously could be observed in neutron-induced reactions only with the greatest difficulty. The steady upgrading of the linac facility by the staff of the Chemistry Division has been of great benefit to the photoneutron work. At the present time we have available an electron pulse that is only ~ 20 psec wide (FWHM) and has a peak intensity of ~ 200 A. The pulse repetition rate is 800 per sec.

a. Photoneutron Resonances from $^{29}\text{Si}(\gamma, n)^{28}\text{Si}$

H. E. Jackson and R. E. Toohey

Analysis of photoneutron resonance yields and angular distributions in the $^{29}\text{Si}(\gamma, n)$ reaction at neutron energies from 10 keV to 1.4 MeV, measured on the Argonne photoneutron facility, provided convincing evidence for a distinct doorway-state type of structure of p-wave resonances in the photon reaction $^{29}\text{Si} + \gamma \rightarrow ^{29}\text{Si}^*$. This structure appears to arise from a "common doorway" state which affects the total neutron cross section in the reaction $^{28}\text{Si} + n \rightarrow ^{29}\text{Si}^*$ in a similar manner. For each resonance in the (γ, n) cross section, the spin, parity, and corresponding ground-state radiation width Γ_{γ_0} were established by measuring the photoneutron angular distribution and resonance yield. At other laboratories, the reduced neutron widths corresponding to the same excited states of ^{29}Si have been determined from measurements of the total neutron cross section, and the concentration of strength in this cross section near a neutron energy of 700 keV has been attributed to a doorway state. In the (γ, n) reactions, levels with $J^\pi = \frac{3}{2}^-$ also appear to be concentrated in a region near 700 keV, and the strong observed correlation

between the corresponding values of Γ_{γ_0} and the resonance neutron widths is characteristic of a common doorway.

Although the decay of isobaric analog states by neutron emission is forbidden, these states may be observable in the (γ, n) reaction if the isobaric-spin impurity in the analog state is sufficiently strong.

An isotropic resonance group observed at 1.093 MeV in the photoneutron spectrum of ^{29}Si is believed to correspond to the isobaric analog of the $J^\pi = \frac{1}{2}^+$ first excited state of ^{29}Al . From the photoneutron and related data, it should be possible to determine the parameters of this state—in particular, the isobaric impurity in its wave function.

b. Valence Component in the Threshold Photoneutron Spectrum of ^{91}Zr

R. E. Toohey and H. E. Jackson

The ground-state radiation widths Γ_{γ_0} for photoneutron resonances of ^{91}Zr have been measured with high resolution during the past year at the Argonne threshold photoneutron facility. The results offer a striking confirmation of the valence model of radiative neutron transitions. In this model, the partial radiation widths of a neutron resonance depend directly on its reduced neutron width γ_n^2 ; the radiative strength arises from an outer (valence) neutron making transitions between single-particle states outside an inert core. A strong correlation of Γ_{γ_0} and γ_n^2 is predicted for the observed resonances, and individual values of Γ_{γ_0} may be calculated for each resonance.

Photons obtained from the pulsed bremsstrahlung beam of the ANL linac irradiated a target enriched to 90% ^{91}Zr ; photoneutrons were detected by high-resolution time-of-flight measurements. The bremsstrahlung end-point energy was adjusted so that the nuclear states excited by photon absorption are low enough that decay by neutron emission can proceed only to the ground state of ^{90}Zr . In the energy range from 1 to 225 keV above threshold, we observed 35 $p_{3/2}$ photoneutron resonances resulting from the E1 absorption of photons by ^{91}Zr . At higher energies,

Fig. 9. Correlation analysis of reduced neutron widths and ground-state radiation widths for photoneutron resonances in the reaction $^{91}\text{Zr}(\gamma, n)^{90}\text{Zr}$. The dotted lines represent the average values for the two partial widths. In the absence of correlations, the four quadrants would be equally populated with experimental points. The correlation coefficient for the sample is 0.59.

the spectrum may be contaminated by d-wave neutrons following M1 absorption. The observed resonances yielded $\langle \Gamma_{\gamma_0} \rangle = 149 \text{ meV}$.

In order to test the valence model, the values of γ_n^2 for these same resonances were deduced from total cross sections of ^{90}Zr , which were measured at the Oak Ridge Linear Accelerator ORELA.

These measurements yielded $\langle \gamma_n^2 \rangle = 0.88 \text{ keV}$. The correlation between Γ_{γ_0} and γ_n^2 was found to be $\rho = +0.59$ (as compared with $\rho = +1$ for perfect correlation), a value in strong disagreement with the value $\rho = 0$ predicted by the usual statistical model.

A comparison of individual resonance widths suggests that the compound-nucleus decay processes are contributing to the widths and interfering with the valence component. The value of $\langle \Gamma_{\gamma_0} \rangle$ calculated from the valence model is only 89 meV. The compound component in $\langle \Gamma_{\gamma_0} \rangle$ may be obtained from the values of Γ_{γ_0} for those resonances with small values of γ_n^2 and therefore small valence contributions. For the ten resonances with $\gamma_n^2 < 0.2 \text{ keV}$, we find $\langle \Gamma_{\gamma_0} \rangle = 62 \text{ meV}$; and subtracting this from $\langle \Gamma_{\gamma_0} \rangle_{\text{total}} = 149 \text{ MeV}$ yields 87 meV for the experimental valence component, in excellent agreement with the theory.

The strength functions calculated from the data are: $(3.9 \pm 0.8) \times 10^{-5}$ for s-wave neutrons, $(3.3 \pm 0.9) \times 10^{-4}$ for p-wave neutrons, and $(2.5 \pm 0.5) \times 10^{-5}$ for E1 absorption of photons. As is usually the case in this mass region, the p-wave neutron strength function agrees well with the nuclear optical model but the s-wave strength function is smaller than predicted. The photon strength function agrees better with the single-particle model than with the giant-resonance model, as expected for valence transitions.

c. Ground-State M1 Radiation Widths in ^{117}Sn and ^{119}Sn

H. E. Jackson and E. N. Strait*

The threshold-photoneutron spectra from enriched targets of ^{117}Sn and ^{119}Sn have been studied in time-of-flight measurements at

* Macalester College, St. Paul, Minnesota.

the ANL photoneutron facility. The resonance structure was resolved for photoneutrons with $E_n < 25$ keV and the average photoneutron cross section was measured in the interval $400 \text{ keV} < E_n < 2.5 \text{ MeV}$. For both nuclei, the spins of excited states associated with resonances below 30 keV were assigned on the basis of resonance yields measured at 90 and 135° . In ^{119}Sn , s-wave transitions have been identified by comparison with measurements of the total neutron cross section of ^{118}Sn . In both targets, the resolved resonance structure below 25 keV gives no suggestion of unusually strong E1 or M1 strength. In earlier studies at Harwell, anomalous peaks were reported in the (γ, n) cross section measured near 1 MeV neutron energy. Such peaks, which would correspond to an excitation energy of ~ 7.8 MeV in both targets, were interpreted as giant resonances in the M1 strength function. However, these peaks are not observed in our Argonne measurements. In the region $400 \text{ keV} < E_n < 2.0 \text{ MeV}$, the new data show a slowly-varying average photoneutron cross section which is approximately consistent with the contribution expected from the tail of the giant dipole resonance. Measurements of photoneutron angular distributions and of their energy dependence suggest that the reaction is dominated by E1 excitation of a mixture of $p_{1/2}$ and $p_{3/2}$ states.

d. Giant M1 Resonance and E1 Doorway States in ^{207}Pb

L. R. Medsker, H. E. Jackson, and R. E. Toohey

The ground-state radiation strength Γ_{γ_0} in ^{207}Pb has been restudied. For each resonance in the (γ, n) reaction, the photoneutron angular distribution and resonance yield were measured. The s-wave resonances due to E1 transitions were identified by comparing the present results with data on total neutron cross sections.

One objective of the present study is to investigate the proposed common doorway state in ^{207}Pb , which has been frequently cited.

An E1 doorway was initially proposed¹ on the basis of $^{206}\text{Pb}(n, n')$ measurements, and evidence was later reported² for a similar concentration of strength in $^{207}\text{Pb}(\gamma, n)$ data. A subsequent detailed analysis of the ^{206}Pb results was inconsistent with the initial explanation in terms of a common two-particle one-hole doorway and instead suggested a particle-vibration type doorway which was not expected to enhance the photon-induced reaction. The reported correlation of strength in the two channels was unexpected in this view. In new measurements made with the improved energy resolution and photon intensity of the Argonne photoneutron facility, we have obtained new information on the resonance spins and the corresponding Γ_{γ_0} . Specifically, the result of a correlation analysis between the neutron widths from $^{206}\text{Pb}(n, n')$ and the present Γ_{γ_0} is $\rho = 0.1$, which is interpreted as consistent with a correlation of zero. We therefore conclude that the (γ, n) reaction gives no evidence for the proposed common doorway state in ^{207}Pb .

Another important feature of the present results is the intensity of p-wave strength. The expected strength of an M1 giant resonance, calculated in terms of a particle-hole pair consisting of an $(i_{11/2})(i_{13/2})^{-1}$ neutron or $(h_{9/2})(h_{11/2})^{-1}$ proton pair coupled to the ^{207}Pb ground state, is 200 eV. From the present study, a lower limit of 108 eV can be placed on the measured integrated M1 strength. Because of M1 + E2 mixing and the absence of total neutron cross-section data for $E_n > 717$ keV, the value of J^π for several resonances could not be assigned definitely in the present study. However, there is a high probability that the contributions of many of these resonances to the total M1 strength exhaust the strength predicted for the M1 giant resonance.

¹J. A. Farrell, G. C. Kyker, Jr., E. G. Bilpuch, and H. W. Newson, Phys. Letters 17, 286 (1965).

²R. J. Baglan, C. D. Bowman, and B. L. Berman, Phys. Rev. C 3, 2475 (1971).

Fig. 10. Photoneutron time-of-flight spectrum for $^{207}\text{Pb}(\gamma, n)$. The flight path was 9 m. The upper spectrum was taken with a recoil detector, the lower with ^6Li glass scintillators. The peaks are labeled with the neutron c.m. energies in keV. The spectrum is dominated by p-wave resonances excited by M1 transitions. Their high intensity indicates the existence of a giant M1 dipole resonance in ^{207}Pb .

C. RESEARCH AT THE DYNAMITRON

The 4-MV Dynamitron accelerator is used as an intense and versatile source of neutron beams and of beams of both light and heavy charged particles. The neutron-physics work during the past year was concentrated on two projects; a continuation of the study of analog resonances by (p,n) reactions and an exploration of the possibilities for studying lifetimes and cross sections in isomeric fission by neutron-induced reactions. Both of these studies exploit the fast and clean pulses now available at the Dynamitron. The investigation of analog resonances was very fruitful during this year, and it is expected to continue for several more years. The experiment on neutron-induced isomeric fission is a very difficult one that appears to us to be worth the risk because it may open a new avenue in fission research. Early indications this year have been promising. In the coming year, that work will be pursued vigorously as long as it appears likely to be successful.

The Dynamitron also continues to support a variety of experiments on effects produced by charged particles. The study and development of carbon-foil strippers for heavy-ion beams (primarily Ni in our experiments) has been outstandingly successful during the past year. Under conditions corresponding to use in the high-voltage terminal of a heavy-ion accelerator, the lifetime of carbon foils has been increased from seconds to hours. Our improved understanding of the damage mechanism now suggests that a substantial further improvement can be obtained.

Experiments involving the channeling and blocking of energetic ions by oriented monocrystalline targets have continued to be productive both in the study of the channeling mechanism and in the use of channeling and blocking to study other phenomena in crystals. These studies have also attracted the interest of staff members from the Materials Science Division, and their participation now enhances the range of skills and knowledge that can be brought to bear on each problem. Next year this program will also include studies of the channeling of positive and negative pions. Those experiments, to be carried out at LAMPF, will exploit the techniques and insights developed in the Dynamitron experiments.

Investigations not sponsored by the Physics Division continue to use a significant fraction of the running time at the Dynamitron. The use of heavy ions to simulate radiation damage produced by fast neutrons (Materials Science Division) will continue in the next year. That work will now be done under the unique conditions prevailing when the sample is simultaneously irradiated by particles from a small Van de Graaff accelerator. The radiation-damage work has also encouraged important developments in the technology of heavy-ion beams. Another promising

new outside use of the Dynamitron, primarily by users from the University of Chicago, is beam-foil spectroscopy using heavy ions in the MeV range.

1. DYNAMITRON OPERATION, USE, AND EQUIPMENT

a. Operational Experience and Continuing Development at the Dynamitron

R. L. Amrein, A. Langsdorf, Jr., F. P. Mooring, and J. R. Wallace

The Dynamitron operated 3121 hours in the period from 22 March 1972 to 15 March 1973. It was used to accelerate protons, deuterons, ^3He , ^4He , ^{12}C , ^{16}O , $^{20,21,22,23}\text{Ne}$, ^{35}Cl , and ^{58}Ni . The beam currents supplied ranged from a few nanoamperes to several hundred microamperes on target. The operating schedule was 24 hours per day, 5 days per week.

The advantage of the Dynamitron, with its rf charging system, is that it has the power to deliver a beam current of at least 6 mA whereas few electrostatic accelerators can deliver as much as 1 mA; and its precision of voltage control and its freedom from voltage fluctuations are at least as good as those of belt-charged machines. Our 4-MV Dynamitron was the first of its type to be put into full-time operation, and initially considerable effort had to be invested in improving the reliability of the rf oscillator and its dc power supply, the series of high-voltage rectifiers in the machine itself, and a system for detecting rf power arcs before they could cause serious damage. These problems have now been solved and have caused no trouble in about the last quarter of the 10 000 hours of running time logged to date.

The remaining operational problems are common to all dc accelerators, except that the desire to exploit the high-current capability in experiments raises problems not encountered previously. These are steadily being ameliorated by continuing engineering efforts.

The beam lines have been altered to accommodate experiments that are continued for a number of scheduling periods and are of

such a nature and complexity that it is impractical to disassemble them after each use of the machine. Two experimental groups now have semipermanent setups placed in tandem on the same beam line. The removal of the 90° electrostatic analyzer has freed two beam lines for experimental use. Beam lines at the larger deflection angles are reserved for measurements that can be completed in one or two scheduling periods; the small-angle lines are reserved for heavy-ion experiments.

As the experimental program at the Dynamitron has grown and become more diversified, many changes and modifications have been necessary. Probably because of heavy ions, high beam currents, radiation damage, or a combination of these, the accelerating tube is short lived; four of the six sections were replaced in December 1972. The operation of the Dynamitron was improved by the addition of vacuum pumping in the terminal (with an NRC Orb-Ion pump), a terminal cooling system (with a belt-driven magnetic-coupled circulating pump), an automatic beam-steering system, an energy-control system (which uses the terminal-voltage signal from the generating voltmeter), a multiple gas-manifold system for source gases, an adjustable fine-tuning capacitor for better balance of the rf voltage applied to the accelerator dees, an automatic vacuum-valve manifold system for the target-room beam lines, a 5-digit meter readout for the generating voltmeter, a National Electrostatic Corporation beam scanner modified by the Electronics Division, and a post-acceleration pulsing system. Some of these are described in more detail in the following subsections. The terminal mass-analyzing system from RDI has arrived but has not been tested or installed in the Dynamitron. A 670-liter/sec turbomolecular pump has been purchased and is being tested and will soon be installed to pump the acceleration tube.

b. Ion-Source Systems

R. L. Amrein, F. P. Mooring, and W. J. Ray, Jr.

The highly diversified experimental program at the Dynamitron places extreme demands on the ion beams that must be supplied. These demands can be met only by using several separate ion-source systems. To date three systems have been used. These are a conventional duoplasmatron for dc beams of light ions, a pulsed system for fast-timing measurements, and a Danfysik ion source for heavy ions. Two new systems have been acquired and will be ready for general use in a few months.

The first of these new systems is one designed to produce very high currents of light ions. Such systems generate a multitude of ion species, all of which are usually injected into the accelerator tube. The new system incorporates magnetic analysis so that all but the desired ion-beam component will be discarded before acceleration. This system will greatly alleviate radiation damage to the accelerator structure and will greatly reduce the possibility of damage by the intense beam. The maximum ion-beam current available for useful purposes will be increased by a large factor.

The second new system is an rf ion source designed specifically to generate doubly charged helium ions. This will in effect double the energy range of the Dynamitron for this ion species. The source has been constructed and bench-tested, but a test on the Dynamitron itself failed. In the environment of terminal, little or no rf power was coupled into the plasma, and few, if any, ions were produced. Since there was not enough time to vary all the coupling parameters, the test had to be abandoned. Additional tests are planned for the near future.

In so far as is possible, experiments that use the same source are scheduled to run in succession; but even so, ion-source systems must be interchanged every two or three weeks to meet the varying requirements on the ion beam. Until recently, such an interchange necessarily involved opening the accelerator tube to air, but now a valve

✓

installed at the high-voltage end of the accelerator tube allows sources to be interchanged without breaking the high vacuum in it. This considerably shortens the time required to recondition the tube so that it can again operate at a high terminal voltage, and it also should prolong the tube life. The valve does not impair the optical properties of the ion beam since its internal surface is cylindrically symmetric about the beam axis.

c. Generating Voltmeter

F. P. Mooring

A generating voltmeter is now being used to monitor the terminal voltage of the 4-MV Dynamitron. An amplifier uses the generated signal to produce a dc voltage that is proportional to the terminal voltage of the accelerator. A simple adjustment allows the dc voltage to be set equal to the numerical value of the terminal voltage in MV. The value is displayed at the control console by a digitized voltmeter.

Experience indicated that the 4-digit voltmeter supplied by the manufacturer was not sensitive enough to read the small variations in the terminal voltage. Hence a 5-digit meter has been installed in parallel with the original one so the fluctuations of the terminal voltage as well as its mean value can now be monitored. Under the present operating conditions, the new meter usually indicates fluctuations of only a few hundred volts peak to peak.

The generating voltmeter system itself is stable to a few parts in 10 000 over a period of many hours, but the output voltage is dependent on the pressure of the insulating gas in the Dynamitron. Hence for accurate measurements (i. e., for an energy uncertainty less than 10 keV), the voltage readings at the pressure being used must be calibrated against some standard reference—e. g., against the ${}^7\text{Li}(p,n){}^7\text{Be}$ threshold.

The energy control system of the Dynamitron has been modified to allow the output voltage of the generating voltmeter to be used as its reference signal. The experimenter now has four options for a

reference signal: that from a voltage divider connected directly to the terminal, that from the generating voltmeter, that from a pair of slits following the switching magnet, and that from a pair of slits following a precision electrostatic analyzer. This system was designed and put into operation by members of the Electronics Division.

d. Post-Acceleration Beam Chopper

F. J. Lynch

The post-acceleration beam chopper described last year has been installed and performs as anticipated. In the rf mode, it clips the ion beam pulse from the terminal of the Dynamitron to less than 1 nsec FWHM. An equally important advantage of using the chopper is that the ratio of the maximum beam current in the pulse to stray current a few nanoseconds away from the peak exceeds 10^6 .

In the broad-range mode, it turns the dc beam on for a specified number of clock intervals and then turns it completely off so the decay of the induced activity can be followed over the time region of interest. The beam is turned on and off in $0.1 \mu\text{sec}$. The basic clock period of 0.1 nsec can be increased in binary steps to 6.7 sec.

e. High-Current Beam-Line System

F. P. Mooring

Until recently, the Dynamitron could accelerate a much larger ion-beam current than could be safely handled by the available beam-line system. Most of the component parts of the system, many of which were salvaged from the old Van de Graaff facility, were designed for beam currents of at most a few tens of microamperes, whereas beam currents of many hundreds of microamperes now are easily accelerated. This posed a high risk of a vacuum accident that could seriously damage the accelerator. In fact, once while an operator was tuning the ion source, he inadvertently generated a large ion current which promptly drilled a

hole through a portion of the beam-transport system. Fortunately, the safety interlocks immediately shut down the accelerator before any other significant damage occurred.

To help prevent such accidents in the future, a variety of beam-line components designed to take the full power of the available ion beam have been designed and built. Among these are beam shutters, beam slits, beam stops, vacuum valves, beam-limiting apertures, and beam pipes. They are now available as shelf items at the Dynamitron facility and will be incorporated into experimental setups as needed.

2. EXPERIMENTS AT THE DYNAMITRON

a. Fission Isomers in Neutron-Induced Reactions

A. J. Elwyn, F. J. Lynch, F. P. Mooring, and M. Fluss*

The recently-installed post-acceleration pulsing system is being utilized along with the pulsed and bunched proton source in the Dynamitron high-voltage terminal to study the production of short-lived fissioning isomers in reactions induced by neutrons. The beam from the accelerator is incident on thick Li metal targets, and neutrons from the ${}^7\text{Li}(p,n){}^7\text{Be}$ reaction strike foils of the fissile samples. Fission events in the foil are detected by Si counters, and the time distribution of fission fragments is determined. The proton-beam pulse shape is monitored continuously during the accumulation of fission events. With the post-acceleration pulsing system in operation, the full-width of the beam pulse at a point corresponding to 10^{-6} times the maximum is about 15–20 nsec, and any residual beam beyond that point is observed to be less than 10^{-6} of the main-beam intensity. Preliminary results for ${}^{235}\text{U}$ targets bombarded with ~ 0.9 -MeV neutrons are in agreement with

*Chemical Engineering Division, ANL.

the observation of the previously observed 70—100 nsec isomer in ^{236}U with an intensity of $\sim 5 \times 10^{-5}$ times the prompt fission cross section.

b. Analysis of the $^{18}\text{O}(\text{p}, \text{n})^{18}\text{F}$ Reaction

J. F. Lemming, A. J. Elwyn, F. T. Kuchnir,^{*} F. P. Mooring,
J. E. Monahan, and R. Finlay[†]

As reported last year, resonance structure was observed in measurements of the angular distribution and the polarization of neutrons produced in the $^{18}\text{O}(\text{p}, \text{n})^{18}\text{F}$ reaction at incident proton energies of 3.0—3.9 MeV. In spite of uncertainties due to the existence of unobserved but open reaction channels, a two-level multichannel R-matrix approach has revealed the existence of two $\frac{3}{2}^{+}$, one $\frac{1}{2}^{+}$, one $\frac{1}{2}^{-}$, and possibly some $\frac{3}{2}^{-}$ and $\frac{5}{2}^{+}$ states in the compound nucleus ^{19}F at excitation energies between about 11 and 11.5 MeV. It is hoped that a more complete R-matrix analysis will reduce some of the ambiguities of the present results and lead to a more nearly unique assignment for the spins and parities of the observed resonances.

^{*}Argonne Cancer Research Hospital, Chicago, Illinois.

[†]Ohio University, Athens, Ohio.

c. Polarization and Differential Cross Sections in Analog-Resonant (p, n) Reactions

A. J. Elwyn and J. E. Monahan

In analyzing proton-induced reactions that excite analog resonances which then neutron decay to low-lying states of the residual nucleus, most previous studies have treated the decay by use of the one-channel formalism proposed by Robson and his collaborators. We have considered a more general approach to an interpretation of such reactions. The general form of the collision matrix elements that describe the process has been obtained on the basis of an R-matrix formalism. Various approximations to the energy-averaged collision matrix elements

have been considered, and we find that phase-correlation effects between the background $T_{<}$ states and other nuclear states may be important in the interpretation of any resonant contributions to neutron polarization in isospin-forbidden (p,n) processes. In fact, the experimental study of both the differential cross sections and the polarization of the neutrons in such reactions might be expected to provide evidence about the role of correlated states in such processes. These general considerations are being applied to the case of a nonzero resonant neutron polarization in the $^{51}\text{V}(p,n)^{51}\text{Cr}$ reaction measured at the Argonne Dynamitron accelerator, as was reported last year.

d. Possible Resonance Structure in the Elastic Scattering of ~ 1 -MeV Neutrons by Y

A. J. Elwyn, J. E. Monahan, S. A. Cox,^{*} J. Adams,[†] and C. Chen[†]

The results of an analysis of the rather weak structure observed in the elastic scattering of ~ 1 -MeV neutrons by ^{89}Y has been submitted for publication in Nuclear Physics. Both the polarization and the angular-distribution data were analyzed by use of a model in which the scattering process is described in terms of resonant amplitudes superimposed on an optical-model background. The results indicate the existence of three resonances at neutron energies between 0.94 and 1.2 MeV—two with spin and parity 1^- and one with 1^+ . The properties of the 1^- resonances suggest that these are the parent states of the proposed $T_{>}$ components of the E1 giant resonance observed near 21 MeV excitation in ^{90}Zr produced in the $^{89}\text{Y}(p,\gamma_0)$ reaction. The resolved resonance structure in this energy region is in reasonable agreement with a recent theoretical calculation of the energies and widths of negative-parity states in ^{90}Y .

^{*} Applied Physics Division, ANL.

[†] Ohio University, Athens, Ohio.

Fig. 11. Energy distributions of neutrons emitted at the indicated laboratory angles when ${}^9\text{Be}$ was bombarded with 14.8-MeV protons (left) and with 20.3-MeV ${}^3\text{He}$ ions (right).

e. Neutrons from Thick Be Targets Bombarded by Charged Particles

F. T. Kuchnir, * L. S. Skaggs, * A. J. Elwyn, and F. P. Mooring

As reported last year, we have measured the energy spectra and angular distribution of the neutrons produced by bombarding thick Be targets by 8- and 16-MeV deuterons at the Argonne tandem. These results are being used in the design of a neutron radiation-therapy facility that involves a 30-in. medical cyclotron at the Argonne Cancer Research Hospital. To compliment these measurements, we have more recently studied the neutron spectra and angular distribution in the bombardment of thick Be targets by 14.8-MeV protons and 20.3-MeV ^3He particles by techniques similar to those utilized in the deuteron measurements. The results suggest that the neutron yield per incident particle at 0° is approximately the same for 8.3-MeV deuterons and 14.8-MeV protons but is only a third as great for the ^3He particles. Further, the median neutron energy at 0° is 3.3 MeV, 2.4 MeV, and 6.3 MeV for 8.3-MeV deuterons, 14.8-MeV protons, and 20.3-MeV ^3He particles, respectively. On the basis of the measurements, it becomes evident that a deuteron beam is the best choice for production of intense fast neutrons for radiotherapy with a 30-in. medical cyclotron.

Fig. 11

* Argonne Cancer Research Hospital, Chicago, Illinois.

f. Lifetimes of Carbon Foils Used As Strippers for Heavy Ions

J. L. Yntema

The lifetime of carbon foils used as strippers for heavy ions has been further lengthened. In the initial experiments, it was shown that the lifetime improved substantially if the foil was heated and that further improvement could be obtained if the foil was coated with a thin layer ($\sim 2 \mu\text{g}/\text{cm}^2$) of Au. In these experiments in which roughly $1 \mu\text{A}$ of 4-MeV Ni^+ ions bombarded a beam spot about 1 mm in diameter, the lifetimes of $10\text{-}\mu\text{g}/\text{cm}^2$ carbon foils were of the order of 30 min.

The effect of the temperature of the foil on the lifetime has been investigated. The contraction of the material in the beam spot seems to be associated with a recrystallization and an increase in the mobility of the clusters around 600°C . By maintaining a temperature of about 500°C and moving the foil slowly to avoid excessive heating of the beam spot, lifetimes in excess of 1 hour were commonly obtained for 3-MeV Ni^{+} beams with intensities in excess of 1 particle μA over a spot less than 1 mm in diameter for both $10\text{-}\mu\text{g}/\text{cm}^2$ and $5\text{-}\mu\text{g}/\text{cm}^2$ carbon foils.

g. Inhibition of Radiation Blistering in Tin Bombarded by Protons and Alpha Particles

R. C. Mikkelson, J. W. Miller, * R. E. Holland, and D. S. Gemmell

Tin monocrystals have been bombarded with large doses ($\sim 5 \times 10^{17}$ particles/ cm^2) of 1.5—4-MeV ions of H and He. Proton irradiations above 225°C produce neither visible surface damage nor degradation of the ability of a crystal to channel the incident particles. Room-temperature irradiations by H or He ions produce little observable damage near the crystal surfaces unless followed by post-irradiation anneals to 220°C or above. After such anneals, however, channeling measurements show permanent deterioration and the surfaces may show deformations such as swelling, blistering, and effervescence.

h. Equilibrium Positions of Au Atoms in Sn As Determined by a Channeling Technique

D. S. Gemmell, R. E. Holland, J. W. Miller, * and J. -C. Poizat

There is strong indirect evidence that the noble metals dissolve at least partially in the interstices of many polyvalent metals. One of these alloy systems, Au in Sn, is particularly suitable for a lattice-location study by the channeling technique. We have studied the back-scattering of ^{20}Ne ions from thick single crystals of Sn and of Sn

* Materials Science Division, ANL.

with dissolved Au. The Au was introduced into Sn crystals by diffusion and then equilibrated. Measurements were performed at 217°C , the temperature of maximum solubility. Angular scans across the $\langle 001 \rangle$, $\langle 100 \rangle$, and $\langle 111 \rangle$ axes were completed for both Sn and dissolved Au. Preliminary results suggest that there is a significant interstitial fraction.

i. Dechanneling Due to Radiation-Induced Defect Clusters in Au

D. S. Gemmell, R. C. Mikkelsen, K. L. Merkle,* P. P. Pronko,*
and J. R. Wrobel*

The rate of dechanneling of 2-MeV He^+ ions incident in the $[001]$ direction of monocrystalline gold films has been determined from the backscattering spectra, and changes in this rate have been studied as a function of exposure to a 2-MeV He^+ beam incident in a random direction. The densities and the size distribution of defect clusters larger than about $20 \text{ \AA}$ across are well known from observations with transmission electron microscopes. Under the assumption that all defect dechanneling is due to defects visible in these micrographs, we find the dechanneling cross section per cluster to be $\sigma_D = 2.3 \times 10^{-14} \text{ cm}^2$ —only about a fifth of the average geometrical cross section observed by transmission electron microscopy.

* Materials Science Division, ANL.

D. RESEARCH AT THE TANDEM VAN DE GRAAFF ACCELERATOR

The tandem is used for research on a number of aspects of nuclear structure. The work with heavy-ion projectiles has continued to increase, somewhat at the expense of the work with lighter ions.

Among the heavy-ion experiments, a study of the $J = 14$ resonance in the $^{16}\text{O} + ^{12}\text{C}$ system has been extended to other nearby nuclei and attempts have been made to study related structures. Systematic explorations of heavy-ion reactions have continued, and a Symposium on this subject was organized. Alpha-transfer reactions on ^{40}Ca —in particular, the $(^6\text{Li}, d)$ reaction—have been studied in some detail.

Outside the heavy-ion work, the experimental study of pairing vibrations in the actinide nuclei has continued. One-nucleon transfer reactions have been used to study particle-particle and particle-hole spectra near closed shells, and new results were obtained for ^{90}Zr , ^{38}Cl , and ^{40}K . The two-neutron transfer $(^3\text{He}, p)$ reaction has been used in investigations of $l = 0$ transitions in the f-p shell. A search for inhibited E2 transitions has also continued, and the results fit into a consistent pattern. Participation in nuclear-data compilation through the Nuclear Information Research Associate program is continuing.

Fig. 12. Facility for the development and testing of ion sources. This work is described in Sec. I. Db(ii).

1. OPERATION AND DEVELOPMENT AT THE TANDEM

a. Operational Experience and Changes in the Equipment

P. Billquist, W. F. Evans, F. P. Mooring, and J. R. Wallace

The FN tandem operated 5273 hours in the period from 16 March 1972 to 15 March 1973. Terminal voltages ranging between 2 and 8.5 MV were used to impart the desired energies to protons, deuterons, $^3\text{He}^{+2}$, $^4\text{He}^{+2}$, $^6\text{Li}^{+3}$, $^7\text{Li}^{+3}$, $^{12}\text{C}^{+5}$, $^{13}\text{C}^{+5}$, $^{14}\text{N}^{+5}$, $^{15}\text{N}^{+5}$, $^{16}\text{O}^{+4,5,6,7}$, $^{18}\text{O}^{+5,6}$, $^{32}\text{S}^{+7}$, $^{35}\text{Cl}^{+5,6,7}$, and $^{19}\text{F}^{+5,6}$. We have made some attempts to produce a boron beam.

The ion-source development now in progress will be discussed in more detail in other sections. The Heinicke radial-extraction Penning ion source has arrived, has been tested on a test bench with proton output, and has been accepted.

The Pelletron charging system for the tandem is scheduled for delivery in June. A corona voltage-distribution system is scheduled for delivery late in 1973. Other improvements to the tandem in the past year include the following. (1) The power supplies for the extractor and the charge exchanger in the source were modified by the Electronics Division to include a more effective regulation system with appropriate circuitry to ignore voltage spikes. (2) New power supplies were provided for steering the beam at the low-energy end of the tandem. (3) An NEC beam-scanner system was installed. (4) The resistors along the accelerator column were bolted firmly to the column structure.

b. Instrumentation at the Tandem

(i) Charging System for the Tandem Van de Graaff Accelerator

P. J. Billquist, F. P. Mooring, and J. R. Wallace

Delivery of the charging system was delayed while the manufacturer undertook a development program to improve the system

and eliminate problems that had arisen in a similar system installed in another tandem. That program was successful, and the system for the Argonne machine is now being manufactured. Delivery is scheduled for June 1973.

(ii) Ion-Source Development at the Tandem

W. F. Evans, F. P. Mooring, and J. L. Yntema

A system for use in testing and developing negative-ion sources has been constructed at the tandem.

A duplicate of the ion-source portion of the duoplasmatron now in use at the tandem is partially completed. A direct-extraction duoplasmatron is being built. A sputtering source that employs K and Li beams has been constructed and is undergoing preliminary tests. A Penning source of Heinicke design has been purchased from High Voltage Engineering and has been tested, and both it and its power supplies have been modified somewhat. The deflection-plate beam-steering system has been completed, and a preacceleration system to allow injection of the beam at energies near 100 keV is now under construction.

As a result of calculations of the trajectories of beams injected into the tandem, one of the einzel lenses in the injection system has been replaced by an electrostatic quadrupole pair. The calculations for the system will be extended when the necessary computer programs have been tested.

(iii) A Voltage-Distribution System for the Tandem

P. J. Billquist, F. P. Mooring, and J. R. Wallace

The voltage-distribution system currently in use in our FN tandem Van de Graaff is a voltage divider consisting of two resistor strings connected in parallel along the insulating support column. It will be replaced by a corona-point voltage-distribution system. Several serious disadvantages of the old resistor system will be alleviated by the change.

Each resistor string consists of 196 individual 400-M Ω resistor assemblies connected in series. Each resistor assembly snaps into position between two successive voltage planes in the accelerator. In the SF₆ insulating gas at high pressure, the force exerted by a small coil spring is insufficient to maintain reliably good electrical contact to the electrodes in the accelerator tube. The resulting arcs at many of these connections lead to voltage instability, erratic operation, and continual damage to neighboring parts of the accelerator. Springs often break and fall into regions of high electrical field. Such an occurrence costs a minimum of two full days of running time while the machine is shut down, the pressure vessel is opened, and the spring is replaced. Occasionally other accelerator parts will have been damaged. Such failures will be eliminated by a corona-point distribution system.

The current flowing through the present resistor strings is proportional to the terminal voltage and hence becomes unreasonably large at high terminal voltages. To eliminate this unnecessarily high load on the charging system, the corona system will be designed so that the tandem operator can control the current along the insulating column.

As resistors age, their values change unpredictably with time and voltage. Consequently the voltage distribution along the accelerator tube gradually becomes more and more nonuniform—an effect that is especially detrimental in inclined-field accelerator tubes such as ours. The nature of the erosion of corona points is such that the voltage gradient along the accelerator tube should remain much more nearly uniform than it does with the resistor divider.

A corona-point system to avoid these problems has been ordered, and delivery is scheduled for December 1973. It will be installed shortly thereafter.

(iv) Beam-Profile Monitors

P. J. Billquist, F. P. Mooring, and J. R. Wallace

A system for continuously monitoring the profile of the ion beam has been purchased and is now in use. It consists of two sets of six sensors and two switching and display units. Hence the profile of the beam can be constantly monitored at two positions simultaneously, and each switching unit can be used to select and display a signal from any one of its six sensors. The beam profile in the horizontal direction is displayed horizontally on the oscilloscope, and that in the vertical direction is displayed vertically. The system has proved to be extremely functional and it greatly simplifies the tuning of the ion beam.

(v) Modifications of the Magnetic-Spectrograph System for Study of Heavy-Ion-Induced Reactions

J. R. Erskine, T. H. Braid, L. R. Greenwood, and E. A. Sutter

The operation of the magnetic-spectrograph system, including the long-wire proportional counter, has been simplified and speeded up by a number of recent improvements. The basic kinematic and plotting programs for the IBM-360 and ASI-2100 computers were modified to make provision for the use of proportional counters and for the study of heavy-ion transfer reactions. The improvements also included the resolution of some special focusing problems that had been encountered and the development of subroutines to calculate the energy loss for heavy ions.

The problem of carbon buildup on the target, which is especially severe for heavy-ion bombardment, was studied and was largely cured by taking two steps. (1) The partial pressure of hydrocarbons in the target chamber was reduced by changing to a vacuum grease with a lower vapor pressure and by replacing the Lucite windows with Pyrex glass. (2) The target was surrounded as completely as possible with a surface cooled with liquid nitrogen.

(vi) Position-Sensitive Proportional Counters¹

L. R. Greenwood, J. C. Stoltzfus, and T. H. Braid

Three versions of the single-anode position-sensitive counter have been used extensively both at the tandem and at the 60-in. cyclotron. Several groups of experimenters have used them in the focal plane of the spectrograph to detect all the standard light ions of hydrogen and helium and also ^6Li , ^7Li , ^{12}C , ^{14}C , ^{15}N , and ^{16}O .

To meet the need for a technique of particle identification, a recently-completed analog-computer circuit calculates the mass of the particle from the position pulse and the energy loss in a conventional thick proportional counter. This should give adequate separation for light ions (except that some supplementary measurements may be needed to distinguish ^3He from T) and also for some heavy ions. For many heavy-ion reactions, however, more sophisticated schemes will be needed—as noted in Sec. (v).

¹ L. R. Greenwood, J. C. Stoltzfus, K. Katori, C. P. Cameron, and T. H. Braid, ANL Physics Division Informal Report No. PHY-1972B.

(vii) Physics Division On-Line Computer System

D. S. Gemmell

The computer system that has been in use at the tandem and Dynamitron accelerators for many years is becoming increasingly difficult to maintain. Furthermore, the limited size of its memory and the difficulties inherent in interfacing it to modern integrated circuitry severely restrict its expansion. To resolve these problems, a PDP-11/45 processor equipped with a disk memory has been added to the computer system at each accelerator. This is interfaced to the existing system via a CAMAC module. The PDP initially will serve mainly as an interface between the old ASI computer and the disk, but as time goes on it will increasingly act as the nucleus of a system that eventually will replace the ASI system. As components in the old system become unmaintainable,

their replacements will be added to the PDP. The CAMAC system of computer interfacing is to be used extensively.

c. University Use of the 8.5-MV Tandem

F. P. Mooring

Use of the Argonne 8.5-MV tandem by outside users has continued at the same rate as during the previous year. For the first time, all outside user groups chose to collaborate with Argonne scientists. This is not a policy set by the Laboratory, but reflects the desires of the visiting user groups. Such collaboration can facilitate the research programs of all concerned. It permits the interjection of new ideas and viewpoints from outside the Laboratory, and offers visiting scientists easier access to sophisticated and expensive experimental facilities.

A list of those institutions whose staff members have used the tandem during the past year is given below; the names of the local collaborators are enclosed in parentheses.

1. Argonne Cancer Research Hospital

Neutron Spectroscopy and Dosimetry for Radiation Therapy

F. T. Kuchnir and L. S. Skaggs (A. J. Elwyn, F. J. Lynch, and F. P. Mooring)

2. Beloit College

Experiments with a Position-Sensitive Proportional Counter

J. C. Stoltzfus (T. H. Braid and L. R. Greenwood)

3. DePaul University

($^3\text{He}, t$) Reactions Induced on ^{41}K

M. S. Greenwood (N. Anantaraman, L. R. Greenwood, and J. P. Schiffer)

4. Illinois Institute of Technology

Investigation of the $^{37}\text{Cl}(^3\text{He}, p)^{39}\text{Ar}$ Reaction

E. L. Sprenkel-Segel (W. C. Corwin and R. E. Segel)

5. Indiana University

$^{16}\text{O} + ^{16}\text{O}$ Inelastic-Scattering and Reaction-Channel Studies

P. Schwandt, P. P. Singh, and D. A. Sink (R. H. Siemssen)

6. Northern Illinois University

Use of the Mössbauer Effect to Study Ion-Beam Damage

R. S. Preston and Tsung-Ming Lin (B. J. Zabransky)

Gamma Decay of High-Spin States in ^{47}Ti

T. P. Sjoreen (C. L. Fink, L. S. Meyer-Schützmeister, and W. Wharton)

7. Northwestern University

Scattering Process Near the Coulomb Barrier

L. R. Greenwood (C. L. Fink, G. C. Morrison, and B. Zeidman)

Study of the $^{12}\text{C}(^{12}\text{C},\alpha)^{20}\text{Ne}$ Reaction

L. R. Greenwood (J. R. Erskine and R. E. Segel)

Heavy-Ion Transfer Reactions with Improved Resolution

L. R. Greenwood (J. R. Erskine, C. L. Fink, and G. C. Morrison)

A Study of the $^{40}\text{Ca}(d,p)^{41}\text{Ca}$ Reaction

L. R. Greenwood and K. K. Seth (L. S. Meyer-Schützmeister, R. E. Segel, and W. Wharton)

Interference in the Inelastic-Scattering Process

L. R. Greenwood (C. L. Fink, A. M. Friedman,* K. Katori, G. C. Morrison, and B. Zeidman)

Study of the $^{40}\text{Ca}(d,p)^{41}\text{Ca}$ Reaction

R. Kalia, A. Saha, and K. K. Seth (L. R. Greenwood)

8. Western Michigan University

Study of Medium-Weight Nuclei Using the $(^3\text{He},p)$ and $(^4\text{He},d)$ Reactions

G. Hardie (T. H. Braid and L. S. Meyer-Schützmeister)

9. Wright-Patterson Air Force Base

States of the Vanadium Isotopes Excited by the $(^3\text{He},t)$ Reaction

J. C. Manthuruthil and C. P. Poirier (L. S. Meyer-Schützmeister)

*Chemistry Division, ANL.

Fig. 13. Spectra of the $^{12}\text{C}(^{12}\text{C}, \alpha)^{20}\text{Ne}$ reaction at 38.5 and 39.5 MeV bombarding energy. Some of the peaks are labeled with their excitation energies (MeV), spins, and parities. Note the large fluctuations in yield for many of the levels—particularly in those for the 9.040-, 12.16-, 13.95-, and 15.93-MeV levels.

2. HEAVY-ION REACTIONS

a. A Detailed Study of the $^{12}\text{C}(^{12}\text{C}, \alpha)^{20}\text{Ne}$ Reaction

L. R. Greenwood, R. E. Segel, J. R. Erskine, and H. T. Fortune

The α -particle excitation functions for the $^{12}\text{C} + ^{12}\text{C}$ reaction have been studied with a position-sensitive proportional counter in a split-pole magnetic spectrograph. The over-all resolution width was ~ 40 keV. The spectra taken from $E_{\text{c.m.}} = 18$ to 25 MeV in steps of 62.5 keV at $\theta_{\text{lab}} = 5^\circ$ showed about 30 sharp peaks corresponding to excitations up to 20 MeV in ^{20}Ne . Strong fluctuations (as great as 10:1 in some cases) were observed in the yields of the various groups. The correlation widths were 150–200 keV. From a comparison of the average cross sections for the feeding of states of the same spin and parity, it can be concluded that the cross sections cannot be explained by a statistical compound-nucleus model. Analysis of the excitation functions with the Ericson fluctuation model suggests that the reaction mechanism has a large direct component which interferes with a statistically fluctuating compound-nucleus component.

b. Persistence of the $^{12}\text{C} + ^{16}\text{O} \rightarrow ^{28}\text{Si}$ Resonance in the $^{13}\text{C}(^{16}\text{O}, ^{17}\text{O})^{12}\text{C}$ Reaction

P. T. Debevec, H. J. Körner, and J. P. Schiffer

Careful correlation analyses have shown the narrow resonance in the $^{12}\text{C} + ^{16}\text{O}$ system at a center-of-mass energy of 19.7 MeV to be the only persistent anomaly over an energy interval of some 10 MeV. In order to study the properties of this singular phenomenon, we have chosen the quasi-elastic process $^{16}\text{O} + ^{13}\text{C} \rightarrow ^{17}\text{O} + ^{12}\text{C}$. Here it was expected that a similar phenomenon might appear more dramatically as the resonant amplitude no longer interferes with elastic scattering.

Fig. 14. Forward-angle excitation functions for $^{13}\text{C} + ^{16}\text{O} \rightarrow ^{12}\text{C} + ^{17}\text{O}$, showing a broad anomaly ($\Gamma \approx 2.5$ MeV) at $E_{\text{c.m.}} = 18.7$ MeV.

Fig. 15. Angular distributions for $^{13}\text{C} + ^{16}\text{O} \rightarrow ^{12}\text{C} + ^{17}\text{O}$, showing an oscillatory structure "on resonance."

Fig. 14

Fig. 15

Forward-angle excitation functions clearly show an anomaly at $E_{\text{c.m.}} = 18.7$ MeV with a width of ~ 2.5 MeV. The angular distribution at 18.7 MeV is strongly forward peaked, but an oscillatory pattern with a phase characteristic of $[P_{14}(\cos \theta)]^2$ is apparent. The observed width and angular distribution here in ^{29}Si are consistent with the resonance in ^{28}Si . Thus the observed structure can be identified as the remnant of the ^{28}Si resonance smeared out in energy and spin in ^{29}Si . The quasi-elastic reaction $^{15}\text{N} + ^{12}\text{C} \rightarrow ^{11}\text{B} + ^{16}\text{O}$ will be used to search for a similar phenomenon in ^{27}Al .

c. Highly Excited States in ^{28}Si

P. T. Debevec, J. P. Schiffer, and W. R. Wharton

Theoretical understanding of the elastic-scattering anomaly found in the $^{12}\text{C} + ^{16}\text{O}$ system at a center-of-mass energy of 19.7 MeV (36.5 MeV excitation in ^{28}Si) is complicated by the fact that only one such anomaly has been identified. In an attempt to explore its interpretation as the spin-14 member of a rotational band, lower members have been sought in the reaction $^{16}\text{O}(^{16}\text{O}, \alpha)^{28}\text{Si}$.

At bombarding energies of approximately 56 MeV, spectra of particles emitted at 5° and $7\frac{1}{2}^\circ$ have been measured with the position-sensitive proportional counter in the focal plane of the Enge split-pole spectrograph. A small number of prominent states have been observed at an excitation energy of ~ 20 MeV. Excitation functions and angular distributions are being investigated in order to obtain information concerning their structure and spin.

d. The $^{16}\text{O} + ^{16}\text{O} \rightarrow \alpha + ^{28}\text{Si}^*$ Reaction

P. Debevec, W. Wharton, and J. P. Schiffer

The $^{16}\text{O}(^{16}\text{O}, \alpha)^{28}\text{Si}$ reaction at incident energies in the vicinity of $E_{\text{lab}} = 56$ MeV has been studied at 5° with the Argonne split-pole spectrograph and a position-sensitive proportional counter. The

spectra, taken with 50-keV resolution width, show a few persistent, strongly excited states around 20 MeV excitation energy. We are studying the energy and angle dependence of these states in more detail in order to be able to set limits on their angular momenta and possibly learn about their structure.

e. The ($^{12}\text{C}, \alpha$) Reaction on Targets of ^{40}Ca and ^{11}B

J. R. Erskine, G. C. Morrison, and J. P. Schiffer

An attempt to observe the $^{40}\text{Ca}(^{12}\text{C}, \alpha)^{48}\text{Cr}$ reaction was unsuccessful. After curing the problem of carbon buildup, we found negligible yield at a bombarding energy of 48 MeV.

Self-supporting ^{11}B targets were tried in preliminary studies of the $^{11}\text{B}(^{12}\text{C}, \alpha)^{19}\text{F}$ reaction. The resulting spectra were found to contain many strongly excited states, which presumably are weak-coupling states simply related to the states seen in the $^{12}\text{C}(^{12}\text{C}, \alpha)^{20}\text{Ne}$ reaction.

f. Reactions and Inelastic Scattering with ^{18}O Ions

K. Katori, C. L. Fink, G. C. Morrison, and J. L. Yntema

The ($^{18}\text{O}, ^{20}\text{Ne}$) and ($^{18}\text{O}, ^{19}\text{F}$) reactions on ^{40}Ca and ^{50}Cr have been studied with 44- and 48-MeV ^{18}O beams. The results confirm the previous observation¹ that the transfer angular distributions that leave the light outgoing particle excited are peaked forward of those that leave the heavy residual nucleus excited. In the inelastic scattering of ^{18}O , we also observe strong excitation of the 2^+ state of the ^{18}O projectile and of ^{50}Cr , ^{58}Ni , and ^{68}Zn target nuclei. In each case, the angular distributions for inelastic scattering exhibit destructive interference between the Coulomb and nuclear excitations. The interference minima for

¹R. H. Siemssen, C. L. Fink, L. R. Greenwood, and H. J. Körner, Phys. Rev. Letters 28, 626 (1972).

excitation of target and of projectile are found at different angles, the minimum for the lighter ^{18}O again occurring more forward.

g. Gamma Spectra from $^{16}\text{O} + ^{45}\text{Sc}$ and $^{16}\text{O} + ^{40}\text{Ca}$ Reactions

W. R. Wharton, L. Meyer-Schützmeister, T. Sjoreen, and G. Hardie

^{45}Sc targets varying in thickness between 0.14 and 1.8 mg/cm^2 have been bombarded with ^{16}O while varying the laboratory energy in 2-MeV steps from 28 to 44 MeV. Gamma spectra were obtained at 90° with a 30-cc Ge(Li) detector of 3.0-keV resolution width. No gamma decays corresponding to sub-Coulomb few-nucleon transfer reactions were seen. A similar negative result has been obtained for ^{40}Ca .

h. Transfer Reactions Induced on ^{88}Sr by ^{16}O

N. Anantaraman, K. Katori, and H. J. Körner

This study was undertaken to explore the systematics for the energy range 44–59 MeV, extending from below the Coulomb barrier to above it. The energies and angular distributions of the outgoing ^{16}O , ^{15}N , ^{14}C , and ^{12}C were measured with semiconductor-counter telescopes. In the (^{16}O , ^{15}N) reaction, the most strongly populated states are the single-particle $p_{1/2}$ ground state and $g_{9/2}$ first excited state of ^{89}Y . Distorted-wave calculations for this reaction have been done with the finite-range, no-recoil code RDRC, with optical-model parameters determined from the elastic scattering of ^{16}O on ^{88}Sr and of ^{15}N on ^{89}Y . With these parameters, the angular distributions of the transfer data are very well fitted for the $p_{1/2}$ and $g_{9/2}$ states but not for the $d_{5/2}$ state at 3.75 MeV excitation. The Q value for this state (-8.8 MeV) is far from the optimum Q value of approximately -5 MeV, so that secondary effects not properly treated in RDRC may well be important. The cross sections predicted for the $p_{1/2}$ and $g_{9/2}$ states by using (^3He , d) spectroscopic factors and bound-state parameters found in the literature are too small

TABLE I. Normalization factors for the $^{88}\text{Sr}(^{16}\text{O}, ^{15}\text{N})$ angular distributions to the $2p_{1/2}$ and $1g_{9/2}$ states in ^{89}Y .

$E_{\text{lab}}(^{16}\text{O})[\text{MeV}]$	$N(g_{9/2})$	$N(p_{1/2})/N(g_{9/2})$
44	1.8	1.03
46	2.6	1.29
48	2.2	1.63
52	2.2	1.63
56	1.9	1.93
59	2.0	2.16
Average = 2.1 ± 0.3		

Fig. 16. Experimental and calculated angular distributions for the $^{88}\text{Sr}(^{16}\text{O}, ^{15}\text{N})$ reaction leading to the ground state of ^{89}Y . The curves are labeled with the respective bombarding energies.

Table I

by a factor of 2—4. More significantly, the relative normalization between the $p_{1/2}$ and $g_{9/2}$ states varies systematically with energy, and it is tempting to ascribe this energy-dependent discrepancy to the neglect of recoil effects in the code. Unambiguous evidence for recoil in the (^{16}O , ^{12}C) reaction was found from the experimental optimum Q values for the ^{12}C spectra. A semiclassical treatment of the (^{16}O , ^{15}N) data verifies the expectation that the probability of transfer is a simple function of the distance of closest approach, independent of energy and angle. Angular distributions for the inelastic scattering of ^{16}O to the 2^+ state of ^{88}Sr show evidence of the Coulomb-nuclear interference process.

i. ^{16}O -Induced Reactions on ^{124}Sn

K. Katori, C. L. Fink, and J. L. Yntema

Proton transfer, α transfer, and elastic scattering were studied in ^{16}O -induced reactions on ^{124}Sn at bombarding energies of 54, 56, and 59 MeV. Counter telescopes were used to separate ^{16}O , ^{15}N , and ^{12}C . The over-all resolution width was ~ 400 keV. The cross sections for the (^{16}O , ^{15}N) and (^{16}O , ^{12}C) reactions are 1—3 mb/sr.

The energy dependence of the shape of the angular distribution of the summed cross section is that characteristic of heavy-ion reactions occurring at bombarding energies in the vicinity of the Coulomb barrier. The angular dependence of Q_{opt} , the Q value at which kinematic considerations result in a maximum cross section, is similar to that for the $^{88}\text{Sr}(^{16}\text{O}, ^{12}\text{C})^{92}\text{Zr}$ reaction. Again the data suggest the necessity of taking the recoil effect into account.

j. ^{16}O -Induced Transfer Reactions on ^{172}Yb

H. J. Körner, K. W. Jones,* R. H. Siemssen, J. P. Schiffer, and A. Schwarzschild*

The optimum Q values and total yields of transfer reactions from $^{16}\text{O} + ^{172}\text{Yb}$ have been studied near the Coulomb barrier by observing

* Brookhaven National Laboratory, Upton, New York.

Fig. 17

Fig. 17. Angular distributions for the $^{124}\text{Sn}(^{16}\text{O}, ^{15}\text{N})^{125}\text{Sb}$ reaction at the three indicated values of $E(^{16}\text{O})$.

Fig. 18. Optimum Q values extracted from the centroids of the energy distributions of the indicated particles emitted in the reactions. The lines correspond to classical calculations.

Fig. 19. The cross sections for the indicated particles emitted in the $^{172}Yb + ^{16}O$ reaction, expressed as the ratio to Rutherford scattering and plotted as a function of the classical distance D of closest approach. The lines are drawn to indicate trends.

^{12}C , ^{14}C , and ^{15}N particles, and the results have been compared with simple classical expectations. Recoil effects are clearly seen. At different energies and angles below the barrier, the transfer probabilities are uniquely determined by the distance of closest approach, with an exponential dependence which appears consistent with the ^{16}O wave function.

Fig. 18

Fig. 19

k. Optimum Q Values in ($^{16}\text{O}, \text{C}$) Reactions Below the Coulomb Barrier
N. Anantaraman, K. Katori, and J. P. Schiffer

The results from several measurements of the ($^{16}\text{O}, \text{C}$) reactions have been analyzed; the energy centroids of carbon spectra have been determined for targets of ^{172}Yb , ^{124}Sn , and ^{88}Sr . Yields measured as a function of angle are available at several incident energies below the Coulomb barrier for each target. The centroids at back angles ($\theta \geq 150^\circ$) seem to be well described by $Q_{\text{opt}} = E_i [Z_f z_f / Z_i z_i (1 + d/D_i)^{-1} - 1]$, where d is the recoil distance and D_i is the distance of closest approach. At more forward angles, these centroid Q values become more positive in accordance with a simple classical expectation that assumes no angular-momentum transfer.

Fig. 20

l. Use of the Magnetic Spectrograph for Heavy-Ion-Induced Transfer Reactions

J. R. Erskine, C. L. Fink, L. R. Greenwood, W. Henning, G. C. Morrison, and J. P. Schiffer

The Engé split-pole magnetic spectrograph with a position-sensitive proportional counter as a focal-plane detector is being used to improve the energy resolution available for the study of heavy-ion-induced transfer reactions. The best resolution width obtainable with silicon counter telescopes is about 200–250 keV, while we have observed resolution widths of about 60 keV in our initial experiments. Better resolution can most likely be achieved with targets of better quality.

Fig. 20. Angle dependence of the optimum Q value extracted from the data for the $^{172}\text{Yb}(^{16}\text{O}, ^{12}\text{C})$, $^{172}\text{Yb}(^{16}\text{O}, ^{14}\text{C})$, $^{124}\text{Sn}(^{16}\text{O}, \text{C})$, and $^{88}\text{Sr}(^{16}\text{O}, ^{12}\text{C})$ reactions. The solid lines correspond to $\Delta L = 0$ transfer with recoil, the dashed lines to no-recoil transfer.

Fig. 21. Spectrum of the $^{90}\text{Zr}(^{16}\text{O}, ^{12}\text{C})^{94}\text{Mo}$ reaction. In these measurements with the split-pole spectrograph and the position-sensitive proportional counter, the resolution width was about 110 keV FWHM, which is sufficient to show some of the detailed structure in the peak of the optimum Q value in the spectrum.

In heavy-ion work, the large number of open reaction channels necessitates the use of an electronic detector instead of photographic emulsions. The detector used is a 50-cm-long position-sensitive proportional counter operated as described by Borkowski and Kopp. It is the one used for many light-ion experiments and has not been specifically optimized for heavy-ion use. An energy-loss signal is derived by summing the position signals from both ends of the counter. The pressure in the counter gas, which is isolated from the vacuum by a 0.5-mil Mylar foil, is about 0.5 atm; and the counter voltage is lower than for light-ion work.

In initial tests, we studied the ^{16}O -induced reactions on targets of $^{40,48}\text{Ca}$ and ^{88}Sr since these reactions had been well studied by counter-telescope techniques. In most cases we were able to achieve a clean separation between the ^{16}O , ^{15}N , and carbon ions recorded by the counter. We could not separate ^{12}C and ^{14}C ions on the basis of their energy-loss signals alone; but because of their mass difference, carbon ions of the same energy are well separated along the focal plane. In this respect, the magnetic analysis has an advantage over counter-telescope systems.

Fig. 21

m. Experimental and Theoretical Study of the $^{48}\text{Ca}(^{16}\text{O}, ^{14}\text{C})^{50}\text{Ti}$ Reaction*
 Y. Cassagnou,[†] R. M. DeVries,[†] M. C. Lemaire,[†] and G. C. Morrison

The $^{48}\text{Ca}(^{16}\text{O}, ^{14}\text{C})$ reaction is a good test case for two-proton transfer, since the first four states of ^{50}Ti are known to have spins 0^+ , 2^+ , 4^+ , and 6^+ , respectively, and to represent a relatively pure $(\pi f_{7/2})^2$ configuration. Thus the systematic behavior of the measured differential cross sections for different L transfer, excitation energies,

* Work done on the FN tandem at the Centre d'Etudes Nucléaires de Saclay while G. C. Morrison was there on foreign assignment.

[†] CEN Saclay, 91 Gif-sur-Yvette, France.

and bombarding energies may be compared with the shapes predicted by different theoretical treatments. To supplement the original Argonne data at 42 and 48 MeV, the reaction was also studied at 59.5 MeV on the Saclay FN tandem. The results of the systematic analysis of the combined data are being prepared for publication.

n. Comparison of Different Four-Particle Transfer Reactions on ^{54}Fe and ^{90}Zr Targets*

Y. Cassagnou,[†] H. Faraggi,[†] G. C. Morrison, and A. Papineau[†]

To date, most information on the transfer of four particles in reactions on heavier nuclei ($A \gtrsim 40$) has come from the reaction ($^{16}\text{O}, ^{12}\text{C}$). In an effort to shed light on the underlying reaction mechanism, and in particular on the role of the structure of the projectile, other heavy-ion transfer reactions such as ($^{18}\text{O}, ^{14}\text{C}$) and ($^{14}\text{N}, ^{10}\text{B}$) have been utilized. For ^{54}Fe , the same states in the ^{58}Ni final nucleus appear to be populated in all three reactions. Indeed, for the ($^{18}\text{O}, ^{14}\text{C}$) and ($^{16}\text{O}, ^{12}\text{C}$) reactions, which have nearly the same Q values, both the over-all shape of the spectra and the intensity ratios of individual peaks were very similar. For ^{90}Zr no structure was resolved, although the over-all shapes were also similar. For each target, the cross section for ^{18}O is $\sim 1/3$ of that for ^{16}O , the ratio being close to that expected from the probability of finding an "alpha" cluster in the respective projectiles.

* Work done on the FN tandem at the Centre d'Etudes Nucléaires de Saclay while G. C. Morrison was there on foreign assignment.

[†] CEN Saclay, 91 Gif-sur-Yvette, France.

o. The $^{58}\text{Ni}(\alpha, \alpha')$ Reaction to the High-Lying States in ^{58}Ni [†]

G. Bruge,* A. Chaumeaux,* R. DeVries,* and G. C. Morrison

This high-resolution study of inelastic α scattering at the Saclay cyclotron was an experiment to examine whether the states excited in scattering were the same as those strongly populated in the heavy-ion α -transfer reactions. The results confirmed that they were indeed the same states and thus de-emphasized their "quartet" nature and showed rather that their excitation in transfer reactions was but one aspect of a more general collectivity. The results have been published.¹

[†] Work done on the cyclotron at the Centre d'Etudes Nucléaires de Saclay while G. C. Morrison was there on foreign assignment.

* CEN Saclay, 91 Gif-sur-Yvette, France.

¹ G. Bruge, A. Chaumeaux, R. DeVries, and G. C. Morrison, Phys. Rev. Letters 29, 295 (1972).

p. Study of γ Rays Following the Heavy-Ion-Induced Transfer Reactions^{*}

R. Ballini,[†] J. Delaunay,[†] J.-P. Fouan,[†] and G. C. Morrison

This work was part of a more general program of (particle, γ) coincidence experiments and Doppler-shift lifetime measurements in progress by the Saclay group. In the course of their work, some very sophisticated equipment using large Ge(Li) γ -ray detectors and solid-state particle detectors with fast electronics and an on-line computer system to handle and analyze their data had been developed.

One experiment was an attempt to use the $^{48}\text{Ca}(^{16}\text{O}, ^{15}\text{N})^{49}\text{Sc}$ reaction to measure the lifetime of the first excited state of ^{49}Sc at 3.08 MeV by Doppler-shift techniques. This state has some theoretical interest, but the experiment was primarily a test of the feasibility of such experiments. Despite the low coincidence yields which necessitated long

^{*} Work done on the FN tandem at the Centre d'Etudes Nucléaires de Saclay while G. C. Morrison was there on foreign assignment.

[†] CEN Saclay, 91 Gif-sur-Yvette, France.

running times, the experiment was completed and is being written up for publication. A second experiment tried to study the γ decay of states populated in heavy-ion transfer reactions. By using bombarding energies close to the Coulomb barrier (for which the particles are mainly emitted at 180°), the efficiency for particle detection could be considerably improved. A preliminary survey of targets of several Sn and Cd isotopes had been made during the period of collaboration, and such experiments are continuing.

3. Li-INDUCED REACTIONS

a. The $^{12}\text{C}(^6\text{Li},d)^{16}\text{O}$ Reaction

P. T. Debevec, H. T. Fortune, and R. E. Segel

At a bombarding energy of 32 MeV, spectra with 30-keV resolution were obtained for the "alpha transfer" reaction $^{12}\text{C}(^6\text{Li},d)^{16}\text{O}$ by using photographic emulsions in the focal plane of the Enge split-pole spectrograph. Angular distributions ($8-32^\circ$ in 3° steps and $140-150^\circ$ in 5° steps) were extracted for all narrow states below an excitation energy of 14.0 MeV.

The unnatural-parity 2^- state at 8.87 MeV was excited less strongly here than at lower bombarding energies, and for this reason it was expected that the extraction of α -particle spectroscopic factors would be more reliable. However, we noticed an anomaly that casts doubt on the assumption that the $(^6\text{Li},d)$ cross section is proportional to the α -particle width. The 4^+ state at 10.353 MeV ($\Gamma_\alpha = 27$ keV) and the 4^+ state at 11.096 MeV ($\Gamma_\alpha = 0.3$ keV) were found to have comparable cross sections in $(^6\text{Li},d)$. As their α -particle widths differ by a factor of 100, such strong excitation of the 11.096-MeV state is evidence for other significant processes. A survey of other four-particle transfer reactions to these states showed the same effect. It appears that the reaction mechanism

is sufficiently complicated that the extraction of spectroscopic factors is unreliable.

b. The $^{18}\text{O}(^6\text{Li}, ^6\text{He})^{18}\text{F}$ Reaction

W. R. Wharton and P. Debevec

Angular distributions of the $^{18}\text{O}(^6\text{Li}, ^6\text{He})^{18}\text{F}$ reaction to the low-lying levels of ^{18}F have been measured at a laboratory energy of 32 MeV. The data were obtained by use of a Si surface-barrier position-sensitive detector in the focal plane of the Enge split-pole spectrograph. These reactions are expected to be quasi-elastic spin-isospin-flip reactions, as has been shown for the similar $^6\text{Li}(^6\text{Li}, ^6\text{He})^6\text{Be}$ reaction.¹ A microscopic DWBA analysis of the data is being made to compare with other quasi-elastic reactions such as (p,p') and (^3He ,t). Microscopic analyses of (^3He ,t) reactions and in particular the $^{18}\text{O}(^3\text{He}, \text{t})^{18}\text{F}$ reaction have failed to predict the shape of the angular distributions to the unnatural-parity states. A microscopic analysis requires an accurate knowledge of the reaction mechanism, the effective nucleon-nucleon interaction, and the wave functions of the nuclear states. It is not always clear which of these is the cause of poor agreement between the theory and the data. The study of the $^{18}\text{O}(^6\text{Li}, ^6\text{He})^{18}\text{F}$ reaction should shed some light on this problem.

¹ W. R. Wharton, Ph. D. Thesis, University of Washington, 1972 (unpublished).

c. α Transfer in the $(^6\text{Li}, \text{d})^{44}\text{Ti}$ Reaction

U. Strohmusch, C. L. Fink, B. Zeidman, R. N. Horoshko,* H. W. Fulbright,* and R. Markham*

The reaction $^{40}\text{Ca}(^6\text{Li}, \text{d})^{44}\text{Ti}$ was studied at an incident energy of 32 MeV in a program initiated in order to ascertain the utility of the $(^6\text{Li}, \text{d})$ reaction as a spectroscopic tool for targets of mass 40 or

* University of Rochester, Rochester, New York.

Fig. 22. Angular distributions for the $^{40}\text{Ca}(^6\text{Li}, d)^{44}\text{Ti}$ reaction at $E_{\text{inc}} = 32 \text{ MeV}$. The curves are the result of DWBA calculations.

greater. The angular distributions obtained showed clear structure corresponding uniquely to the angular momentum transferred in the reaction.

Fig. 22

An analysis utilizing the zero-range DWBA and an assumption of α -cluster transfer was surprisingly successful in fitting the data. Inasmuch as (${}^6\text{Li}, d$) cross sections are of the order of magnitude of those for (${}^{16}\text{O}, {}^{12}\text{C}$) reactions and the angular distributions contain information about nuclear structure, further studies are desirable. A report of this work has been published.¹

¹U. Strohhusch, C. L. Fink, B. Zeidman, R. N. Horoshko, H. W. Fulbright, and R. Markham, Phys. Rev. Letters 29, 735 (1972).

d. ${}^6\text{Li}$ and ${}^7\text{Li}$ Elastic and Inelastic Scattering in the Calcium Region
C. L. Fink, U. Strohhusch, and B. Zeidman

Elastic-scattering angular distributions have been measured for ${}^6\text{Li}$ on ${}^{40}\text{Ca}$, ${}^{44}\text{Ca}$, ${}^{48}\text{Ca}$, and ${}^{50}\text{Ti}$ and for ${}^7\text{Li}$ on ${}^{40}\text{Ca}$ at an incident energy of 32 MeV. The slopes of the angular distributions are similar in all cases, but the diffraction structure observed is considerably enhanced for ${}^6\text{Li}$ on ${}^{40}\text{Ca}$. The results were analyzed in terms of a standard optical-model potential. Several discrete families of parameters—each with an associated continuous ambiguity—were found to give equally good descriptions of the elastic scattering. To reproduce the damping of the diffraction structure, it was necessary to increase both the imaginary well depth and the diffuseness. This is consistent with the idea that the damping is due to channels that are neglected in the DWBA formalism. In particular, the effect of the neglect of the inelastic scattering to the first 2^+ state is being calculated by use of a coupled-channel calculation. If this inelastic-scattering channel is the major reason for the observed damping, then the optical-model potential used for ${}^{40}\text{Ca}$ should be able to describe the elastic scattering for the other nuclei. This method may also remove some of the ambiguity in the optical-model potentials.

Fig. 23

Fig. 23. Angular distributions obtained for ${}^6\text{Li}$ elastic scattering at an incident energy of 32 MeV. Except for ${}^{44}\text{Ca}$, the curves have been shifted for clarity. The solid curves connecting the points are to aid the eye.

Inelastic angular distributions to the first 2^+ state of ^{44}Ca and ^{50}Ti have been obtained with ^6Li as a projectile. In the case of ^7Li , angular distributions were obtained for the $\frac{1}{2}^-$ state of ^7Li as well as for the first 3^- and 2^+ state of ^{40}Ca . Macroscopic DWBA calculations as well as coupled-channel calculations are in progress in order to extract deformation parameters.

e. The (^7Li , ^6Li) Reaction on ^{40}Ca and ^{56}Fe

C. L. Fink, K. Katori, and B. Zeidman

The (^7Li , ^6Li) reaction is being studied as a part of the ^7Li inelastic-scattering program. Angular distributions have been obtained for states in ^{41}Ca for an incident energy of 32 MeV and for states in ^{57}Fe for incident energies of 18, 20, and 24 MeV. The same states excited in (d,p) reactions appear to be excited by the (^7Li , ^6Li) reaction. If one uses the optical-model parameters from the previous studies and the single-particle wave functions and spectroscopic factors from the (d,p) work, then there are no free parameters left in the DWBA analysis. We intend to use these parameters to study the no-recoil approximation by means of the code RDRC of Tobocman. Tentative results at 32 MeV for ^{41}Ca indicate that the absolute magnitude of the theoretical cross section is in agreement with experiment but that the theoretical angular distributions are peaked too far forward.

f. Interference Between Coulomb and Nuclear Potentials in ^7Li Inelastic Scattering on ^{56}Fe

C. L. Fink, K. Katori, G. C. Morrison, and B. Zeidman

Several recent experiments involving α , ^6Li , and ^{16}O particles have shown a destructive interference between the Coulomb and nuclear potentials for inelastic scattering. Because the Coulomb part of the interaction is believed to be well known, a study of this

Fig. 24. Angular distributions for $^{56}\text{Fe}(^7\text{Li}, ^7\text{Li})$ elastic and inelastic scattering. The full line and closed circles indicate excitation of the target; the dotted lines and open circles indicate excitation of the projectile. For clarity, the cross section for the 2^+ state of ^{56}Fe has been reduced by a factor of ten. The curves are drawn to aid the eye.

interference may lead to additional information on the nuclear interaction. In particular, since the nuclear part of the excitation in a macroscopic theory is expected to depend on the optical-model parameters used to describe elastic scattering, this method may also provide information about the optical-model parameters. We have extended the above method by using ${}^7\text{Li}$ as a projectile that can itself be excited.

The general features of the angular distributions are in agreement with this simple idea of interference between Coulomb and nuclear forces. At 18 MeV the destructive interference for the first excited 2^+ state of ${}^{56}\text{Fe}$ is shallow because the Coulomb term is dominant. For the $\frac{1}{2}^-$ state (0.477 MeV) of ${}^7\text{Li}$, however, the Coulomb term is smaller and therefore the minimum is much deeper. As the incident energy is increased, the nuclear part of the interaction becomes comparable to that of Coulomb interaction, and consequently the interference minimum both for the 2^+ state of ${}^{56}\text{Fe}$ and for the $\frac{1}{2}^-$ state of ${}^7\text{Li}$ is observed to deepen. Qualitatively, these results are in agreement with macroscopic DWBA calculations. A detailed investigation of the exact shape and magnitude of this interference is in progress.

Fig. 24

g. An Attempt to Study the ${}^{90}\text{Zr}({}^6\text{Li}, d){}^{94}\text{Mo}$ Reaction

U. Strohmusch and J. P. Schiffer

A beam of 32-MeV ${}^6\text{Li}$ ions has been used to study the $({}^6\text{Li}, d)$ reaction on a ${}^{90}\text{Zr}$ target. Deuterons were detected with the Argonne split-pole magnetic spectrograph. Deuteron groups corresponding to the low-lying states of ${}^{94}\text{Mo}$ were observed with cross sections of a few $\mu\text{b/sr}$. Because of deuterons from target contaminants (chiefly oxygen), only a limit of $\sim 20 \mu\text{b/sr}$ may be placed for single states at higher excitation. The results will be compared with DWBA calculations that have been normalized to the ${}^{40}\text{Ca}({}^6\text{Li}, d){}^{44}\text{Ti}$ reaction.¹

¹U. Strohmusch, C. L. Fink, B. Zeidman, R. N. Horoshko, H. W. Fulbright, and R. Markham, Phys. Rev. Letters 29, 735 (1972).

Fig. 25. Typical proton spectrum from the $^{28}\text{Si}(d,p)^{29}\text{Si}$ reaction at $\theta_{\text{lab}} = 41^\circ$ and bombarding energy $E_d = 16 \text{ MeV}$. The excitation energies of states in ^{29}Si are indicated in MeV.

4. CHARGED-PARTICLE SPECTROSCOPY WITH LIGHT IONS

a. No New States in ^{16}N

P. T. Debevec

Spectra for the previously unreported reaction $^{13}\text{C}(\alpha, p)^{16}\text{N}$ were obtained at forward angles by use of photographic emulsions in the focal plane of the Enge split-pole spectrograph. With 8-keV resolution, no new states were identified below an excitation energy of 4.5 MeV. Thus the 0^+ $T=1$ two-particle two-hole state, which has escaped detection in neutron scattering and in all charged-particle transfer reactions, remains unidentified.

b. Levels in ^{29}Si by Means of the $^{28}\text{Si}(d, p)$ Reaction

L. R. Medsker and J. L. Yntema

The recent proposal¹ of a common doorway state consisting of a $2p_{3/2}$ neutron coupled to the ^{28}Si ground state has led to new questions about the distribution of $2p_{3/2}$ strength at high excitation energies in ^{29}Si . The present study is an attempt to obtain further information by use of the (d, p) reaction. Experiments with the split-pole magnetic spectrograph at the tandem Van de Graaff have used both NTB emulsion plates and the gas-filled proportional counter. About 20 levels have been identified with excitation energies in the range 8–11 MeV. Analysis of the data is in progress and comparisons with $^{29}\text{Si}(\gamma, n)$ and $^{28}\text{Si}(n, n')$ measurements are planned.

¹H. E. Jackson and R. E. Toohey, Phys. Rev. Letters 29, 379 (1972).

c. Study of the $(d_{3/2} f_{7/2})$ Interaction by Means of the $^{37}\text{Cl}(d, p)^{38}\text{Cl}$ and $^{39}\text{K}(d, p)^{40}\text{K}$ Reactions

C. L. Fink and J. P. Schiffer

The (d, p) reactions on ^{37}Cl and ^{39}K were studied at $E_d = 12$ MeV in order to identify all $\ell = 3$ components. A discrepancy between

TABLE II. $(d_{3/2}^f 7/2)$ n-p matrix elements (MeV).

J_π	From ^{34}Cl and ^{34}S	From ^{38}Cl
2^-	-1.69	-1.69
3^-	-0.59 ± 0.09	$-0.94 \rightarrow -0.68$
4^-	-0.31 ∓ 0.09	-0.38
5^-	-1.04	-1.02

Table II

the lowest states of ^{38}Cl and the predictions from our earlier work^{1,2} on ^{34}Cl and ^{34}S seems to be accounted for by the observed fragmentation of the 3^- state in ^{38}Cl . Corresponding fragmentation is expected in ^{40}K ; though it could not be seen in the data, it is within the limits of uncertainty. Results on $\ell = 1$ transitions have also been obtained.

¹J. R. Erskine, D. J. Crozier, J. P. Schiffer, and W. P. Alford, Phys. Rev. C 3, 1976 (1971).

²D. J. Crozier, Nucl. Phys. A198, 209 (1972).

d. The $(d_{5/2}^g 9/2)$ Interaction from $^{91}\text{Zr}(^3\text{He}, \alpha)^{90}\text{Zr}$ Reaction

H. Fann, U. Strohmusch, and J. P. Schiffer

The $\ell = 4$ strength from the $^{91}\text{Zr}(^3\text{He}, \alpha)$ reaction was used to identify members of the $d_{5/2}^g 9/2$ multiplet in ^{90}Zr . These states appeared to be remarkably pure, very nearly exhausting the sum-rule limit. Only the 2^+ strength appears to be fragmented. The multiplet, through the Pandya transformation, yields the $T = 1$ $(d_{5/2}^g 9/2)$ particle-particle matrix elements and, combined with other data, the $T = 0$ matrix elements. Those matrix elements are in excellent agreement with those calculated with an effective interaction which was derived from data near $A = 208$ and 34.¹

Fig. 26

¹N. Anantaraman and J. P. Schiffer, Phys. Letters 37B, 229 (1971).

Fig. 26. Two-nucleon matrix elements for nonidentical orbits. The data shown (from left to right) are respectively from the $A \approx 34$, $A \approx 208$, and $A \approx 208$ studies and from the present study of the $A \approx 90$ region of the periodic table.

e. Neutron Pickup on ^{41}K

P. T. Debevec and C. L. Fink

The neutron-pickup reaction $^{41}\text{K}(^3\text{He}, ^4\text{He})^{40}\text{K}$ has been studied at a bombarding energy of 24 MeV. Spectra with 30-keV resolution were obtained over the angular range from 10° to 40° in 5° steps by use of the position-sensitive proportional counter in the focal plane of the Enge split-pole spectrograph.

Neutron pickup on ^{41}K is unique in that it allows the study of two-particle two-hole states with a one-nucleon transfer reaction. In particular, the excitation of the first and second $T=2$ states can be compared with that of states of the $T=1$ configuration. The $^{41}\text{K}(d, t)^{40}\text{K}$ reaction will also be studied to obtain accurate spectroscopic information.

f. The $^{41}\text{K}(^3\text{He}, t)^{41}\text{Ca}$ and $^{89}\text{Y}(^3\text{He}, t)^{89}\text{Zr}$ Reactions

M. Stautberg Greenwood, L. R. Greenwood, N. Anantaraman, and Maria Pluta

During the summer of 1972, data on the 4—7.7-MeV region of excitation energies in ^{41}Ca were taken with the position-sensitive proportional counter at the tandem. One of the purposes was to search for and, if possible, to obtain an angular distribution for the excited analog state thought to be located at $E_x = 7.14$ MeV. Some of the more prominent excited states among the many seen in this region were at 5.39, 5.49, 5.54, 5.63, 5.72, 5.81, 5.96, 6.07, 6.32, 6.47, 6.57, 6.65, 6.74, 6.82, 6.91, 6.99, 7.12, 7.21, 7.50, 7.55, and 7.61 MeV. The data analysis is nearing completion, and angular distributions (each with data points at 12 angles) will be obtained for most of these states.

A large part of the data on the lower excited states populated in the $(^3\text{He}, t)$ reactions on ^{41}K and ^{89}Y targets were analyzed by Maria Pluta for a M. S. thesis in physics at DePaul University, June 1972.

The distorted-wave $L = 2$ angular distributions gave a very good fit to the data, even at forward angles. However, the ground-state transitions

Fig. 27. The $L = 3$ and 5 differential cross sections for the $^{41}\text{K}(^3\text{He}, t)^{41}\text{Ca}$ reaction.

Fig. 28. The $L = 4$ and 6 differential cross sections for the $^{89}\text{Y}(^3\text{He}, t)^{89}\text{Zr}$ reaction.

in the two nuclei were not easily fitted by the DW theory—especially at forward angles. For ^{89}Y , we obtained many broad angular distributions indicative of $L \geq 4$.

Fig. 28

g. A Study of ^{47}Ti Levels with the $^{45}\text{Sc}(\alpha, d)^{47}\text{Ti}$ Reaction

L. Meyer-Schützmeister, G. Hardie, and T. H. Braid

Fig. 29

Many levels in ^{47}Ti have been studied with the $^{45}\text{Sc}(\alpha, d)$ reaction induced by the 25-MeV α beam from the Argonne tandem Van de Graaff. The experimental results have been compared with those obtained in earlier studies with the $^{45}\text{Sc}(^3\text{He}, p)^{47}\text{Ti}$ reaction. Although both reactions involve transfer of an n-p pair to the target nucleus, they strongly excite different sets of levels. In the $(^3\text{He}, p)$ reaction, these levels are associated with orbital angular-momentum transfers $L_{np} = 0$ or $L_{np} = 0 + 2$ while in the (α, d) reaction the strongly-populated levels show angular distributions typical of orbital angular-momentum transfers $L_{np} > 2$. The difference is due to kinematical effects, as is shown by DWBA calculations.

The levels strongly excited by the $^{45}\text{Sc}(\alpha, d)^{47}\text{Ti}$ reaction with $L_{np} > 2$ are at $E_x = 2.753, 3.572, \text{ and } 4.492$ MeV. It is reasonable to assume that they are high-spin states and might well be connected by strong γ transitions. Unfortunately the $^{45}\text{Sc}(\alpha, d)$ reaction has a large negative Q value and a rather small cross section. Consequently a study of the γ decay by the $(\alpha, d\gamma)$ reaction is difficult, and we have decided to study the γ decay of these high-spin states by heavy-ion bombardment of a suitable target.

In an earlier study, levels in ^{47}Ti at $E_x = 0.16, 2.61, 2.83, \text{ and } 3.22$ MeV were strongly populated by the $^{45}\text{Sc}(^3\text{He}, p)^{47}\text{Ti}$ reaction with either $L_{np} = 0 + 2$ or 0 and were found to have spin assignments of $\frac{5}{2}^-$ or $\frac{7}{2}^-$. This $(^3\text{He}, p)$ study indicated that the 3.22-MeV state was an antianalog with $J^\pi = \frac{7}{2}^-$. In the present (α, d) study, we see all of these four states, but the one at 3.22 MeV is populated much more weakly

Table III

Fig. 29. Deuteron spectra from the $^{45}\text{Sc}(\alpha, d)^{47}\text{Ti}$ reaction, as measured at the angles of 22 and 7° to the incoming beam of 25-MeV alphas. Three deuteron groups (those labeled 14, 22, and 29) have unusual angular distributions in that the maximum cross section is at about 20°. This indicates that the orbital angular momentum transferred by the captured n-p pair is $L_{np} = 6$ and makes a high spin likely for these states.

TABLE III. Some ^{47}Ti levels populated by both the $(^3\text{He}, p)$ and the (α, d) reaction on ^{45}Sc .

J^π	E_x (MeV)	Angle (deg)	$d\sigma/d\Omega$ (in $\mu\text{b/sr}$) (α, d)	$d\sigma/d\Omega$ (in $\mu\text{b/sr}$) ($^3\text{He}, p$)
$\frac{7}{2}^-$	0.16	7	16.8	6.4
$\frac{7}{2}^-$	2.61	7	19.0	13.8
$(\frac{7}{2}^-, \frac{5}{2}^-)$	2.83	7	25.8	42
$\frac{7}{2}^-$	3.22	7	~ 3.5	20

than the others, as expected for an antianalog. Hence the earlier conclusion that the 3.22-MeV state is an antianalog is supported by the (α, d) study.

h. Levels in ^{97}Nb by Means of the $^{96}\text{Zr}(^3\text{He}, d)$ Reaction

L. R. Medsker and J. P. Schiffer

The $^{96}\text{Zr}(^3\text{He}, d)$ reaction has been restudied with the 22-MeV $^3\text{He}^{++}$ beam from the tandem Van de Graaff. The angular

Fig. 30. Typical deuteron spectrum from the $^{96}\text{Zr}(^3\text{He}, d)^{97}\text{Nb}$ reaction. The excitation energies of the states are given in MeV.

Fig. 31. Energy-level schemes of ^{97}Nb as deduced from β -decay, $(d, ^3\text{He})$, and $(^3\text{He}, d)$ measurements. These data are compared with the results of shell-model calculations in which ^{97}Nb is treated as a ^{88}Sr core plus three protons and six neutrons.

Fig. 30

distributions in the range $8-60^\circ$ were measured with a split-pole magnetic spectrograph, and spectra were recorded on NTB emulsion plates.

Fig. 31

Approximately 40 levels in ^{97}Nb were observed at energies up to 4 MeV excitation and, in many cases, the comparison of the angular distribution with DWBA calculations permitted the determination of l transfers and spectroscopic factors. Although a few low-lying states due to the configurations $g_{9/2}$ and $p_{1/2}$ were identified, the level scheme was found to be quite complex, as expected for nuclei away from major closed shells.

TABLE IV. Measured mean lives in ^{36}Cl .

Transition $E_i \rightarrow E_f$ (keV) (keV)	Adopted τ (fsec)	Transition $E_i \rightarrow E_f$ (keV) (keV)	Adopted τ (fsec)
0.788 $\rightarrow$ 0	3000 ± 1200	2.993 $\rightarrow$ 0	90 ± 12
1.163 $\rightarrow$ 0	3000 ± 1200	3.100 $\rightarrow$ 2.471	215^{+70}_{-40}
1.601 $\rightarrow$ 0	800 ± 150	3.205 $\rightarrow$ 1.163	140 ± 20
1.952 $\rightarrow$ 0 $\rightarrow$ 0.788	1800^{+1000}_{-500}	3.332 $\rightarrow$ 1.601 $\rightarrow$ 1.960	105 ± 10
1.960 $\rightarrow$ 0	60 ± 15	$\rightarrow$ 2.471	
2.471 $\rightarrow$ 1.952	470 ± 50	3.473 $\rightarrow$ 0	< 35
2.492 $\rightarrow$ 1.163	60 ± 10	$\rightarrow$ 1.960	
2.519 $\rightarrow$ 0.788	7500^{+7500}_{-2500}	3.599 $\rightarrow$ 2.471	60 ± 20
2.676 $\rightarrow$ 0	< 10	3.633 $\rightarrow$ 1.163 $\rightarrow$ 1.952	30 ± 15
2.810 $\rightarrow$ 0.788 $\rightarrow$ 1.952	2700 ± 1000	3.662 $\rightarrow$ 0	(< 80)
2.868 $\rightarrow$ 0	< 15	3.723 $\rightarrow$ 2.810	70 ± 15
2.896 $\rightarrow$ 0 $\rightarrow$ 1.960	860 ± 80	3.965 $\rightarrow$ 0	< 30
		3.996 $\rightarrow$ 1.960	30 ± 10

5. γ -RAY SPECTROSCOPY WITH CHARGED-PARTICLE-INDUCED REACTIONS

a. γ -Ray Decay in ^{36}Cl

A. S. Yousef, E. L. Sprenkel-Segel, and R. E. Segel

The decays of 24 states below 4 MeV in ^{36}Cl have been studied by use of p- γ coincidences. The excited states were populated by the $^{35}\text{Cl}(d,p)$ reaction with 3.5-MeV deuterons bombarding enriched PbCl_2 targets. Branching ratios were determined and the mean lives of the states were measured by the attenuated-Doppler-shift method. While the level scheme is complex, it is possible to discuss many of the transitions in terms of simple shell-model configurations. Radiative rates among some of the lowest levels are compared with a recent shell-model calculation.

Table IV

b. Spectroscopy of ^{39}Ar

E. L. Sprenkel-Segel, W. C. Corwin, and R. E. Segel

Targets of PbCl_2 enriched in ^{37}Cl were bombarded with 17-MeV ^3He particles, and the resulting proton spectrum was analyzed with a split-pole magnetic spectrograph. Data were taken every 2.5° between 5° and 30° . The strongest peak in the spectrum was that corresponding to the first analog state, which was found to be at $E_x = 9.097$ MeV. This $J=\frac{3}{2}^-$ $T=\frac{5}{2}^-$ state is presumably formed from ^{37}Cl by adding a pair of $f_{7/2}$ nucleons coupled to $J = 0$, $T = 1$. One also expects a low-lying antianalog state in which the same pair of particles coupled together in the same way is added to ^{37}Cl to form a $J=\frac{3}{2}^+$ $T=\frac{3}{2}^+$ state, which a recent prediction¹ puts at ~ 3.0 MeV. The strongly forward-peaked state at 3.396 MeV is the most prominent state below 4 MeV forward of 10° , but

Fig. 32

¹ D. H. Gloeckner, R. D. Lawson, and F. J. D. Serduke, Phys. Rev. C 7, 1913-1926 (May 1973).

Fig. 32. Proton yield of the $^{37}\text{Cl}(^3\text{He},p)^{39}\text{Ar}$ reaction, with the magnetic spectrograph placed at 10° to the incident 17-MeV ^3He beam. Carbon and oxygen in the target produce impurity peaks.

it does not dominate the spectrum in its energy region. It thus appears to be at least partially the antianalog of the ^{39}Cl ground state, but there may be considerable fragmentation to higher levels.

c. γ Decay of High-Spin States in ^{47}Ti

T. Sjoreen, L. Meyer-Schützmeister, and G. Hardie

High-spin states in ^{47}Ti are populated by the $^{45}\text{Sc}(\alpha, d)$ reaction. However, the small cross section makes it difficult to carry out γ -decay studies. Instead, we have been able to study the γ decay of these high-spin states by using the compound-nucleus reaction $^{45}\text{Sc} + \alpha \rightarrow ^{47}\text{Ti} + n + p + \gamma$, which populates these high-spin states with a much larger cross section than does the (α, d) reaction.

Initially, γ spectra were obtained with a single Ge(Li) detector by bombarding a 1 mg/cm^2 ^{45}Sc target with ^4He ions from the tandem accelerator, the beam energies ranging from 11 to 25 MeV in steps of 2 MeV. The excitation functions of individual γ rays showed that the cross section for the compound reaction leading to ^{47}Ti levels had a maximum at 23 MeV. At this energy, γ - γ coincidence measurements were performed in order to study the γ decay of ^{47}Ti . Two 30-cc Ge(Li) detectors with resolutions (FWHM) of 2.4 keV and 3.0 keV were positioned opposite each other at 90° to the beam. The timing system employed constant-fraction discriminators which provided a time resolution of 5 nsec FWHM for a dynamic range of 22:1. With these data and earlier results from a study of the direct (α, d) reaction, we find that the strongest observed γ cascade proceeds through all of the high-spin states seen in the (α, d) reaction.

Fig. 33

Fig. 33. Gamma rays in coincidence with the 703-keV γ ray in ^{47}Ti .

d. Radiative Capture into ^{55}Co and ^{57}Co

L. Meyer-Schützmeister, R. E. Segel, E. L. Sprenkel-Segel,
J. V. Maher, D. von Ehrenstein, G. C. Kiang,* R. J. Nemanich,*
and J. F. Tonn

The giant-dipole resonance in the Co isotopes has been investigated by studying radiative capture by Fe isotopes. The $^{54}\text{Fe}(p, \gamma_0)$ and $^{56}\text{Fe}(p, \gamma_0)$ reactions were studied, and in both cases the yield curve showed evidence of an isospin-split giant resonance. As predicted by theory, the energy splitting was greater in the isotope with higher isospin and the relative strength in the $T_>$ component was less. Extensive angular-distribution measurements indicated that in both cases the two isospin components had significantly different angular distributions: the coefficient of the second Legendre polynomial was positive for the low side of the resonance (where the $T_<$ component is assumed to be located) and negative on the high side. This discovery that the angular distributions depend on isospin may help to solve the long-standing problem of the nearly constant angular distributions in self-conjugate nuclei.

* Northern Illinois University, DeKalb, Illinois.

e. E2 Isomers in Odd-Neutron Nuclei

R. E. Holland, F. J. Lynch, and B. D. Belt

We have recently reported a number of inhibited E2 transitions between low-lying levels in odd-neutron nuclei. We have completed a rather detailed comparison between a larger body of data on E2 transition rates and the predictions of the pairing-plus-quadrupole model. Under certain simplifying assumptions, the reduced E2 transition rate can be written as

$$B(E2; j_i \rightarrow j_f) = B(\text{s. p.}; j_i \rightarrow j_f) (U_i U_f - V_i V_f)^2 \left[1 + \frac{2}{5} \chi \frac{B(E2)}{\Delta E} \right]^2, \quad (1)$$

where χ is the quadrupole coupling constant, $B(E2)$ is the reduced transition rate for the $0 \rightarrow 2$ transition, and ΔE is the energy of this transition

Fig. 34

Fig. 34. The ratio $B(E2)/B(s.p.)$ of the observed reduced transition rate $B(E2)$ to the single-particle rate $B(s.p.)$, plotted as a function of a parameter derived from the pairing-plus-quadrupole model. This parameter was obtained from experimentally determined values of the occupation numbers V_j^2 from (d,p) and (d,t) reactions, the energy ΔE and the $B(E2; 0 \rightarrow 2)$ of the transition in the adjacent even-even isotope, and the quadrupole-coupling constant χ . The diagonal line is calculated from Eq. (1). A closed circle was plotted for each transition for which both (d,p) and (d,t) data exist for determining V_j and U_j , an open circle for each one for which the data are more fragmentary. The scatter in the points on the left-hand side of the figure can be attributed to the lack of precision in experimentally determined occupation numbers V_j^2 , while on the right-hand side of the figure, the assumptions made in obtaining Eq. (1) are not justified.

in the neighboring even-even nucleus. The occupation numbers U_i , U_f , V_i , and V_f are determined from published experimental data on pickup and stripping reactions. The data are in reasonable agreement with the predictions from this equation. A report on this work has been submitted for publication.

f. Nuclear Data Sheets for A = 95, 96, and 97

L. R. Medsker and J. P. Schiffer

This work is part of the Nuclear Data Compilation Program supported by the National Science Foundation through the National Academy of Sciences. The 1960 versions of Nuclear Data Sheets for A = 95 and 96 have been revised^{1,2} on the basis of experimental data from approximately 300 papers and communications. The data have been evaluated and utilized to construct level and decay schemes. A draft of the A = 97 compilation has recently been completed.³

Fig. 35

¹ L. R. Medsker and D. J. Horen, Nucl. Data B8, No. 1 (1972).

² L. R. Medsker, Nucl. Data B8, No. 6 (1972).

³ L. R. Medsker, Nucl. Data B10, No. 1 (1973).

6. STRUCTURE OF ACTINIDE NUCLEI

a. Single-Particle States in Actinide Nuclei

J. R. Erskine, A. M. Friedman,* R. R. Chasman,* and T. H. Braid

A program to study single-particle excitations in actinide nuclei has been in progress for several years. Magnetic-spectrograph data on the (d,p) and (d,t) reactions on many actinide targets have resulted in extensive knowledge of single-particle states for neutrons. The targets are prepared with the isotope separator in the Argonne Chemistry Division. Those studied to date are ^{230}Th , ^{232}Th , ^{234}U , ^{236}U , ^{238}U , ^{240}Pu ,

* Chemistry Division, ANL.

^{242}Pu , ^{244}Cm , ^{246}Cm , and ^{248}Cm . Analyses of our data on the product nuclei ^{235}U , ^{243}Cm , ^{245}Cm , ^{247}Cm , and ^{249}Cm were published in previous years,¹ and a paper² on ^{241}Pu and ^{243}Pu was published last year.

Our analysis during the year just completed has concentrated on the product nuclei ^{229}Th , ^{231}Th , ^{233}U , and ^{237}U . A supply of ^{244}Pu has also been obtained and we hope to make a target in the near future.

These data are a unique source of information on single-particle states in actinide nuclei. This knowledge is of crucial importance for shell-model calculations of single-particle states, for detailed explanation of excited 0^+ states observed with (p,t) and (t,p) reactions, and for interpretation of recent data on two-quasiparticle states in actinide nuclei.

¹T. H. Braid, R. R. Chasman, J. R. Erskine, and A. M. Friedman, Phys. Rev. C 1, 275 (1970); C 4, 247 (1971).

²T. H. Braid, R. R. Chasman, J. R. Erskine, and A. M. Friedman, Phys. Rev. C 6, 1374 (1972).

b. Two-Quasiparticle States in Actinide Nuclei

K. Katori, A. M. Friedman,* R. R. Chasman,* and J. R. Erskine

Two-quasiparticle states in ^{236}U , ^{236}Np , ^{238}Np , ^{242}Am , ^{244}Am , ^{248}Cf , and ^{250}Cf were studied through the (d,p) and (d,t) reactions.

The neutron single-particle states $\frac{1}{2}+[631]$, $\frac{5}{2}+[622]$, $\frac{1}{2}-[501]$, $\frac{5}{2}-[503]$, and $\frac{3}{2}-[501]$ coupling to the other neutron or proton single-particle states in the target were obtained in two-quasiparticle configurations.

Fig. 36

*Chemistry Division, ANL.

Fig. 36. Spectrum of the $^{249}\text{Cf}(d,t)^{248}\text{Cf}$ reaction. Six rotational bands built on two-quasiparticle excitations are indicated. One of the most interesting features of this spectrum is the $K^\pi = 2^-$ octupole band near 600 keV excitation. Strong mixing with the $K^\pi = 2^-$ two-quasiparticle band near 1400 keV makes it possible to observe this octupole band in a one-particle transfer reaction.

The energy splittings between states with parallel and anti-parallel coupling were calculated on the assumption of an effective two-body residual interaction, and the results were compared with the experimental splittings. For a Rosenfeld force, 8 out of 12 pairs with the $T = 1$ component can be reproduced by a calculation with a Gaussian form factor and with $r_0 = 1.5$ fm and $V_0 = -100$ MeV.

c. A Study of ^{249}Bk , ^{241}Am , and ^{231}Pa with Proton-Transfer Reactions

J. R. Erskine, G. Kyle, R. R. Chasman,* and A. M. Friedman*

Many new single-proton excited states in actinide nuclei have been found in this study, which was made possible by the higher energy beam available from the MP tandem accelerator at the University of Minnesota. Most of the techniques used are similar to those used at Argonne in the extensive long-term investigations of single-neutron excitation.¹

In the present study, the (α, t) and $(^3\text{He}, d)$ reactions were used to populate the single-proton excited states. The energies of these states were found to be well described by theoretical calculations under the assumption of a deformed Woods-Saxon potential well. The absolute cross sections, however, are not well understood. Agreement between measured and calculated cross sections is much worse for the proton-transfer data than for the previously studied neutron-transfer data.

* Chemistry Division, ANL.

¹ For example, T. H. Braid, R. R. Chasman, J. R. Erskine, and A. M. Friedman, Phys. Rev. C 1, 275 (1970).

d. Pair Correlations in Actinide Nuclei

D. Albright, A. Friedman,* K. Katori, and J. P. Schiffer

Our earlier report¹ that the (p, t) reaction on even- A actinide targets proceeds systematically to excited 0^+ states has led to several

* Chemistry Division, ANL.

¹ J. V. Maher, J. R. Erskine, A. M. Friedman, R. H. Siemssen, and J. P. Schiffer, Phys. Rev. C 5, 1380 (1972).

TABLE V. Distribution of excited $L = 0$ strength in (p,t) reactions.

Final nucleus	Excitation (keV)	$\sigma/\sigma_{g.s.}$
$^{224}_{88}\text{Ra}$	920	0.095
	1220	0.22
$^{233}_{92}\text{U}$	190	0.23
	375	1.0 ^a
	690	0.14
	(1186	0.025)
	1640	0.09
	(1890	0.05)
	1940	0.04
$^{235}_{93}\text{Np}$	835	0.07
	962	0.13
	1260	0.06
	1818	0.04
$^{237}_{94}\text{Pu}$	145	1.0 ^a
	800	0.20
$^{238}_{94}\text{Pu}$	945	0.11
	1134	0.01
$^{241}_{95}\text{Am}$	952	0.07
	1550	0.04
	(1590	0.015)
	(2225	0.028)

^aThis is the strongest $L = 0$ state seen. The other excited $L = 0$ states are normalized to this yield.

Fig. 37. The trend in pair binding energies, as shown by the Q values for strong $L = 0$ transitions in (p,t) reactions. Several of the Q values shown are for states identified from other sources. The points labeled "lowest $L = 0$ (g.s.)" represent the ground-state-to-ground-state Q values for even-neutron targets. For odd- N targets, the lowest $L = 0$ transitions proceed to the state (usually an excited one) in which the odd neutron remains in the same orbit. The odd-even anomalies in the curves for the lowest $L = 0$ transitions indicate that blocking the valence orbit affects the pairing energy. The absence of such anomalies in the curve for the "second $L = 0$ " transitions to excited states is evidence that the valence orbits do not participate in this excitation.

Fig. 38. Excitation energies of the states that contain the excited $L = 0$ strength in the even-neutron actinides. In a few of the cases shown, the excited $L = 0$ state is known only from a decay.

theoretical speculations regarding the nature of these pairing vibrations.

We have now extended our study to a few additional even-A targets and to some odd-proton and odd-neutron targets as well. The latter in particular may shed some light on the question of the microscopic constituents of the pairing vibration. Detailed analysis is in progress.

e. Coupled-Channel Calculations for Sub-Coulomb Transfer Reactions on Actinide Nuclei

J. R. Erskine and T. Tamura

Extensive measurements of the absolute cross sections for (d,p) and (d,t) reactions on ^{232}Th and ^{238}U targets have been made at sub-Coulomb bombarding energies.¹ At these energies, uncertainties in optical-model parameters have little effect on the cross sections. Serious discrepancies (disagreements by a factor of 2—6) were found to exist between measured and calculated cross sections.

One of the sources of these discrepancies was thought to be inelastic-scattering effects, which were neglected in the original report.¹ In the present study, the size of the inelastic-scattering contributions to the cross section has been determined in a series of calculations with the computer code MARS (written by T. Tamura and T. Udagawa). This code is based on the coupled-channel Born approximation (CCBA), an extension of the well-known distorted-wave Born approximation (DWBA). Deformed single-particle wave functions with good radial tails were computed with the coupled-channel code NEPTUNE (written by T. Tamura).

In the $^{238}\text{U}(d,t)^{237}\text{U}$ reaction at 8.5 MeV bombarding energy, the inclusion of the inelastic-scattering terms causes a 10—15% modification in the magnitude of the cross section for the transfer reaction to the $J = \frac{1}{2}$, $\frac{3}{2}$, and $\frac{5}{2}$ levels in the ground-state band. This relatively small change in the cross section suggests that inelastic-scattering effects are not the explanation for the discrepancies noted above.

¹ J. R. Erskine, Phys. Rev. C 5, 959 (1972).

Fig. 39. Yield curves, computed with and without inelastic scattering contributions (labeled CCBA and DWBA, respectively), for the ground-state transition in the $^{238}\text{U}(d,t)^{237}\text{U}$ reaction. At the lowest bombarding energy, the difference between the two curves is small. At $E_d = 12$ MeV, changes in the optical-model parameters would probably allow the CCBA curve to fit the data points.

E. RESEARCH AT THE CYCLOTRON

The 60-in. cyclotron provides beams of 23.3-MeV deuterons, 36-MeV ^3He , and 46-MeV alpha particles, all with energy spreads less than 25 keV. The availability of these beams, whose particle energies are considerably higher than are obtainable at the FN tandem, allows flexibility in the Charged Particle Physics program. The high-resolution beams, together with the magnetic spectrograph and focal-plane detector, make possible experiments that complement work on the FN tandem. During the past year a modest effort has been spent on a series of experiments to study properties of nuclei by transfer and charge-exchange reactions.

a. Improvements on the Spectrograph at the Cyclotron

T. H. Braid

The advent of the position-sensitive proportional counter as a data-recording device for the focal plane of magnetic spectrographs has made desirable a number of improvements on the Enge spectrograph at the cyclotron. An independent counter system has been built, and an analog computer system (just being completed) will make possible identification of the particle emerging from a reaction. More sophisticated identification can be made by entering the Sigma 7 computer in the Chemistry Division via a remote terminal which already exists in the data area and which is being brought into service for this purpose.

In order to make optimum use of these possibilities and to minimize the time spent in making initial adjustments, it is highly desirable to provide remote control of a number of parameters for which such control was not previously necessary. These include the setting of the target changer, the angle of the spectrograph, and the position of the counter in the focal plane. Suitable controls are now being designed.

b. Double-Focusing Uniform-Field Magnet with Circular Poles¹

J. J. Livingood

Double focusing of charged particles by a magnet with uniform field and circular poles can be obtained for any single deflection angle by directing the beam at an appropriate point away from the axis of the poles. For a bend of 119.25° , the aberration arising from radially divergent ions is eliminated.

¹ J. J. Livingood, Rev. Sci. Instr. 44, 80-81 (1973).

c. The $^{43}\text{Ca}(d, ^3\text{He})^{42}\text{K}$ Reaction

T. H. Braid and J. L. Yntema

This reaction was studied with counter telescopes a few years ago at the cyclotron. The measurements have now been repeated with the proportional counter and the split-pole spectrograph since application of the sum rule indicated that some transitions corresponding to $2s_{1/2}$ and $1d_{3/2}$ proton pickup had been missed in the earlier work. A level at about 630 keV, previously masked by the strong transition to the 680-keV level, is observed with an $\ell = 0$ angular distribution. The 1.2-MeV level clearly is a doublet, whose members are separated by about 60 keV and appear to have equal widths. The level at 1.63 MeV is masked over a much smaller portion of the angular range, and a number of weak transitions not observed in the previous experiment can now be identified and analyzed.

d. The $^{44}\text{Ca}(d, ^3\text{He})^{43}\text{K}$ Reaction

J. L. Yntema and T. H. Braid

The $(d, ^3\text{He})$ reaction on ^{44}Ca is being restudied with the position-sensitive counter in the magnetic spectrograph. The spectra, which have been recorded from 18 to 30° , show better resolution than in previous measurements. In consequence, weaker levels can be seen

Fig. 40

Fig. 40. Spectrum of the $^{43}\text{Ca}(d, {}^3\text{He})^{42}\text{K}$ reaction at 21° , obtained with the 20-cm proportional counter on the split-pole spectrograph at the 60-in. cyclotron.

clearly. Since this is particularly true for the levels at the higher excitations, it should be possible to assign ℓ values to these weaker states.

e. The (d,t) Reaction on Even-A Germanium Isotopes

J. L. Yntema

The (d,t) reactions on ^{70}Ge , ^{72}Ge , ^{74}Ge , and ^{76}Ge have been studied with the split-pole spectrograph and Kodak NTB plates at the 22.5-MeV deuteron beam of the Argonne 60-in. cyclotron. An excitation range up to $Q = -7.2$ MeV can be studied before the elastically scattered deuterons interfere with the tritons. The resolution width is about 17 keV FWHM. The reaction has been studied from 9° to 40° in 3° steps for all four isotopes. The plates were scanned with the automatic plate scanner, and to satisfy its requirements the total exposure had to be limited because of the considerable background flux of neutrons in the experimental area. The results are being analyzed with the normal computer programs. Preliminary results appear to indicate some $2d_{5/2}$ neutron admixture in ^{76}Ge . Since the $2d_{5/2}$ shell is fairly well separated from the $1g_{9/2}$ shell and the latter is less than half filled, it follows that the germanium isotopes are quite deformed.

f. The $^{96}\text{Ru}(^3\text{He},t)^{96}\text{Rh}$ Reaction

L. R. Medsker, T. H. Braid, and J. L. Yntema

A recently prepared target of enriched ^{96}Ru makes possible the investigation of the $(^3\text{He},t)$ reaction leading to ^{96}Rh , about which little is known. The data have been obtained with the proportional counter and the split-pole spectrograph at the cyclotron. This study should provide information about the proton-neutron interaction in this mass region, and additional spectroscopic information will also be useful for the evaluation of data on the β decay to levels in ^{96}Ru . Further acquisition and analysis of data are planned.

Fig. 41. Spectrum of the $^{76}\text{Ge}(d,t)^{75}\text{Ge}$ reaction induced by the 22.5-MeV deuteron beam of the 60-in. cyclotron and recorded on photographic plates in the split-pole spectrograph.

II. MEDIUM-ENERGY PHYSICS

The basic idea behind our Medium-Energy Physics program is that it should form an important link between low-energy nuclear physics and intermediate-energy physics. We believe that the strong nuclear-physics program based on Argonne facilities will lead in a natural way to the generation of ideas for good experiments that require the higher energy of LAMPF. In order to implement this idea with minimum effort, we have created a small group whose main task is to master the technological problems involved in the use of LAMPF and which serves as an interface through which other staff members at Argonne can work easily and effectively at LAMPF. With this approach to our participation in the Medium-Energy Physics program, we expect to contribute a much wider range of ideas and talents than would be possible for a small group of specialists who represent only themselves.

The Medium-Energy work in the past year has been devoted to preparation for LAMPF experiments and to some work that was done at the ZGS but that is closely related to the research program that we will later pursue at LAMPF. Several Argonne staff members have spent substantial periods of time at Los Alamos during the past year in preparation for the anticipated experiments. One staff member (T. P. Wangler) is almost continuously at Los Alamos and is participating in the preparation of the experimental channels, primarily the EPICS and the Low-Energy Pion Channels.

(a) Experiments for Which Argonne Staff Members Carry the Main Responsibility

Three of the experiments that are primarily Argonne responsibilities have been given high priority and will probably be carried out during the first year of LAMPF operation. These are:

- (1) Pion Channeling (D. S. Gemmell, T. H. Braid, R. E. Holland, J. -C. Poizat, J. P. Schiffer, T. P. Wangler, and B. Zeidman). This is an experiment to explore the transmission of pions through monocrystals and to study the energy loss and reaction rate. It is to be done on the EPICS channel and is scheduled to start before the full EPICS spectrometer is completed. This work is discussed further in the first of the reports below (Sec. II. 1a).
- (2) Survey of Pion Scattering by Complex Nuclei (T. H. Braid, A. J. Elwyn, H. E. Jackson, G. C. Morrison, J. P. Schiffer, H. A. Thiessen,* and B. Zeidman). This experiment on targets of ^{28}Si ,

* Los Alamos Scientific Laboratory, Los Alamos, New Mexico.

^{60}Ni , ^{88}Sr , ^{208}Pb , and ^{238}U is scheduled to be done as soon as the full EPICS channel is available for use.

- (3) Pion-Induced Nuclear γ Rays (L. R. Greenwood, L. Meyer-Schützmeister, R. P. Redwine, J. P. Schiffer, R. E. Segel, and T. P. Wangler). This experiment, which is an outgrowth of very startling results obtained last year at the ZGS, is to be done early in the operation of the Low-Energy Pion Channel. Some other preliminary measurements are under way at the ZGS and others are planned for the University of Maryland cyclotron. This work is discussed further in the second of the reports below (Sec. II. 1b).

The following more difficult experiment, also primarily an Argonne responsibility, has also been approved and will probably be done during the second year of LAMPF operation.

- (4) Inelastic Pion Scattering from Light Nuclei: ^6Li , ^{10}B , and ^{14}N (S. I. Baker,* H. E. Jackson, G. C. Morrison, H. Plendl,† K. K. Seth,‡ R. H. Siemssen, and B. Zeidman). Angular distributions will be measured at energies near the 3,3 resonance (~ 200 MeV) for the low-lying $T=0$ and $T=1$ levels in self-conjugate nuclei. In addition, there will be a measurement of nuclear de-excitation γ rays in order to get an estimate of the $(\pi^\pm, \pi^0)$ cross section to excited states.

(b) Other Experiments in Which Argonne Staff Members Participate

- (1) Study of π^+ -Induced Double-Charge-Exchange Reactions (K. K. Seth,‡ Victor Perez-Mendez,§ John Sperinde,§ H. A. Thiessen,|| and B. Zeidman).
- (2) Search for (p, π) Reactions with the HRS (H. A. Thiessen,|| N. Tanaka,|| R. Macek,|| and B. Zeidman).
- (3) Pion Double-Charge-Exchange Reactions (J. Amato,|| R. L. Burman,|| and B. Zeidman).

* Illinois Institute of Technology, Chicago, Illinois.

† Florida State University, Tallahassee, Florida.

‡ Northwestern University, Evanston, Illinois.

§ Lawrence Radiation Laboratory, Berkeley, California.

|| Los Alamos Scientific Laboratory, Los Alamos, New Mexico.

- (4) Study of the Microscopic Structure of Collective Modes by Use of Medium-Energy Protons (E. R. Flynn,* N. Tanaka,* J. Spencer,* O. Hansen,[†] N. Hintz,[‡] and B. Zeidman).

* Los Alamos Scientific Laboratory, Los Alamos, New Mexico.

[†] Niels Bohr Institute, Copenhagen, Denmark.

[‡] University of Minnesota, Minneapolis, Minnesota.

1. MEDIUM-ENERGY EXPERIMENTS

a. Pion Channeling

D. S. Gemmell, T. H. Braid, R. E. Holland, J. C. Poizat, J. P. Schiffer, T. P. Wangler, and B. Zeidman

Two research proposals have been submitted to and accepted by the Los Alamos Meson Facility (LAMPF). We propose to measure the channeling properties of positive and negative pions ($E_{\pi} = 50-100$ MeV) in thin single crystals. The initial experiments will measure the energy deposited in a thin dE/dx Si detector as a function of the orientation between the detector and the pion beam. Later experiments will use a magnetic spectrometer to measure energy losses and angular distributions for pions transmitted through various thin crystals. The main aims of the work will be to directly compare the channeling of positive and negative particles, to study energy-loss processes under channeling conditions, and to see how well the classical and the diffraction channeling theories fit the data obtained with these intermediate-mass particles.

b. K-Mesic and Antiprotonic Atoms in the Interaction Between Hadrons and Nuclei

P. D. Barnes,* S. Dytman,* M. Eckhaus,[†] R. A. Eisenstein,*
D. A. Jenkins,[‡] J. R. Kane,[†] A. R. Kunselman,[§] W. C. Lam,*
J. Miller,* R. J. Powers,[‡] R. P. Redwine, B. L. Roberts,[†]
J. P. Schiffer, R. E. Segel, R. B. Sutton,* and R. E. Welsh[†]

We have identified a large number of nuclear γ rays associated with negative kaons stopped in Ni, Cu, Si, and Al. Prominent among these for both the Cu and the Ni targets are transitions that take place in even-even nuclei lighter than the target by up to about twelve nucleons. In both cases, the total intensity of all of the identified nuclear γ rays amounts to about twice that of the strongest x ray.

We have measured the energies and widths of the x-ray lines from the $4f \rightarrow 3d$ transition in antiprotonic atoms of ^{14}N and ^{16}O and have discussed the results in terms of a phenomenological optical potential. We have also observed the x-ray line from the $3d \rightarrow 4p$ transition in the antiprotonic ^4He atom.

The nuclear γ -ray study raised the possibility that when a large amount of energy is deposited in a nucleus, α particles and/or α -particle-like nuclei are very preferentially emitted. We therefore plan to follow up this work by looking at the nuclear γ rays accompanying the interaction of fast pions ($E_{\pi} \approx 350$ MeV) and fast protons ($E_p \approx 100$ MeV) with a selection of nuclei spanning the periodic table. In addition, an experiment has been approved at LAMPF to study the nuclear γ rays from π -mesic atoms and also to look for α particles emitted when pions interact with nuclei.

* Carnegie-Mellon University, Pittsburgh, Pennsylvania.

[†] College of William & Mary, Williamsburg, Virginia.

[‡] Virginia Polytechnic Institute and State University, Blacksburg, Virginia.

[§] University of Wyoming, Laramie, Wyoming.

2. DEVELOPMENT OF LAMPF FACILITIES; INSTRUMENTATION

a. System to Analyze Measurements of Fields in EPICS Magnets

Thomas P. Wangler

The Energetic Pion Channel and Spectrometer (EPICS) is a high-resolution system designed for pion-scattering experiments at LAMPF. The pion channel consists of four bending magnets and a crossed-field separator. The spectrometer consists of a quadrupole triplet and two bending magnets. The system was initially designed in first order by use of the program TRANSPORT, and a design momentum resolution of the order of $\Delta p/p \approx 10^{-4}$ was finally achieved by using the program MOTR—a Monte Carlo ray-tracing optimization program that allows the parameters representing the positions, effective edge shapes, etc. of the magnets to be adjusted in order to minimize a quantity such as the size of the beam spot at some specified location. MOTR traces rays by numerical integration through magnetic fields rather than by the approximate matrix-multiplication procedure.

The magnets were designed with up to fourth-order effective-edge curves. These curves can be adjusted somewhat by displacing the field clamps at the ends of each magnet. In addition, the magnets will be built with a series of trim windings by which the midplane fields can be adjusted. For the final adjustment of the system, the measured fields will be used as a guide to the final optimization through resetting of trim windings and movement of field clamps.

(i) Field measurements. In order to achieve the desired resolution, the magnetic fields must be measured after the magnets have been assembled, and the results must be used to predict the performance of the actual system. Any aberrations discovered in these field measurements can be corrected by moving the field clamps and adjusting the currents in the trim coils.

The fields in the midplane of each dipole magnet will be measured with a small cylindrical coil positioned by stepping motors. The integrated signals from the coil (which measure the relative field changes from point to point) will be recorded on magnetic tape by a PDP-11 computer.

(ii) New developments. The program MOTR, which was used in the design, will be used to evaluate the performance of the system on the basis of the measured fields and also to determine how the positions of the field clamps and the currents in the trim windings should be adjusted to achieve a final optimization of the system. The following paragraphs describe developments and modifications to facilitate this analysis.

(a) An integration routine already operational on the CDC-6600 computer has been modified so that it reads magnetic-field data and integrates along a chosen path to find the locations of the effective field boundaries of the magnet.

(b) A general least-squares fitting routine for the CDC-6600 computer has been written. It will read magnetic-field data from the tape and will fit selected formulas to the data. A general multipole expansion, which is expected to describe the effect of the trim windings, can be fitted to the central field. The field B_y in the fringe regions can then be fitted by the function

$$B_y = \frac{B_0}{1 + \exp C(s)},$$

where B_0 is the central field and $C(s) = C_0 + C_1 s + C_2 s^2 + C_3 s^3 + C_4 s^4 + C_5 s^5$. Here s is a dimensionless parameter such that g_s is the distance from the point of field evaluation to the effective-edge curve expressed in terms of the full gap g of the dipole, and the C_i are coefficients. The effective-edge curve is parameterized in terms of four coefficients RAP, CAT, CFV, and CNN through the expression

$$z = \text{RAP}(x^2/R_w^2) + \text{CAT}(x^3/R_w^3) + \text{CFV}(x^4/R_w^4) + \text{CNN}(x^5/R_w^5),$$

where R_w may be chosen to be the horizontal width of the magnet, the origin of coordinates is at the intersection of the effective field boundary and the central axis in the midplane, and the x and z axes lie in the midplane. The most general fit to the fringe-field data is a ten-parameter fit involving the six C parameters and the four effective-field-boundary parameters simultaneously. After these parameters have been determined from the least-squares fit, they can be read by MOTR and used to evaluate the performance of the system.

(γ) The CDC-7600 program MOTR has been modified so that the central field of the dipole magnets can be described by a general multipole expansion up to the fifth power. The rays can now be integrated numerically through the field, whereas the previous method was to evaluate the parameters of a helix in a constant field. This new description is capable of accurately representing the trim windings.

(iii) Tests on a low-energy pion magnet. Some parts of this package of analytic tools have been tested by use of magnetic-field measurements recently made on a dipole magnet in the low-energy pion channel. The fitting routine was applied both to fringe-fields calculated prior to the measurements and also to the actual measured fields. The results indicate no serious changes from the expected fringe-field parameters; the accuracy of the fringe-field formula used was about as expected. Furthermore, the midplane data points used extended out to nearly the full horizontal width of the gap of the magnet. It should be pointed out that the accuracy of the above formula for the fringe field B_y of the EPICS magnet is such that the values obtained in a detailed computer calculation are reproduced within an rms deviation of about 1 part in 10^4 . Thus the fringe-field formula should describe the EPICS magnets better than it did the low-energy pion magnets.

TABLE VI. Fitted fringe-field parameters.

	Fit to calculated fields	Fit to measured data on axis	Fit to 1200 measured midplane values
C_0	0.0637	0.0851	0.0795
C_1	3.21	3.27	3.27
C_2	-0.361	-0.428	-0.390
C_3	1.58	1.42	1.45
C_4	-0.121	-0.140	-0.169
C_5	-0.219	-0.122	-0.110
RAP	...	...	1.70
CAT	...	...	-0.895
CFV	...	...	-0.255
CNN	...	...	0.956
RMS	0.92×10^{-3}	1.33×10^{-3}	2.0×10^{-3}

b. A Monte Carlo Ray-Tracing Routine for the EPICS Channel

Thomas P. Wangler

The Monte Carlo ray-tracing program LLURCH, previously used for particle-beam-transport studies at the Argonne Zero Gradient Synchrotron, has been translated from the IBM 360 to the CDC 6600 at Los Alamos. The new changes allow the program to read matrix elements from the beam-design program TRANSPORT. Given the positions of magnets, particle separator, and slits, the program can trace Monte Carlo generated rays through the system. Scattering and losses in slits are included, as is decay of the particles. Studies of pion decay are now in progress.

c. Multi-Wire Proportional Counters

T. H. Braid

A review paper on the general subject has been published.¹

Recent work has been concentrated on the construction of a multi-wire counter for use in a muon-channeling experiment at LAMPF. The position is read out by measuring the delay of pulses induced in a helical delay line which serves as the cathode. The properties of such helical delay lines are being investigated to establish the resolution in position for a number of different geometrical configurations such as will be useful for different applications—e. g. , for use in the focal plane of a spectrograph.

¹ T. H. Braid, Proc. Roy. Soc. (Edinburgh) A70, 9 (1972).

III. THEORETICAL PHYSICS

The theoretical physics program is focused primarily upon the closely linked problems of nuclear structure, nuclear scattering and reactions, nuclear forces, and nuclear matter. Other areas of investigation include hypernuclear theory, elementary-particle theory, and relativity theory.

The theoretical group consists of regular staff members, postdoctoral research associates, graduate students, and long- and short-term visiting scientists. Two regular staff members hold joint appointments with universities. Most of the others serve occasionally at academic institutions under short-term arrangements. An important mission of the theoretical group is active partnership in the experimental programs of the Physics Division through collaborations, courses, seminars, and mutual criticism.

The major programs of theoretical research for the past several years have been computer-based studies of nuclear structure via the deformed and spherical shell models and related studies of nuclear forces and nuclear matter. Computational methods for diverse nuclear problems have evolved in the course of these studies and now constitute a major resource of the Physics Division.

The major shift in our theoretical attention during the past year has been in the direction of reactions involving heavy ions. This program has been undertaken primarily in support of the Physics Division's experimental effort in heavy-ion physics. Our investment in computational methods and in the nuclear shell model is expected to play a central role in the analysis of heavy-ion reactions.

A significant by-product of our research into computational methods for nuclear theory has been the development and dissemination of the "Speakeasy" computer language, which has now been exported to many other research institutions. That program continues to interact to mutual advantage with the nuclear research that gave rise to it.

1. NUCLEAR SCATTERING AND REACTIONS INVOLVING HEAVY IONS

a. Studies of Heavy-Ion Transfer Reactions

D. H. Gloeckner, M. H. Macfarlane, and F. J. D. Serduke

We have started a systematic study of reactions wherein a single nucleon or a cluster of nucleons is transferred directly from one complex nucleus to another. The analysis of such processes has three distinct aspects: (1) treatment of the internal structure of the nuclear states involved and of the way in which this structure influences the transition rates, (2) study of the mathematical transformations connecting functions of the various radius and momentum vectors that enter the description of the reaction process, and (3) treatment of the reaction mechanisms.

Computer programs are being written to carry out the computations involved in this study. In the first of the three phases of the calculation listed above—the treatment of the internal nuclear structure—the existing Argonne system of shell-model programs is used extensively. In the second—the vector transformations—there is considerable overlap with the Hartree-Fock calculations of Chang and Macfarlane (Sec. III. 2d). The reaction model used is the standard distorted-wave Born approximation (DWBA) and the coupled-channel theory of direct reactions. Our aim is to develop efficient ways of implementing those reaction models without using a partial-wave decomposition of the optical-model wave functions.

b. Semiclassical Treatment of Heavy-Ion Transfer

G. Theodorou and M. H. Macfarlane

It is well known that many aspects of heavy-ion direct reactions accord well with a semiclassical description of the reaction processes; the reacting nuclei appear to move into and out of the region

of interaction along well-defined orbits. We are studying the range of validity and the physical implications of such approximations in the most direct way imaginable; the "eikonal" approximation (with action functions integrated along the true classical orbits and not merely along straight-line segments) is used to generate the pertinent $\vec{r}$ -space optical-model wave functions $\psi(\vec{k}, \vec{r})$ that enter the distorted-wave treatment of the heavy-ion direct reactions. The resulting semiclassical DWBA cross sections are then compared with those calculated exactly. For such calculations, it is almost essential to carry out the DWBA calculations without partial-wave expansion of the scattering wave functions.

c. Structure Amplitudes for Multinucleon Transfer

D. Kurath

The widespread use of heavy-ion projectiles has led to experiments in which several nucleons are transferred between the target and projectile. Some of the striking results imply that strongly correlated clusters, such as α particles, are being transferred. In order to interpret the results in terms of nuclear structure, one must extract such cluster-transfer amplitudes from the shell-model wave functions. General procedures for such calculations have been developed, and were applied to obtain α -structure amplitudes in the $1p$ shell. A report of these results has been published.¹

¹ D. Kurath, Phys. Rev. C 7, 1390 (1973).

d. Dependence of α -Structure Amplitudes on Configuration Space

D. Kurath and I. S. Towner*

The degree to which α transfer is possible depends strongly on the configurations of the nuclear states participating in the transfer. The α -transfer operator can be written in a way that indicates this process

* Chalk River Nuclear Laboratories, Chalk River, Ontario.

will have many of the features of transfer of two identical nucleons. In particular, single-particle states of small angular momentum will be especially important. There will also be a notable correlation between states easily excited in a transfer and states easily excited in inelastic scattering. A simple formula to exhibit these features quantitatively has been developed.

e. CCBA Analysis of Heavy-Ion Reactions

K. S. Low and T. Tamura

The data on the $^{40}\text{Ca}(^{18}\text{O}, ^{20}\text{Ne})^{38}\text{Ar}$ reactions studied by Katori et al. (Sec. I. D2f) showed that the angular distribution of the reaction leaving the ^{20}Ne in the 2^+ state is vastly different from those of reactions leaving it or ^{38}Ar in other states. Since the latter distributions are fitted by the usual no-recoil DWBA calculation while the former is not, and since ^{20}Ne is a well deformed nucleus, it would be natural to see whether the coupled-channel Born approximation (CCBA) might solve the problem. We have thus undertaken a no-recoil CCBA calculation and have found that the anomalous 2^+ cross section can indeed be explained in this way. However, since the present reaction is known to violate the criterion for the validity of the no-recoil approximation, an exact finite-range CCBA calculation has to be made. Such a calculation is in progress and the result will be obtained shortly.

In the course of this work we found a technique by which the finite-range calculation for the present reaction can be carried out extremely fast, and we are investigating its more general applicability. If this generality is confirmed, the new technique would allow exact finite-range DWBA or CCBA calculations to be performed at least ten times and possibly a hundred times as fast as before.

Fig. 42. No-recoil CCBA fit of $^{20}\text{Ne}(0^+)$ and $^{20}\text{Ne}(2^+)$ cross sections for the $^{40}\text{Ca}(^{18}\text{O}, ^{20}\text{Ne})^{38}\text{Ar}$ reaction.

Fig. 43. The experimental and theoretical energy levels in the argon isotopes.

2. NUCLEAR STRUCTURE

a. Properties of the Argon Isotopes

D. H. Gloeckner, R. D. Lawson, and F. J. D. Serduke

Shell-model studies of low-lying states of the isotopes $^{39}\text{Ar}_{21}$, $^{40}\text{Ar}_{22}$, and $^{41}\text{Ar}_{23}$ have been completed. Two distinct model spaces are used—one with proton holes in the $d_{3/2}$ orbital and neutrons in the $f_{7/2}$ orbital ($\pi d_{3/2}^{-2} \nu f_{7/2}^n$; $n = 1, 2, 3$) and an extended space with the neutrons permitted to enter the $2p_{3/2}$ orbital [$\pi d_{3/2}^{-2} (\nu f_{7/2} \nu p_{3/2})^n$]. The neutron-neutron, neutron-proton, and proton-proton effective interactions are determined empirically from the level structure of neighboring nuclei. With the extended model, the observed level spectra are satisfactorily reproduced. E2 and M1 transitions are also calculated and compared with available experimental data; all M1 transitions are predicted to be substantially inhibited relative to single-particle estimates, in agreement with the observed trend. Several experiments are suggested. This work has been accepted for publication in the Physical Review.

Fig. 43

b. Inhibited Transitions and Isomeric States in the N = 50 Isotones

D. H. Gloeckner, M. H. Macfarlane, R. D. Lawson, and F. J. D. Serduke

In an earlier study,¹ level schemes of the N = 50 nuclei $^{89}\text{Y}_{50}$, $^{90}\text{Zr}_{50}$, $^{91}\text{Nb}_{50}$, $^{92}\text{Mo}_{50}$, and $^{93}\text{Tc}_{50}$ were discussed on the basis of a shell model with $^{88}\text{Sr}_{50}$ as an inert core and valence protons restricted to the $2p_{3/2}$ and $1g_{9/2}$ orbitals. This study accounted for the twenty pertinent level energies then known, with an rms deviation of 53 keV between theory and experiment. Since then some 27 additional level energies have been measured, including several in $^{94}\text{Ru}_{50}$. Furthermore

¹S. Cohen, R. D. Lawson, M. H. Macfarlane, and M. Soga, Phys. Letters 10, 195 (1965).

it has become clear that the earlier model does not satisfactorily account for observed E2 transition rates. The new study examines modifications in the effective shell-model interaction that bring the computed transition rates (including those of strongly-inhibited transitions) into acceptable agreement with experiment without significantly affecting the level schemes. Isomeric $\frac{17}{2}^-$ states are predicted at around 2 MeV in ^{91}Nb and 2.2 MeV in ^{93}Tc . This work has been published in Physics Letters.²

²D. H. Gloeckner, M. H. Macfarlane, R. D. Lawson, and F. J. D. Serduke, Phys. Letters 40B, 597 (1972).

c. SU(3) Shell-Model Program for Nuclei with $A = 12-20$

A. Müller-Arnke

The configuration structure of unnatural-parity excited states of nuclei around ^{16}O is still imperfectly known. In particular, the relative importance of (1p, 2s1d) and (2s1d, 2p1f) excitations needs detailed investigation. A system of computer programs has been written to carry out shell-model calculations with three active major shells. The classification of states with respect to center-of-mass excitations, orbital symmetry, and SU(3) symmetry applied here is suited for an investigation of various sorts of truncation of the model space based on supermultiplet and SU(3) symmetry and of the role of c.m. excitations in such truncations.

As a first application of these programs, negative-parity states in ^{17}O and ^{19}F will be studied.

d. Hartree-Fock Studies of Deformed Nuclei by Use of Density-Dependent and Three-Body Effective Interactions

B. D. Chang and M. H. Macfarlane

We are writing computer programs to carry out Hartree-Fock calculations for deformed nuclei (both axially symmetric and axially asymmetric) by use of the effective interaction of Skyrme, Brink, and

Vautherin.¹ This effective interaction has been shown to give an excellent description of the sizes and binding energies of spherical closed-shell nuclei throughout the periodic table. We plan to apply these programs to light nuclei that are far from the stability line but may be accessible to study with the newer generation of heavy-ion accelerators by (Heavy ion, xn) reactions. Examples of particular interest here are $^{76}_{38}\text{Sr}_{38}$ —probably the most massive $N = Z$ nucleus knowable to man—and light nuclei with many excess neutrons such as $^{16}_6\text{C}$, $^{28}_{10}\text{Ne}$, etc. Our approach is to treat the Skyrme interaction as a phenomenological effective interaction to be used in Hartree-Fock studies of nuclei not readily accessible to other sorts of microscopic theoretical description.

¹D. Vautherin and D. M. Brink, Phys. Letters 32B, 149 (1970).

3. NUCLEAR FORCES, NUCLEAR SCATTERING, AND NUCLEAR MATTER

a. Separable Potentials for the $^3S_1 - ^3D_1$ N-N Interaction Steven Pieper

There is considerable need for a low-rank separable potential that accurately reproduces the experimental phases and bound-state data in the $^3S_1 - ^3D_1$ nucleon-nucleon channel. An extensive attempt is being made to determine such a potential, paying particular attention to the quadrupole moment and D-state probability of the deuteron. Calculations with the standard form factors have not succeeded in producing a good fit, and more complicated form factors will now be considered.

b. Perturbative Calculation of Nucleon-Deuteron Scattering Steven Pieper

A program originally developed by the author at Case Western Reserve University has been adapted to Argonne's System 360

Fig. 44. The nucleon-to-deuteron spin-transfer coefficient for elastic nucleon-deuteron scattering at four different energies. The data points and curves are labeled with their energies in MeV.

computer and extended somewhat. This program computes the elastic nucleon-deuteron partial-wave amplitudes by use of a two-potential formalism in which part of the two-nucleon interaction is treated exactly via the Faddeev equations and the rest is included as a first-order perturbation. The results have been compared with an exact calculation recently published by P. Doleschall. The perturbation approach appears suitable for the qualitative features of the N-d polarizations, but for quantitative comparisons with data it will be necessary to include more of the N-N interaction in the exact part of the calculation than is presently done. Recently measured spin-transfer coefficients in N-d scattering have also been computed, and the results are in agreement with the limited data presently available.

Fig. 44

c. The Inverse Problem with Constraints

J. E. Monahan, C. M. Shakin,* and R. M. Thaler*

In nuclear physics, the inverse problem is defined to be that of finding a two-body interaction potential that reproduces given nucleon-nucleon scattering amplitudes. It is well known that there is a nondenumerable set of such potentials and that different members of this set can give rise to different off-shell T-matrix elements, and, hence, different results in many-body calculations. It would be useful, therefore, to solve the inverse problem subject to further constraints, particularly with respect to the off-shell behavior of the T matrix. A method for such a solution is being prepared for publication.

*Case Western Reserve University, Cleveland, Ohio.

d. Electric Form Factors of the Deuteron

F. Coester and A. Ostebee

High-energy electron-deuteron scattering experiments probe the short-range part of the deuteron wave function. The wave function

can be quite different for different phase-shift-equivalent nucleon-nucleon potentials. The purpose of this investigation was to determine to what extent these data can rule out otherwise acceptable phenomenological potentials. Since we want the form factors to be sensitive to the short-range part of the wave function, the momentum transfer q should have the largest possible value that is consistent with the requirement that meson-exchange effects should be negligible; $q^2 \approx 10-13 \text{ fm}^{-2}$ appears to be a reasonable compromise.

The deuteron wave functions computed from conventional potentials (Hamada-Johnston or Reid) differ very little from each other. The corresponding variation of the electric form factor is of the order of 1%, much less than the experimental error. We have distorted these wave functions by short-range unitary transformations that alter the wave functions drastically for $r \lesssim 1.2 \text{ fm}$. These transformations change the form factor by about 10% in either direction. The form factor is raised by Baker transformations that remove the hard core. A short-range change in the S-D mixture was designed to lower the D-state probability without appreciable effect on the quadrupole moment. These transformations lower the form factor by about 10%.

Relativistic corrections are also of the order of 10%. Formulae for these corrections have been derived by F. Gross on the basis of quantum field theory. The question to be answered is therefore whether these corrections are applicable in conjunction with purely phenomenological potentials. Form-factor expressions to order M^{-2} have been derived within the framework of the Bakamjian-Thomas theory. The relativistic corrections so derived are inherently ambiguous. A simple but arbitrary prescription within this framework yields the result of Gross. To justify this prescription, the nonrelativistic limit of the potential must be local and must be consistent with an underlying field theory.

Elastic electron-deuteron scattering is not a sensitive tool with which to probe the merits of purely phenomenological potentials.

e. Relativistic Effects in Phenomenological Nucleon-Nucleon Potentials

F. Coester, P. Havas,^{*} and H. W. Woodcock^{*}

In a classical theory of relativistic interacting particles without fields, one must give up either the notion of invariant world lines or the canonical equations of motion. In an expansion in powers of the velocity v/c , both theories are equivalent to order $(v/c)^2$. If the classical equations of motion are obtained from a conventional field theory by elimination of the fields, then the nonrelativistic potential is local and the correction terms of order $(v/c)^2$ are definite functionals of this potential. The Darwin Hamiltonian is the oldest example. In the corresponding quantum-mechanical development, one eliminates the quantized fields by projecting into the two-particle subspace of the Hilbert space. The construction of the effective Hamiltonian in that subspace is unambiguous only for the long-range part of the potential. At best that means $r \gtrsim 1$ fm. We have again the result that the nonrelativistic potential must be local but the correction terms of order $(v/c)^2$ are ambiguous unless we invoke correspondence to the classical theory. Conventions employed in the literature on one-boson exchange potentials violate that correspondence requirement. Further work on the relation between Bethe-Salpeter kernels and potentials is expected to remove the ambiguity.

^{*} Temple University, Philadelphia, Pennsylvania.

f. Relativistic Effects in Nuclear Matter

F. Coester and F. J. D. Serduke

There are two kinds of relativistic effects: (a) effects on the form of the potential and (b) effects due to the center-of-mass motion of the nucleon pairs within the nucleus. This work deals with

effects of type (b). Effects of type (a) can only be consequences of quantum field theory.

The phenomenological two-body potential V fitted to phase shifts via the usual Lippman-Schwinger equation must be interpreted as the interaction term in the square of the rest energy h . That is,

$$V = (1/4m)(h^2 - h_0^2) = (1/4m)(h_0 v + v h_0 + v^2),$$

where $v = h - h_0$. These operators V and v differ from the ordinary interaction Hamiltonian defined as

$$V = H - H_0,$$

where $H = (P^2 + h^2)^{1/2}$. For realistic nucleon-nucleon forces, it is not legitimate to expand in powers of v/m or k/m if the momentum k is above the Fermi level. It is possible to obtain the binding energy per particle in the Brueckner approximation by expanding in powers of p/m only for $p \leq k_F$. We have done this to order m^{-2} and have incorporated the correction terms in the nuclear-matter programs. Subroutines for both V and v are required for the computation. If V is a conventional potential (e.g., the Reid soft-core potential), then the equation for v cannot be solved by iteration. Other attempts at numerical solution have failed so far.

We have fitted several rank-2 potentials v to phase shifts and deuteron properties, obtained V , and computed the binding energy per particle for different densities. The potentials are quite unrealistic since saturation occurs at much too high a density ($k_F \approx 3$ fm). At normal density, the relativistic effects decrease the binding by about 1.8 MeV or 10%.

Fig. 45. Three-body correlation energy vs Fermi momentum for nuclear matter. A spin-independent S-wave force (the 1S_0 component of the Reid potential) was used.

g. Three-Body Correlations in Nuclear Matter

B. Day and F. Coester

The binding energy of nuclear matter, as calculated from the reaction-matrix theory, contains an uncertainty of several MeV per nucleon. Accurate three-body calculations for nuclear matter would substantially reduce this uncertainty. Accurate three-body calculations in momentum space have previously been done for an S-state force.¹ Substantial cancellation between the attractive and repulsive parts of the force led to a three-body correlation energy of less than one MeV per particle. Three-body correlations were found to lower the equilibrium density of nuclear matter by 6%. This method is being extended in a straightforward way to more complicated two-body forces, with the ultimate goal of treating the best available phenomenological potentials such as the Reid potential.

¹ B. D. Day, F. Coester, and A. Goodman, Phys. Rev. C 6, 1992 (1972).

h. Boson Expansion Technique Applied to the Description of the Nuclear Collective Motions

D. Braunschweig and T. Tamura

The fourth-order boson expansion technique, which Kishimoto and Tamura applied to the description of Sm isotopes in particular, was rather successful in that it very naturally reproduced the transition from vibrational to deformed nature in going from ¹⁴⁸Sm to ¹⁵⁴Sm. The spacings between states belonging to the same band, the quadrupole moments of these states, and the transitions between them were all in good agreement with experiment. The only unsatisfactory feature was that the heads of excited bands were usually predicted too high. In the hope that the inclusion of the sixth-order term would solve this problem, we have undertaken the calculation of such a correction. Unfortunately, the results so far indicate that the effect of the sixth-order term is to worsen rather than improve the fourth-order results. We are now searching for possible ways to remedy this situation.

4. COMPUTING LANGUAGE AND TECHNIQUE FOR SCIENTIFIC RESEARCH

a. The "Speakeasy" User Community

S. Cohen

The "Speakeasy" system was initially developed as part of a theoretical nuclear physics program that required efficient access to the facilities of a large-scale computer system. The primary design specification was to avoid involving the scientist in the operational details of the computer. These requirements led to the development of a computer language that is now evolving into an increasingly powerful and widely applicable system that grows with the accumulation of operations provided by users.

"Speakeasy" is now operational in two basic forms: the time-sharing and batch versions. Both are now used extensively at Argonne by persons in many divisions of the Laboratory. The use by universities, research laboratories, and others has grown rapidly during the past year. The known users now include approximately 20 research institutions (including universities and national laboratories), 5 commercial companies, the Federal Reserve System board of governors, and two computer networks. Several of these users have contributed significantly to the strength of the system.

b. Documentation of "Speakeasy"

S. Cohen, J. K. Fink, R. N. Kimmel, K. Rich, * F. J. D. Serduke,
and C. M. Vincent

Since the power and versatility of "Speakeasy" are continually being augmented by contributions from the user community, there is a continuing need for up-to-date information for both new and established users. This is provided by the Help documents, each of which is a concise description of one word or feature of the "Speakeasy" system.

* National Accelerator Laboratory, Batavia, Illinois 60510.

These have been grouped according to the subject or classification of each word, so that a user interested only in one specific topic need not search a list of all the words available. To keep users abreast of new developments, a new document is added to the Help library whenever a new word or feature is added to the system and the document "News" tells about new features and recent modifications. The Help documents can be called directly by an interactive user, and a compilation of them (item 4 in the list below) has been issued for users of the batch versions.

Four reports describing the nature and use of "Speakeasy" have been issued in the past year.

1. An Introduction to "Speakeasy" (Argonne National Laboratory Report ANL-7995), S. Cohen and C. M. Vincent
2. "Speakeasy"-3: The "Speakeasy" System (Physics Division Informal Report PHY-1972A), S. Cohen
3. "Speakeasy"-3: Linkules and Interfaces (Physics Division Informal Report PHY-1972C), S. Cohen, R. N. Kimmel, K. Rich,* and F. J. D. Serduke
4. The "Speakeasy" Help Documents (Physics Division Informal Report PHY-1972G), J. K. Fink

The first is a reissue of a report written in 1968, the second is an extension of it with particular emphasis on interactive usage, the third describes the mechanism for adding new operations to the libraries, and the fourth is a compilation of the Help documents. In addition, an occasional "Newsletter" describes recent modifications and gives other useful information.

*National Accelerator Laboratory, Batavia, Illinois 60510.

5. OTHER THEORETICAL PHYSICS

a. Λ -Particle Binding in Nuclear Matter: the Λ Well Depth

A. R. Bodmer and D. M. Rote*

A paper entitled "Reaction Matrix Calculations of the Λ -Particle Binding in Nuclear Matter for Central ΛN Potentials" was completed and has now been published.¹ This paper presents the most comprehensive extant results and analysis of the Λ well depth for a wide range of local central ΛN potentials with repulsive cores. From these results, the well depth can be obtained for any such potential that is likely to be proposed.

The Λ well-depth problem was reviewed in an invited paper² for a conference on the nuclear many-body problem. In addition to summarizing the Argonne investigations, it renewed the discussion of the implications of the Λ well depth for the ΛN interaction and pointed out the outstanding problems in this field. Further work in this area will be addressed in general to the question of higher-order contributions and in particular to the contribution from the coupling between the ΛN and ΣN channels and to the relation between this and three-body ΛNN forces.

*Center for Environmental Studies, Argonne.

¹A. R. Bodmer and D. M. Rote, Nucl. Phys. A201, 145 (1973).

²A. R. Bodmer and D. M. Rote, in Proceedings of the Symposium on the Present Status and Novel Developments in the Nuclear Many-Body Problem, Rome, 19-23 September 1972, to be published.

b. Collapsed Nuclei and Nuclear Collapse

A. R. Bodmer

The implications of the possible existence of collapsed nuclei C_A have been the subject of continued study. These are considered to be states of baryon number A with much lower energy and much smaller size than ordinary nuclei of mass number A . The approach has been

phenomenological and emphasizes such aspects as the stability of ordinary nuclei and of the matter in neutron stars against nuclear collapse, the possible properties of C_A if they should exist, and the processes by which such entities might be produced and detected.

The initial paper on this subject¹ discussed the stability of ordinary nuclei against nuclear collapse and used a very approximate equation of state of nuclear matter to calculate the saturation barrier separating the normal and the collapsed states. During the past year, the model of the collapse has been improved—in particular, by use of more realistic equations of state. The investigation has also been extended to the collapse of nuclear matter in massive stellar objects such as neutron stars, whose central densities may exceed those of nuclei by perhaps an order of magnitude. The stability of dense nuclear matter and the catastrophic collapse of massive stellar objects has also been considered. The properties of C_A and their modes of production and detection have also been investigated. The work to date has been reported in an invited paper at a conference on the nuclear many-body problem.²

Work along these lines continues, with particular emphasis on improving the model of nuclear collapse and on the stability and catastrophic nuclear collapse of stellar objects. This work is closely related to the problems of nuclear matter at high densities and of the associated properties of the nuclear interactions. These questions are thus also of interest for considerations of the interior of neutron stars where hyperons may be abundant, and thus are also related to the work on hypernuclear interactions (described in the immediately preceding report).

¹A. R. Bodmer, Phys. Rev. D 4, 1601 (1971).

²A. R. Bodmer, in Proceedings of the Symposium on the Present Status and Novel Developments in the Nuclear Many-Body Problem, Rome, 19—23 September 1972.

c. Mutually Orthogonal Orthogonalized Plane Waves

G. E. Juras,* J. E. Monahan, C. M. Shakin,* and R. M. Thaler*

The method of orthogonalized plane waves (OPW) is an important one in the study of crystalline solids. This method generates a set of "modified plane-wave" states that are not mutually orthogonal, although they are orthogonal to the bound states. Much of the complexity in OPW structure calculations arises because of the use of this nonorthogonal basis. An alternative procedure that utilizes a set of mutually orthogonal basis vectors has been proposed.¹

*Case Western Reserve University, Cleveland, Ohio.

¹G. E. Juras, J. E. Monahan, C. M. Shakin, and R. M. Thaler, Phys. Rev. B 5, 4000 (1972).

d. Presymmetry of Classical Relativistic Fields¹

Y. Avishai and H. Ekstein

The physical act of accelerating observation instruments has an obvious counterpart in Newtonian physics: It is the transformation induced by $(\vec{x}, t) \rightarrow (\vec{x} + \frac{1}{2} \vec{a} t^2, t)$. In special relativity, a theoretical counterpart for physical acceleration has been introduced only for a small subset of measurement procedures, such as clocks and yardsticks, but not for such instruments as accelerometers. We propose a general theoretical counterpart for physical accelerations in Minkowski space. In the algebra $\mathcal{O}$ of observation procedures, it induces automorphisms, not of $\mathcal{O}$ but of a point subalgebra $\mathcal{O}_x \subset \mathcal{O}$ that is associated to a single point x . From the postulates of presymmetry, we deduce a generalized version of Newton's second law; an acceleration-invariant subset $\bigcup_{(x|x_0=0)} \mathcal{O}_{xc}$ of instant observation procedures provides complete predictive power. The main technical contribution of the paper is the introduction of a topological algebra $\mathcal{O}$ in which local subsets associated to a single point are proper (although unbounded) subalgebras, whose automorphisms are discussed.

¹Y. Avishai and H. Ekstein, Phys. Rev. D 7, 983 (1973).

e. An Explicit Physical Interpretation of General Relativity

Y. Avishai and H. Ekstein

Previously formulated assumptions on the presymmetry of classical relativistic field theories, slightly changed and augmented, are used to derive Einstein's equivalence principle. General relativity appears as a system of operationally testable covariance (more precisely, presymmetry) principles which include the Poincaré group of special relativity and the family of acceleration groups M_x that induce automorphisms of the algebras $\mathcal{O}_x$ of observation procedures at the points x .

The principal deviation from the usual curved-manifold formulation of general relativity is based on the observation (accepted by most authors) that all points are intrinsically equivalent, which we interpret as the operationally testable statement: Motion induces an isomorphism of point observation procedures. The intrinsic physical space-time is therefore homogeneous, i. e., its group of automorphisms is transitive. From among the few such spaces that are available, we choose the flat V_4 space as the one in which observation apparatus is located. The motion of observed objects, on the other hand, is more naturally described in Einstein's pseudo-Riemannian manifold. For consistency, it must then be assumed that observed objects at large distances have rectilinear motions and, hence, that the manifold is asymptotically flat. Since the precise operational meanings of "frame of reference" and "curvilinear coordinates" are not unambiguous in the usual language, we do not know whether this paper is a paraphrase of older two-metric theories.

The present interpretation starts with a formulation of the operationally testable axiomatic assumptions (loosely speaking, covariance and causality) and the physical reasons for them. An operational form of the equivalence principle is then stated and its relationship to the conventional statements is discussed. On this basis, the algebras of observation procedures $\mathcal{O}$ and of observables $\mathcal{X}$ are concretely realized

as Abelian algebras of unbounded functionals on linear carrier spaces of tensor-valued functions on Minkowski and Euclidean space, respectively. The only substantially new element, in comparison to the two previous papers on the algebras associated to classical field theories, is a concrete realization of the acceleration automorphisms of point algebras $\mathcal{O}_x$. The equivalence principle is derived as a theorem. The principal conclusion is that the equations of motion of a given system have to be modified in the presence of a gravitational field by adding to the partial derivative of the field a term that has the form of an affine connection. This fact is used to introduce another, more natural, representation of the algebra $\mathcal{U}$ of observables: instead of functionals on a carrier space of tensor-valued functions on a flat space, one considers a carrier space of functions on a Riemannian manifold. Thereby, the substantial identity of our results with Einstein's theory is demonstrated.

f. Production of Coherent Mixtures of Resonances in the Quark Model

Harry J. Lipkin

The production of a coherent mixture of the f^0 and a degenerate s-wave resonance is described in the quark model by classifying the two resonances in the $J = 2$ and $J = 0$ states of the same 3P configuration. The model predicts experimentally observed decay angular distributions, including the cancellation of the peak in the center of the d-wave by s-wave interference. A report on this work has been accepted for publication in the Physical Review.

g. Quark-Model Predictions for Reactions with Hyperon Beams

Harry J. Lipkin

Quark-model predictions are discussed for Primakoff excitation of hyperon resonances, total hyperon-nucleon cross sections, and diffractive excitation. The U-spin selection rule forbidding electromagnetic excitation of negatively charged decuplet resonances is shown to

hold even in the presence of large SU(3)-symmetry breaking. A new model for diffractive excitation is presented which suggests the existence of new hyperon resonances, not yet discovered, which would be observed in diffractive excitation but only weakly coupled to two-body formation and decay channels. The SU(3) partners of the Roper resonance N(1470) might be such states and be found with hyperon beams. A report on this work has been published in the Physical Review.¹

¹H. J. Lipkin, Phys. Rev. D 3, 846 (1973).

h. New Finite-Energy Sum Rules Based on ρ and ω Exchange

Harry J. Lipkin

New finite-energy sum rules relate the isospin dependence of low-energy s-channel amplitudes to the ratio of ρ - and ω -exchange contributions in the Regge region. Applications to NN, KN, $K\Delta$, and $N\Delta$ scattering are discussed. Results include the isospin dependence of $\bar{N}N$ annihilation, SU(6) symmetry breaking in the couplings of strange baryon resonances to the KN system, and predictions for exotic production in Δ -exchange reactions. A report on this work has been published in the Physical Review.¹

¹H. J. Lipkin, Phys. Rev. D 7, 237 (1973).

i. Experimental Tests for Exotics in the Baryon-Antibaryon System

Harry J. Lipkin

A new FESR based on dominance of ρ and ω exchange for high-energy odd-signature amplitudes gives quantitative estimates for production of doubly-charged exotic meson resonances via Δ exchange in nucleon-antinucleon and pion-nucleon reactions. Absence of exotic resonances with predicted cross sections would indicate serious disagreement with two-component duality. Observation of nonresonant exotic states could test for a "third component." A report on this work has been prepared for publication.

j. Light-Cone Relations for the Strangeness-Changing Structure Functions

Harry J. Lipkin and E. A. Paschos*

Light-cone relations are obtained in the scaling limit among the $\Delta S = 0$ and $\Delta S = 1$ structure functions. The main conclusions are: (i) there are kinematic regions where the $\Delta S = 1$ transitions are 7% of the $\Delta S = 0$ transitions; (ii) there are differences of the inclusive cross sections which isolate the $\Delta S = 1$ transitions; and (iii) application of the results to isoscalar nuclei eliminates the ambiguities arising in the extraction of the neutron data. A report on this work has been published in the Physical Review.¹

* National Accelerator Laboratory, P.O. Box 500, Batavia, Illinois.

¹ H. J. Lipkin and E. A. Paschos, Phys. Rev. D 6, 814 (1972).

k. Symmetry Relations for Deep Inelastic Processes

Harry J. Lipkin and E. A. Paschos*

Relations between structure functions conventionally obtained from quark-parton or light-cone models are shown to follow from model-independent symmetry assumptions common in hadron scattering. Exotic t-channel exchanges are forbidden. No strong-interaction symmetry beyond isospin is assumed and SU(3) is used only for vertices involving currents. Relations originally derived for nucleon targets hold for any isospin mirror pair and apply to complex targets appearing in the Mueller formalism for inclusive processes in the target fragmentation region. New relations are derived. A report on this work has been published in the Physical Review Letters.¹

* National Accelerator Laboratory, P.O. Box 500, Batavia, Illinois.

¹ H. J. Lipkin and E. A. Paschos, Phys. Rev. Letters 29, 525 (1972).

IV. EXPERIMENTAL ATOMIC PHYSICS

The program in Atomic and Classical Physics consists of five distinct types of work: the photoionization of gases and vapors, the interactions of charged particles incident on surfaces and thin films, Mössbauer-effect measurements, atomic-beam research, and radio-frequency plasmas.

Most of this work is closely related to other programs of the Laboratory or to the applied-research needs of the AEC and of the nation. One example of this is our work on the interaction between nuclear radiations and metal surfaces. This research program has been providing the first quantitative data of the kinds needed for understanding the problems caused when the vacuum wall of a fusion reactor is bombarded by radiations from the thermonuclear plasma.

Fig. 46. A recently assembled surface-analysis station containing a quadrupole mass spectrometer and an Auger spectrometer. This system is being tested and will be used in studies of the interactions of energetic particles with solids (Sec. IV.2, especially Sec. IV.2c).

1. INTERACTION OF VACUUM-ULTRAVIOLET RADIATION WITH GASES AND VAPORS

This work involves high-resolution studies of the various ways in which vacuum-ultraviolet radiation interacts with gases and vapors. In one phase of the program, the ions produced by selected vacuum-ultraviolet radiation is measured mass spectrometrically. A new instrument consisting of a high-resolution 3-m monochromator and a quadrupole mass filter for ion detection and mass analysis has been put into operation and used for studies of the photoionization and fragmentation of O_2 , H_2O , H_2 , and CO_2 . Ion-molecule reactions in simple atomic and molecular systems (e.g., mixtures of hydrogen and rare gas) have been studied with emphasis on detecting the effects of the internal energy of the reactant ions. Several types of reactions (e.g., chemi-ionization, collisional ionization, and electron exchange) in which highly excited Rydberg states of atoms and molecules interact to produce ionized products have been studied as a function of the quantum numbers n and l of the excited electron. At the same time, the older 1-m monochromator has been used in studies of $HO\cdot$ and F_2O and in a new investigation of the free radicals (e.g., atomic O and N) generated in electrical discharges.

Measurements on the electrons produced concomitantly in the photoionization process provide another tool for studying such problems. These data provide valuable additional information regarding the higher ionization potentials of molecules, the bonding or nonbonding properties of the orbitals involved, and the details of the potential curves of the excited ionic states. The cylindrical-mirror photoelectron energy analyzer constructed at Argonne has achieved a capability that is unique at the present time—the ability to study not only permanent gases but also molecular systems generated as beams. A number of significant problems have now been investigated with this instrument, as described in more detail below.

a. Photoionization Studies with the New 3-m Monochromator and Quadrupole Mass Filter

(i) Photoionization Mass Spectrometer with High-Resolution Monochromator

W. T. Jivery and W. A. Chupka

A new photoionization mass spectrometer apparatus which incorporates a 3-m vacuum-ultraviolet monochromator and a quadrupole

mass filter has been put into operation. The optical monochromator has attained a resolution of 0.04 Å in the first-order spectrum (0.013 Å in third order) with usable photon intensities. In order to attain the necessary photon intensities with such narrow photon band widths, an improved gas-discharge lamp and a new high-power pulse generator have been developed. The photon flux has been increased by roughly a factor of five over that from our previous light source.

Differential pumping allows satisfactory operation of the mass filter with sample pressures greater than 10^{-2} mm in typical ionization chambers and much higher pressures in more enclosed chambers. An ionization chamber cooled by liquid nitrogen, the ion and photon detectors, and automated data-accumulation systems are now operating successfully.

(ii) High-Resolution Photoionization Mass-Spectrometric Study of the O₂ Molecule

W. A. Chupka, P. M. Dehmer, W. T. Jivery, and J. Berkowitz

The photoionization of the O₂ molecule has been studied from its threshold to 600 Å with a photon band width of 0.09 Å at 78 and at 300°K. This resolution is very significantly better than that used by earlier workers and has led to a better understanding of several phenomena. The ion-pair formation process

is of particular interest since it allowed a more accurate determination of the electron affinity of the O atom, for which Branscomb et al. had obtained the value 1.465 ± 0.005 eV and Berry et al. had obtained 1.478 ± 0.002 eV. Our value, based on analysis of the rotational structure resolved at threshold, is 1.461 ± 0.004 eV. It agrees with the above value of Branscomb et al. and also with their recent unpublished value 1.462 ± 0.006 eV. The cross-section curve for ion-pair formation is highly structured. The details of the structure strongly indicate that

Figs. 47,
48

Fig. 47. Photoionization cross section of O_2 , measured with 0.09-Å resolution width in the region just above threshold (1027.1 Å). Strong autoionization features are shown.

Fig. 48. Cross section for the photon-absorption process forming $O^+ + O^-$ from O_2 . The thresholds for the more abundant thermally-populated rotational states of O_2 are indicated.

the predissociating states excited by photon absorption are highly excited Rydberg states converging to one or possibly two electronically excited states of the O_2^+ ion and that these states are strongly predissociated because their attractive branches on the energy-level diagram cross the curves for one or more bound excited O_2 states that correlate with O^+ and O^- ions. This inference is also supported by a theoretical calculation of M. Krauss (U.S. National Bureau of Standards) which shows that three such curves should exist. The dissociative-ionization process occurs both by direct transitions to the repulsive part of an O_2^+ potential curve and by autoionization followed by dissociation.

(iii) Photoionization Mass Spectrometry of H_2O and H_2O_2

W. A. Chupka, W. T. Jivery, and J. Berkowitz

The molecules H_2O and H_2O_2 were studied by photoionization mass spectrometry at moderate photon band widths ($0.4 \text{ \AA}$), the purpose being to more accurately determine the values of both the ionization potential of the OH radical and the heat of formation of the HO_2^+ ion. The latter quantity is of considerable current interest since it determines the proton affinity of the O_2 molecule; and this, in turn, can be used as a standard by several groups of workers who can determine differences of proton affinities very accurately. The ionization potential of OH was tentatively determined to be 12.97 eV by a measurement of the difference in thresholds for formation of H^+ and OH^+ from H_2O and making some small corrections to take account of a slight difference in threshold behavior. A similar but slightly less accurate value is obtained from data on H_2O_2 . The heat of formation of the HO_2^+ ion was determined to be 268.0 kcal/mole at $0^\circ K$.

(iv) High-Resolution Photoabsorption, Photoionization, and
Chemi-ionization Studies of the Hydrogen Molecule

W. A. Chupka and W. T. Jivery

Relative absorption and photoionization cross sections for the H_2 molecule (both pure parahydrogen and "ordinary" hydrogen) have been measured with photon band widths down to about $0.013 \text{ \AA}$ in selected wavelength regions. The ionization threshold region very clearly shows the effects of autoionization by rotation, and the observed structure is in excellent agreement with the recent analysis of Herzberg and Jungen. Some ionization by collision just below threshold is conclusively demonstrated. Absorption and chemi-ionization measurements were made in the region of the threshold for photodissociation of the H_2 molecule. Beutler-Fano profiles were accurately measured for predissociating states and were found to be in serious disagreement with recent photographic measurements by other workers. The resonance-shape parameters Γ and q were found to be very much different from those reported in the literature. The difference is readily attributed to errors in the photographic technique. Chemi-ionization has been studied at high photon resolution to obtain an accurate determination of the velocity dependence of the chemi-ionization reaction of the metastable H atom and to study the mechanism of the chemi-ionization reaction of the highly excited Rydberg states of the H_2 molecule. The latter reaction is shown to be strongly related to the ion-molecule reactions of the H_2^+ ion.

(v) Ion-Molecule Reactions in Mixtures of Rare Gas and Hydrogen
by High-Resolution Photoionization Mass Spectrometry

W. A. Chupka and W. T. Jivery

Reactions between R^+ and H_2 and between H_2^+ and R, where R is a rare gas, have long generated great interest and activity among mass spectroscopists and kineticists. One interesting aspect of the problem is the effect of various forms of internal energy on reaction

probability. In our most recent experiments on some exothermic reactions in these systems, we have measured the relative probability of reaction of the ground state ($^2P_{1/2}$) and first excited state ($^2P_{3/2}$) of the rare gas ions Ar^+ and Kr^+ with hydrogen molecules in the ground rotational state at 78°K. In the case of Ar^+ , the use of low temperature and narrow photon band width was necessary for a completely unambiguous measurement which showed that the excited $^2P_{1/2}$ state reacted with about 25% higher probability than the ground state. In the case of Kr^+ , the effect was reversed, with the excited state reacting with only about 40% of the probability of the ground state. If both reactions proceeded adiabatically (i.e., with reactants and products remaining on the same adiabatic potential surface), the excited $^2P_{1/2}$ state is expected to be completely unreactive at low temperatures since the reactants correlate with electronically excited products (i.e., the reaction would be very endoergic). The results observed indicate a very effective "surface jumping" mechanism in the case of Ar^+ and only a moderately effective one for Kr^+ . This is in qualitative agreement with predictions based on the form of the potential surfaces as calculated elsewhere by semiempirical methods, but the study indicates several respects in which these surfaces are not accurate.

(vi) Reactions of Highly Excited Rydberg States of Rare Gases

W. A. Chupka, S. Antos, and W. T. Jivery

The reactions of argon and krypton atoms in highly excited Rydberg states with ground-state atoms of the same gas and with other atoms and molecules have been studied with photon band widths of 0.08 and 0.14 Å. The goal of the present research was to attempt to understand the dependence of various reactions on the values of the quantum numbers n and l of the excited electron. With the resolution available, Rydberg transitions with values of n up to about 25 were readily resolved. Present and previous investigations in this laboratory had established that the

probability of electron-transfer reactions of the type $\text{Kr}^* + \text{SF}_6 \rightarrow \text{Kr}^+ + \text{SF}_6^-$ dropped extremely rapidly with decreasing values of n (in contrast to the behavior of chemi-ionization reactions of the type $\text{Kr}^* + \text{Kr} \rightarrow \text{Kr}_2^+ + e^-$) even for values of n for which the electron-transfer reaction is still very endoergic. One hypothesis advanced to explain this difference in behavior postulates that the electron transfer actually occurs with high probability in the case of low values of n , but at such close distances between reactants that the resulting ion pair is trapped in the resulting Coulomb well and eventually decays via other processes that do not produce charged particles but which would very probably de-excite the Kr^* . In the present experiments, the total probability of destruction (by de-excitation or ionization) of Kr^* and of Ar^* by SF_6 was measured as a function of n and was found to have the same strong decrease with decreasing n as was observed for electron transfer. Thus the above hypothesis is very probably incorrect, and an explanation in terms of the velocity dependence of the electron-capture cross section is strongly suggested.

b. Photoionization Studies with the 1-m Monochromator

(i) Photoionization of HOF with Mass Analysis

J. Berkowitz, E. H. Appelman,* and W. A. Chupka

The ionization yields of HOF^+ , O^+ , and OH^+ have been studied as a function of wavelength in the photoionization of HOF. The first ionization potential of HOF is 12.71 ± 0.01 eV. The threshold for O^+ formation, 14.34 eV, leads to $\Delta H_f^0(\text{HOF}) = -22.8 \pm 1$ kcal/mole. The threshold for OH^+ formation, 15.07 eV, leads to a value for $\Delta H_f^0(\text{HOF})$ in good agreement with the above result if one of two discrepant values for $\Delta H_f^0(\text{OH}^+)$ is chosen. This choice implies that the ionization potential

* Chemistry Division, ANL.

for OH is $12.9_0 \pm 0.05$ eV. The proton affinity of OF is 5.8_2 eV. Pronounced structure in the ionization yield curves is interpreted as vibrational autoionization in the region near threshold and as electronic autoionization at higher photon energies.

(ii) Photoionization Mass Spectrometry of F_2O

J. Berkowitz, P. M. Dehmer, and W. A. Chupka

The photoionization efficiencies of the ions F_2O^+ and OF^+ were measured in a photoionization mass spectrometric study of F_2O . The adiabatic first ionization potential was determined to be 13.11 ± 0.01 eV. The region within 0.5 eV of the threshold showed structure attributed to vibrational autoionization. Additional peaks at 13.81, ~ 15 , and $\sim 15\frac{1}{2}$ eV were interpreted as Rydberg levels that decay by an electronic autoionization mechanism and which converge to the second ionization potential at 16.17 eV.

An upper limit for the appearance potential of OF^+ ($0^\circ K$) was found to be 14.43_8 eV, grossly different from the electron-impact value of 15.8 ± 0.2 eV. The current result yielded $\Delta H_f^0(OF) = +26.1 \pm 2.3$ kcal/mole and $I.P.(OF) = 12.7_9 \pm 0.1_0$ eV.

(iii) Photoionization of Atomic Oxygen

P. M. Dehmer, J. Berkowitz, and W. A. Chupka

The photoionization efficiency of the O^+ ion from atomic oxygen was measured between 925 and 625 Å at a resolution of 0.83 Å. Atomic oxygen was produced by flowing a 3:1 mixture of O_2 and Ar through a dc discharge.

The data showed an autoionization peak corresponding to every peak seen in absorption, including those transitions for which autoionization is forbidden on the basis of Russell-Saunders coupling. This is significant since these autoionization peaks were not observed in previous photoionization studies and they were not predicted since the

transitions were seen in emission spectra. (In studies of emission spectra of atomic oxygen, transitions were seen only if autoionization was forbidden; no emission lines were seen if autoionization was allowed. It was then assumed that the observance of emission lines precluded a competing autoionization process.) We found, however, that many of the most intense autoionization peaks were from these "forbidden" transitions. This can be attributed to the breakdown of Russell-Saunders coupling, though this is not normally expected in an atom as light as oxygen.

The experimental resolution was not sufficient to resolve the multiplet structure for each transition. However, a convolution calculation using the known position of the multiplets, the statistical weight for each multiplet transition, and an assumed Gaussian line shape with $\text{FWHM} = 0.83 \text{ \AA}$ accurately reproduced the observed peak shapes for the two transitions whose term values were well separated from any other terms. In the case of closely spaced transitions, mutual perturbations of the multiplet intensities prevented such comparisons.

(iv) Photoionization of Atomic Nitrogen

P. M. Dehmer, J. Berkowitz, and W. A. Chupka

The photoionization efficiency of the N^+ atom from atomic nitrogen was measured between $875 \text{ \AA}$ and $600 \text{ \AA}$ at a resolution of $0.83 \text{ \AA}$. Atomic nitrogen was produced by flowing a N_2 -He mixture through a dc discharge. The fraction of He was experimentally adjusted to give the best signal-to-noise ratio and usually constituted about 20% of the total sample.

Autoionization peaks observed at 692.7 , 647.5 , 621.6 , and $619.8 \text{ \AA}$ correspond to the members of a single Rydberg series. In the energy region 850 — $600 \text{ \AA}$, the only Rydberg series for which autoionization is allowed is the one converging to the third excited state of the N^+ ion ($2s2p^3, {}^5S^0$). The observed peaks correspond to the $n = 3$ — 7 transitions of this series. All the line profiles are asymmetrical, with

a sharp edge toward shorter wavelengths. No structure was observed in the photoionization efficiency curve above 700 Å, although such structure had been alluded to in a previous photoionization study of this system. This "structure" was most likely an experimental artifact resulting from the use of a line source rather than a continuum source for the ionizing radiation.

c. Photoelectron Spectroscopy with the Cylindrical-Mirror Analyzer

(i) The High-Temperature Vapors GaX_3 and InX_3 (X = Cl, Br, or I)

J. Berkowitz and J. L. Dehmer*

We had previously demonstrated that the diatomic group III halides (e. g., TlX and InX , where X = Cl, Br, or I) revealed the ionic nature of their chemical bonding in their photoelectron spectra (PES). We have since examined the PES of the trivalent forms of these systems, in particular GaX_3 and InX_3 to see if a transition to covalent bonding could be discerned. The observed analogy between the PES of these systems and those of the boron trihalides previously studied once again demonstrates the similarity of molecular orbital sequences for a homologous series of molecules. The spectrum of GaI_3 is representative of the group. The uppermost ten valence orbitals are various combinations of halogen p orbitals, consistent with the D_{3h} symmetry of this molecule. The splitting of the e' orbital is due to spin-orbit interaction, but the splitting of the e'' orbital may be due to nonplanarity of the ionic state.

(ii) The High-Temperature Vapors TlF and Tl_2F_2

J. Berkowitz, J. L. Dehmer,* and L. C. Cusachs†

Unlike the other thallium monohalides, which vaporize to produce predominantly diatomic molecules, thallium monofluoride vaporizes

* Radiological and Environmental Research Division, ANL.

† Loyola University, New Orleans, Louisiana.

Fig. 49. He (I) photoelectron spectrum of GaI₃. The initial orbitals for each peak can be assigned in D_{3h} symmetry as a₂' for A, e' for B and E, e'' for C and D, and e' for F and H (not shown).

are formed (as they are observed to be in Penning-ionization spectroscopy of Cd) and (b) to measure the partial cross sections for formation of the various states.

The present experiments on Zn and Cd were compared with previously published results on Hg. Photoelectron spectroscopy yields only the one-electron excitation to 2S and 2D states. The energies of these states agree with spectroscopic values, which have been incorrectly tabulated in recent reviews. Of particular interest are the $^2D_{5/2}$: $^2D_{3/2}$ ratios. The statistical weights of these states are 3:2. Such an intensity ratio is observed for Zn, but drastically different ones are obtained for Cd and Hg. We are exploring the possibility of explaining this result in terms of j-j coupling or of relativistic and dynamic effects.

(iv) Photoelectron Spectra of Butyl Naphthalene and Butyl Dinaphthalene

J. Berkowitz, J. L. Dehmer,^{*} and M. Szwarc[†]

The electron-impact mass spectrum of butyl dinaphthalene

suggests that the molecule coils up, its opposite ends joining and forming a gross cyclic structure. The question posed is: Does this cyclization occur for the neutral species, or does it occur after ionization? If it occurs before ionization, the photoelectron spectrum (which is a picture of the valence orbital structure) would be expected to be strongly perturbed. On the other hand, the photoelectron spectrum of the molecule as drawn would be expected to be similar to that of

^{*} Radiological and Environmental Research Division, ANL.

[†] State University of New York, Syracuse, New York.

We have obtained the photoelectron spectra of molecular species (A) and (B) and found them to be quite similar, with almost identical first ionization potentials and similar π orbital structures in the near valence region. We therefore conclude that cyclization must occur after ionization.

(v) Photoelectron Spectrum of HOF

J. Berkowitz, J. L. Dehmer,^{*} and E. H. Appelman[†]

The molecular species HOF has recently been prepared for the first time at Argonne. We have observed three bands in the He (I) photoelectron spectrum of this molecule. They can be interpreted by analogy with the diatomic halogens and to the recently reported ClF. The first two bands can be identified with the out-of-plane and in-plane components of the π_g -like outermost orbital of the diatomic halogens, split by the C_s symmetry of HOF. The first ionization potential is found to be 12.69 ± 0.03 eV, in close agreement with the photoionization value 12.71 ± 0.01 eV reported in Sec. IV.1b(i).

^{*}Radiological and Environmental Research Division, ANL.

[†]Chemistry Division, ANL.

(vi) Comparison of Photoelectron Spectral Intensities and Franck-Condon Factors for H_2 , HD, and D_2

J. Berkowitz and R. Spohr

We have used a He (I) source to produce the photoionization reaction

in H_2 , HD , and D_2 , and have measured the relative intensities of the resulting vibrational bands with a cylindrical-mirror analyzer. These relative intensities differ significantly from squared overlap integrals (Franck-Condon factors) based on accurate potential curves for the $\text{X } ^1\Sigma_g^+$ and $\text{X } ^2\Sigma_g^+$ states but are in good agreement with calculations performed by Y. Itikawa,* who included the variation of transition moment with internuclear distance and with the kinetic energy of the departing electron.

*Radiological and Environmental Research Division, ANL.

(vii) Band Envelopes, Rotational Transitions, and the $^2\Pi_{3/2}$ - $^2\Pi_{1/2}$ Spin-Orbit Splitting of HF^+

J. Berkowitz, T. E. H. Walker,* and P. M. Dehmer

The removal of an electron from the uppermost occupied orbital of HF results in the formation of HF^+ in a $^2\Pi$ state. This state is split by spin-orbit interaction into $^2\Pi_{3/2}$ and $^2\Pi_{1/2}$, the separation being roughly equal to 2/3 of the spin-orbit splitting in atomic fluorine—i.e., about 33 meV. For this transition, the various rotational contributions to a particular vibrational band do not permit a clean splitting of these two states in the photoelectron spectrum. However, by calculating the various rotational line strengths, convoluting them with a known experimental line shape, and using the spin-orbit separation as a parameter, it is possible to compare the calculated band envelope with the experimental one. A good fit has been obtained with a spin-orbit splitting of 36.0 meV, but the sensitivity of the matching is still being explored. A by-product of this fitting is a more accurate first ionization potential of HF . For DF , our current value is $\text{I.P.} = 16.058 \pm 0.003 \text{ eV}$.

*Northwestern University, Evanston, Illinois.

d. Beam-Foil Auger Spectroscopy

J. Berkowitz, J. L. Dehmer,^{*} D. S. Gemmell, and J. L. Yntema

A carbon foil has been placed on the axis of a concentric-cylindrical-mirror analyzer, a few centimeters upstream from the object focal region. Multiply charged ions from the tandem or Dynamitron, traveling along the cylinder axis, are directed at the carbon foil. The ions leave the carbon foil in various states of excitation and decay by emitting radiation or (in some cases of metastability) by emitting electrons in an Auger process. The kinetic energy of the electrons is measured in the cylindrical mirror analyzer. In this way, the states responsible for electron emission can be identified and their lifetimes can be deduced. Our initial experiments have detected electrons from several ion beams, but instability in the ion source and problems of angular definition have thus far prevented the attainment of a well-resolved spectrum.

^{*}Radiological and Environmental Research Division, ANL.

2. INTERACTION OF ENERGETIC PARTICLES WITH SOLIDS

The major part of this program is concerned with physical phenomena that occur when solid surfaces are bombarded by various MeV radiations and with the practical consequences of these phenomena for the walls of a controlled thermonuclear reactor. The irradiations are carried out partly at a 2-MeV Van de Graaff accelerator at Argonne and partly at a high-intensity neutron source at Lawrence Livermore Laboratory.

Energetic (MeV) particles penetrating through solids participate in such primary processes as energy loss and charge exchange and cause such secondary phenomena as sputtering, electron emission, and x-ray emission. In an amorphous solid, the projectile will make random changes in direction in successive collisions; in a monocrystalline solid, the projectile can be guided by the regular lattice arrangement—e.g., through the spaces between the planes (planar channeling) or along channels formed by parallel rows of atoms (axial channeling). These channeling effects can in turn affect a number of the primary and secondary processes. Several of the experiments described below were undertaken to determine how the structure of the bombarded target affected some particular primary process (e.g., charge exchange, particle polarization, or energy loss) or such secondary phenomena as sputtering or blistering.

Among these diverse surface phenomena, three were identified^{1,2} as particularly troublesome for the operation of controlled thermonuclear fusion reactors. These processes, still only poorly understood, are (1) the formation and subsequent rupture of gas bubbles formed in the surface layers of metals under particle impact (radiation blistering), (2) sputtering by MeV neutrons, and (3) particle emission from and flaking of surfaces irradiated with energetic photons.

¹M. Kaminsky, in *Fusion Reactor First Wall Materials*, edited by L. C. Ianiello, U.S. Atomic Energy Commission Report No. WASH-1206 (1972), p. 63.

²M. Kaminsky, *Proceedings of the 7th Symposium on Fusion Technology*, Grenoble, France, 24 October 1972 (Commission of the European Communities, Luxembourg, 1972), Report No. EUR 4938 e, p. 41.

a. The Effect of Channeling on the Shape and Density of Radiation Blisters on Monocrystalline Metals

M. Kaminsky and S. K. Das

The study¹ of monocrystalline surfaces was undertaken to gain a better understanding of the basic mechanisms underlying the

¹M. Kaminsky and S. K. Das, *Appl. Phys. Letters* 21, 443 (1972).

Fig. 50. Secondary-electron scanning electron micrographs of (111) surfaces of monocrystalline niobium after irradiation at 900°C with 0.5-MeV He^+ ions well channeled along the [111] axis. The total dose was 1.0 C/cm². The two micrographs were taken at different magnifications, as indicated.

blistering process—in particular, to learn whether projectile channeling would have a measurable effect on the blistering process.

When a (111) surface of a niobium target held at 900°C was irradiated to a total dose of 1.0 C/cm^2 of $0.5\text{-MeV } ^4\text{He}^+$ incident within $<0.1^{\circ}$ from the [111] direction (so the ^4He ions were well channeled), the resulting blisters had a conspicuous threefold symmetry. Their prongs are aligned rather perfectly along the traces of {110} planes of the host niobium lattice, parallel to one set of $\langle 112 \rangle$ directions. This result suggests preferential blister nucleation between planes with maximum interplanar spacing. Another (striking) result is that the prongs of the blisters are aligned along only one set of $\langle 112 \rangle$ directions of the host lattice (e.g., along the directions $\neg$) and not along the other equivalent set (λ). It appears that the observed asymmetry cannot readily be explained by the formation of a void superlattice.

Fig. 50

When a similar target surface was irradiated just as specified above except that the helium beam was incident in a nonchanneling direction, the blisters were smaller than those produced by channeled He ions but their density ($\sim 8 \times 10^8 \text{ blisters/cm}^2$) was more than two orders of magnitude greater. The reason is that radiation damage near the surface is greater for unchanneled than for channeled ions and this damage facilitates the nucleation of blisters.

These studies will be continued during the next year to determine how the blister shape and size changes for different crystallographic orientations of the surface plane. Special emphasis will be given to a further exploration of the observed asymmetry in the alignment of the blister prongs along one set of crystallographic directions but not along the other equivalent set.

b. The Effect of Irradiation Temperature on Blister Morphology

M. Kaminsky and S. K. Das

The blistering of monocrystalline Nb surfaces has been investigated at room temperature and at 700 and 900°C for 0.5- and 1.5-MeV He^+ projectiles. For a total dose of 1.0 C/cm² of 0.5-MeV channeled helium ions incident normally on a (111) surface of a Nb target at 900°C, almost all the observed blisters have a crow-foot shape with threefold symmetry, as described in the preceding report. When the target temperature is lowered to 700°C, a mixture of crow-foot and dome-shaped blisters is observed; and at room temperature only dome-shaped blisters form. For unchanneled projectiles, the blister density after irradiation at 900°C is more than two orders of magnitude greater than for channeled ones as mentioned in the preceding report. However, the effect of channeling is not so pronounced for room-temperature irradiation. A report on this part of the study has been accepted for publication in the Journal of Applied Physics.

The average blister size appears to increase (i) with decreasing target temperature, (ii) with increasing degree of channeling, (iii) with increasing projectile energy, and (iv) with increasing total dose in the range studied (0.1—1.0 C/cm²). The critical dose for helium blister formation in niobium is temperature dependent and is more than 0.1 C/cm² for room-temperature irradiation. For targets at 700—900°C, the critical dose is less than 0.1 C/cm².

During the next year, these studies will be extended to V. It is hoped that these measurements will help to uncover some of the basic mechanisms underlying the blistering process.

Fig. 51

Fig. 51. Scanning electron micrographs of (111) monocrystalline niobium surfaces after irradiation to a total dose of $1.0\ \text{C}/\text{cm}^2$ with 0.5-MeV He^+ . In (a)–(c), the ions were incident parallel to the surface normal. (a) Target irradiated at 900°C . (b) Irradiation at 700°C . (c) Irradiation at room temperature. (d) Same as (a) except that the ions were incident $\sim 5^\circ$ off the surface normal.

c. Radiation Blistering of Polycrystalline Metals

(i) Irradiation of Nb by D^+ Ions

M. Kaminsky and S. K. Das

For cold-worked polycrystalline niobium irradiation at room temperature to total doses of 0.1 and 1.0 C/cm^2 with normally incident 0.5-MeV D^+ ions, no blisters could be resolved with a scanning electron microscope (resolution limit $\approx 200 \text{ \AA}$). However, blistering was observed when a similar target at $700^\circ C$ was irradiated to a total dose of 1.6 C/cm^2 of normally-incident 0.25-MeV D^+ ions; the average blister diameter was $\sim 0.4 \mu m$ and the average blister density was $\sim 2 \times 10^8$ blisters/ cm^2 . If the total dose was increased to 3.0 C/cm^2 , the average blister size increased to $\sim 3 \mu m$. The grain orientation affected the shape of the blisters significantly. For example, blisters with a threefold symmetry in the plane of the irradiated surface (similar to the crowfoot-shaped He blisters) could be observed on certain grains.

Under otherwise similar conditions, much less blistering is produced by irradiating Nb with deuterons than with helium. This difference can be related to the tremendous differences between the solubilities and diffusivities of these gases in niobium, in which the diffusion coefficient for deuterium is $D(D) = 1.3 \times 10^{-4} \text{ cm}^2/\text{sec}$ at $800^\circ C$ while that for helium goes from $D(He) = 10^{-19} \text{ cm}^2/\text{sec}$ at $600^\circ C$ to $10^{-14} \text{ cm}^2/\text{sec}$ at $1200^\circ C$. A report on this work has been accepted for publication in Radiation Effects.

These studies will be extended to stainless steel since this material is of interest for controlled thermonuclear devices.

(ii) Irradiation of Nb by He^+ Ions

S. K. Das and M. Kaminsky

The radiation blistering of polycrystalline niobium surfaces at room temperature has been investigated for different doses of helium

ions implanted at 0.5 MeV and for different amounts of initial defect structure in the samples. The cold-worked samples show large blisters (up to 500 μm in diameter), many of which are ruptured. In samples annealed before irradiation, the blistering at low doses (0.1 C/cm^2) was lower than in the cold-worked sample, but at a higher dose (1.0 C/cm^2) the blistering was observed¹ to be even greater. Not only was the skin ruptured at many different places, but in one area the first skin had already peeled off and the second skin had started to rupture in many places. These first results at a total doses of 1.0 C/cm^2 indicate that the surface erosion of annealed polycrystalline niobium by 0.5-MeV helium blistering is approximately three orders of magnitude faster than the combined erosion by sputtering by 5.0-keV deuterons and tritons and 3.5-MeV helium ions. Therefore helium blistering can severely limit the lifetime of a fusion-reactor component bombarded by helium projectiles.

Preliminary results on the skin thickness of ruptured blisters indicate a close relationship between the thickness and both the projected range of the ions and the peak in the defect distribution. These results indicate that this type of measurements represents a novel and rather simple technique for determining the projected ranges of ions — especially for light ions. We plan to develop this technique further during the next year and to test existing range theories (e.g., those of Lindhard and of Scharf and Schiott).

¹ S. K. Das and M. Kaminsky, J. Appl. Phys. 44, 25 (1973).

(iii) A Comparative Study of Blistering in Nb, V, and V-20%Ti

S. K. Das and M. Kaminsky

The radiation blistering of the surfaces of three structural materials of interest for controlled thermonuclear reactors — namely V, V-20%Ti, and Nb — has been studied for different doses of 0.5-MeV helium ions implanted in targets at temperatures ranging from room temperature to 900°C . The degree of blistering (defined as the ratio of

Fig. 52. Scanning electron micrographs of annealed polycrystalline metal surfaces after irradiation with 0.5-MeV $^4\text{He}^+$ ions to a total dose of 1.0 C/cm^2 . Left: Niobium. (a) Secondary-electron image after irradiation at room temperature. (b) Back-scattered-electron image after irradiation at 600°C . (c) Secondary-electron image after irradiation at 900°C . Center: Vanadium. (a) Secondary-electron image after irradiation at room temperature. (b) Back-scattered-electron image after irradiation at 900°C . Right: V-20%Ti alloy. Back-scattered-electron images after irradiation (a) at room temperature and (b) at 900°C .

the area covered by blisters to the total irradiated area) decreases with increasing irradiation temperature for all three materials studied. For example, for a total dose of 1.0 C/cm^2 of 0.5-MeV He^+ ions, increasing the irradiation temperature from room temperature to 900°C reduced the degree of blistering from 87 to 12.5% for Nb, from 52 to 1.7% for V, and from 47.2 to 7.4% for V-20%Ti. These results suggest that helium blistering will be an important erosion process in most of the structural materials being considered for fusion reactors. A report on this work has been accepted for publication in the Proceedings of the Texas Symposium on the Technology of Controlled Thermonuclear Fusion Experiments and The Engineering Aspects of Fusion Reactors, Austin, Texas, November 20-22, 1972.

Fig. 52

These studies will be continued during the next year to determine the dependence of blistering on such important irradiation parameters as the type of projectiles and their energy range, the projectile flux density, the total dose, the target temperature, the target material and structure, and the angle of incidence.

(iv) He Blistering in Nb Damaged by 14-MeV Neutron Irradiation

M. Kaminsky and S. K. Das

In an actual D-T fusion reactor, the first wall will be subjected to simultaneous bombardment of various projectiles such as 14-MeV neutrons and helium projectiles. We have started experiments to determine how the defect clusters formed in polycrystalline Nb by 14-MeV neutron irradiation will affect the subsequent blister formation by helium-ion irradiation. These measurements will be vigorously pursued during the next year and will probably be extended to other structural materials of interest for controlled thermonuclear reactors.

d. Sputtering by MeV Neutrons

M. Kaminsky and J. H. Peavey

During the operation of large steady-state D-T fusion reactors, extremely high fluxes of 14-MeV neutrons ($3-10 \times 10^{14}$ neutrons $\text{cm}^{-2} \text{sec}^{-1}$) will penetrate the first wall. In addition to these, even higher fluxes ($3-5 \times 10^{15}$ neutrons $\text{cm}^{-2} \text{sec}^{-1}$) from (n,2n) reactions, scattering, and the like in the blanket region will backstream through the first wall. Such high fluxes of energetic neutrons (especially the 14-MeV component) make the neutron energy spectrum of a D-T fusion reactor substantially different from that of a fission reactor. Therefore, physical sputtering, thermal spikes, and other mechanisms of particle release from walls bombarded with energetic neutrons can be expected to be substantially more effective in a fusion reactor than in a fission reactor. The plasma contamination and first-wall erosion as a result of MeV neutron sputtering therefore need to be studied. Both experimental and theoretical results on sputtering by MeV neutrons are very scarce and contradictory, and measurements on Nb, V, V-Ti alloys, and other fusion-reactor materials are completely lacking. Even the order of magnitude of the yields for 14-MeV neutron sputtering is still not known with certainty. Therefore such studies are now imperative.

The apparatus for the study of sputtering by 14-MeV neutrons was designed, constructed, and tested, during the past year and was shipped to Livermore for our run at the ICP 14-MeV neutron source there. In this run, Nb, V, stainless steel, and other targets at room temperature were irradiated and are now being studied. As soon as the results from this run have been analyzed, we plan to study MeV neutron sputtering as a function of the temperature, material, and structure of the target and of the energy, flux, and dose of the neutrons.

e. Development of Techniques for Measuring Surface Contaminations
in Very Small Concentrations (10^{-1} — 10^{-4} Monolayers)

M. Kaminsky and P. Dusza

In order to measure the sputtering yield from 14-MeV neutrons, it was necessary to develop independent techniques for measuring the small amounts of sputtered material deposited on highly cleaned substrates. After careful calibration, the Rutherford-backscattering technique and the ion-microprobe method yielded the most reliable and self-consistent results for surface contaminants in concentrations equivalent to a small fraction of a monolayer. An Auger spectrometric technique is being developed and further work will continue.

f. Phenomena Induced by Photon Impact

M. Kaminsky, J. Peavey, and S. Das

Energetic photons (e. g. , synchrotron radiation, bremsstrahlung, x rays, and γ rays from nuclear reactions) impinging on fusion-reactor components such as the walls of a plasma container or of a divertor produce a variety of processes. Some of these are photo-desorption of adsorbed or absorbed gases, photo-decomposition of surface compounds, photo-catalysis leading to a reaction between adsorbed molecules and the vacuum wall, photoelectron emission, sputtering by the conversion of high electronic-excitation energy into displacement energy, rapid vaporization as a result of the high surface temperature and temperature gradients produced by photon absorption in layers near the wall surface, and possibly cracking of the bulk material and flaking of the surface. One should also consider the desorption of adsorbed or absorbed gases under the impact of energetic photoelectrons, e. g. , those that return to the wall under the action of a high external magnetic field. At present there is a complete lack of knowledge of the degree to which these processes will affect a plasma container material under the extreme operating conditions of a fusion reactor.

Several experiments to measure the effects of photon impact were designed during the past year: the outgassing of fusion-reactor materials will be measured with a quadrupole mass spectrometer, changes in surface composition will be studied with an Auger spectrometer, and surface erosion will be examined with a scanning electron microscope. Some of the components of a surface-analysis system have been acquired and the system is being constructed.

g. Polarization of Particles by Channeling

M. Kaminsky

Studies of the polarization of channeled deuterons by passage through a foil of ferromagnetic monocrystalline material magnetized to saturation have been continued along the following three lines.

Test of a theory of the polarization mechanism. The theoretical models proposed by Ebel and by Brandt and Sizman, which offer an explanation of the large polarization values observed in the original Argonne experiment on the polarization of channeled deuterons, are being tested in a continuing series of measurements. The nickel crystals used earlier are replaced by iron monocrystals, since Ebel's theory predicts that the degree of polarization of the channeled deuterons should be less in the iron. During the past year, a second monocrystalline iron ingot was obtained and two (111) foils (respectively 1.2 and 2.5 μm thick) were cut from it. In the experiments, a foil was magnetized to saturation parallel to its $[01\bar{1}]$ axis and a mass-analyzed highly-collimated beam of D^+ ions (half angle of divergence = 0.01°) was incident on it within 0.1° of a $[111]$ direction. A preliminary value for the tensor polarization is $P_{22} = 0.21 \pm 0.03$, which is larger than the value obtained with the Fe foils used last year but is smaller than the value $P_{22} = -0.32 \pm 0.01$ found earlier for the Ni (110) foils. This observation is in qualitative agreement with Ebel's theory.

X

These experiments are being continued to reduce the statistical errors present in the preliminary runs and to investigate the dependence of the P_{22} value on the crystallographic direction which the channeled beam traverses.

Polarization of ^3He . The design of experiments to study the polarization of ^3He by channeling through Ni monocrystals has been continued during the last year. This technique promises to produce more intense polarized ^3He beams than are obtained by other existing techniques. The design of equipment and the preparation of monocrystalline foils will take a good part of the coming year.

Source of D^- ions for tandem. In these studies, neutral atoms with polarized nuclei (produced by the channeling technique) will be converted into negative ions by passing them through a thin monocrystalline "adder" foil. Subsequently the polarized negative ions can be injected into the Physics Division tandem Van de Graaff. The present experimental efforts are directed towards the production of thin (500—1000 Å) adder foils with a high degree of monocrystallinity, uniform thickness, and large usable area ($\sim 0.1 \text{ cm}^2$).

h. Polarization of Particles by Small-Angle Scattering

M. Kaminsky

A continuing effort is directed toward the improvement of a new method¹ of producing a polarized beam of neutral atoms. In this method, energetic ions are polarized by traversing a set of parallel small-bore capillaries drilled through a foil of monocrystalline ferromagnetic material magnetized to saturation. In small-angle scattering from the walls of these capillaries, some of the ions capture polarized electrons. The resulting beam of polarized neutral atoms then passes adiabatically through a weak uniform magnetic field to permit the polarization to be transferred to the nucleus by hyperfine interaction.

¹ M. Kaminsky, U.S. Patent No. 3,700,899, issued 24 October 1972.

The past year was spent mainly in exploring techniques for drilling parallel small-bore capillaries (diameter = $0.1-1.0\text{ }\mu\text{m}$) through the monocrystalline ferromagnetic foils. The perforated foils produced by electron-beam drilling were found to be superior to those produced by the photo-etch and other techniques tested. The capillaries we have been able to produce so far have had length/diameter ratios of only 25:1, though ratios of 100:1 to 1000:1 would be desirable. Studies of the neutralization rate and energy loss of the ions scattered from the capillary walls have been started. There are indications that further work may lead to a method of polarizing even heavy ions.

i. Preparation and Characterization of Thin Monocrystalline Foils

M. Kaminsky, T. Campana, and P. Dusza

During the past year we have continued an extensive program to develop techniques for preparing thin monocrystalline target foils ($1.5-2.5\text{ }\mu\text{m}$ thick) with large usable areas ($6-25\text{ mm}^2$). Such techniques as optical polishing and lapping, electropolishing, and ion milling were used in appropriate combinations to obtain thin monocrystalline Fe foils for the experiments on deuteron polarization by channeling and monocrystalline Nb, V, and V-20%Ti targets for studies of radiation blistering. The techniques have been improved significantly.

The plasma guns of the recently built ion milling apparatus were redesigned and reconstructed so that material would be removed uniformly from a large area of the target being milled (i. e., from a region $\sim 6\text{ mm}$ in diameter). Another advantage of the new design is that the power supply no longer is overloaded when the discharge in the gun is started since the starting voltage is $\sim 1\text{ kV}$ instead of the previous $\sim 4.5\text{ kV}$. Our intention is to place the plasma guns into an ultrahigh-vacuum chamber to eliminate the virtual leaks and other drawbacks of the present chamber.

This work will be actively pursued and the characterization of the targets will receive increasing emphasis during the coming year.

j. Operation of the 2-MV Van de Graaff Accelerator

R. Amrein, T. Campana, P. Dusza, and J. R. Wallace

The 2-MV Van de Graaff has operated 3338 hours from 16 March 1972 to 15 March 1973. It was used to accelerate protons, deuterons, and ^4He .

A minimum of maintenance has been required. Extended runs have been possible because of the stability of the machine and the addition of a TV camera so that the machine can be monitored by Dynamitron operators when the regular operators are not on duty.

k. Microscopic Location of ^{17}O , ^{18}O , and ^{15}N

G. R. Ringo and V. E. Krohn

A technique by which the tracer isotopes ^{17}O , ^{18}O , and ^{15}N could be located (possibly simultaneously) within a resolution diameter of 1 μm or better would have obvious value in biological research. We believe this could best be done by scanning a specimen with a focused beam of ions (e.g., Ne^+) to convert the tracer isotopes to ions which would be identified in a mass spectrometer with high resolution (a resolution of, say, 5000). The high-resolution mass spectrometer is available, and we now have a beam diameter of about 5 μm and a beam current of more than 0.2 nA. The system we designed to collect secondary ions appears to be working with good efficiency. It collects about 10% of the secondary ions into a phase-space volume accepted by the high-resolution mass spectrometer. The next step in the program is to measure secondary-ion yields from a number of materials of biological significance, and later we may attempt to develop a much sharper beam by using a field-emission source.

3. MÖSSBAUER MEASUREMENTS

The Mössbauer program in the Physics Division uses the effect for a variety of problems that may be classified as being of three kinds: (a) fundamental studies that make use of the Mössbauer effect because of its ability to reveal extremely small changes in γ -ray energy, (b) pioneering studies in areas whose character is not yet well established, and (c) measurements of interest to nuclear physics.

a. Mössbauer Studies of Ions in Aqueous Glass

S. L. Ruby and B. J. Zabransky

The study of short-range order (sro) in glasses has become especially interesting since a new continuous-random-network model predicts perfect sro for monatomic systems such as amorphous Si and Ge. Most older theories had pictured a glass as made up of some form of microcrystallites (with perfect sro) surrounded by disordered interfaces (with poor sro). We have used the Mössbauer technique, which is very sensitive to local order, to study iron ions in frozen aqueous solutions of FeCl_2 in H_2O . The conditions for glass preparation had been determined in earlier work.

At high temperatures and at low concentrations, other techniques indicated that the dominant ion species was the hexaquo ion $\text{Fe}^{2+}(\text{H}_2\text{O})_6$. The question then was whether low-temperature glasses at high concentration would show Mössbauer patterns characteristic of such new ions as $\text{Fe}^{2+}(\text{Cl}^-)_x(\text{H}_2\text{O})_{6-x}$ or whether local order (i.e., the hexaquo ion) would always be preserved. The glass spectra turned out to be nearly like those from the crystal $\text{FeCl}_2 \cdot 9\text{H}_2\text{O}$ (which contains the hexaquo ion as a subunit) and very different from spectra from crystals that contain $\text{Fe}(\text{Cl})_x(\text{H}_2\text{O})_{6-x}$, with $x = 0, 2$, and 4 . The remaining differences between the glass spectrum and the nonahydrate spectra have been studied extensively and now can be plausibly explained as due to a contribution from the disordering of second-nearest neighbors and less

close neighbors. A report on this work has been accepted for publication in Perspectives in Mössbauer Effect Spectroscopy.

b. ^{57}Fe Mössbauer Spectroscopy with ^{57}Mn Sources

R. S. Preston and B. J. Zabransky

This experiment deals with ion implantation of high-energy particles and a search for nuclear reactions to produce ^{57}Mn for use as a Mössbauer isotope to study certain radiation-damage phenomena. During the past decade, the study of radiation damage has rapidly increased in importance as a result of the ever increasing role that nuclear reactors play in society. Many of the limitations placed on power reactors are directly related to materials problems caused by radiation damage.

A number of investigators have studied radiation damage by use of Coulomb excitation of ^{57}Fe nuclei and by the $^{56}\text{Fe}(n, \gamma)^{57}\text{Fe}^*$ reaction. These reactions leave the excited ^{57}Fe nuclei with large enough kinetic energies to produce local collision damage as they come to rest. Since the half-life for the subsequent emission of the Mössbauer γ ray is only 10^{-7} sec, there is insufficient time for this damage to anneal out, and the Mössbauer spectra are seen to be perturbed by effects related to the details of the damage in the vicinity of the stopped ^{57}Fe nuclei. This fact is the basis for a promising technique for studying radiation damage by using ^{57}Mn as the parent isotope for the Mössbauer source. It can be produced in reactions that leave the atoms with enough energy to produce collision damage, but the half-life for decay is 1.7 min so that annealing experiments are possible.

The present experiment is the first to observe the Mössbauer spectrum of ^{57}Fe produced by the decay of the 1.7-min ^{57}Mn parent. The reactions in which we were able to produce ^{57}Mn were

The bombardment of a thin ${}^{48}\text{Ca}$ target by ${}^{12}\text{C}$ produces ${}^{57}\text{Mn}$ nuclei with large enough recoil velocities that they can escape from the target, travel through vacuum, and penetrate into a sample of the material to be studied. The spectrum of γ rays from these implanted atoms can be observed, but the yield of 14-keV γ rays is too low to be useful for a Mössbauer experiment.

The three reactions involving ${}^{55}\text{Mn}$ as a target produce very low yields of ${}^{57}\text{Mn}$.

Fig. 53. An ion-implantation Mössbauer spectrum of ${}^{57}\text{Fe}$ in Cr_2O_3 . The ${}^{57}\text{Fe}$ was produced by the reaction ${}^{54}\text{Cr} + {}^4\text{He} \rightarrow {}^{57}\text{Mn} + \text{p}$. The solid line shows the contribution of ${}^{57}\text{Fe}$ in substitutional Cr sites in Cr_2O_3 ; the dashed line shows the contribution of ${}^{57}\text{Fe}$ in interstitial sites in Cr_2O_3 .

The reaction of α particles on ^{54}Cr has a high yield, but the ^{57}Mn atoms do not have enough recoil energy to get out of a thin Cr target. When a thick target is used, the yield is high enough that radiation damage in the bombardment target can be studied. A Mössbauer study of radiation damage produced by ^{57}Mn atoms in Cr_2O_3 has demonstrated the utility of the method. The spectrum shows that 80% of the ^{57}Fe atoms are in a site (believed to be substitutional) producing a broad line. The remaining 20% of the ^{57}Fe atoms are located on a site (believed to be interstitial) producing slightly broadened quadrupole-split doublets. This method should be applicable to the study of radiation damage in any substance that contains Cr. This experiment was carried out at room temperature. Further experiments at both lower and higher temperatures are planned so that the annealing of the radiation damage can be studied.

Fig. 53

Additional nuclear reactions are still being investigated in the hope of producing a high yield of ^{57}Mn atoms with large enough recoil energies that they can be injected into any material.

c. Mössbauer Experiments with the 93.26-keV Transition in ^{67}Zn

G. J. Perlow, W. Potzel, L. E. Campbell, and L. E. Conroy

Mössbauer measurements of the 93.26-keV transition in ^{67}Zn were performed with sources of ^{67}Ga in ZnO single crystals and ZnO powder as absorber. The high resolution obtained by the 93.26-keV transition makes it possible to observe the nuclear Zeeman effect in an external magnetic field of a few hundred oersteds. The magnetic moment of the $\frac{1}{2}^-$ first-excited state was determined by a quasi-null method to be $\mu(\frac{1}{2}^-) = +0.58 \pm 0.03 \mu_N$. The electric field gradient in ZnO was found to be positive.

A new quartz-crystal spectrometer has been developed for velocities up to 0.5 mm/sec. Experiments with sources of ^{67}Ga in zinc metal and ^{67}Ga in copper metal are in progress.

Fig. 54. Angular variation of the recoilless fraction of the 81-keV γ ray of ^{133}Cs in Cs_2Cs . The curve is calculated on the assumption that the mean-square vibrational amplitudes in the three lattice directions are related by $\overline{x^2} = \overline{y^2} \neq \overline{z^2}$.

d. The Anisotropic Debye-Waller Factor of CsC_8 and the Quadrupole Moment of the First Excited State in ^{133}Cs

L. E. Campbell, G. L. Montet,^{*} and G. J. Perlow

Analysis of measurements with the Mössbauer effect of the 81-keV state of ^{133}Cs has been completed. The absorbers were C_8Cs intercalation compounds, in which the carbon was in the form of aligned pyrolytic graphite. A huge directional anisotropy was found for the recoil-free fraction $f(\theta)$, where θ is the angle between the γ ray and the symmetry axis of the sample. The value of f decreased by a factor of 20 from $\theta = 0$ to $\theta = 90^\circ$. The maximum value of f was 4%. The data can be well fitted by a model containing two zero-point amplitudes, one in the graphite plane and one perpendicular to it. Fig. 54

In the noncubic environment of the Cs ion, the quadrupole moment of the 81-keV state causes an incompletely resolved hyperfine splitting. The ground-state quadrupole moment is very small, so that the splitting can with good accuracy be assigned to the excited state. This gives $e^2qQ = 1.6$ mm/sec. However, the ground-state quadrupole coupling in this system is not too small to have been measured by nmr. With the nmr results we obtain $|Q_{\text{exc}}/Q_{\text{gnd}}| = 88 \pm 6$, a huge ratio. In combination with a reported value of 0.0023 ± 0.0003 b for $|Q_{\text{gnd}}|$ we obtain $|Q_{\text{exc}}| = 0.20 \pm 0.03$ b. Our quadrupole coupling is positive, but the analysis does not give us the sign of the moment.

^{*} Solid State Science Division, ANL.

e. Lifetime of the ^{197}Au Mössbauer γ Ray

Frank J. Lynch

The lifetime of the 77.34-keV state of ^{197}Au has been remeasured in an attempt to resolve the discrepancy between the earlier value obtained by delayed coincidence and the value inferred from a recent Mössbauer measurement of the linewidth of the 77.34-MeV γ ray

Fig. 55. Delayed-coincidence spectrum of ^{197}Pt and a prompt-coincidence spectrum taken with a ^{22}Na source under the same conditions. The jagged curves represent the raw data with the background subtracted. Each smooth delayed-coincidence curve was obtained by folding the prompt curve with a simple exponential decaying with the indicated half-life.

(as described in the next report). The new measurements were made with the advanced delayed-coincidence techniques pioneered here at Argonne.

A ^{197}Pt source was prepared by a short neutron irradiation of a ^{196}Pt metal foil in the CP-5 reactor. The measurement of delayed coincidences between the 77.34-keV γ ray of ^{197}Au and the 191.5-keV γ ray that precedes it in the cascade following the β decay of ^{197}Pt yielded the half-life $\tau_{1/2} = 1.93 \pm 0.03$ nsec, in agreement with the earlier delayed-coincidence measurements.

Fig. 55

To check the remote possibility that the half-life in the crystalline source was shorter because of an enhanced internal-conversion coefficient, the experiment was repeated with a Pt source dissolved in aqua regia. The result, $\tau_{1/2} = 1.98 \pm 0.05$ nsec, does not differ significantly from that obtained with the metal foil.

A paper describing this work has been accepted for publication in the Physical Review.

f. Anomalous Narrow Mössbauer Linewidth in ^{197}Au

W. Potzel and G. J. Perlow

In Mössbauer measurements of the 77.34-keV transition in ^{197}Au with thin absorbers of AuCN and $\text{KAu}(\text{CN})_2$, an average linewidth of 1.54 ± 0.05 mm/sec was found.¹ This value is only 80% of the commonly accepted natural width obtained from lifetime measurements. The latter, however, are in agreement with our results in absorbers of gold metal. To investigate this anomaly further, experiments have been performed with absorbers of gold metal of various grades of purity and at temperatures of liquid helium, liquid nitrogen, and liquid oxygen. The results seem to indicate that there is no significant change of the linewidth with purity or temperature. The recent failure of other laboratories to corroborate our values of the linewidth for AuCN and $\text{KAu}(\text{CN})_2$ has led

¹ W. Potzel and G. J. Perlow, Phys. Rev. Letters 29, 910 (1972).

us to undertake a series of computer simulations in order to investigate the statistical treatment of the data in the computer fitting procedure. This investigation is in progress.

4. ATOMIC-BEAM RESEARCH

The atomic-beam program in 1973—74 will concentrate primarily on the study of heavy unstable nuclei. An essential aspect of this research is that it is carried out in collaboration with staff members of the Chemistry Division. This collaborative effort results in the application of a much wider range of skills than would otherwise be available.

A second, more exploratory, effort in this program will be an attempt to develop well controlled positron and positronium beams. If this development succeeds, the beams are expected to be useful for a wide range of experiments on properties of matter and in quantum electrodynamics.

a. Hyperfine Structure of Stable Isotopes

W. J. Childs and L. S. Goodman

The atomic-beam hfs measurements of $^{147,149}\text{Sm}$, described briefly last year, have now been analyzed in detail.¹ The measurements have been corrected for second-order hfs and then compared with theoretical predictions. These data are consistent to a very high order with the three-parameter formulation of the Sandars-Beck effective-operator theory and with the Conway-Wybourne eigenvectors for the $^7F_{1-6}$ states of Sm. The earlier apparent failure of these eigenvectors when other authors applied them to their data is now resolved. The Sandars-Beck parameters found from the data have been compared with the ab initio relativistic Hartree-Fock-Slater calculations of A. Rosen and were found to agree within a few percent. That Rosen could calculate the wholly relativistic contact-dipole parameter to within 7% is particularly noteworthy.

¹W. J. Childs and L. S. Goodman, Phys. Rev. A 6, 2011 (1972).

b. Hyperfine-Structure Studies of Radioactive Isotopes

H. Diamond,* L. S. Goodman, and H. E. Stanton

Two problems are currently under investigation in the radioactive-isotope program. Independent measurements of the A factor and of the magnetic dipole moment of a neptunium isotope in its atomic ground state would be very helpful in tying down parameters needed to complete the interpretation of some optical-spectroscopy data. Measurements on ^{239}Np have been started with this end in mind. It is hoped that measurements of the hyperfine structure and determination of the nuclear moments of $^{254\text{m}}\text{Es}$ will shed more light on the nuclear structure of the odd-odd, high-mass isotopes. Such measurements have been started, but their rate of progress will depend directly on the production of ^{253}Es and on competitive demands from other users.

The spin of the Np isotope has been measured previously. The goal of the present experiments is to find the hfs constants and the nuclear magnetic dipole moment. Preliminary values of magnetic-dipole and electric-quadrupole interaction constants are $A = 811 \pm 9$ MHz and $B = 620 \pm 140$ MHz, respectively.

The observations of the $^{254\text{m}}\text{Es}$ experiments confirmed the $I = 2$ spin assignment and established preliminary values of the hfs constants $A = 1018 \pm 12$ MHz and $B = -2380 \pm 160$ MHz.

c. Atomic and hfs Spectroscopy of ^{221}Fr

H. Diamond,* M. S. Fred,* L. S. Goodman, B. Greenebaum, and F. S. Tomkins*

Almost nothing is known about the atomic wave functions and the associated atomic spectrum of francium, the heaviest of the alkali atoms. The isotope ^{221}Fr occurs in the radioactive decay chain of the long-lived ^{229}Th . A few milligrams of the Th isotope have been obtained, and from this about 10^{10} atoms of the 4.8-min Fr can be expected

* Chemistry Division, ANL.

in equilibrium. The Fr vapor will be produced and contained in an absorption cell in the cavity of a broad-band dye laser. The lines of the absorption spectrum of Fr, which are expected to be enhanced by interaction with the laser system, will be observed with conventional optical-spectroscopy apparatus.

Spin-exchange optical-pumping experiments are also planned in order to measure the hyperfine separation of the ground state, the magnetic dipole moment, and the spin of ^{211}Fr .

d. Low-Energy Positron and Positronium Experiments

L. S. Goodman

Recent research has provided the surprise that some small fraction of the positrons that are absorbed and thermalized in a metal such as copper are emitted from the surface of the absorber monoenergetically at a very low energy ($\sim 0.3-1$ eV). With such a source, it is possible to form beams of positrons for scattering experiments. It is also expected that by the use of techniques that are standard with proton-electron systems, it will be possible to produce beams of positronium also. Such a source will allow radio-frequency spectroscopy and quantum-electrodynamics experiments to be performed. The source is now under construction and the first experiments are expected to be tried in the coming year.

5. RADIO-FREQUENCY PLASMAS

The central purpose of this research is to advance the understanding of the basic properties of low-pressure plasmas produced by rf (microwave) fields, with special emphasis on aspects relevant to controlled thermonuclear research (CTR). The three lines of experimental and theoretical investigation being pursued are (a) confinement of plasmas by microwave fields in cylindrical resonant cavities, (b) production of high-density bounded plasmas in resonant cavities, and (c) properties of plasmas excited by microwave fields in toroidal cavities. An additional line of research is a parametric study of Tokamak plasma and geometric parameters based on a model developed by Russian CTR workers.

a. Confinement of Low-Density Plasma in a Microwave Cavity

A. J. Hatch and C. F. Shelby

We have reported the first observation of steady-state rf confinement of plasma in the quadrupole electric mode of a resonant cavity.¹ This work established that the regime of rf confinement is at pressures below the electron mean-free-path limit of the diffusion theory of rf breakdown and at field strengths for which the depth of the confinement quasipotential well is in the range of $1-2\frac{1}{2}$ times the ionization potential of the background gas. The next logical and desirable phase of this work is to measure the properties of the confined plasma—its density, temperature, floating potential, and spatial distribution. This work is planned for mid-1973.

¹C. F. Shelby and A. J. Hatch, Phys. Rev. Letters 29, 834 (1972).

b. Computer Simulation of RF Confinement of Plasma

A. J. Hatch and J. L. Shohet

We have completed the first phase of computer simulation of rf confinement of plasmas, in which the gross aspects of confinement have been observed. The second phase (already begun) is a study of some of the accessible and significant internal properties of rf confinement—e. g.,

electron and ion densities, temperatures, spatial distributions, and evidence of plasma oscillations.

A new study of hybrid resonance phenomena (combined effects of plasma oscillations and cyclotron resonance effects in superposed rf electromagnetic and static magnetic fields) has been started. This has required only minor modifications in the computer code as used for the rf confinement studies. Hybrid resonance phenomena have potential application to rf heating of plasmas in controlled thermonuclear reactors.

c. Bounded Plasmas in Resonant Cavity Fields

A. J. Hatch and J. Hamann

Experimental studies of high-density plasmas produced in a small-diameter quartz tube on the axis of a cylindrical cavity have been continued. A major problem has been obtaining a satisfactory match to the input impedance and coupling rf power effectively to the cavity-plasma system. The theoretical approach to this matching and coupling problem appears to be formidable and to the best of our knowledge has not been explored. Thus our approach is to treat the system experimentally as one having a conventional lossy dielectric load and to attempt various operating methods. These include tuning-stub impedance matching and frequency-shifting the driving rf source (a tunable 2-kW cw klystron power amplifier) to follow the resonant frequency of the plasma-loaded cavity. High-density microwave plasmas have potential applicability to controlled thermonuclear research, beam sources, lasers, and plasma chemistry.

d. Plasmas in Toroidal Resonant Cavities

A. J. Hatch, S. G. Sanders, M. Hasan, and J. Robinson

Preliminary experimental and analytical studies of the empty-cavity-mode spectrum of a sectorized copper torus have been completed. A new heavy-wall torus has been obtained and is being modified

Fig. 56. Empty-cavity-mode spectrum of the sectored copper torus (central portion) compared with spectra calculated for an analog cylindrical cavity (upper portion) and an analog coaxial cavity (lower portion). Double and quadruple mode splitting is accounted for on the basis of intrinsic mode splitting in the azimuthal coordinate θ of the analog cylindrical cavity and to nonintrinsic splitting in the circumferential coordinate z . The latter splitting results from circumferential perturbations due to the sectored structure of the cavity which was formed by brazing together the beveled ends of twelve sectors of circular cylinders. The coaxial-cavity model has the advantage of providing calculated values of the azimuthally split frequencies.

for low-pressure use without a vacuum liner. This cavity approximates the shape of a geometrically perfect torus much more closely than does the sector copper torus. The aluminum torus will be used for studies of the properties of unbounded plasmas excited by various types of modes. Paralleling this experimental work is a theoretical attempt to obtain the eigenvalues for a torus from a solution of the Helmholtz scalar equation. These studies of microwave-induced plasmas in toroidal systems are of interest in controlled thermonuclear research.

e. Parametric Study of Tokamak Plasma Systems

A. J. Hatch and J. F. Etzweiler

Computation of the design parameters of tokamak fusion reactors on the basis of the model of Golovin et al. has been simplified by establishing a hierarchy of independent reactor parameters based on their permissible ranges of values. The wide-range parameters are the first-wall loading P_w and the blanket thickness T_B . The narrow-range parameters are the poloidal β_p of the plasma and the stability coefficient q . The unvaried parameters are the ratio of plasma radius to wall radius y , the maximum toroidal magnetic field B_m , and the plasma temperature $T_e = T_i$. Computations have been made through the full ranges of all the above parameters. All computations are for the optimum value of the aspect ratio A that minimizes B_m . The computed values of (1) P_T vs β_p and q for selected values of P_w and T_B , (2) P_T vs P_w and T_B for selected values of β_p and q , and (3) major radius R , wall radius r_w , and other dependent parameters vs P_w for selected values of β_p , q , and T_B have been plotted for use in preliminary design studies of tokamak systems. This work has been completed.

V. PUBLICATIONS FROM 1 APRIL 1972 THROUGH 31 MARCH 1973

The papers listed here are those whose publication was noted by the reporting unit of the Laboratory in the 1-year period stated above. The dates on the journals therefore often precede this period, and some dated within the period will be listed subsequently. The list of "journal articles and book chapters," which also includes letters and notes, is classified by topic; the arrangement is approximately that followed in the Table of Contents of this Annual Review. The "reports at meetings" include abstracts, summaries, and full texts in volumes of proceedings; they are listed chronologically.

A. BOOKS

1. MÖSSBAUER EFFECT DATA INDEX COVERING THE 1970 LITERATURE

edited by J. G. Stevens and V. E. Stevens*

Plenum Publishing Corporation, New York, 1972

B. PUBLISHED JOURNAL ARTICLES AND BOOK CHAPTERS

1. GAMMA-RAY INTENSITY STANDARDS: THE REACTIONS

$^{14}\text{N}(n,\gamma)^{15}\text{N}$, $^{35}\text{Cl}(n,\gamma)^{36}\text{Cl}$ AND $^{53}\text{Cr}(n,\gamma)^{54}\text{Cr}$

G. D. Loper and G. E. Thomas

Nucl. Instr. Methods 105, 453-460 (1972)

2. p-WAVE NEUTRON RESONANCES IN ^{203}Tl AND ^{205}Tl

G. E. Thomas, L. M. Bollinger, and R. E. Coté

Nucl. Phys. A193, 643-646 (1972)

*University of North Carolina at Asheville, North Carolina.

3. $^{238}\text{U}(n, \gamma)^{239}\text{U}$ AND STATES OF ^{239}U
L. M. Bollinger and G. E. Thomas
Phys. Rev. C 6, 1322-1338 (October 1972)
4. DOORWAY STATES AND BACKGROUND CROSS SECTIONS IN
 $^{29}\text{Si}(\gamma, n)$
H. E. Jackson and R. E. Toohey
Phys. Rev. Lett. 29, 379-382 (7 August 1972)
5. $^{208}\text{Pb}(\gamma, n)^{207}\text{Pb}$ AND THE GIANT M1 RESONANCE
R. E. Toohey and H. E. Jackson
Phys. Rev. C 6, 1440-1443 (October 1972)
6. NEUTRON DECAY FROM THE ^{49}Ca GROUND-STATE ANALOG
IN ^{49}Sc
A. J. Elwyn, F. T. Kuchnir, J. E. Monahan, F. P. Mooring,
J. F. Lemming, and W. G. Stoppenhagen*
Phys. Rev. C 6, 1730-1741 (November 1972)
7. POSSIBLE RESONANCE STRUCTURE IN THE ELASTIC SCATTERING
OF NEUTRONS BY Y NEAR $E_n = 1$ MeV
A. J. Elwyn, J. E. Monahan, S. A. Cox (Applied Physics Division),
J. Adams,[†] and C. Chen[†]
Nucl. Phys. A202, 241-256 (1973)
8. CHANNELING OF PROTONS IN THIN BaTiO_3 CRYSTALS AT
TEMPERATURES ABOVE AND BELOW THE FERROELECTRIC
CURIE POINT
D. S. Gemmell and R. C. Mikkelson
Phys. Rev. B 6, 1613-1635 (1 September 1972)
9. INHIBITION OF RADIATION BLISTERING IN TIN BOMBARDED BY
PROTONS AND ALPHA PARTICLES
R. C. Mikkelson, J. W. Miller (Materials Science Division),
R. E. Holland, and D. S. Gemmell
J. Appl. Phys. 44, 935-937 (March 1973)
10. THE PROPORTIONAL COUNTER AS A POSITION-SENSITIVE DEVICE
T. H. Braid
Proc. Roy. Soc. Edinb. A70, 9-26 (1971, 1972)

* Ohio University, Lancaster, Ohio.

[†] Ohio University, Athens, Ohio.

11. $^{12}\text{C}(^{16}\text{O},\alpha)^{24}\text{Mg}$ EXCITATION FUNCTIONS AND STATISTICAL-MODEL CALCULATIONS FOR HIGH-SPIN STATES IN ^{24}Mg
L. R. Greenwood, K. Katori, R. E. Malmin, T. H. Braid,
J. C. Stoltzfus, and R. H. Siemssen
Phys. Rev. C 6, 2112-2126 (December 1972)
12. RESONANCE IN $^{12}\text{C} + ^{16}\text{O}$ SCATTERING AT $E_{\text{c.m.}} \approx 19.7$ MeV
R. E. Malmin, R. H. Siemssen, D. A. Sink,* and P. P. Singh*
Phys. Rev. Lett. 28, 1590-1593 (12 June 1972)
13. $(^{16}\text{O}, ^{15}\text{N})$ REACTIONS ON fp-SHELL TARGET NUCLEI
G. C. Morrison, H. J. Körner, L. R. Greenwood, and R. H. Siemssen
Phys. Rev. Lett. 28, 1662-1665 (19 June 1972)
14. ^{16}O -INDUCED TRANSFER REACTIONS ON fp-SHELL TARGET NUCLEI. I. THE $(^{16}\text{O}, ^{15}\text{N})$ ONE-PROTON TRANSFER REACTION
H. J. Körner, G. C. Morrison, L. R. Greenwood, and R. H. Siemssen
Phys. Rev. C 7, 107-121 (January 1973)
15. EVIDENCE FOR SHAPE OR QUASIMOLECULAR RESONANCES IN THE $^{16}\text{O} + ^{16}\text{O}$ INTERACTION
P. P. Singh,* D. A. Sink,* P. Schwandt,* R. E. Malmin, and R. H. Siemssen
Phys. Rev. Lett. 28, 1714-1717 (26 June 1972)
16. $^{18}\text{O} + ^{16}\text{O}$ ELASTIC SCATTERING IN THE ENERGY RANGE $E_{\text{c.m.}} = 13-33$ MeV
R. H. Siemssen, H. T. Fortune, A. Richter, and J. W. Tippie (Applied Mathematics Division)
Phys. Rev. C 5, 1839-1849 (June 1972)
17. BACKWARD-ANGLE ELASTIC SCATTERING OF ^{16}O ON ^{40}Ca AND ^{48}Ca
K. O. Groeneveld, L. Meyer-Schützmeister, A. Richter, and U. Strohmusch
Phys. Rev. C 6, 805-810 (September 1972)
18. MEASUREMENTS OF NUCLEAR RADII BY HEAVY-ION SCATTERING
A. M. Friedman (Chemistry Division), R. H. Siemssen, and J. G. Cuninghame†
Phys. Rev. C 6, 2219-2223 (December 1972)

*Indiana University, Bloomington, Indiana.

†Atomic Energy Research Establishment, Harwell, England.

19. $^{58}\text{Ni}(\alpha, \alpha')^{58}\text{Ni}$ AND THE NATURE OF HIGH-LYING STATES IN ^{58}Ni
G. Bruge,* A. Chaumeaux,* R. DeVries,* and G. C. Morrison
Phys. Rev. Lett. 29, 295-298 (31 July 1972)
20. α TRANSFER TO ^{44}Ti BY THE $(^6\text{Li}, d)$ REACTION
U. Strohmusch, C. L. Fink, B. Zeidman, R. N. Horoshko,[†]
H. W. Fulbright,[†] and R. Markham[†]
Phys. Rev. Lett. 29, 735-738 (11 September 1972)
21. $^{19}\text{F}(d, p)^{20}\text{F}$ AND THE NUCLEAR STRUCTURE OF ^{20}F
H. T. Fortune, G. C. Morrison, R. C. Barse, J. L. Yntema,
and B. H. Wildenthal[‡]
Phys. Rev. C 6, 21-29 (July 1972)
22. REACTION $^{27}\text{Al}(d, p)^{28}\text{Al}$ at $E_d = 23$ MeV
J. V. Maher, H. T. Fortune, G. C. Morrison, and B. Zeidman
Phys. Rev. C 5, 1313-1322 (April 1972)
23. ENERGY LEVELS OF ^{34}S FROM THE $^{33}\text{S}(d, p)^{34}\text{S}$ REACTION
D. J. Crozier
Nucl. Phys. A198, 209-227 (1972)
Ph.D. Thesis, University of Chicago, Chicago, Illinois
(December 1972)
24. STUDY OF THE (d, p) REACTION ON ^{92}Zr AND ^{94}Zr
H. Fann and U. Strohmusch
Phys. Rev. C 6, 2299-2303 (December 1972)
25. NUCLEAR LEVELS IN ^{233}Th EXCITED BY NEUTRON CAPTURE
AND (d, p) REACTIONS
T. von Egidy,[§] O. W. B. Schult,[§] D. Rabenstein,[§] J. R. Erskine,
O. A. Wasson,^{||} R. E. Chrien,^{||} D. Breitig,[¶] R. P. Sharma,[¶]
H. A. Baader,[¶] and H. R. Koch[¶]
Phys. Rev. C 6, 266-284 (July 1972)

* Centre d'Etudes Nucléaires de Saclay, 91 Gif-sur-Yvette, France.

[†] Nuclear Structure Research Laboratory, University of Rochester, Rochester, New York.

[‡] Michigan State University, East Lansing, Michigan.

[§] Physik-Department, Technische Universität München, Germany.

^{||} Brookhaven National Laboratory, Upton, L.I., New York.

[¶] Physik-Department, Technische Universität München, Germany and Research Establishment Risö, Denmark.

26. ELECTROMAGNETIC TRANSITION RATES IN ^{28}Al
J. V. Maher, G. B. Beard, G. H. Wedberg, E. Sprenkel-Segel,
A. Yousef, B. H. Wildenthal,* and R. E. Segel
Phys. Rev. C 5, 1322-1329 (April 1972)
27. STUDY OF ^{47}Ti WITH THE $^{45}\text{Sc}(^3\text{He},p)^{47}\text{Ti}$ AND $^{45}\text{Sc}(^3\text{He},p\gamma)^{47}\text{Ti}$
REACTIONS
L. Meyer-Schützmeister, J. W. Smith, G. Hardie, H. Siefken,
K. T. Knöpfle,[†] M. Rogge,[†] and C. Mayer-Böricke[†]
Nucl. Phys. A 199(3), 593-623 (1973)
28. STUDY OF THE ^{50}V NUCLEUS WITH THE $(^3\text{He},d)$, $(^3\text{He},\alpha)$,
 $(^3\text{He},p)$, AND $(^3\text{He},p\gamma)$ REACTIONS
J. W. Smith, L. Meyer-Schützmeister, T. H. Braid, P. P.
Singh,[‡] and G. Hardie[§]
Phys. Rev. C 7, 1099-1119 (March 1973)
29. STUDY OF ^{57}Co WITH THE $^{56}\text{Fe}(^3\text{He},d)$ AND $^{56}\text{Fe}(^3\text{He},d\gamma)$
REACTIONS
G. Hardie, T. H. Braid, L. Meyer-Schützmeister, and J. W.
Smith
Phys. Rev. C 5, 1600-1613 (May 1972)
30. NUCLEAR DATA SHEETS FOR $A = 95$
L. R. Medsker
Nucl. Data B 8, 29-76 (1972)
31. POPULATION OF 0^+ STATES IN ACTINIDE AND $A \approx 190$ NUCLIDES
BY THE (p,t) REACTION
J. V. Maher, J. R. Erskine, A. M. Friedman (Chemistry
Division), R. H. Siemssen, and J. P. Schiffer
Phys. Rev. C 5, 1380-1389 (April 1972)
32. POPULATION OF 0^+ EXCITED STATES IN ^{238}Pu AND ^{240}Pu
BY SINGLE-NEUTRON TRANSFER REACTIONS
A. Friedman (Chemistry Division) and K. Katori
Phys. Rev. Lett. 30, 102-105 (15 January 1973)

* Michigan State University, East Lansing, Michigan.

[†] Institut für Kernphysik der Kernforschungsanlage Jülich; Jülich,
Germany.

[‡] Indiana University, Bloomington, Indiana.

[§] Western Michigan University, Kalamazoo, Michigan.

33. REACTION-SPECTROSCOPY STUDIES OF THE ACTINIDE ELEMENTS.
III. LEVELS IN ^{241}Pu AND ^{243}Pu
T. H. Braid, R. R. Chasman (Chemistry Division), J. R. Erskine, and A. M. Friedman (Chemistry Division)
Phys. Rev. C 6, 1374-1384 (October 1972)
34. DOUBLE FOCUSING UNIFORM FIELD MAGNET WITH CIRCULAR POLES
J. J. Livingood
Rev. Sci. Instr. 44, 80-81 (January 1973)
35. $^{69,71}\text{Ga}(\text{d},\text{p})$ AND $^{71}\text{Ga}(\text{d},\text{t})$ REACTIONS
J. L. Yntema
Phys. Rev. C 7, 140-149 (January 1973)
36. STUDY OF ^{95}Nb BY MEANS OF THE $^{94}\text{Zr}(\text{}^3\text{He},\text{d})$ REACTION
L. R. Medsker and J. L. Yntema
Phys. Rev. C 7, 440-445 (January 1973)
37. TESTS ON SUPERCONDUCTING HELIX RESONATORS
R. Benaroya (Chemistry Division), A. H. Jaffey (Chemistry Division), K. Johnson (Chemistry Division), T. Khoe (Accelerator Division), J. J. Livingood, J. M. Nixon (Chemistry Division), G. W. Parker (Chemistry Division), W. J. Ramler (Chemistry Division), J. Aron (Chemistry Division), and W. A. Wesolowski (Chemistry Division)
Appl. Phys. Lett. 21, 235-236 (1 September 1972)
38. NUCLEAR γ RAYS ASSOCIATED WITH STOPPED KAONS
P. D. Barnes,* R. A. Eisenstein,* W. C. Lam,* J. Miller,* R. B. Sutton,* M. Eckhause,[†] J. Kane,[†] R. E. Welsh,[†] D. A. Jenkins,[‡] R. J. Powers,[‡] R. Kunselman,[§] R. P. Redwine, R. E. Segel, and J. P. Schiffer
Phys. Rev. Lett. 29, 230-233 (24 July 1972)
39. STRONG-INTERACTION EFFECTS IN ANTIPROTONIC ATOMS
P. D. Barnes,* S. Dytman,* R. A. Eisenstein,* W. C. Lam,* J. Miller,* R. B. Sutton,* D. A. Jenkins,[‡] R. J. Powers,[‡] M. Eckhause,[†] J. R. Kane,[†] B. L. Roberts,[†] R. E. Welsh,[†] A. R. Kunselman,[§] R. P. Redwine, and R. E. Segel
Phys. Rev. Lett. 29, 1132-1134 (23 October 1972)

* Carnegie-Mellon University, Pittsburgh, Pennsylvania.

[†] College of William & Mary, Williamsburg, Virginia.

[‡] Virginia Polytechnic Institute, Blacksburg, Virginia.

[§] University of Wyoming, Laramie, Wyoming.

40. ON THE IMPULSE-APPROXIMATION TREATMENT OF ALLOWED MUON CAPTURE IN ${}^6\text{Li}$
Nimai C. Mukhopadhyay
Phys. Lett. 40B(2), 157-160 (1972)
Ph.D. Thesis, University of Chicago, Chicago, Illinois (1972)
41. FIRST 0^+ EXCITED STATE OF ${}^{16}\text{O}$ IN THE α -PARTICLE MODEL OF LIGHT NUCLEI
Y. Avishai
Phys. Rev. C 6, 677-679 (September 1972)
42. MAGNETIC MULTIPOLE PROPERTIES OF ${}^{38}\text{Cl}$ AND ${}^{40}\text{K}$
D. Kurath and R. D. Lawson
Phys. Rev. C 6, 901-907 (September 1972)
43. INHIBITED TRANSITIONS AND ISOMERIC STATES IN THE N=50 ISOTONES
D. H. Gloeckner, M. H. Macfarlane, R. D. Lawson, and F. J. D. Serduke
Phys. Lett. 40B(6), 597-601 (1972)
44. OCCUPATION NUMBERS AND SHELL CLOSURE IN THE ZIRCONIUM ISOTOPES
David Gloeckner
Phys. Lett. 42B, 381-384 (25 December 1972)
Ph.D. Thesis, University of Chicago, Chicago, Illinois (1972)
45. MUTUALLY ORTHOGONAL ORTHOGONALIZED PLANE WAVES
George E. Juras,* J. E. Monahan, C. M. Shakin,* and R. M. Thaler*
Phys. Rev. B 5, 4000-4002 (15 May 1972)
46. NEW ISOSPIN PREDICTIONS FOR ONE- AND TWO-PARTICLE INCLUSIVE REACTIONS
A. J. Macfarlane
Phys. Rev. D 6, 326-328 (1 July 1972)
47. ISOSPIN AND SU₃ EQUALITIES FOR STRONG, ELECTROMAGNETIC AND WEAK INCLUSIVE PROCESSES
A. J. Macfarlane
Nuovo Cimento Lett. 4, 186 (1972)

* Case Western Reserve University, Cleveland, Ohio.

48. THREE-BODY CORRELATIONS IN NUCLEAR MATTER
B. D. Day, F. Coester, and A. Goodman
Phys. Rev. C 6, 1992-2010 (December 1972)
49. GENERALIZED GAP EQUATIONS AND THE COHERENCE OF THE
 α - α PAIR FIELD
A. L. Goodman
Nucl. Phys. A186(3), 475-492 (1972)
50. REACTION-MATRIX CALCULATIONS OF THE Λ -PARTICLE
BINDING IN NUCLEAR MATTER FOR CENTRAL AN POTENTIALS
A. R. Bodmer and D. M. Rote (Argonne Center for Environmental
Studies)
Nucl. Phys. A201(1), 145-178 (1973)
51. IS THE MAXWELL FIELD LOCAL?
Y. Avishai, H. Ekstein, and J. E. Moyal (Applied Mathematics
Division)
J. Math. Phys. 13, 1139-1145 (August 1972)
52. CAUSAL INDEPENDENCE
Y. Avishai and H. Ekstein
Foundations of Physics 2(4), 257-270 (October 1972)
53. SCATTERING WITHOUT SCATTERING OPERATOR
H. Ekstein
Ann. Phys. (N. Y.) 74(2), 303-313 (December 1972)
54. PRESYMMETRY OF CLASSICAL RELATIVISTIC FIELDS
Y. Avishai and H. Ekstein
Phys. Rev. D 7, 983-991 (15 February 1973)
55. INTERFERENCE EFFECTS PRODUCED BY MODULATED
PARTICLE BEAMS
H. J. Lipkin and M. Peshkin
J. Appl. Phys. 43, 3037-3040 (July 1972)
56. PRODUCTION OF COHERENT MIXTURES OF RESONANCES IN
THE QUARK MODEL
Harry J. Lipkin
Phys. Rev. D 7, 1561-1563 (1 March 1973)
57. QUARK-MODEL PREDICTIONS FOR REACTIONS WITH HYPERON
BEAMS
Harry J. Lipkin
Phys. Rev. D 7, 846-852 (1973)

58. NEW FINITE-ENERGY SUM RULES BASED ON ρ AND ω EXCHANGE
Harry J. Lipkin
Phys. Rev. D 7, 237-242 (January 1973)
59. LIGHT CONE RELATIONS FOR THE STRANGENESS CHANGING
STRUCTURE FUNCTIONS
Harry J. Lipkin and E. A. Paschos*
Phys. Rev. D 6, 814 (1972)
60. SYMMETRY RELATIONS FOR DEEP-INELASTIC PROCESSES
Harry J. Lipkin and E. A. Paschos*
Phys. Rev. Lett. 29, 525-529 (21 August 1972)
61. ION-MOLECULE REACTIONS BY PHOTOIONIZATION TECHNIQUES
William A. Chupka
Chap. 3 in Ion-Molecule Reactions, edited by J. L.
Franklin (Plenum Press, New York, 1972), Vol. 1,
pp. 33-76
62. PHOTOIONIZATION MASS SPECTROMETRIC STUDY OF NO.
A CLOSER LOOK AT THE THRESHOLD REGION
P. C. Killgoar, Jr., G. E. Leroy,[†] J. Berkowitz, and W. A.
Chupka
J. Chem. Phys. 58, 803-806 (15 January 1973)
63. THE DISSOCIATION ENERGY OF FLUORINE
J. Berkowitz and Arnold C. Wahl (Chemistry Division)
Advances in Fluorine Chemistry, edited by J. C. Tatlow,
R. D. Peacock, and H. H. Hyman (Butterworths, London,
1973), Vol. 7, pp. 147-174
64. PHOTOIONIZATION OF HOF WITH MASS ANALYSIS
J. Berkowitz, E. H. Appelman (Chemistry Division), and W. A.
Chupka
J. Chem. Phys. 58, 1950-1954 (1 March 1973)
65. Erratum: EXPERIMENTAL POTENTIAL ENERGY CURVES FOR
 $X^2\Pi$ AND $^2\Sigma^+$ STATES OF HF^+ [Chem. Phys. Letters 11, 21
(15 September 1971)]
J. Berkowitz
Chem. Phys. Lett. 14, 292 (15 May 1972)

*National Accelerator Laboratory, Batavia, Illinois.

[†]Michigan State University, East Lansing, Michigan.

66. PHOTOELECTRON SPECTROSCOPY OF HIGH-TEMPERATURE VAPORS. II. CHEMICAL BONDING IN THE GROUP III MONO-HALIDES
J. Berkowitz and J. L. Dehmer (Radiological and Environmental Research Division)
J. Chem. Phys. 57, 3194-3201 (15 October 1972)
67. EFFECT OF CHANNELING AND IRRADIATION TEMPERATURE ON THE MORPHOLOGY OF BLISTERS IN NIOBIUM
M. Kaminsky and S. K. Das
Appl. Phys. Lett. 21, 443-445 (1 November 1972)
68. RADIATION BLISTERING OF POLYCRYSTALLINE NIOBIUM BY HELIUM-ION IMPLANTATION
S. K. Das and M. Kaminsky
J. Appl. Phys. 44, 25-31 (January 1973)
69. SECONDARY-ION COLLECTION SYSTEM FOR AN ION-MICROPROBE ANALYZER OF HIGH MASS RESOLUTION
V. E. Krohn and G. R. Ringo
Rev. Sci. Instr. 43, 1771-1772 (December 1972)
70. MÖSSBAUER STUDIES OF GLASSES AND SUPERCOOLED LIQUIDS
S. L. Ruby
J. Non-Cryst. Solids 8-10, 78-84 (June 1972)
Amorphous and Liquid Semiconductors (Proceedings of the Fourth International Conference, Ann Arbor, 9-13 August 1971), edited by M. H. Cohen and G. Lucovsky (North-Holland Publishing Co., Amsterdam, 1972), pp. 78-84
71. SOME UNUSUAL CRYSTALLIZATION PHENOMENA IN FROZEN AQUEOUS SOLUTIONS
S. L. Ruby, A. Bernabei, and B. J. Zabransky
Chem. Phys. Lett. 13(4), 382-385 (1972)
72. USEFUL INFORMATION FOR Fe^{57} MÖSSBAUER SPECTROSCOPY
J. G. Stevens and R. S. Preston
Mössbauer Effect Data Index Covering the 1970 Literature, edited by J. G. Stevens and V. E. Stevens (Plenum Publishing Corporation, New York, 1972), Appendix G, pp. 16-22
73. MÖSSBAUER STUDY OF THE SURFACE BARRIER TO THE DIFFUSION OF IRON INTO ALUMINUM
R. S. Preston
Metallurgical Transactions 3, 1831-1835 (July 1972)

74. NUCLEAR GAMMA RESONANCE STUDIES ON MATRIX-ISOLATED FeCl_2 MOLECULES AT 4.2°K
T. K. McNab, D. H. W. Carstens (Chemistry Division), D. M. Gruen (Chemistry Division), and R. L. McBeth (Chemistry Division)
Chem. Phys. Lett. 13(6), 600-601 (1972)
75. ANOMALOUSLY NARROW MÖSSBAUER LINEWIDTH IN ^{197}Au
W. Potzel and G. J. Perlow
Phys. Rev. Lett. 29, 910-913 (2 October 1972)
76. HYPERFINE STRUCTURE OF THE $3d^8 4s^2 \ ^3F_2$ METASTABLE ATOMIC STATE OF ^{61}Ni
W. J. Childs and B. Greenebaum
Phys. Rev. A 6, 105-111 (July 1972)
77. HYPERFINE-STRUCTURE CONSTANTS AND g_J VALUES OF $^5\text{I}_{4,5,6,7,8}$ ATOMIC STATES OF $^{143,145}\text{Nd}$
W. J. Childs and L. S. Goodman
Phys. Rev. A 6, 1772-1786 (November 1972)
78. REANALYSIS OF THE HYPERFINE STRUCTURE OF THE $4f^6 6s^2 \ ^7F$ MULTIPLY IN $^{147,149}\text{Sm}$, INCLUDING MEASUREMENTS FOR THE 7F_6 STATE
W. J. Childs and L. S. Goodman
Phys. Rev. A 6, 2011-2021 (December 1972)
79. OBSERVATION OF RADIO-FREQUENCY CONFINEMENT OF A PLASMA
Charles F. Shelby and Albert J. Hatch
Phys. Rev. Lett. 29, 834-837 (25 September 1972)

C. PUBLISHED REPORTS AT MEETINGS

Problems of Modern Nuclear Physics, Proceedings of the Second Problem Symposium on Nuclear Physics, Novosibirsk, June 1970 (Publishing House "Nauka," Moscow, 1972)

1. COULOMB ENERGIES AND NUCLEAR RADII

John P. Schiffer

pp. 246-256

Fourth Symposium on the Structure of Low-Medium Mass Nuclei, University of Kansas, 12-14 October 1970, edited by J. P. Davidson (University Press of Kansas, Lawrence/Manhattan/Wichita, 1972)

2. LIFETIMES OF BOUND STATES

R. E. Segel

pp. 112-145

Computing as a Language of Physics, Lectures presented at an International Seminar Course, International Centre for Theoretical Physics, Trieste, 2-20 August 1971 (International Atomic Energy Agency, Vienna, 1972)

3. THE DELPHI-SPEAKEASY SYSTEM

S. Cohen

pp. 521-528

Abstracts of Contributions to the IVth International Conference on High Energy Physics and Nuclear Structure, Dubna, USSR, 7-11 September 1971 (Joint Institute for Nuclear Research, Dubna, 1971)

4. NUCLEAR STRUCTURE STUDIES WITH EPICS AT LAMPF

H. A. Thiessen,* D. E. Nagle,* S. E. Sobottka,[†]
and B. Zeidman

p. 147

International Conference on Multiply-Charged Heavy-Ion Sources and Accelerating Systems, Gatlinburg, Tennessee, 25-28 October 1971

5. LIFETIME OF CARBON FOILS BOMBARDED BY 4-MeV Ni

J. L. Yntema

IEEE Trans. Nucl. Sci. NS-19(2), 272-273 (April 1972)

* University of California, Los Alamos Scientific Laboratory, Los Alamos, New Mexico.

[†] University of Virginia, Charlottesville, Virginia.

Fusion Reactor First Wall Materials, Summary of a Meeting Held at AEC (Germantown), 27-28 January 1972, edited by L. C. Ianiello, U.S. Atomic Energy Commission Report No. WASH-1206 (April 1972)

6. SURFACE PHENOMENA

E. E. Donaldson,* F. W. Young, Jr.,[†] M. S. Kaminsky,
and N. Laegreid[‡]
pp. 79-84

7. SURFACE EFFECTS

M. Kaminsky
pp. 63-67

Abstracts of Papers Presented at the 163rd American Chemical Society Meeting, Boston, 10-14 April 1972

8. PHOTOELECTRON SPECTROSCOPY OF INORGANIC MOLECULES WITH He (I) RADIATION

J. Berkowitz
abstract No. INOR-50

9. A PHOTOIONIZATION STUDY OF NO₂

P. C. Killgoar,[§] G. E. Leroi,[§] J. Berkowitz, and W. A. Chupka
abstract No. PHYS-130

American Physical Society, Washington, D.C., 24-27 April 1972

10. X-RAYS AND NUCLEAR GAMMA RAYS FROM KAONIC ATOMS

P. D. Barnes,^{||} R. A. Eisenstein,^{||} W. C. Lam,^{||}
J. Miller,^{||} R. B. Sutton,^{||} D. A. Jenkins,[¶] R. J.
Powers,[¶] M. Eckhause,** J. Kane,** R. Welsh,**
R. Kunselman,^{††} R. Redwine, R. Segel, and J. Schiffer
Bull. Am. Phys. Soc. 17, 454 (1972)

* Washington State University, Pullman, Washington.

[†] Oak Ridge National Laboratory, Oak Ridge, Tennessee.

[‡] Pacific Northwest Laboratory, Battelle Memorial Institute, Richland, Washington.

[§] Michigan State University, East Lansing, Michigan.

^{||} Carnegie-Mellon University, Pittsburgh, Pennsylvania.

[¶] Virginia Polytechnic Institute, Blacksburg, Virginia.

** College of William & Mary, Williamsburg, Virginia.

^{††} University of Wyoming, Laramie, Wyoming.

APS, Washington, D. C. (cont'd.)

11. DETERMINATION OF THE SPIN-CUTOFF PARAMETER
FROM NEUTRON-CAPTURE γ RAYS
L. M. Bollinger, G. D. Loper, and G. E. Thomas
Bull. Am. Phys. Soc. 17, 556 (1972)

12. STUDY OF UNPAIRED STATES OF ACTINIDE NUCLEI
THROUGH SINGLE-NEUTRON TRANSFER REACTIONS
K. Katori and A. M. Friedman (Chemistry Division)
Bull. Am. Phys. Soc. 17, 463 (1972)

13. SEARCH FOR THE "PYGMY" RESONANCE IN $^{197}\text{Au}(n, \gamma)^{198}\text{Au}$
G. D. Loper, L. M. Bollinger, and G. E. Thomas
Bull. Am. Phys. Soc. 17, 580 (1972)

14. RADIATIVE PROTON CAPTURE BY ^{54}Fe AND ^{56}Fe
R. J. Nemanich, G. C. Kiang, D. von Ehrenstein,
E. L. Sprenkel-Segel, L. Meyer-Schützmeister,
J. V. Maher, and R. E. Segel
Bull. Am. Phys. Soc. 17, 584 (1972)

15. (p, t) REACTIONS ON ACTINIDE NUCLEI
J. P. Schiffer, K. Katori, A. Friedman (Chemistry
Division), and D. Albright
Bull. Am. Phys. Soc. 17, 463 (1972)

16. $J^\pi = 1^+$ LEVELS IN ^{48}V
J. W. Smith, L. Meyer-Schützmeister, R. D. Lawson,
T. H. Braid, G. Hardie,* and P. P. Singh†
Bull. Am. Phys. Soc. 17, 582 (1972)

17. $^{41}\text{K}(^3\text{He}, t)$ AND $^{89}\text{Y}(^3\text{He}, t)$ REACTIONS
M. M. Stautberg-Greenwood, M. Pluta, N. Anantaraman,
J. P. Schiffer, and L. R. Greenwood
Bull. Am. Phys. Soc. 17, 445 (1972)

18. ANTI-PROTONIC ATOMIC X-RAYS
R. B. Sutton,‡ P. D. Barnes,‡ R. A. Eisenstein,‡
W. C. Lam,‡ J. Miller,‡ D. A. Jenkins,§ R. J.
Powers,§ M. Eckhause,|| J. Kane,|| R. Welsh,||
R. Kunselman,¶ R. Redwine, and R. Segel
Bull. Am. Phys. Soc. 17, 453 (1972)

* Western Michigan University, Kalamazoo, Michigan.

† Indiana University, Bloomington, Indiana.

‡ Carnegie-Mellon University, Pittsburgh, Pennsylvania.

§ Virginia Polytechnic Institute, Blacksburg, Virginia.

|| College of William & Mary, Williamsburg, Virginia.

¶ University of Wyoming, Laramie, Wyoming.

APS, Washington, D. C. (cont'd.)

19. ABSOLUTE INTENSITIES OF THERMAL-NEUTRON CAPTURE γ RAYS
G. E. Thomas, G. D. Loper, and L. M. Bollinger
Bull. Am. Phys. Soc. 17, 580 (1972)
20. SPINS OF ^{139}Ba LEVELS FROM THE $^{138}\text{Ba}(\vec{d}, p)$ REACTION WITH POLARIZED DEUTERONS
D. von Ehrenstein and M. C. Tsangarides
Bull. Am. Phys. Soc. 17, 511 (1972)
21. LIFETIMES OF LOW-LYING LEVELS IN ^{36}Cl
A. S. Yousef, E. L. Sprenkel-Segel, and R. E. Segel
Bull. Am. Phys. Soc. 17, 485-486 (1972)

Conference Program and Abstracts, 4th Annual Spring Meeting of the Metallurgical Society of AIME, Boston, 8-11 May 1972

22. SURFACE EFFECTS IN THERMONUCLEAR DEVICES AND REACTORS
Manfred Kaminsky
Abstract 182, p. 55

American Physical Society, Albuquerque, New Mexico, 5-7 June 1972

23. RADIATION BLISTERING IN NIOBIUM
M. Kaminsky and S. Das
Bull. Am. Phys. Soc. 17, 678-679 (May 1972)
24. ENERGY SPLITTING OF EXCITED TWO-QUASIPARTICLE STATES IN EVEN-A DEFORMED NUCLEI
K. Katori and F. Weller
Bull. Am. Phys. Soc. 17, 674 (May 1972)

European Conference on Nuclear Physics, Aix-en-Provence, France, 26 June-1 July 1972

25. NUCLEAR STRUCTURE WITH HEAVY-ION TRANSFER REACTIONS
G. C. Morrison
Suppl. J. Phys. (Paris) 33, C5-111-126
(August-September 1972)
26. STUDY OF THE ELASTIC SCATTERING OF ^{16}O ON ^{90}Zr AND OF THE REACTION $^{90}\text{Zr}(^{16}\text{O}, ^{12}\text{C})^{94}\text{Mo}$ AT 58 MeV
Y. Cassagnou,* H. Faraggi,* G. Morrison, and A. Papineau*

Communications (Journal de Physique, Paris, 1972), p. 78

*Département de Physique Nucléaire, CEN Saclay, BP 2, 91-Gif-sur-Yvette, France.

European Conference on Nuclear Physics, Aix-en-Provence (cont'd.)

27. ($^6\text{Li}, d$) REACTION ON Ca ISOTOPES

U. Strohmusch, C. L. Fink, B. Zeidman, R. N. Horoshko,*
H. W. Fulbright,* and R. Markham*

Communications (Journal de Physique, Paris,
1972), p. 70

First Topical Conference on RF Plasma Heating, American Physical
Society, Lubbock, Texas, 6-8 July 1972

28. PLASMAS IN TOROIDAL CAVITIES

A. J. Hatch, S. G. Sanders, and J. Robinson
Bull. Am. Phys. Soc. 17, 773 (July 1972)

29. APPROXIMATE MODELS OF TOROIDAL CAVITIES

S. G. Sanders, A. J. Hatch, and J. Robinson
Bull. Am. Phys. Soc. 17, 774 (July 1972)

Cyclotrons—1972 (Proceedings of the Sixth International Cyclotron
Conference, Vancouver, Canada, 18-21 July 1972), edited by J. J.
Burgerjon and A. Strathdee (American Institute of Physics, New York,
1972), AIP Conference Proceedings No. 9

30. DESIGN OF A NEUTRON THERAPY FACILITY FOR A
30-INCH CYCLOTRON

Franca T. Kuchnir,[†] Lester S. Skaggs,[†] A. J. Elwyn,
F. P. Mooring, and N. A. Frigerio (Biological and
Medical Research Division)
pp. 638-645

International Conference on Applications of the Mössbauer Effect,
Ayeleth Hashahar, Israel, 28-31 August 1972

31. ANISOTROPY OF THE DEBYE-WALLER FACTOR FOR
THE CESIUM ION OF C_8Cs IN PYROLYTIC GRAPHITE

L. E. Campbell, G. L. Montet (Solid State Science
Division), and G. J. Perlow
Scientific Program and Contributed Papers,
edited by M. Pasternak (Technical Information
Department, Soreq Nuclear Research Center,
Yavne, Israel, 1972), pp. H-10—H-11

* University of Rochester, Rochester, New York.

[†] Argonne Cancer Research Hospital, Chicago, Illinois.

Applications of the Mössbauer Effect, Ayeleth Hashahar, Israel (cont'd.)

32. QUADRUPOLE MOMENT OF THE FIRST EXCITED STATE IN ^{133}Cs FROM THE MÖSSBAUER EFFECT IN CESIATED PYROLYTIC GRAPHITE

L. E. Campbell, G. L. Montet (Solid State Science Division), and G. J. Perlow
Scientific Program and Contributed Papers,
pp. A-14—A-15

33. EXPERIMENTS WITH THE MÖSSBAUER EFFECT IN ^{67}Zn
Gilbert J. Perlow

Perspectives in Mössbauer Spectroscopy,
Proceedings of the Conference, edited by S. G. Cohen and M. Pasternak (Plenum Press, New York/London, 1973), pp. 221-237

34. OBSERVATION OF NARROW ABSORPTION LINES IN MÖSSBAUER EXPERIMENTS ON ^{197}Au

W. Potzel and G. J. Perlow
Scientific Program and Contributed Papers,
pp. A-12—A-13

35. MÖSSBAUER STUDIES OF AQUEOUS LIQUIDS AND GLASSES
S. L. Ruby

Perspectives in Mössbauer Spectroscopy,
pp. 181-194

Abstracts of Papers Presented at the 164th American Chemical Society Meeting, New York, 28 August-1 September 1972

36. STUDIES OF TWO QUASI-PARTICLE STATES IN ACTINIDE NUCLEI

A. M. Friedman (Chemistry Division), Kenji Katori,
and R. R. Chasman (Chemistry Division)
abstract No. NUCL-47

Few Particle Problems in the Nuclear Interaction, Proceedings of the International Conference on Few Particle Problems in the Nuclear Interaction, Los Angeles, 28 August-1 September 1972, edited by I. Slaus, S. A. Moszkowski, R. P. Haddock, and W. T. H. van Oers (North-Holland Publishing Co., Amsterdam, 1972)

37. LOW-LYING 0^+ STATES OF ^{16}O IN THE α -PARTICLE MODEL OF LIGHT NUCLEI

Y. Avishai
pp. 940-943

Few Particle Problems in the Nuclear Interaction, Los Angeles (cont'd.)

38. STRONG INTERACTION EFFECTS IN ANTIPROTONIC ATOMS

P. D. Barnes,* S. Dytman,* R. A. Eisenstein,* W. C. Lam,* J. Miller,* R. B. Sutton,* R. J. Powers,[†] M. Eckhause,[‡] J. R. Kane,[‡] B. L. Roberts,[‡] R. E. Welsh,[‡] A. R. Kunselman,[§] R. P. Redwine, and R. E. Segel

pp. 944-948

39. PERTURBATIVE CALCULATION OF SPIN OBSERVABLES IN ELASTIC NUCLEON-DEUTERON SCATTERING

Steven C. Pieper

pp. 308-313

Proceedings of the International Conference on Nuclear Moments and Nuclear Structure, Osaka, Japan, 4-8 September 1972

40. QUADRUPOLE MOMENTS OF ^{11}C , ^{11}B , AND ^{12}B

D. Kurath and A. Arima^{||}

Suppl. J. Phys. Soc. Japan 34, 529 (1973)

Proceedings of the XVI International Conference on High Energy Physics, University of Chicago and National Accelerator Laboratory, 6-13 September 1972, edited by J. D. Jackson, A. Roberts, and Rene Donaldson (National Accelerator Laboratory, Batavia, Illinois, 1973)

41. CONCLUSIVE EXPERIMENTS TO SEARCH FOR $\bar{\text{B}}\text{B}$ EXOTICS AND A NEW FESR

H. J. Lipkin

Vol. 1, pp. 195-197

42. QUARK MODEL PREDICTIONS FOR REACTIONS WITH HYPERON BEAMS

H. J. Lipkin

Vol. 1, p. 197

* Carnegie-Mellon University, Pittsburgh, Pennsylvania.

[†] Virginia Polytechnic Institute and State University, Blacksburg, Virginia.

[‡] College of William & Mary, Williamsburg, Virginia.

[§] University of Wyoming, Laramie, Wyoming.

^{||} State University of New York, Stony Brook, New York.

Proceedings of the 19th National Symposium of the American Vacuum Society, Chicago, Illinois, 2-5 October 1972

43. SURFACE BLISTERING OF POLYCRYSTALLINE NIOBIUM
BY HELIUM-ION IMPLANTATION

S. K. Das and M. Kaminsky

J. Vac. Sci. Technol. 10, 273 (January/February
1973)

First USA-Japan Computer Conference Proceedings, Tokyo, 3-5
October 1972 (American Federation of Information Processing Societies,
Inc., 210 Summit Avenue, Montvale, New Jersey 07645, 1972)

44. SPEAKEASY: "RAKUGO"

Stanley Cohen

pp. 222-230

Proceedings of the 1972 Proton Linear Accelerator Conference,
Los Alamos, 10-13 October 1972, Los Alamos Scientific Laboratory
Report No. LA-5115

45. PROGRESS IN THE DEVELOPMENT OF SUPERCONDUCTING
RESONATORS FOR HEAVY ION ACCELERATION

R. Benaroya (Chemistry Division), A. H. Jaffey (Chemistry
Division), K. Johnson (Chemistry Division), T. Khoe
(Accelerator Division), J. J. Livingood, J. M. Nixon
(Chemistry Division), G. W. Parker (Chemistry Division),
W. J. Ramler (Chemistry Division), J. Aron (Chemistry
Division), K. E. Gray (Solid State Science Division),
and W. A. Wesolowski (Chemistry Division)

pp. 168-174

1972 Annual Meeting of the Optical Society of America, San Francisco,
California, 17-20 October 1972

46. NUCLEAR MOMENTS OF ^{237}Np

Mark Fred (Chemistry Division), William J. Childs,
Frank S. Tomkins (Chemistry Division), and Jean E.
Blaise*

J. Opt. Soc. Am. 62, 1343 (1972)

Twenty-Fifth Annual Gaseous Electronics Conference with Symposia on
Arcs and Gaseous Plasma Lasers, The University of Western Ontario,
London, Ontario, Canada, 17-20 October 1972

47. CONFINEMENT REGIME OF RADIOFREQUENCY BREAK-
DOWN AND DISCHARGE

A. J. Hatch and C. F. Shelby

Bull. Am. Phys. Soc. 18, 805 (1973)

* Laboratoire Aimé Cotton, Orsay, France.

Proceedings of the 7th Symposium on Fusion Technology, Grenoble, France, 24-27 October 1972 (Commission of the European Communities, Luxembourg, 1972), Report No. EUR 4938 e

48. SURFACE EFFECTS IN THERMONUCLEAR DEVICES
AND REACTORS

Manfred Kaminsky

pp. 41-49

Division of Nuclear Physics, American Physical Society, Seattle,
Washington, 2-4 November 1972

49. A STUDY OF ^{248}Bk , ^{241}Am , AND ^{231}Pa WITH PROTON-
TRANSFER REACTIONS

J. R. Erskine, G. Kyle,* A. Friedman (Chemistry
Division), and R. Chasman (Chemistry Division)

Bull. Am. Phys. Soc. 17, 928 (October 1972)

50. THE $^{91}\text{Zr}(^3\text{He}, \alpha)^{90}\text{Zr}$ REACTION AND THE $(g_{9/2}^{-1} d_{5/2})_{T=1}$
MULTIPLY

H. Fann, L. R. Greenwood, U. Strobusch, and J. P.
Schiffer

Bull. Am. Phys. Soc. 17, 909-910 (October 1972)

51. ALPHA STRUCTURE FACTORS FOR 1p-SHELL TARGETS

D. Kurath

Bull. Am. Phys. Soc. 17, 912 (October 1972)

52. THRESHOLD PHOTONEUTRON RESONANCES FROM
 $^{207}\text{Pb}(\gamma, n)^{206}\text{Pb}$

L. R. Medsker, H. E. Jackson, and R. E. Toohey

Bull. Am. Phys. Soc. 17, 901 (October 1972)

53. COMPARISON OF $^{45}\text{Sc}(^3\text{He}, p)^{47}\text{Ti}$ AND $^{45}\text{Sc}(\alpha, d)^{47}\text{Ti}$
REACTIONS

L. Meyer-Schützmeister, G. Hardie, and T. H. Braid

Bull. Am. Phys. Soc. 17, 932 (October 1972)

54. ^{16}O -INDUCED REACTION ON ^{172}Yb BELOW THE COULOMB
BARRIER

J. P. Schiffer, H. J. Körner, R. H. Siemssen, K. W.
Jones,[†] and A. Schwarzschild[†]

Bull. Am. Phys. Soc. 17, 913 (October 1972)

* University of Minnesota, Minneapolis, Minnesota.

[†] Brookhaven National Laboratory, Upton, L.I., New York.

Division of Nuclear Physics, APS, Seattle (cont'd.)

55. THE $^{90}\text{Zr}(^6\text{Li}, d)^{94}\text{Mo}$ REACTION

U. Strohmusch and J. P. Schiffer

Bull. Am. Phys. Soc. 17, 913 (October 1972)

Southeastern Section of the American Physical Society, Birmingham, Alabama, 16-18 November 1972

56. ISOMERISM IN ^{111}Sn

B. Belt, R. E. Holland, and F. J. Lynch

Bull. Am. Phys. Soc. 18, 260 (February 1973)

American Physical Society, Los Angeles, California, 27-29 December 1972

57. POPULATION OF 0^+ EXCITED STATES IN ^{238}Pu AND ^{240}Pu BY SINGLE-NEUTRON TRANSFER

K. Katori and A. M. Friedman (Chemistry Division)

Bull. Am. Phys. Soc. 17, 1180 (1 December 1972)

58. ^{16}O -INDUCED REACTIONS ON ^{124}Sn

J. L. Yntema, C. L. Fink, and K. Katori

Bull. Am. Phys. Soc. 17, 1180 (1 December 1972)

American Physical Society, New York, 29 January-1 February 1973

59. ^{16}O -INDUCED REACTIONS ON ^{88}Sr BELOW AND ABOVE THE COULOMB BARRIER

N. Anantaraman, K. Katori, and H. J. Körner

Bull. Am. Phys. Soc. 18, 136 (1973)

60. ELASTIC SCATTERING OF ^6Li BY TARGETS IN THE Ca REGION

C. L. Fink, L. R. Greenwood, U. Strohmusch, and B. Zeidman

Bull. Am. Phys. Soc. 18, 135 (1973)

61. THE $^{39}\text{K}(d, p)^{40}\text{K}$ AND $^{37}\text{Cl}(d, p)^{38}\text{Cl}$ REACTIONS AT 12 MeV

J. P. Schiffer and C. L. Fink

Bull. Am. Phys. Soc. 18, 116 (1973)

Abstracts of Papers Presented at the American Chemical Society Meeting, Newport Beach, California, 29 January-1 February 1973

62. DEVELOPMENT OF SUPERCONDUCTING RESONATORS FOR HEAVY ION ACCELERATOR

R. Benaroya (Chemistry Division), L. M. Bollinger, A. H. Jaffey (Chemistry Division), K. W. Johnson (Chemistry Division), T. K. Khoe (Accelerator Division), J. J. Livingood, J. M. Nixon (Chemistry Division), G. W. Parker (Chemistry Division), W. J. Ramler (Chemistry Division), J. Aron (Chemistry Division), K. E. Gray (Solid State Science Division), and W. A. Wesolowski (Chemistry Division)

p. 3

1973 Particle Accelerator Conference—Accelerator Engineering and Technology, San Francisco, California, 5-7 March 1973

63. DEVELOPMENT AND OPERATION OF A PROTOTYPE SUPERCONDUCTING LINAC FOR HEAVY-ION ACCELERATION

J. Aron (Chemistry Division), R. Benaroya (Chemistry Division), L. Bollinger, A. H. Jaffey (Chemistry Division), K. Johnson (Chemistry Division), T. Khoe (Accelerator Division), J. J. Livingood, J. M. Nixon (Chemistry Division), G. W. Parker (Chemistry Division), W. Ramler (Chemistry Division), and W. A. Wesolowski (Chemistry Division)

Bull. Am. Phys. Soc. 18, 186 (February 1973)

64. STABILITY AND REPRODUCIBILITY OF SUPERCONDUCTING HELIX RESONATORS FOR HEAVY ION ACCELERATION

R. Benaroya (Chemistry Division), L. Bollinger, A. H. Jaffey (Chemistry Division), K. Johnson (Chemistry Division), T. Khoe (Accelerator Division), W. Ramler (Chemistry Division), and W. A. Wesolowski (Chemistry Division)

Bull. Am. Phys. Soc. 18, 187 (February 1973)

Symposium on Heavy-Ion Transfer Reactions. Volume I - Invited Papers; Volume II - Contributed Papers, Argonne National Laboratory, Argonne, Illinois, 15-17 March 1973, Physics Division Informal Report PHY-1973B (March 1973)

65. A SYSTEMATIC STUDY OF THE $^{88}\text{Sr}(^{16}\text{O}, ^{15}\text{N})$ REACTION: EVIDENCE FOR RECOIL EFFECTS

N. Anantaraman, K. Katori, and H. J. Körner

Volume II - Contributed Papers, pp. 403-412

Symposium on Heavy-Ion Transfer Reactions, ANL (cont'd.)

66. OPTIMUM Q VALUES FOR ($^{16}\text{O}, \text{C}$) REACTIONS BELOW THE COULOMB BARRIER

N. Anantaraman, K. Katori, and J. P. Schiffer

Volume II - Contributed Papers, pp. 413-417

67. THE $^{90}\text{Zr}(^{16}\text{O}, ^{12}\text{C})^{94}\text{Mo}$ REACTION

P. Bonche,* Y. Cassagnou,* H. Faraggi,* A. Jaffrin,*

R. Legrain,* G. Morrison, and A. Papineau*

Volume II - Contributed Papers, pp. 441-450

68. THE INTERFERENCE OF COULOMB AND NUCLEAR EXCITATIONS FOR A PROJECTILE EXCITED VIA INELASTIC SCATTERING

K. Katori, C. L. Fink, G. C. Morrison, J. L. Yntema, and B. Zeidman

Volume II - Contributed Papers, pp. 557-572

69. FORM FACTORS FOR TRANSFER REACTIONS

Dieter Kurath

Volume I - Invited Papers, pp. 221-234

70. FINITE-RANGE COUPLED-CHANNEL BORN APPROXIMATION FOR HEAVY-ION TRANSFER REACTIONS

K. S. Low and T. Tamura

Volume II - Contributed Papers, pp. 655-661

American Physical Society, San Diego, California, 19-22 March 1973

71. DECHANNELING DUE TO RADIATION INDUCED DEFECT CLUSTERS IN Au

D. S. Gemmell, R. C. Mikkelsen, K. L. Merkle

(Materials Science Division), P. P. Pronko (Materials

Science Division), and J. R. Wrobel (Materials Science Division)

Bull. Am. Phys. Soc. 18, 479 (1973)

* CEN Saclay, France.

D. TOPICAL REPORTS

1. AN INTRODUCTION TO SPEAKEASY

S. Cohen and C. M. Vincent

Argonne National Laboratory Topical Report ANL-7995
(January 1973) (A slight revision of PHY-1968E)

2. SOME COMMENTS ON THE POWER-BALANCE PARAMETERS
Q AND ϵ AS MEASURES OF PERFORMANCE FOR FUSION POWER
REACTORS

P. J. Persiani (Applied Physics Division), W. C. Lipinski
(Reactor Analysis and Safety Division), and A. J. Hatch
Argonne National Laboratory Topical Report ANL-7932
(June 1972)

3. SURVEY OF THERMONUCLEAR-REACTOR PARAMETERS

P. J. Persiani (Applied Physics Division), W. C. Lipinski
(Reactor Analysis and Safety Division), and A. J. Hatch
Argonne National Laboratory Topical Report ANL-7807
(October 1972)

E. PHYSICS DIVISION INFORMAL REPORTS

1. THE DELPHI-SPEAKEASY SYSTEM

Stanley Cohen

Physics Division Informal Report PHY-1971E (October
1971)

2. SPEAKEASY-3; LINKULES AND INTERFACES

S. Cohen, R. N. Kimmel, F. J. D. Serduke, and K. Rich*
Physics Division Informal Report PHY-1972C (May 1972)

3. THE SPEAKEASY HELP DOCUMENTS

J. K. Fink

Physics Division Informal Report PHY-1972G (July 1972)

* National Accelerator Laboratory, Batavia, Illinois.

4. A POSITION-SENSITIVE PROPORTIONAL-COUNTER SYSTEM FOR USE IN THE ENGE SPLIT-POLE SPECTROGRAPH
L. R. Greenwood, J. C. Stoltzfus, K. Katori, C. P. Cameron,
and T. H. Braid
Physics Division Informal Report PHY-1972B (May 1972)
5. HEAVY-ION SCATTERING IN THE MASS-16 REGION
Ronald E. Malmin
Physics Division Informal Report PHY-1972F (June 1972)
Ph.D. Thesis, Indiana University, Bloomington, Indiana
6. SYMPOSIUM ON HEAVY-ION TRANSFER REACTIONS. VOLUME I - INVITED PAPERS; VOLUME II - CONTRIBUTED PAPERS, Argonne National Laboratory, Argonne, Illinois, 15-17 March 1973
J. P. Schiffer
Physics Division Informal Report PHY-1973B (March 1973)
7. ELASTIC AND INELASTIC SCATTERING OF HEAVY IONS
Rolf H. Siemssen
Physics Division Informal Report PHY-1972D (June 1972)

F. PATENT

1. METHOD FOR PRODUCING A BEAM OF POLARIZED ATOMS
Manfred S. Kaminsky
U.S. Patent No. 3,700,899 (24 October 1972)

VI. STAFF MEMBERS OF THE PHYSICS DIVISION

The Physics Division staff for the year ending 31 March 1973 is listed below. Although the members are classified by programs, it must be understood that many of them work in two or more of the areas. In such cases, the classification indicates only the current primary interest.

In the period from 1 April 1972 through 31 March 1973, there were 39 temporary staff members and visitors (including 14 postdoctoral fellows), 23 graduate students, and 23 undergraduates. In these lists, the Temporary Scientific Staff are those with appointments for ≥ 9 months, while Visitors are on shorter appointments. Research Participants come to Argonne part-time for research while continuing their work at their own institutions.

SLOW-NEUTRON PHYSICS

Permanent Scientific Staff

S. Bradley Burson, Ph.D., University of Illinois, 1946

Victor E. Krohn, Ph.D., Case Western Reserve University, 1952

G. R. Ringo, Ph.D., University of Chicago, 1940

Robert K. Smither, Ph.D., Yale University, 1956

George E. Thomas, Jr., B.A., Illinois Wesleyan University, 1943

Temporary Scientific Staff

* Gerald D. Loper, Jr., Ph.D., Oklahoma State University, 1964
(From Wichita State University)

* Floyd J. Zehr, Ph.D., Syracuse University, 1967
(From Westminster College)

* No longer at Argonne as of 31 March 1973.

Visitors

Duane J. Buss, Ph.D., University of Notre Dame, 1966
(Research participant from Illinois Benedictine College)

* Bernard Hamermesh, Ph.D., New York University, 1944
(From Cleveland State University)

Technical Staff

Charles H. Batson

Graduate Students

* Arthur R. Adams (Argonne Thesis Student, Northern Illinois University)
Robert J. Goebbert (Argonne Thesis Student, Northern Illinois University)

THRESHOLD PHOTONEUTRON EXPERIMENTS

Permanent Scientific Staff

Harold E. Jackson, Jr., Ph.D., Cornell University, 1959

Temporary Scientific Staff

Larry R. Medsker, Ph.D., Indiana University, 1971
(Also Nuclear Information Research Associate on fellowship
from the National Science Foundation)

Graduate Student

[†] Richard E. Toohey (Argonne Thesis Student, University of Cincinnati)

FAST-NEUTRON REACTIONS

Permanent Scientific Staff

Alexander J. Elwyn, Ph.D., Washington University, 1956

* No longer at Argonne as of 31 March 1973.

[†] Transferred to Radiological and Environmental Research Division, ANL on
2 April 1973.

Alexander Langsdorf, Jr., Ph.D., Massachusetts Institute of Technology, 1937

F. P. Mooring, Ph.D., University of Wisconsin, 1951

Graduate Student

* John F. Lemming (Argonne Thesis Student, Ohio University)

CHARGED-PARTICLE REACTIONS

Permanent Scientific Staff

Thomas H. Braid, Ph.D., Edinburgh University, 1950

† John R. Erskine, Ph.D., University of Notre Dame, 1960

Donald S. Gemmell, Ph.D., Australian National University, 1960

Robert E. Holland, Ph.D., University of Iowa, 1950

Frank J. Lynch, B.S., University of Chicago, 1944

Luise Meyer-Schützmeister, Ph.D., Technical University of Berlin, 1943

‡ George C. Morrison, Ph.D., University of Glasgow, 1957

§ John P. Schiffer, Ph.D., Yale University, 1954

|| Ralph E. Segel, Ph.D., Johns Hopkins University, 1955

* Rolf H. Siemssen, Ph.D., University of Hamburg, 1963

*‡ Dieter von Ehrenstein, Ph.D., University of Heidelberg, 1960

** Thomas P. Wangler, Ph.D., University of Wisconsin, 1964

* No longer at Argonne as of 31 March 1973.

† Temporarily at University of Minnesota, Minneapolis, Minnesota (September 1971—August 1972).

‡ Temporarily at CEN Saclay, France (August 1971—August 1972).

§ Associate Director of Physics Division. Joint appointment with the University of Chicago.

|| Joint appointment with Northwestern University.

*‡ Joint appointment with Northern Illinois University.

** Assigned to work at the Los Alamos Meson Physics Facility as part of the Medium Energy activity, as described in Secs. II. 2a, b.

J. L. Yntema, Ph.D., Free University of Amsterdam, 1952

[†] Benjamin Zeidman, Ph.D., Washington University, 1957

Temporary Scientific Staff

Paul T. Debevec, Ph.D., Princeton University, 1972
(Presidential Internship Program)

Charles L. Fink, Ph.D., University of Pittsburgh, 1971

* Lawrence R. Greenwood, Ph.D., Rice University, 1970

Walter Henning, Ph.D., Technische Hochschule München, 1968
(From Technische Universität München, Germany)

[‡] Kenji Katori, Ph.D., The University of Tokyo, 1967
(From Tokyo University of Education, Tokyo, Japan)

* Hans-Joachim Körner, Ph.D., University of Hamburg, 1963
(From Technische Universität München, Germany)

* Raymond C. Mikkelsen, Ph.D., University of Illinois, 1965
(From Macalester College)

Jean-Claude Poizat, Ph.D., Université Claude Bernard de Lyon, 1972
(From Université Claude Bernard de Lyon, France)

*§ Udo Strohmusch, Ph.D., University of Frankfurt, 1966
(From University of Freiburg, Freiburg, Germany)

William R. Wharton, Ph.D., University of Washington, 1972
(Presidential Internship Program)

Visitors

* Huoo-Long Fann, Ph.D., University of Maryland, 1964
(From Merrimack College)

Margaret Stautberg Greenwood, Ph.D., University of Colorado, 1966
(Research participant from DePaul University)

Gerald Hardie, Ph.D., University of Wisconsin, 1962
(Research participant from Western Michigan University)

Esther L. Segel, Ph.D., University of Rochester, 1960
(Research participant from Illinois Institute of Technology)

* No longer at Argonne as of 31 March 1973.

[†] Temporarily at the State University of New York at Stony Brook
(1 March—4 May 1972).

[‡] Transferred to the Chemistry Division, ANL on 1 October 1972.

§ On a fellowship from the German Science Foundation.

* Kamal K. Seth, Ph.D., University of Pittsburgh, 1957
(From Northwestern University)

G. T. Wood, Ph.D., Washington University, 1956
(Research participant from Cleveland State University)

Technical Staff

John J. Bicek

William F. Evans

Joseph E. Kulaga

Elizabeth A. Sutter

James N. Worthington

Graduate Students

Dennis C. Albright (Argonne Thesis Student, University of Chicago)

Narayanaswami Anantaraman (Argonne Thesis Student, University of Chicago)

William C. Corwin (Argonne Thesis Student, Illinois Institute of Technology)

* Gary S. Kyle (Argonne Thesis Student, University of Minnesota)

Charles R. McClenahan (Argonne Thesis Student, Northwestern University)

* Maria E. Pluta (Argonne Thesis Student, DePaul University)

Robert P. Redwine (Argonne Thesis Student, Northwestern University)

Terrence P. Sjoreen (Argonne Thesis Student, Northern Illinois University)

Jeffrey F. Tonn (Argonne Thesis Student, Northwestern University)

* Marios C. Tsangarides (Graduate Student Visitor, Northern Illinois University)

* Abdelhadi S. Yousef (Argonne Thesis Student, Illinois Institute of Technology)

DEVELOPMENT OF EQUIPMENT AND ACCELERATORS

Permanent Scientific Staff

† Lowell M. Bollinger, Ph.D., Cornell University, 1951

‡ David C. Hess, Ph.D., University of Chicago, 1949

* No longer at Argonne as of 31 March 1973.

† Director of the Physics Division; on leave to the Superconducting Linac Project since June 1972.

‡ Joint appointment as Associate Editor of the Journal of Applied Physics and Applied Physics Letters.

[†] John J. Livingood, Ph.D., Princeton University, 1929
Jack R. Wallace, B.A., College of Wooster, 1942

ATOMIC-BEAM STUDIES

Permanent Scientific Staff

[‡] William J. Childs, Ph.D., University of Michigan, 1956
John A. Dalman
Leonard S. Goodman, Ph.D., University of Chicago, 1952
Henry E. Stanton, Ph.D., University of Chicago, 1944

Visitor

Ben Greenebaum, Ph.D., Harvard University, 1965
(Research participant from University of Wisconsin—Parkside)

MÖSSBAUER-EFFECT STUDIES

Permanent Scientific Staff

[§] Gilbert J. Perlow, Ph.D., University of Chicago, 1940
^{*||} Richard S. Preston, Ph.D., Yale University, 1954
Stanley L. Ruby, B.A., Columbia University, 1947

Temporary Scientific Staff

Walter Potzel, Ph.D., Technische Universität München, 1971

^{*} No longer at Argonne as of 31 March 1973.

[†] Emeritus.

[‡] Temporarily at the Institut für Angewandte Physik der Universität Bonn, Bonn, Germany (August 1972—August 1973).

[§] Joint appointment as Editor of the Journal of Applied Physics and Applied Physics Letters.

^{||} Joint appointment with Northern Illinois University.

- * Charles E. Skov, Ph.D., University of Nebraska, 1963
(From Monmouth College)

Visitor

- * Sedong Kim, Ph.D., University of California, Berkeley, 1965
(From Seton Hall University)

Technical Staff

- William C. Harper
* Peter A. Reed
Bruce J. Zabransky

THEORETICAL PHYSICS

Permanent Scientific Staff

- † Arnold R. Bodmer, Ph.D., Manchester University, 1953
Fritz Coester, Ph.D., University of Zurich, 1944
Stanley Cohen, Ph.D., Cornell University, 1955
‡ Benjamin Day, Ph.D., Cornell University, 1963
Hans Ekstein, Ph.D., University of Berlin, 1934
Dieter Kurath, Ph.D., University of Chicago, 1951
§ Robert D. Lawson, Ph.D., Stanford University, 1953
|| Malcolm H. Macfarlane, Ph.D., University of Rochester, 1959
¶ James E. Monahan, Ph.D., St. Louis University, 1953

* No longer at Argonne as of 31 March 1973.

† Joint appointment with the University of Illinois, Chicago Circle Campus.

‡ Temporarily on a Guggenheim Fellowship at the Niels Bohr Institute, Copenhagen, Denmark (August 1971—August 1972).

§ Temporarily on leave at the State University of New York, Stony Brook (October 1972—May 1973).

|| Joint appointment with the University of Chicago.

¶ Temporarily at Ohio University, Athens, Ohio (October 1971—June 1972).

[†] Murray Peshkin, Ph. D. ; Cornell University, 1951

*[‡] Norbert Rosenzweig, Ph.D., Cornell University, 1951

Temporary Scientific Staff

* Yshai Avishai, Ph.D., Weizmann Institute of Science, 1970

Joanne K. Fink, Ph.D., University of Pittsburgh, 1972
(Presidential Internship Program)

David H. Gloeckner, Ph.D., University of Chicago, 1972

*[§] Harry J. Lipkin, Ph.D., Princeton University, 1950
(From Weizmann Institute of Science, Rehovot, Israel)

|| Arnold Mueller-Arnke, Ph.D., Technische Hochschule Darmstadt, 1967
(From Technische Hochschule Darmstadt, Germany)

Steven C. Pieper, Ph.D., University of Illinois, 1970

Franklin J. D. Serduke, Ph.D., University of California, Davis, 1970

Taro Tamura, Ph.D., Tokyo University, 1955
(AUA-ANL Distinguished Appointee from University of Texas)

* || Friedrich G. Weller, Ph.D., University of Heidelberg, 1970
(From Kernforschungszentrum Karlsruhe, Germany)

Visitors

* Stephan J. Krieger, Ph.D., University of California, Berkeley, 1963
(From University of Illinois at Chicago Circle Campus)

* Leonard Schlessinger, Ph.D., University of California, Berkeley, 1967
(From University of Iowa)

Graduate Students

David Braunschweig (Graduate Student Visitor, University of Texas)

Bei-dwo Chang (Argonne Thesis Student, University of Chicago)

* Frederica Darema (Argonne Thesis Student, Illinois Institute of Technology)

Richard N. Kimmel (Argonne Thesis Student, University of Chicago)

Kum Sang Low (Graduate Student Visitor, University of Texas)

* No longer at Argonne as of 31 March 1973.

[†] Acting Director of the Physics Division.

[‡] Temporarily at the State University of New York at Albany (September 1971—June 1972).

[§] Joint appointment with the National Accelerator Laboratory.

|| On a fellowship from the German Science Foundation.

- * Nimai C. Mukhopadhyay (Argonne Thesis Student, University of Chicago)
George Theodorou (Argonne Thesis Student, University of Chicago)

INTERACTION OF ULTRAVIOLET PHOTONS WITH GASES

Permanent Scientific Staff

- † Joseph Berkowitz, Ph.D., Harvard University, 1955
William A. Chupka, Ph.D., University of Chicago, 1951

Temporary Scientific Staff

- Patricia M. Dehmer, Ph.D., University of Chicago, 1972
(Presidential Internship Program)

Visitor

- * Frederic M. Glaser, Ph.D., Ohio State University, 1963
(From Pan American University)

Technical Staff

Warren T. Jivery

Graduate Student

- * Edward J. Darland (Argonne Thesis Student, Michigan State University)

INTERACTION OF PARTICLE BEAMS WITH SOLIDS

Permanent Scientific Staff

- Santosh K. Das, Ph.D., University of California, Berkeley, 1971
Manfred S. Kaminsky, Ph.D., University of Marburg, Germany, 1957
* Jerris H. Peavey, Ph.D., University of Wisconsin, 1972

- * No longer at Argonne as of 31 March 1973.

- † Joint appointment with Northwestern University.

Technical Staff

* Neil C. Barringer

Peter J. Dusza

PLASMA PHYSICS

Permanent Scientific Staff

Albert J. Hatch, M.S., University of Illinois, 1947

Temporary Scientific Staff

* Steven G. Sanders, Ph. D., University of South Carolina, 1965
(From Southern Illinois University)

ADMINISTRATIVE

Permanent Scientific Staff

† Charles Egger, B.S., Virginia Polytechnic Institute, 1944

† Francis E. Throw, Ph. D., University of Michigan, 1940

* No longer at Argonne as of 31 March 1973.

† Assistant Director of the Physics Division.