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PHYSICS DIVISION

ANNUAL PROGRESS REPORT

FOR PERIOD ENDING DECEMBER 31, 1965

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PHYSICS DIVISION

ANNUAL PROGRESS REPORT

For Period Ending December 31, 1965

J. L. Fowler, Director
H. B. Willard, Associate Director

MAY 1966

OAK RIDGE NATIONAL LABORATORY
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FOREWORD

This is the eighth Physics Division progress report made on an annual basis. As in previous years the report contains the abstracts for papers which have been published since the last annual report, or which have been prepared for publication. In all such cases, reprints or preprints of the articles are available. Preliminary results of work in progress are reported, as previously, in more detail. Since this work is of a preliminary nature, the authors should be contacted with regard to the inclusion of any of these results in other publications.

At the end of the research contributions there is a brief description of the 3.0-Mv, 5.5-Mv, and Tandem Van de Graaff facilities, including a cross reference to reports and papers resulting from research done on each.

"Indexing words" or "key words" for experimental papers on nuclear structure have been supplied by the authors in the fashion now accepted by the journal *Nuclear Physics*.

TABLE OF CONTENTS AND SUMMARY

SEARCH FOR THE NEUTRAL A MESONS

H. O. Cohn, W. M. Bugg, G. T. Condo, and R. D. McCulloch 1

A search was made for the neutral A_1 and A_2 mesons in the three-pion system. Strong evidence was found for a resonance at the mass value of the A_2 meson; however, it was shown that this particle is not the neutral A_2 meson. An enhancement at the mass value for the A_1 was demonstrated through curve fitting, and the properties of this resonance were analyzed.

SEARCH FOR A NEUTRAL SCALAR MESON

H. O. Cohn, W. M. Bugg, G. T. Condo, R. D. McCulloch, G. Lutjens, and N. Gelfand 5

Abstract of published paper: *Phys. Rev. Letters* **15**, 906 (1965).

EXCHANGE MECHANISM FOR ω PRODUCTION IN π^+-n INTERACTIONS

H. O. Cohn, W. M. Bugg, and G. T. Condo 5

Abstract of published paper: *Phys. Letters* **15**, 344 (1965).

HIGH-RESOLUTION ELECTRON MICROSCOPY

T. A. Welton 5

A method is described for obtaining combined chromatic and spherical correction in an electron microscope, thereby permitting a resolution of 1 A. The essential features of a practical system embodying these ideas are described.

CONFORMATIONAL THEORY FOR PROTEINS AND POLYNUCLEOTIDES

T. A. Welton and J. F. Pizzo 8

A computer program is being written for attempted computation of the three-dimensional structure of proteins and other complex molecules.

INTEGRATION OF THE THREE-BODY WAVE EQUATIONS

J. H. Marable and T. A. Welton 10

A method for calculating three-body wave functions has been developed. The method is especially useful in regions where the three particles interact strongly and may be applied to the solution of scattering as well as bound-state problems.

A THREE-NUCLEON INTERACTION

D. R. Harrington 10

Abstract of paper to be published in the *Physical Review*.

A STUDY OF THE HARTREE-FOCK APPROXIMATION AS APPLIED TO FINITE NUCLEI

K. T. R. Davies, S. J. Krieger, and M. Baranger 11

Abstract of paper to be submitted to *Nuclear Physics*.

OSCILLATOR BRACKETS FOR HARTREE-FOCK CALCULATIONS

M. Baranger and K. T. R. Davies 11

Abstract of paper to be published in *Nuclear Physics*.

NUCLEAR GROUND-STATE PROPERTIES OF ^{16}O BY AN EXTENSION OF THE EDEN-EMERY METHOD

A. D. MacKellar and R. L. Becker 11

Abstract of published paper: *Phys. Letters* **18**, 308 (1965).

NUCLEAR GROUND-STATE PROPERTIES OF ^{16}O BY AN EXTENSION OF THE EDEN-EMERY METHOD
A. D. MacKellar 12

Abstract of Ph.D. Thesis, Texas A and M University; ORNL-TM-1374.

SHELL-MODEL STUDIES OF NUCLEI IN THE REGION A = 90
R. M. Tarbutton, J. B. McGrory, and W. T. Pinkston 13

A shell-model calculation of the nuclei ^{87}Rb, ^{88}Sr, ^{89}Y, and ^{90}Zr is described, in which the residual interaction is represented by a phenomenological Gaussian-shaped potential.

POLARIZATION-ASYMMETRY EQUALITY AND THE MEASUREMENT OF SPIN-FLIP IN INELASTIC SCATTERING FROM NUCLEI
G. R. Satchler 13

Abstract of paper submitted for publication in *Physics Letters*.

INELASTIC SCATTERING AND THE NUCLEAR SHELL MODEL
G. R. Satchler 13

Abstract of paper submitted for publication in *Nuclear Physics*.

SHELL-MODEL FORM FACTORS FOR THE $^{90}Zr(p,p')$ REACTION
M. B. Johnson, L. W. Owen, and G. R. Satchler 14

Abstract of paper submitted for publication in *Physical Review*.

ANALYSIS OF THE SCATTERING OF 40-Mev PROTONS
M. P. Fricke and G. R. Satchler 14

Abstract of published paper: *Phys. Rev.* **139**, B567 (1965).

ADIABATIC MODEL FOR A DEUTERON OPTICAL POTENTIAL
M. B. Johnson 14

Optical potentials for a deuteron were calculated assuming the sum of a neutron and proton optical potential averaged over the internal motion of the deuteron.

LOCAL ENERGY APPROXIMATION FOR FINITE RANGE IN STRIPPING REACTIONS
J. K. Dickens, R. M. Drisko, F. G. Perey, and G. R. Satchler 15

Abstract of published paper: *Phys. Letters* **15**, 337 (1965).

OPTICAL-MODEL ANALYSIS OF THE SCATTERING OF 24.7-Mev ALPHA PARTICLES
Lynne McFadden and G. R. Satchler 15

Abstract of paper submitted for publication in *Nuclear Physics*.

DEPENDENCE OF ANGULAR DISTRIBUTION IN THE (α,p) REACTION ON THE TOTAL ANGULAR-MOMENTUM TRANSFER
L. L. Lee, Jr., A. Marinov, C. Mayer-Boricke, J. P. Schiffer, R. H. Bassel, R. M. Drisko, and G. R. Satchler 16

Abstract of published paper: *Phys. Rev. Letters* **14**, B533 (1965).

ANALYSES OF THE SCATTERING OF NUCLEAR PARTICLES BY COLLECTIVE NUCLEI IN TERMS OF THE COUPLED-CHANNEL CALCULATION
T. Tamura 16

Abstract of published paper: *Rev. Mod. Phys.* **37**, 679 (1965).

EXCITATION OF THE UNNATURAL-PARITY 3^+ STATE IN ^{24}Mg IN THE INELASTIC SCATTERING OF ALPHA PARTICLES
T. Tamura 17

Abstract of published paper: *Nucl. Phys.* **73,** 241 (1965).

COUPLED-CHANNEL CALCULATION OF THE PHASE VARIATION IN THE SCATTERING OF ALPHA PARTICLES BY NICKEL ISOTOPES
T. Tamura 17

Abstract of published paper: *Nucl. Phys.* **73,** 81 (1965).

STATIC QUADRUPOLE MOMENT OF THE FIRST EXCITED 2^+ STATE OF ^{114}Cd
T. Tamura and T. Udagawa 18

Abstract of published paper: *Phys. Rev. Letters* **15,** 765 (1965).

FORTRAN PROGRAMS FOR THE CLEBSCH-GORDAN AND RACAH COEFFICIENTS AND THE 9-j SYMBOL
T. Tamura 18

Abstract of unpublished paper: ORNL-3877-revised (November 1965).

THE NUCLEON-NUCLEON INTERACTION FROM NUCLEON-NUCLEUS SCATTERING
R. M. Haybron 18

An attempt to find the best set of two-nucleon phase shifts for the impulse-approximation description of high-energy proton scattering is under way.

REFRACTION EFFECTS IN DWIA PROTON SCATTERING
R. M. Haybron 19

The effects of refraction in the inelastic scattering of high-energy protons is being investigated.

EXCITATION OF QUADRUPOLE AND OCTUPOLE LEVELS OF ^{12}C, ^{16}O, AND ^{40}Ca BY 156-Mev PROTONS
R. M. Haybron and H. McManus 19

Abstract of published paper: *Phys. Rev.* **140,** B638 (1965).

INELASTIC SCATTERING OF HIGH-ENERGY PROTONS IN THE COLLECTIVE THEORY OF EXCITATIONS
R. M. Haybron 20

Abstract of paper to be published in *Nuclear Physics.*

HIGH-ENERGY INELASTIC SCATTERING OF NUCLEONS; THE DISTORTED-WAVE IMPULSE APPROXIMATION
R. M. Haybron and H. McManus 20

Abstract of published paper: *Phys. Rev.* **136,** B1730 (1964).

NUCLEAR FORM FACTORS FROM INELASTIC ELECTRON SCATTERING
R. M. Haybron, M. B. Johnson, and R. J. Metzger 20

The data from inelastic electron scattering on nuclei is fitted with a search procedure which produces form factors to describe inelastic scattering of nuclear projectiles, especially protons, and also for comparison to the results of structure calculations.

THE ^{90}Zr(p,p′) REACTION AT 18.8 Mev AND THE NUCLEAR SHELL MODEL

W. S. Gray, R. A. Kenefick, J. J. Kraushaar, and G. R. Satchler 21

Abstract of paper submitted for publication in the *Physical Review*.

NUCLEAR REACTIONS. ^{90}Zr(p,p), (p,p′), E = 18.8 Mev. Measured $\sigma(E_p, \theta)$. ^{90}Zr deduced levels, l, β.

PROTON EXCITATION OF VIBRATIONAL STATES OF ^{126}Te

G. C. Pramila, R. Middleton, T. Tamura, and G. R. Satchler 21

Abstract of published paper: *Nucl. Phys.* **61**, 448 (1965).

THE ^{40}Ca(d,d), (d,d′), AND (d,p) REACTIONS WITH 12.8-Mev DEUTERONS

H. Niewodniczanski, J. Nurzynski, A. Strzalkowski, and G. R. Satchler 22

Abstract of paper submitted for publication in the *Physical Review*.

NUCLEAR REACTIONS. ^{40}Ca(d,d′), ^{40}Ca(d,p), E = 12.8 Mev; measured $\sigma(E_{d'}, \theta)$, $\sigma(E_p, \theta)$. ^{40}Ca deduced deformation parameters; ^{41}Ca deduced spectroscopic factors.

STUDY OF THE ^{40}Ca(d,p)^{41}Ca GROUND-STATE REACTION AT E_d = 14.3 Mev

S. A. Hjorth, J. X. Saladin, and G. R. Satchler 22

Abstract of published paper: *Phys. Rev.* **138**, B1425 (1965).

DEUTERON EXCITATION OF TWO-PHONON STATES IN ^{60}Ni

T. Tamura and R. K. Jolly 23

Abstract of published paper: *Phys. Letters* **18**, 295 (1965).

INELASTIC SCATTERING OF DEUTERONS FROM ^{60}Ni AND ^{114}Cd

J. K. Dickens, F. G. Perey, and G. R. Satchler 23

Abstract of paper submitted for publication in *Nuclear Physics*.

NUCLEAR REACTIONS. ^{60}Ni(d,d′), E = 9.89, 10.86, 11.92, and 13.56 Mev; ^{114}Cd(d,d′), E = 8, 9, 10, 11, 12, 13, 14, 15 Mev. Measured $\sigma(E_{d'}, \theta)$. Enriched targets.

THE ELASTIC SCATTERING OF 5.5- TO 10.0-Mev ^{3}He PARTICLES BY ^{27}Al NUCLEI

K. H. Bray, J. Nurzynski, and G. R. Satchler 23

Abstract of published paper: *Nucl. Phys.* **67**, 417 (1965).

NUCLEAR REACTIONS. ^{27}Al(^{3}He,^{3}He)^{27}Al, $E_{^3\mathrm{He}}$ = 5.5 to 10.0 Mev; measured $\sigma(\theta)$. Natural target.

GRAVITATIONAL ACCELERATION OF FREE NEUTRONS

J. W. T. Dabbs, J. A. Harvey, D. Paya, and H. Horstmann 24

Abstract of published paper: *Phys. Rev.* **139**, B756 (1965).

ELECTRIC DIPOLE MOMENT OF THE NEUTRON

P. D. Miller, J. K. Baird, W. Dress, and N. F. Ramsey 24

An experiment is in progress to detect and measure a possible electric dipole moment of the neutron. Historical background and design parameters of the apparatus are given, together with a calculated sensitivity. The current status of construction of the apparatus is outlined.

A LOW-PASS FILTER FOR COLD NEUTRONS TO BE USED IN A SEARCH FOR A NEUTRON ELECTRIC DIPOLE MOMENT

P. D. Miller 26

Abstract of ORNL-TM-1149.

STRONG p-WAVE NEUTRON RESONANCES IN ^{120}Sn, ^{118}Sn, AND ^{124}Sn

J. A. Harvey and Toyojiro Fuketa 26

Several resonances have been determined to be strong p-wave resonances from transmission measurements upon thick samples of enriched isotopes.

NUCLEAR REACTIONS. ^{120}Sn, ^{118}Sn, ^{124}Sn; measured σ_T. ^{121}Sn, ^{119}Sn, ^{125}Sn deduced levels, π, J. Enriched target.

LEVEL SPACING AND s-WAVE NEUTRON STRENGTH FUNCTION OF THE ODD-Z, ODD-N NUCLIDE ^{138}La

J. A. Harvey and G. G. Slaughter 28

The level spacing and the s-wave neutron strength function of ^{138}La have been determined from transmission measurements from 0.2 to 2000 ev.

NUCLEAR REACTIONS. ^{138}La; measured σ_{nT}. Deduced resonance parameters, E_0, $2g\Gamma_n^o$, Γ_γ; level density and $\overline{\Gamma_n^o}/D$. Enriched target.

PARAMETERS OF NEUTRON RESONANCES IN ^{180}W

Hans Jung, R. C. Block, and G. G. Slaughter 30

Parameters are determined for five resonances in ^{180}W from transmission measurements up to 400 ev.

NUCLEAR REACTIONS. ^{180}W; measured σ_{nT}. Deduced resonance parameters, E_0, Γ_n, Γ_n^o; level density and $\overline{\Gamma_n^o}/D$. Enriched and natural targets.

THE PARAMETERS OF THE NEUTRON RESONANCES IN ^{182}W, ^{183}W, ^{184}W, AND ^{186}W

R. C. Block, R. W. Hockenbury, and J. E. Russell 31

Average level spacings and s-wave neutron strength functions of the tungsten isotopes have been obtained from transmission and capture cross-section measurements.

NUCLEAR REACTIONS. ^{182}W, ^{183}W, ^{184}W, ^{186}W; measured $\sigma_{nT}(E)$, $\sigma_{n\gamma}(E)$. Deduced resonance parameters, E_0, Γ_n, Γ_γ, J; level densities and $\overline{\Gamma_n^o}/D$ for isotopes. Enriched targets.

LEVEL STRUCTURE OF ^{183}W, ^{185}W, AND ^{187}W FROM THERMAL-NEUTRON CAPTURE GAMMA RAYS

M. J. Martin, J. A. Harvey, and G. G. Slaughter 36

The gamma-ray spectra following thermal-neutron capture in tungsten targets enriched in ^{182}W, ^{183}W, ^{184}W, and ^{186}W have been measured with a lithium-drifted germanium detector.

NUCLEAR REACTIONS. ^{182,183,184,186}W(n,γ), E = thermal; measured $\sigma(E_\gamma)$, I_γ. Enriched targets.

HIGH-RESOLUTION MEASUREMENTS OF GAMMA RAYS FROM THERMAL- AND RESONANCE-NEUTRON CAPTURE IN THE ISOTOPES OF TIN

J. A. Harvey, G. G. Slaughter, and M. J. Martin 37

Lithium-drifted germanium crystals were used to measure gamma-ray spectra from capture of thermal and resonance neutrons in the isotopes of tin.

NUCLEAR REACTIONS. ^{116,117,118,119,120,122,124}Sn(n,γ), E = thermal and resonance neutrons; measured $\sigma(E_\gamma)$, I_γ. Deduced levels ^{117,118,119,120,121,123,125}Sn. Enriched targets.

TOTAL CROSS SECTIONS FOR KILOVOLT NEUTRONS OF EVEN-ODD NUCLEI IN THE REGION OF THE 3s STRENGTH-FUNCTION RESONANCES

W. M. Good, D. Paya, R. Wagner, and T. Tamura 42

Abstract of paper to be published.

NUCLEAR REACTIONS. ^{43}Ca, ^{47}Ti, ^{49}Ti, ^{53}Cr, ^{57}Fe, ^{63}Cu, ^{65}Cu, measured $\sigma_T(E)$, $E \leq 60$ kev. ^{44}Ca, ^{48}Ti, ^{50}Ti, ^{54}Cr, ^{58}Fe, ^{64}Cu, ^{66}Cu, deduced levels, Γ, level density, resonances, resonance parameters, Γ_n^o/D. Enriched targets.

s-WAVE NEUTRON STRENGTH FUNCTIONS OF ISOTOPES IN THE 3s RESONANCE REGION 40 < A < 70.

R. Wagner, W. M. Good, and D. Paya 42

Abstract of paper presented at International Conference on the Study of Nuclear Structure with Neutrons, Antwerp, Belgium, July 19–23, 1965.

NUCLEAR REACTIONS. ^{43}Ca, ^{47}Ti, ^{49}Ti, ^{53}Cr, ^{57}Fe, ^{63}Cu, ^{65}Cu, measured $\sigma_T(E)$, $E \leq 60$ kev. ^{44}Ca, ^{48}Ti, ^{50}Ti, ^{54}Cr, ^{58}Fe, ^{64}Cu, ^{66}Cu, deduced levels, Γ, level density, resonances, resonance parameters, Γ_n^o/D. Enriched targets.

NEUTRON RESONANCE STRUCTURE AND s-WAVE STRENGTH FUNCTION OF THE EVEN ISOTOPES OF ZIRCONIUM

J. A. Biggerstaff, W. M. Good, and H. Kim 43

Abstract of paper presented at International Conference on the Study of Nuclear Structure with Neutrons, Antwerp, Belgium, July 19–23, 1965.

NUCLEAR REACTIONS. ^{90}Zr, ^{92}Zr, ^{94}Zr, ^{96}Zr, ^{95}Zr, ^{97}Zr, measured $\sigma_T(E)$, $E \leq 60$ kev. ^{91}Zr, ^{93}Zr, deduced levels, level density, resonances, resonance parameters, Γ_n^o/D. Enriched targets.

TOTAL CROSS SECTIONS OF EVEN ISOTOPES OF ZIRCONIUM

W. M. Good and H. Kim 44

Abstract of paper to be published.

NUCLEAR REACTIONS. ^{90}Zr, ^{92}Zr, ^{94}Zr, ^{96}Zr, measured $\sigma_T(E)$, $E = 60$ kev. ^{91}Zr, ^{93}Zr, ^{95}Zr, ^{97}Zr, deduced levels, level density, resonances, resonance parameters, Γ_n^o/D. Enriched targets.

A STUDY OF THE RESONANCES IN NEUTRON BOMBARDMENT OF ^{206}Pb AND ^{207}Pb

J. R. Bird, J. A. Biggerstaff, J. H. Gibbons, W. M. Good, and R. L. Macklin 44

Abstract of paper presented at International Conference on the Study of Nuclear Structure with Neutrons, Antwerp, Belgium, July 19–23, 1965.

NUCLEAR REACTIONS. ^{206}Pb(n,γ), ^{207}Pb(n,γ), $E_n = 12$ to 80 kev; measured $\sigma(E;n,n)$, $\sigma(E,n\gamma)$, γ-ray spectra. ^{207}Pb, ^{208}Pb E_r, Γ_n, Γ_γ, Γ_{γ_i}. Enriched targets.

STUDY OF THE GAMMA-RAY SPECTRA EMITTED IN THE RESONANCE CAPTURE OF NEUTRONS BY ^{19}F

J. R. Bird, J. A. Biggerstaff, J. H. Gibbons, and W. M. Good 45

Abstract of published paper: *Phys. Rev.* **138**, B20 (1965).

NUCLEAR REACTIONS. ^{19}F(n,γ), $E_n = 27$ and 49 kev; measured E_γ, I_γ. Deduced radiation widths.

NEUTRON RESONANCE CAPTURE IN 2s1d SHELL NUCLEI

I. Bergqvist, J. A. Biggerstaff, J. H. Gibbons, and W. M. Good 45

Abstract of paper presented at International Conference on the Study of Nuclear Structure with Neutrons, Antwerp, Belgium, July 19–23, 1965.

NUCLEAR REACTIONS. $^{19}F(n,\gamma)$, ^{27}Al(n,γ), ^{24}Mg(n,γ), ^{32}S(n,γ), $E_n = 12$ to 80 kev; measured $\sigma(E;n,\gamma)$, γ-ray spectrum; ^{20}F, ^{28}Al, ^{25}Mg, ^{33}S deduced $M1/E1$.

NEUTRON RESONANCE CAPTURE IN 2s1d SHELL NUCLEI

I. Bergqvist, J. A. Biggerstaff, J. H. Gibbons, and W. M. Good 46

Abstract of published paper: *Phys. Letters* **18**, 323 (1965).

NUCLEAR REACTIONS. (n,γ) on targets mass 19–40, $E_n = 20$ to 120 kev; measured E_γ, I_γ. Deduced radiation widths.

FAST-NEUTRON CAPTURE GAMMA-RAY SPECTRUM FROM ^{238}U$(n,\gamma)^{239}$U

I. Bergqvist 46

Abstract of paper presented at International Conference on the Study of Nuclear Structure with Neutrons, Antwerp, Belgium, July 19–23, 1965.

NUCLEAR REACTIONS. ^{238}U(n,γ); $E_n = 30$ kev; measured γ-ray spectrum; ^{239}U deduced $M1/E1$. Enriched target.

NEUTRON CAPTURE CROSS SECTIONS FROM 5 TO 100 kev

R. L. Macklin and J. H. Gibbons 46

Abstract of paper to be published in the Proceedings of International Conference on the Study of Nuclear Structure with Neutrons, Antwerp, Belgium, July 19–23, 1965.

ABSOLUTE VALUE AND ENERGY DEPENDENCE OF THE ^{3}He(n,p)T REACTION

R. L. Macklin and J. H. Gibbons 47

Abstract of paper to be published in the Proceedings of International Conference on the Study of Nuclear Structure with Neutrons, Antwerp, Belgium, July 19–23, 1965.

NUCLEAR REACTIONS. $T(p,n)^3He$, E_{th} –1.4 Mev, deduced $^3He(n,p)T$ by reciprocity, $5 < E_n$ (kev) < 300.

ENERGY DEPENDENCE OF THE $^{10}B(n,\alpha)/^{10}B(n,\alpha\gamma)$ CROSS-SECTION RATIO

R. L. Macklin and J. H. Gibbons 47

Abstract of published paper: *Phys. Rev.* **140**, B324 (1965).

NUCLEAR REACTIONS. $^{10}B(n,\alpha)/^{10}B(n,\alpha\gamma)$, thermal, 30, 110, 160 kev.

METHOD FOR OBTAINING BURSTS OF POLARIZED NEUTRONS OF ENERGY 10 TO 700 kev

J. W. T. Dabbs and J. A. Harvey 47

A Monte Carlo polarization calculation shows essentially no depolarization.

n-d SCATTERING – VECTOR POLARIZATION OF RECOIL DEUTERONS FROM A POLARIZED NEUTRON BEAM

H. B. Willard, S. T. Thornton, and C. M. Jones 49

Abstract of paper to be published in Proceedings of International Conference on Polarization Phenomena of Nucleons, Karlsruhe, Germany, September 6–10, 1965.

INTERACTION OF 350-kev POLARIZED NEUTRONS WITH ORIENTED ^{165}Ho NUCLEI

R. Wagner, P. D. Miller, T. Tamura, and H. Marshak 49

Abstract of published paper: *Phys. Rev.* **139**, 29B (1965).

TOTAL CROSS SECTION FOR 14-Mev NEUTRONS USING ALIGNED ^{165}Ho NUCLEI

H. Marshak, A. C. B. Richardson, and T. Tamura 50

Abstract of published paper: *Phys. Rev. Letters* **16**, 194 (1966).

NUCLEAR REACTIONS. ^{165}Ho (aligned), σ_T, 14 Mev.

DIFFERENTIAL NEUTRON SCATTERING FROM NITROGEN

C. H. Johnson, J. L. Fowler, and R. L. Kernell 50

Recent measurements of differential scattering of neutrons from nitrogen at the resonant energies 1.595, 1.779, and 2.250 Mev confirm earlier published results and assignments of resonant parameters. New measurements extend to 3.207 Mev and include two new resonances.

NUCLEAR REACTIONS. $^{14}N(n,n)$, E_n = 1.779–3.207 Mev, measured $\sigma(\theta)$; ^{15}N, deduced resonance parameters.

DIFFERENTIAL SCATTERING OF NEUTRONS FROM ^{208}Pb AT RESONANT ENERGIES

J. L. Fowler 54

Abstract of a paper submitted to the *Physical Review*.

NUCLEAR REACTIONS. $^{208}Pb(n,n)^{208}Pb$, E_n = 0.715–1.761 Mev, measured $\sigma(\theta)$, deduced resonance parameters ^{209}Pb.

NEUTRON INELASTIC SCATTERING PROGRAM

J. A. Biggerstaff, Y. Cassagnou, W. E. Kinney, M. V. Harlow, Jr., J. M. McConnell, F. G. Perey, and P. H. Stelson 54

Development of experimental equipment and procedures for measuring fast-neutron inelastic scattering cross sections by the flight-timing method is essentially complete and is reviewed. A summary of recent results is given in an accompanying paper, and a few examples are presented.

LACK OF STRUCTURE IN ^{235}U FISSION CROSS SECTION IN THE NEUTRON ENERGY RANGE FROM 150 TO 335 kev

R. L. Macklin and J. H. Gibbons 57

Abstract of published paper: *Phys. Rev. Letters* **16**, 248 (1966).

FISSION FRAGMENT ENERGY CORRELATION MEASUREMENTS FOR ^{239}Pu AND ^{241}Pu THERMAL-NEUTRON-INDUCED FISSION

J. H. Neiler, F. J. Walter, and H. W. Schmitt 58

Experimental results, based on the recently published absolute energy calibrations of solid-state detectors for fission fragments, are given for ^{239}Pu and ^{241}Pu thermal-neutron fission.

PROMPT NEUTRON EMISSION IN ^{252}Cf SPONTANEOUS FISSION

H. W. Schmitt, Frances Pleasonton, and R. W. Lide 69

The method of simultaneous measurement of both fission fragment energies and one fragment velocity for determination of neutron-emission properties of fission fragments has been developed. Results for ^{252}Cf spontaneous fission show good agreement with those of the direct neutron-counting experiments.

FRAGMENT ENERGY CORRELATION MEASUREMENTS FOR ^{252}Cf SPONTANEOUS FISSION AND ^{235}U THERMAL-NEUTRON FISSION

H. W. Schmitt, J. H. Neiler, and F. J. Walter 76

Abstract of published paper: *Phys. Rev.* **141**, 1146 (1966).

CORRELATED FRAGMENT ENERGY MEASUREMENTS AND MASS-vs-ANGLE CORRELATIONS IN ^{226}Ra + p FISSION

H. W. Schmitt, J. W. T. Dabbs, and P. D. Miller 77

Abstract of paper to be published in the *Physical Review*.

EVALUATION OF SEMICONDUCTOR DETECTORS FOR FISSION-FRAGMENT ENERGY MEASUREMENTS

H. W. Schmitt and Frances Pleasonton 77

Abstract of paper to be published in *Nuclear Instruments and Methods*.

RESPONSE OF SILICON FISSION DETECTORS TO CHANNELED ^{127}I AND ^{40}Ar IONS

C. D. Moak, J. W. T. Dabbs, and W. W. Walker 78

When very heavy ions were directed along the crystalline channels of silicon fission detectors, a threefold improvement in energy resolution was obtained for particles remaining in the channels. For such channeled particles the usual pulse-height defect was reduced by more than a factor of 10. The results seem to fit certain theoretical explanations of detector nonlinearities found in the literature, in which the nonlinearities are ascribed to the predominance of atomic collision processes near the end of the range.

AN INVESTIGATION OF THE ^{9}Be(^{3}He,p)^{11}B REACTION AT LOW ENERGIES

W. R. Coker, M. M. Duncan, J. L. Duggan, and P. D. Miller 83

Abstract of paper submitted for publication in *Nuclear Physics*.

NUCLEAR REACTIONS. ^{9}Be(^{3}He,p)^{11}B, E_p = 1–3 Mev, $\sigma(\theta)$ measured for p to ^{11}B states at 4.46, 5.03, 7.30, 8.57, and 8.93 Mev.

SCATTERING AND REACTIONS INDUCED BY THE PROTON BOMBARDMENT OF ^{14}N

J. K. Bair, C. M. Jones, S. T. Thornton, M. L. West, and H. B. Willard 83

Scattering and reactions induced by the proton bombardment of ^{14}N have been measured for $4 \leq E_p \leq 5.6$ Mev.
NUCLEAR REACTIONS. $^{14}N(p,p)^{14}N$, $^{14}N(p,p_1)^{14}N^*$, $E_p = 4-5.6$ Mev, $\sigma(\theta)$ measured.

TOTAL NEUTRON YIELD FROM THE REACTION $^{14}C(\alpha,n)^{17}O$

J. K. Bair, J. L. C. Ford, Jr., and C. M. Jones 84

Abstract of paper to be published in the *Physical Review*.
NUCLEAR REACTIONS. $^{14}C(\alpha,n)$, measured $\sigma(E)$ 2.5 Mev $\leq E \leq$ 5.1 Mev, deduced ^{18}O level E, Γ, alpha-particle strength function.

$^{51}V(p,n)^{51}Cr$ CROSS SECTION FROM THRESHOLD TO 2.25 Mev

J. H. Gibbons and R. L. Macklin 84

Abstract of paper to be published in *Nuclear Instruments and Methods* (letter to the editor).
NUCLEAR REACTIONS. $^{51}V(p,n)^{51}Cr$, E_{th}–2.25 Mev, $\sigma(4\pi)$ absolute.

AN INVESTIGATION OF (p,n) REACTION MECHANISM VIA ISOSPIN ANALOG RESONANCES

H. J. Kim and R. L. Robinson 84

Neutron angular distributions and excitation functions from the reactions $^{88}Sr(p,n)^{88}Y$ g.s., $^{89}Y(p,n)^{89}Zr$ g.s., and $^{89}Y(p,n)^{89}Zr^*$ ($\frac{1}{2}^-$, 590 kev) are measured around the $d_{5/2}$ analog resonances (incident energies ~5 Mev).

NUCLEAR REACTIONS. $^{88}Sr(p,n)^{88}Y$ g.s., $^{89}Y(p,n)^{89}Zr$ g.s., $^{89}Y(p,n)^{89}Zr^*$ ($\frac{1}{2}^-$, 590 kev), time-of-flight spectra.

CROSS SECTIONS FOR ANALOG RESONANCES IN ^{75}As, ^{111}Cd, AND $^{113}Cd(p,n)$ REACTIONS

R. L. Kernell and C. H. Johnson 85

Abstract of paper to be published in proceedings of APS Topical Conference on "Isobaric Spin in Nuclear Physics," Tallahassee, Fla., Mar. 17–19, 1966.
NUCLEAR REACTIONS. $^{75}As(p,n)$, $^{111}Cd(p,n)$, $^{113}Cd(p,n)$, E = 2.7 to 5.6 Mev; measured $\sigma(E)$; deduced widths of analog resonances. Enriched targets.

PROTON STRENGTH FUNCTIONS FOR $89 < A < 130$

C. H. Johnson and R. L. Kernell 86

Cross sections for (p,n) reactions were measured for 3.0- to 5.8-Mev protons on several natural elements for $89 \leq A \leq 130$, and these results were used to help reevaluate our earlier measurements on 25 isotopes in this mass region. The resulting proton strength function shows a minimum near $A = 90$ which is deeper than predicted by resonance effects for the usual optical potential.
NUCLEAR REACTIONS. $^{93}Nb(p,n)$, $^{103}Rh(p,n)$, $^{105}Pd(p,n)$, $^{109}Ag(p,n)$, $^{111}Cd(p,n)$, $^{115}In(p,n)$, $^{119}Sn(p,n)$, $^{125}Te(p,n)$, E = 3.0 to 5.8 Mev; measured $\sigma(E)$. Enriched targets.

SCATTERING OF PROTONS FROM Kr IN THE VICINITY OF LOW-LYING ISOSPIN ANALOG STATES

H. J. Kim, C. M. Jones, H. B. Willard, and J. K. Bair 89

Elastic and inelastic proton scattering cross sections for krypton are measured for the incident energy range 3 to 6 Mev. Two resonances are seen, and they are interpreted to be the analog states of low-lying states of ^{85}Kr.
NUCLEAR REACTIONS. $Kr(p,p)Kr$, $E_p = 3-6$ Mev, $\sigma(\theta)$ for elastic and inelastic scattering.

ELASTIC AND INELASTIC PROTON SCATTERING FROM ^{106}Pd AND ^{108}Pd

R. L. Robinson, J. L. C. Ford, Jr., P. H. Stelson, and G. R. Satchler 90

Abstract of paper submitted for publication in the *Physical Review*.
NUCLEAR REACTIONS. $^{106,108}Pd(p,p')$, E_p = 12, 13 Mev; measured $\sigma(\theta)$. $^{106,108}Pd$ deduced levels, β_2, β_3. Enriched targets.

ELASTIC AND INELASTIC SCATTERING OF 13-Mev PROTONS FROM ^{107}Ag AND ^{112}Cd

J. L. C. Ford, Jr., P. H. Stelson, and R. L. Robinson 90

The elastic and inelastic scattering of 13-Mev protons from ^{107}Ag and ^{112}Cd has been measured. Values for the quadrupole and octupole deformations were obtained by fitting the experimental cross sections with the results of distorted-wave calculations. The ^{107}Ag data are compared with the predictions of the single-particle core-coupling model.

NUCLEAR REACTIONS. ^{107}Ag, ^{112}Cd(p,p'), enriched targets, E_p = 12.94, 13 Mev; measured $\sigma(\theta)$. ^{107}Ag, ^{112}Cd deduced levels, β_2, β_3.

COULOMB EXCITATION

R. L. Robinson 95

Abstract of paper to be published in the Proceedings of the Conference on Bases for Nuclear Spin-Parity Assignments.

COULOMB EXCITATION OF STATES IN THE CHROMIUM NUCLEI

F. K. McGowan, P. H. Stelson, R. L. Robinson, W. T. Milner, and J. L. C. Ford, Jr. 95

Results are presented from Coulomb excitation of states in the nuclei ^{50,52,53,54}Cr with ^{4}He and ^{16}O ions.

NUCLEAR REACTIONS. ^{50,52,53,54}Cr$(^{16}$O$,^{16}$O$'\gamma)$, ^{50,52,53,54}Cr$(\alpha,\alpha''\gamma)$, enriched targets, E = 30–39 Mev, E_α= 4–5.6 Mev; measured γ, $\gamma\gamma$ spectra, E_γ, $\gamma(\theta)$. ^{50,52,53,54}Cr, deduced levels, J, π, $B(E2)$, $B(M1)$.

COULOMB EXCITATION OF ^{106,108,110}Pd

R. L. Robinson, F. K. McGowan, P. H. Stelson, W. T. Milner, and J. L. C. Ford, Jr. 97

Coulomb excitation effected with oxygen ions and alpha particles is used to study the properties of collective states in ^{106,108,110}Pd.

NUCLEAR REACTIONS. ^{106,108,110}Pd$(^{16}$O$,^{16}$O$'\gamma)$, E = 42–49 Mev, ^{106,108,110}Pd $(\alpha,\alpha'\gamma)$, E = 9–10 Mev, measured I_γ, E_γ, $\gamma\gamma$-coincidence; deduced $B(E2)$'s, $B(E3)$'s. Enriched targets.

INFORMATION ON CONVERSION COEFFICIENTS FROM COULOMB EXCITATION AND LIFE-TIME MEASUREMENTS

P. H. Stelson 103

Abstract of paper to be published in *Internal Conversion Processes*.

NUCLEAR TRANSITION PROBABILITY, B(E2), FOR $0^+_{g.s.} \rightarrow 2^+_{first}$ TRANSITIONS AND DEFORMATION PARAMETERS, β_2

P. H. Stelson and L. Grodzins 103

Abstract of published paper: *Nucl. Data* 1, 21 (1965).

GAMMA-RAY ENERGIES DETERMINED WITH A LITHIUM-DRIFTED GERMANIUM DETECTOR

R. L. Robinson, P. H. Stelson, F. K. McGowan, J. L. C. Ford, Jr., and W. T. Milner 104

Abstract of published paper: *Nucl. Phys.* **74**, 281 (1964).

RADIOACTIVITY. ^{7}Be, ^{22}Na, ^{51}Cr, ^{54}Mn, ^{60}Co, ^{65}Zn, ^{88}Y, ^{137}Cs, ^{198}Au, ^{203}Hg, ^{207}Bi; measured E_γ. ^{102,106}Rh, measured E_γ, I_γ.

NUCLEAR REACTIONS. ^{48}Ti, ^{50}Cr, ^{56}Fe, ^{64,66,68,70}Zn, ^{70,72,74,76}Ge, ^{75}As, ^{76,78,80,82}Se, ^{79}Br, ^{94,96,98,100}Mo, ^{96,100,104}Ru, ^{104,106,108,110}Pd, ^{106,108,110,112,114,116}Cd, ^{116,117,118,120,122,124}Sn, ^{121,123}Sb, ^{122,124,126,128,130}Te, ^{195}Pt$(\alpha,\alpha'\gamma)$, E = 6–9 Mev; measured E_γ. ^{77}Se, ^{119}Sn$(\alpha,\alpha'\gamma)$, E = 6–9 Mev; measured E_γ, I_γ. ^{18}O$(\alpha,n\gamma)$ ^{21}Ne, E = 6–9 Mev; measured E_γ. ^{21}Ne deduced level. Enriched targets.

OBSERVATION OF RECOILLESS EMISSION OF GAMMA RAYS FOLLOWING COULOMB EXCITATION

D. Seyboth, F. E. Obenshain, and Gordon Czjzek 104

Abstract of published paper: *Phys. Rev. Letters* **14**, 954 (1965).

OBSERVATION OF THE MÖSSBAUER EFFECT FOLLOWING COULOMB EXCITATION OF ^{73}Ge

Gordon Czjzek, J. L. C. Ford, Jr., F. E. Obenshain, and Dietrich Seyboth 105

Abstract of paper presented at the Autumn Meeting of the American Physical Society, Chicago, October 28–30, 1965; also abstract of paper to be submitted for publication in *Physics Letters*.

MÖSSBAUER MEASUREMENTS OF THE ^{57}Fe HYPERFINE STRUCTURE COUPLING IN FeRh ALLOYS NEAR 50 at. % RHODIUM

J. O. Thomson, L. D. Roberts, D. W. Forester, F. E. Obenshain, and H. Wegener 105

A study of the Fe-Rh system for compositions near 50 at. % rhodium has been made through the use of the Mössbauer effect for iron. The iron hfs spectrum as a function of temperature is compared with a theoretical model for the alloy.

MAGNETIC MOMENT OF THE 77.3-kev FIRST EXCITED STATE OF ^{197}Au

D. Seyboth, L. D. Roberts, J. O. Thomson, F. E. Obenshain 110

From the Mössbauer absorption spectra for 0.50 and 1.00 at. % gold in iron, the value of the magnetic moment of the 77.3-kev first excited state of ^{197}Au was determined to be $\mu^* = 0.402 \pm 0.025$ nuclear magneton.

^{197}Au HYPERFINE STRUCTURE COUPLING AND ISOMER SHIFT FOR $Au_{0.01}Cu_{x-0.01}Ni_{1-x}$ ALLOYS

J. W. Burton, L. D. Roberts, and J. O. Thomson 111

Through the use of the Mössbauer effect for ^{197}Au, the hfs coupling was found to follow closely the magnetic behavior of Cu-Ni alloys. The isomer shift was found to increase with increasing atomic percent nickel, with a slightly positive curvature.

SOLID STATE AND NUCLEAR RESULTS FROM THE MEASUREMENT OF THE HYPERFINE STRUCTURE COUPLING OF ^{197}Au IN ORDERED Au-Mn ALLOYS

D. O. Patterson, L. D. Roberts, J. O. Thomson, P. Lyman, and R. G. Scurlock 112

The hyperfine coupling of ^{197}Au in ordered AuMn, Au_2Mn, and Au_3Mn has been measured using the Mössbauer effect. The results reflect the crystalline and magnetic structure for the different systems. Values are given for the isomer shift, magnetic field, and electric field gradient for ^{197}Au in the alloys.

SOLID STATE AND NUCLEAR RESULTS FROM A MEASUREMENT OF THE PRESSURE DEPENDENCE OF THE ENERGY OF THE RESONANCE GAMMA RAY OF ^{197}Au

L. D. Roberts, D. O. Patterson, J. O. Thomson, and R. P. Levey 116

It has been determined that the ^{197}Au nucleus is larger in its first excited than in its ground state. It has been confirmed that in all the gold alloys thus far studied the electronic charge density near the gold nucleus is greater than it is in metallic gold.

OPTICS OF THE TOTAL REFLECTION OF NUCLEAR RESONANT RADIATION BY ^{57}Fe

S. Bernstein, E. C. Campbell, and C. W. Nestor, Jr. 120

Abstract of published paper: *J. Phys. Chem. Solids* **26**, 883 (1965).

ANISOTROPIC ENERGY LOSSES IN A FACE-CENTERED CUBIC CRYSTAL FOR HIGH-ENERGY ^{79}Br AND ^{127}I IONS

S. Datz, T. S. Noggle, and C. D. Moak 121

Abstract of published paper: *Phys. Rev. Letters* **15**, 254 (1965).

METHOD FOR OBTAINING SECOND DERIVATIVES IN ELECTRON TUNNELING
J. W. T. Dabbs 121

An intermodulation technique is shown to be twice as sensitive as the second-harmonic method.

ALKALI-ATOM–HALOGEN-MOLECULE REACTIONS IN MOLECULAR BEAMS; THE SPECTATOR STRIPPING MODEL
R. E. Minturn, Sheldon Datz, and R. L. Becker 124

Abstract of paper to appear in the *Journal of Chemical Physics* (February 1966).

MEASUREMENT OF THE RELATIVE ABUNDANCES AND RECOIL ENERGY SPECTRA OF FRAGMENT IONS PRODUCED AS THE INITIAL CONSEQUENCES OF X-RAY INTERACTION WITH CH_3I, HI, AND DI
T. A. Carlson and R. M. White 125

Abstract of paper submitted for publication.

CHARGE DISTRIBUTIONS OF KRYPTON IONS FOLLOWING PHOTOIONIZATION IN THE M SHELL
M. O. Krause and T. A. Carlson 125

Abstract of paper to be published.

RELATIVE INTENSITIES OF PROMINENT LMM AUGER TRANSITIONS IN KRYPTON
M. O. Krause 126

Abstract of published paper: *Phys. Letters* **19**, 14 (1965).

RELATIVE ABUNDANCES OF IONS FORMED AS THE RESULT OF INNER-SHELL VACANCIES IN ATOMS
T. A. Carlson, W. E. Hunt, and M. O. Krause 126

Abstract of paper to be submitted for publication.

THE LEAST-SQUARES ADJUSTMENT OF ATOMIC ENERGY LEVELS
K. L. Vander Sluis 126

Abstract of paper to be published in the *Journal of the Optical Society of America* (1966).

THE SPECTRA OF ^{208}Po AND THE HYPERFINE STRUCTURE OF ^{209}Po
G. W. Charles 127

Abstract of paper to be submitted for publication.

CHARGED-PARTICLE CROSS-SECTION DATA CENTER
F. K. McGowan, H. J. Kim, and W. T. Milner 127

Progress on the compilation of nuclear cross-section data for charged-particle-induced reactions is outlined.

STATUS REPORT ON THE 3-Mv VAN DE GRAAFF ACCELERATOR
J. P. Judish and R. L. Macklin 127

The 3-Mv Van de Graaff was used about 3000 hr, chiefly as a pulsed neutron source; 98% of the research done with it involved neutron reactions in the 3000- to 6000-kev range.

STATUS REPORT ON THE 5.5-Mv VAN DE GRAAFF ACCELERATOR
R. L. Robinson and W. T. Newton 129

The activities associated with the 5.5-Mv Van de Graaff accelerator during 1965 are summarized.

OAK RIDGE TANDEM ACCELERATOR
C. D. Moak and G. F. Wells 131

During 1965 the tandem accelerator was operated for a total of 2186 hr. Ions used were H, D, ^{3}He, ^{14}N, ^{16}O, ^{19}F, ^{35}Cl, $^{79,81}Br$, and ^{127}I.

SCATTERING CHAMBER FOR GASEOUS TARGETS
C. M. Jones, J. W. Johnson, and R. M. Beckers 132

A new scattering chamber, designed primarily for gaseous targets, has been constructed.

THIN, LARGE-AREA, GASTIGHT PLASTIC WINDOWS FOR CRYOGENIC AND NUCLEAR APPLICATIONS
J. W. T. Dabbs 133

Leak rates were $\sim 6 \times 10^{-8}$ cm^3 sec^{-1} cm^{-2} for 40 μg/cm^2 at room temperature.

PUBLICATIONS 136

PAPERS PRESENTED AT SCIENTIFIC AND TECHNICAL MEETINGS 140

FOREIGN TRAVEL AND ASSIGNMENTS 145

ANNOUNCEMENT 145

PERSONNEL ASSIGNMENTS 146

ADVISORY COMMITTEE 147

SPECIAL LECTURE SERIES 147

AMERICAN PHYSICAL SOCIETY 148

VISIT BY USSR LOW-ENERGY TEAM TO ORNL 148

MISCELLANEOUS ACTIVITIES OF DIVISIONAL PERSONNEL 149

ACTIVITIES RELATED TO EDUCATIONAL INSTITUTIONS 152

ORNL PHYSICS SEMINARS 162

SEARCH FOR THE NEUTRAL *A* MESONS

H. O. Cohn
W. M. Bugg[1]
G. T. Condo[1]
R. D. McCulloch[2]

It was first established by Bellini *et al.*[3] and by Huson and Fretter[4] from analysis of heavy-liquid bubble chamber film and by Goldhaber *et al.*[5] from a study of the reaction

$$\pi^{\pm} + p \longrightarrow \pi^{\pm} + p + \pi^{+} + \pi^{-} \qquad (1)$$

that a large enhancement exists in the three-pion mass system in the mass interval 1.0 to 1.4 Bev. Subsequently, Chung *et al.*,[6] Lander *et al.*,[7] and the ABBBHM Collaboration[8] succeeded in resolving this enhancement into what has become known as the $A_1(1090)$ and $A_2(1310)$ mesons. At the present writing, the latter seems to be firmly established as a "bona fide" resonance by virtue of its decay into $\eta\pi$ and $K\bar{K}$ as well as into its principal mode of $\rho\pi$.[9] Further, its production via $\bar{p}p$ interactions[10] as well as πN collisions implies that it is not a kinematical effect. The status of the A_1 is somewhat more nebulous. Evidence for its production has evolved only from πN interactions, and decay modes other than $\rho\pi$ have not been established. This has led to several suggestions[11] that its origin may be of a purely kinematical nature and that the A_1 may have no dynamical basis. Results on the neutral three-pion system ($\pi^+\pi^-\pi^0$) have, to a large part, been restricted to systems with mass less than 1.2 Bev or else have resulted from an interaction where the final state contains more than three pions, for example,

$$\pi^{+} + p \longrightarrow \pi^{+} + p + \pi^{+} + \pi^{-} + \pi^{0} . \qquad (2)$$

Since the A_1 and A_2 have integral spin and were found in both singly charged states, it is assumed that they have isotopic spin 1. It is therefore of considerable interest to investigate the neutral three-pion system for evidence for the neutral counterparts to the charged A_1 and A_2 modes.

Experimental Procedure

We have examined the $\pi^+\pi^-\pi^0$ system produced in the reaction

$$\pi^{+} + d \longrightarrow (p) + p + \pi^{+} + \pi^{-} + \pi^{0} , \qquad (3)$$

(p) being a spectator proton. The data were obtained from an exposure of the BNL 20-in. deuterium chamber to 3.29-Bev/c incident π^+ mesons. All events accepted for the analysis were required to have two definite protons, identifiable by curvature and ionization, which restricts us to momentum transfers to the pion system (Δ^2) of $\lesssim 50$ (in units of m_π^2).

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[2]Central Data Processing Facility, Union Carbide Nuclear Division.

[3]G. Bellini *et al.*, *Nuovo Cimento* **29**, 896 (1963).

[4]F. R. Huson and W. B. Fretter, *Bull. Am. Phys. Soc.* **8**, 325 (1963).

[5]G. Goldhaber *et al.*, *Phys. Rev. Letters* **12**, 336 (1964).

[6]S. U. Chung *et al.*, *Phys. Rev. Letters* **12**, 621 (1964).

[7]R. L. Lander *et al.*, *Phys. Rev. Letters* **13**, 346 (1964).

[8]Aachen-Berlin-Birmingham-Bonn-Hamburg-London (I. C.)-München Collaboration, *Phys. Letters* **10**, 226 (1964).

[9]G. Goldhaber, UCRL-11971 (1965).

[10]A. Bettini *et al.*, presented at the 1964 Dubna Conference.

[11]R. T. Deck, *Phys. Rev. Letters* **13**, 169 (1964); U. Maor and T. A. O'Halloran, Jr., *Phys. Letters* **15**, 281 (1965).

The Three-Pion Spectrum

Figure 1 contains the three-pion mass spectrum obtained from all events of reaction (3) which satisfied our scanning criteria. A fit to the data of the form:

$$\text{Phase space} \times \left[1 + \sum \frac{A_i}{(M - M_i)^2 + (\Gamma_i/2)^2} \right] ,$$

where the phase space is for the three-pion system and the sum is over the clearly observed resonances at mass values of the η, ω, and A_2, was attempted. The widths and intensities were parametrically adjusted. No acceptable fit was obtained that did not display a preponderance of events in the mass region between the ω and A_2. The curve shown on Fig. 1, therefore, includes a Breit-Wigner-shaped resonance at the A_1 mass and is a much improved fit. Although the H meson[12] and an $\eta\pi\pi$[13] particle are known to exist at 960 Mev, no such resonance was included in the fit spectrum.

[12] Aachen-Berlin-Birmingham-Bonn-Hamburg-London-München Collaboration, *Phys. Letters* **11**, 167 (1964).

[13] M. Goldberg *et al.*, *Phys. Rev. Letters* **12**, 546 (1964); G. Kalbfleisch *et al.*, *Phys. Rev. Letters* **12**, 527 (1964).

Reaction (3) in contrast to reaction (1) is not dominated by isobar formation. In fact, while there is some evidence for the reaction

$$\pi^+ + n \longrightarrow (N^*)^+ + \rho^0$$

and also, to a lesser extent, for the reaction

$$\pi^+ + n \longrightarrow (N^*)^0 + \rho^+ ,$$

there is no evidence for $(N^*)^{++}$ formation. Because of the low intensity for direct ρ or N^* production, and also since the three-pion mass for those events whose final state is $\rho + N^*$ contributes little to the 3π mass in the region of 0.9 to 1.4 Bev, it was felt that the analysis of the 3π system could better proceed, without limiting the sample of events.

The A_1 Meson

The broad general enhancement observed from 0.9 to 1.2 Bev could be accounted for by production of both A_1 and H mesons, by introduction of the one-pion exchange phase space, or by some other kinematic mechanism. An analysis of this region regardless of its identification may shed light on this question. The Dalitz plot for events in the mass region of the A_1 is shown in Fig. 2*a*.

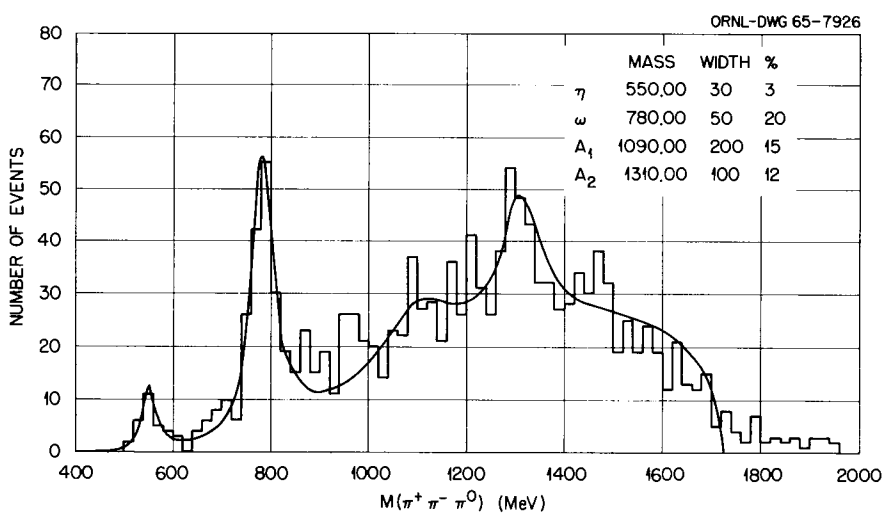

Fig. 1. Three-Pion Effective Mass Spectrum for the Reaction $\pi^+ + d \rightarrow (p) + p + \pi^+ + \pi^- + \pi^0$.

ORNL-DWG 66-2269

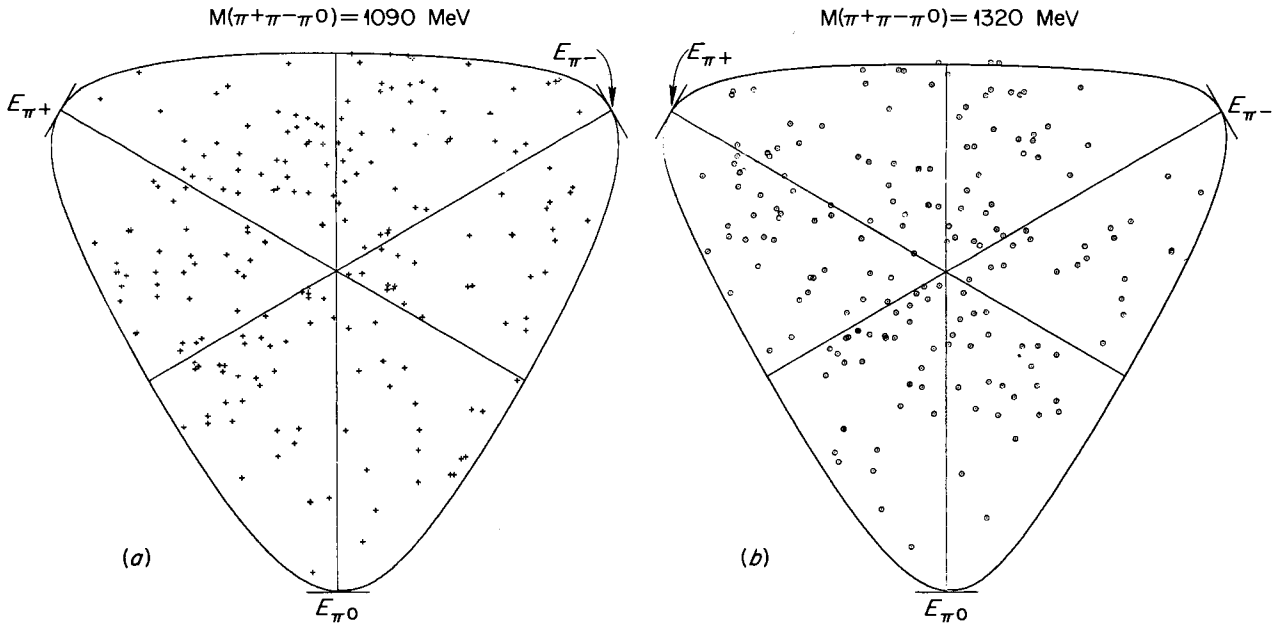

Fig. 2. Dalitz Plots for the π^+, π^-, π^0 System for Effective Mass (*a*) in the A_1 Mass Region and (*b*) in the A_2 Mass Region.

We see that while ρ^+ and ρ^- manifest themselves above ordinary phase space in quantities appropriate to the decay of an isospin 1 resonance (especially when account is taken of the directly produced ρ^+ mesons), there is no evidence for any ρ^0 enhancement in this region. This is difficult to understand on the basis of the kinematical mechanisms proposed to vitiate the dynamical basis of the A_1. On that basis, one would expect the enhancement in the A_1 region to be due to an excess of ρ^0 and ρ^+ mesons, since our reaction excludes ρ^- production via the OPEM. The dipion mass spectra for the events in the A_1 mass region are shown in Fig. 3*a*, *b*, and *c*. The $\pi^+\pi^-$ spectrum (Fig. 3*a*) does not show a ρ^0 peak; however, the $\pi^+\pi^0$ spectrum (Fig. 3*b*) displays a pronounced ρ^+ peak. Neither of these results was affected by cuts in the four-momentum transfer (Δ^2) to the three-pion system. The $\pi^-\pi^0$ spectrum (Fig. 3*c*) displays a ρ^- peak but less pronounced than the ρ^+, when all Δ^2 are included. Restriction to low Δ^2, however, causes the ρ^- peak to disappear. Were it not for the latter effect, one would be tempted to identify the A_1 meson as a particle rather than a kinematic effect. However, because of the pathological behavior of the ρ^- peak as a function of Δ^2, such an identification is not wholly justified.

The A_2 Meson

The A_2 meson has been relatively firmly established as an $IJ^{PG} = 1,2^{+-}$ resonance of mass $\sim$1320 Mev and with $\Gamma \cong 70$ Mev. The presence of a clear enhancement indicative of A_2^0 production is evident in Fig. 1. It is noted that this enhancement appears strongly without the usual restriction to events without $N^*(1238)$ production. If our enhancement at 1260 to 1380 Mev were the A_2^0, then the I spin assignment of unity would require equal numbers of ρ^+ and ρ^- mesons in its decay products. The Dalitz plot, as well as its dipion projections (Fig. 2*b*), while quite possibly demonstrating some ρ^+ production, shows virtually no ρ^- production.

Similar results have been attributed to the Michigan bubble chamber group by Vander Velde[14]

[14] J. C. Vander Velde, *Phys. Rev. Letters* **16**, 69 (1966).

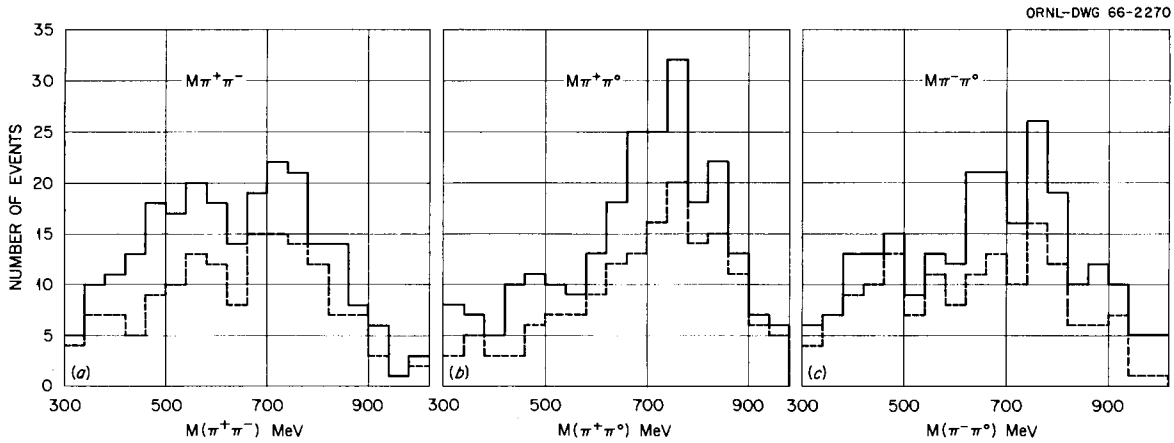

Fig. 3. Two-Pion Effective Mass Distribution for Events in A_1 Mass Region. The dashed curve represents a cut in four-momentum transfer: (a) π^+, π^-; (b) π^+, π^0; (c) π^-, π^0.

and have been presented by the SOBB collaboration,[15] both in π^+d film. This latter group has concluded, however, that even though they were unable to demonstrate the $\rho\pi$ decay of this resonance, it should probably be identified as the A_2^0.

In order to further substantiate the different character of our 1.32-Bev enhancement, we have plotted the distribution of the cosine of the angle between the incoming π^+ and the normal to the decay plane of the resonance in the resonances rest system. Figure 4 illustrates this angular distribution, which is $\sim\sin^2\theta$. This result is vastly different from a similar one reported by Alitti *et al.*[16] for the charged A_2. While their distribution is in excellent agreement with that expected for a $J^P = 2^+$ particle, the neutral resonance observed here yields a distribution which, according to Zemach,[17] is characteristic of a 1^+ or 1^- particle. The calculations of Zemach do not include the effects of absorption of lower partial waves, which were found to be required for the ω meson. If our resonance is to correspond to a 1^+ or 1^- particle, the absence of absorptive corrections would be difficult to understand for this reason. If our resonance were to correspond to the A_2^0, then the dependence of the spin-density matrix elements on charge as well as the absence of the $\rho\pi$ decay would require theoretical justification beyond our power.

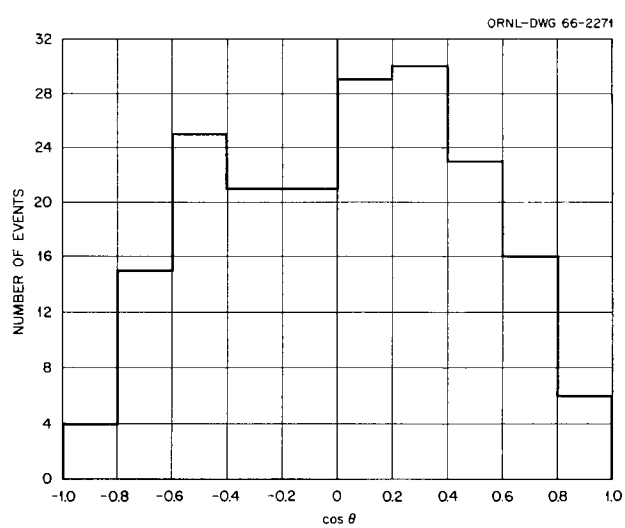

Fig. 4. Decay-Plane Angular Distribution of the 1.32-Bev Resonance.

[15] Saclay-Orsay-Bari-Bologna Collaboration, *Phys. Letters* **11**, 347 (1964).

[16] J. Alitti *et al.*, *Phys. Letters* **15**, 69 (1965).

[17] C. Zemach, *Phys. Rev.* **133**, B1201 (1964).

SEARCH FOR A NEUTRAL SCALAR MESON[1]

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Recently there has been theoretical speculation and experimental evidence for the existence of a $J = 0^+$, $T = 0$ pion-pion resonance (ϵ^0). Investigation of $\pi^+ + d$ interactions at 3.29 Bev/c π^+ momentum failed to show evidence for such a neutral scalar meson in two independent experiments. Neither the $\pi^+\pi^-$ nor the $\pi^0\pi^0$ systems display evidence for a resonance near 700 Mev/c^2 dipion mass.

[1]Abstract of paper published in *Phys. Rev. Letters* **15**, 906 (1965).

[2]Consultant from the University of Tennessee.

[3]Central Data Processing Facility, Union Carbide Nuclear Division.

[4]Columbia University, New York, N.Y.

[5]University of Chicago and Enrico Fermi Institute for Nuclear Studies, Chicago.

EXCHANGE MECHANISM FOR ω PRODUCTION IN π^+-n INTERACTIONS[1]

H. O. Cohn
W. M. Bugg[2]
G. T. Condo[2]

The exchange mechanism for ω production in $\pi^+ + n$ interactions is studied through an analysis of angular correlation in

$$\pi^+ + d \longrightarrow p + p + \pi^+ + \pi^- + \pi^0$$

interaction. Values for the spin matrix elements ρ_{00} and $\rho_{1,-1}$ are obtained and compared to the one-ρ exchange model.

[1]Abstract of paper published in *Phys. Letters* **15**, 344 (1965).

[2]Consultant from the University of Tennessee.

HIGH-RESOLUTION ELECTRON MICROSCOPY

T. A. Welton

Further study has been performed of the available methods for possible improvement of the resolution of the electron microscope. All of these methods have been in the literature for many years, following the proof by Scherzer[1] that the primary spherical aberration of a conventional electron lens, with axial symmetry, is necessarily of one sign. It was later pointed out by Scherzer[2] that several methods existed which seemed capable of compensating the spherical aberration. The two most promising of these methods appear to be the use of the "film lens" and the use of optical elements without axial symmetry, both of which have been further explored, with results to be given. In the same paper, Scherzer pointed out

[1]O. Scherzer, *Z. Physik* **101**, 593 (1936).

[2]O. Scherzer, *Optik* **2**, 114 (1947).

that the use of cylindrical lenses could allow first-order chromatic correction.

The film lens is conveniently regarded as an outgrowth of the focusing grid lens, which at one time was popular for improving the quality of ion beams. An elementary calculation shows that the charge density on the grid (if uniform) acts as a simple lens, while a quadratic radial variation of the charge density introduces a primary spherical aberration. Simple geometrical considerations show that if the spherical aberration of the axially symmetric conventional objective lens is to be compensated, then the grid must have a potential of such sign that it becomes a diverging lens. The aperture of the film lens must then be chosen small enough to yield adequate spherical correction without destroying the overall convergence of the combination.

The grid lens is not in fact useful in electron microscopy, since diffraction phenomena there play a controlling role. Each opening in the grid acts as a very small-aperture electrostatic lens. If these lenses are all properly oriented to produce a coincident image, the desired resolution will still not be obtained, even though a very small-aperture lens may have a very small spherical aberration. This is so because of the very large diffraction spreading of each image. If coherence can be maintained between the overlapping amplitudes due to all the apertures, then interference can give a sharp central maximum, so that high resolution seems to have been regained. Unfortunately, this interference maximum is only the zero-order peak of a complicated diffraction pattern. It is only when all orders except the zero order fall outside the field of view that high resolution can in principle be achieved. In this way, we are finally forced to use a film whose only regularity is at the atomic level, to give adequate angular separation for the orders of diffraction.

Existing data indicate strongly that a graphite film of thickness 100 A, a beryllium film of 150 A, or an aluminum film of 75 A will transmit a 100-kev electron beam with only about 10% loss by elastic or inelastic scattering. This film must span the 0.025-cm-diam aperture occupied by the image beam of a high-resolution microscope at the position of maximum radial extent. The film, in addition, must sustain a considerable electrical force, since it is charged by induction. The lens electrodes should have a bore and spacing of about 0.1 cm, with a potential difference of about 5000 v. Insulation seems adequate, and the electric force can probably be sustained by a reasonably intact film, particularly graphite.

Two rather different arrangements have been explored. The symmetrical film lens has the film electrode, at negative potential, mounted symmetrically between two grounded electrodes. Although the film has a position of equilibrium (because of the symmetry), it is unstable, and a considerable tension must be exerted to yield stability. This configuration is subject to the disadvantage that it cannot be positioned too close to the object plane, because of the disturbance of the electric field by the sample holder.

Another configuration, which appears feasible and probably preferable, is the asymmetric film lens. In this arrangement the film terminates a section of the microscope which is a few kilovolts off from ground potential. The film is followed by an insulating gap of about 0.1 cm and then by a grounded electrode with a central hole of about 0.1 cm radius. The film is not now at a position of equilibrium, and will consequently suffer a severe mechanical force. It appears, however, that graphite can withstand this force, and the configuration possesses the important advantage that no electric field invades the object plane. This feature allows optimal positioning of the film, as well as a much more substantial film support member. It is accordingly the conclusion of this study that the asymmetric configuration offers the better chance of practical realization.

The other attractive alternative proposed by Scherzer, involving the use of noncircular lenses (cylindrical lenses in the optical analogy), has also been explored. Scherzer's original suggestion, made before the invention of strong focusing, was incorporated into an actual microscope by Seeliger,[3] who showed that the primary spherical aberration could in fact be removed. After the invention of strong focusing, this idea was taken up by others, notably Archard,[4,5] Burfoot,[6] and

[3] R. Seeliger, *Optik* **8**, 311 (1951).

[4] G. D. Archard, *Proc. Phys. Soc. (London)* **B68**, 156 (1955).

[5] G. D. Archard, *Proc. Phys. Soc. (London)* **B72**, 135 (1958).

[6] J. C. Burfoot, *Proc. Phys. Soc. (London)* **B66**, 775 (1953).

Meyer,[7] from the theoretical point of view, as well as by Möllenstedt[8] on the experimental side. Although it was realized by Archard[5] that the conventional "round" objective is in fact unnecessary, with equivalent optics being obtainable from a combination of quadrupoles, it has appeared convenient to retain the round lens for the initial formation of nearly spherical converging waves from the electrons scattered by the object.

One of Archard's quadrupole configurations[4] (his System B) has particularly simple properties and has been here used as an element in a very attractive correction system.

It should first be pointed out that, although the primary spherical aberration is the irreducible cause of poor resolution in the conventional electron microscope, it does not by any means completely control the situation. In the best existing instruments, perhaps 4 A of the achievable 6-A resolution is primary spherical aberration, while roughly 1 A each should be attributed to chromatic aberration and astigmatism. If we attempt to reduce the effect of spherical aberration essentially to zero over an aperture of 0.04 radian (rather than the conventional 0.01 radian), thus reducing the previous 4-A contribution to 1 A, we will find a much enhanced chromatic effect. This radial smearing effect is described by

$$\delta r = f\alpha \frac{\delta f}{f},$$

where

α = angular aperture in radians at the object,

f = focal length of the objective,

$\frac{\delta f}{f}$ = composite fractional spread in focal length resulting from source voltage radiation, initial electron energy spread, and objective current variations.

If we set $f = 0.3$ cm, $\alpha = 0.04$ radian, and require $\delta r = 1$ A, we must then achieve

$$\frac{\delta f}{f} \simeq 10^{-6}.$$

The inaccuracy of control of source voltage with respect to objective current is between two and five times this figure in the best conventional instruments. Some improvement in control is no doubt possible, but it is to be expected that the inherent energy spread of electrons emitted from a cathode will be at least several tenths of a volt. For a 100-kev beam, $\delta f/f$ will therefore be uncomfortably large, and chromatic error would then be the principal source of definition loss in a high-resolution instrument.

In view of the above considerations, some sort of chromatic correction, in addition to spherical and astigmatic correction, appears to be of great importance. The alternative is the incorporation in the electron source of an extraordinarily high-resolution electron energy spectrometer.

As originally shown by Scherzer,[2] the use of non-rotationally-symmetric lenses permits chromatic correction. Practical design and construction of a system simultaneously corrected for spherical and chromatic aberration seems, however, not to have been attempted. A study has accordingly been performed of a system of four identical quadrupoles. For a ray deviating in the x direction from the optical (z) axis, the sequence is $+l-2l+l-$, where $+(-)$ indicates convergence (divergence), and the quantities between the signs are the spacings between principal planes of adjacent elements. For the standard momentum p_0 (the center of the momentum range to be used), the focal length of each lens is also l. The above sequence behaves, for paraxial rays and momentum p_0, as though no optical elements were present. It can be fully corrected for primary spherical aberration by addition of three suitably adjusted octupole lenses, two of which coincide with the intermediate quadrupoles, and the third at the center of the array. This combination of octupoles can in fact be used to make the primary spherical aberration equivalent, at momentum p_0, to that of a round lens, but with either sign. If this array of four quadrupoles (plus correcting octupoles) is placed following a conventional objective, the combination can then be adjusted to have zero primary spherical aberration at p_0, as originally shown by Archard.[4]

If a further identical set of four quadrupoles is placed after the first set, in sequence

$$+l-2l+l-2l-l+2l-l+,$$

[7] W. E. Meyer, *Optik* 18, 69 (1961).

[8] G. Möllenstedt, *Optik* 13, 209 (1956).

it has been shown that, for paraxial rays, the system is free of astigmatism for first-order changes in momentum from the standard value, although such a momentum change will introduce convergence proportional to the momentum deviation. If a system of eight electric quadrupoles is made to follow a conventional magnetic objective with spacing *a* between the adjacent principal planes, the free parameters *a* and *l* can therefore be used to cancel the first-order chromatic aberration of the total system. The primary spherical aberration at p_0 can be canceled as before, and it appears possible even to cancel the first-order momentum variation of the primary spherical aberration, as well as the secondary spherical aberration, if these latter two corrections should become important.

Plans are under way to construct a sophisticated instrument based on this method of simultaneous spherical and chromatic correction. According to present plans, it will use 100-kev electrons from a conventional microscope supply. These will be formed by an illuminating system (necessarily more complex than the conventional system) into a beam of diameter about 100 A at the object plane. At this point, the beam is parallel and coherent over the full diameter. The objective system will probably begin with a conventional round lens followed by the previously described correcting system. Some increase (factor of 2 or 3) in objective focal length over conventional practice will probably be made to ease constructional problems, since the resulting increased aberration is to be compensated in any event. Three subsequent stages of magnification will bring the initial field of 100 A up to 1 cm (10^6 electron optical magnification), in a distance of 2 to 3 m. At this image size, an electron-sensitive detector can be introduced with spatial resolution adequate to match that of the optical system. For example, a 100-line scan of the 1-cm sensitive area of a Vidicon optically coupled at unit magnification to a CsI scintillator will yield the required 0.01-cm resolution ($\approx 10^6 \times 1$ A).

With the probably otherwise desirable increase in scale of the lenses over conventional practice, the vacuum vessel can be a metallic, nonferrous tube with all magnetic structure outside the tube for easy access and adjustment. Gasketing will be held to a minimum to achieve a vacuum of 10^{-7} to 10^{-8} torr. It appears feasible to supply a $\frac{1}{4}$-wave phase shift for the source wave in the back focal plane of the objective, in order to obtain nearly ideal phase contrast. The excitation of the magnetic portion of the objective system must clearly be regulated with extreme accuracy with respect to the voltages in the electric portion, and this requirement may in fact force more serious consideration of the desirability of using a high-resolution momentum selector before the object plane.

CONFORMATIONAL THEORY FOR PROTEINS AND POLYNUCLEOTIDES

T. A. Welton J. F. Pizzo[1]

The sequence hypothesis of molecular biology states that the sequence of amino acids in a protein or that of nucleotides in DNA or RNA, in conjunction with the characteristics of the surrounding aqueous medium, completely determines the physical form taken by these molecules. In particular, there is excellent evidence that a polyamino acid, or polynucleotide, with biologically significant sequence but incorrect three-dimensional structure, when placed in an aqueous medium of correct intracellular pH and ionic strength, will quickly and reliably assume a fully functional form. The apparent truth of this rather sweeping generalization suggests a novel approach to the currently important problem of the determination of conformation (three-dimensional form) for a wide variety of biologically significant molecules. Such conformational determinations

[1]ORINS Summer Research Participant from Lamar Institute of Technology, Beaumont, Tex.

can presently be made only by a complex x-ray structure analysis, which in turn depends on the availability of a pure, crystallizable substance. An additional stringent requirement is that, with present techniques of analysis, several isomorphous replacements with one or more heavy atoms per unit cell must also exist. These requirements are likely to rule out all but a small number of molecules from consideration, so that real progress on the all-important problem of the structure-function relationship for enzyme and s-RNA demands perfection of some other technique for attacking the conformation problem. Two other points are of importance. First, the conformation of a molecule in crystalline form is likely to be very different from that which it maintains in aqueous suspension, so that a real attack on the structure-function problem may be difficult and uncertain if only crystalline conformations are available. The second point is that if a pure enzyme or s-RNA is available (and the required separation techniques are becoming very sophisticated and precise, indeed!) there exists a reliable procedure (selective enzymatic digests, with identification of fragments by ultraviolet absorbance, colorimetry, etc.) for determination of amino acid or nucleotide *sequence*.

We may accordingly take it as given that the *structural organic formula* of any of a wide variety of biologically significant molecules is (or can be) known. From the apparent truth of the sequence hypothesis, we further assert that a systematic, reasonably accurate enumeration and description of the forces acting between different portions of a given molecule will allow, in principle, a computation of the process by which a molecule of correct sequence (structural formula), but nonfunctional conformation, relaxes into the biologically functional conformation which we require.

We have undertaken the job of enumerating and quantifying the various intramolecular forces, with a view to writing and testing a comprehensive computer program for conformational calculations by the method sketched above. We believe that we now have adequate analytical forms, with easily determined parameters, for the energies of bond stretching, bond bending, nonbonded repulsion, and electrostatic interactions (including hydrogen bonding and forces between ionized groups). Torsional energies for rotations about bonds will be included, but (as observed by many authors) the present information on such energies is inadequate for real calculation. We plan to adjust the constants required to describe bond torsion by appeal to known crystal structures, where torsional effects are frequently very important. It should also be pointed out that there exists good evidence that presently feasible molecular Hartree-Fock calculations are adequate for determination of the required torsional energies, as well as for more precise determination of some of the other intramolecular energies.

Thermal agitation can be explicitly treated by including a random force from the aqueous medium, with power spectrum properly proportional to the viscous resistance coefficients, which must be included to allow the molecule to relax into its equilibrium conformation, rather than simply vibrating in a completely meaningless fashion. The sole remaining important forces, which we lump under the term "solvent interaction," arise from differences in adhesive and cohesive energies of parts of the molecule with each other, with the solvent molecules, and solvent molecules with one another. These forces are of short range (roughly the diameter of the water molecule) and large enough to be reasonably important at room temperature. We plan to include these effects (which are really electrostatic interactions with solvent molecules) as an integral part of the treatment of the electrostatic energies. To do this, the water molecules within and close to the large molecule will be explicitly treated in exactly the same fashion as are parts of the large molecule, with of course no *chemical* bonding assumed between individual solvent molecules, or between them and the large molecule. Such treatment increases only moderately the complexity of the calculation, but should add greatly to its reliability.

The computer program (for the IBM 360, in its final form) is presently in an advanced stage of planning, with writing and preliminary testing scheduled for the coming summer. It is anticipated that *small* polypeptides (which often have accurately known crystal structures) will be handled adequately. The program will be designed to accommodate proteins of interesting size (100 to 200 amino acids), but only detailed experience will allow us to estimate its effectiveness for such complex problems.

INTEGRATION OF THE THREE-BODY WAVE EQUATIONS

J. H. Marable T. A. Welton

A new method for finding wave functions for three-body systems has been developed. The method uses a coordinate system which separates the center of mass translation, the rotations of the principal axes about the center of mass, and the internal motions, and at the same time minimizes the appearance of gyroscopic terms which arise from the interaction between internal and rotational motions. In particular, the rotational motion is specified by three Euler angles, while the internal motion is specified by two angular variables and a radial variable which vanishes when the three particles coalesce at a point and which increases without limit as two or more of the three particles diverge.

By the use of these coordinates, a single internal radial variable plus angular variables, the problem takes on some of the aspects of the two-body problem. The wave function is expanded in terms of products of a radial function with an angular function, the latter being a generalization of the spherical surface harmonics in three-dimensional space to six-dimensional space.

The problem reduces to a set of coupled differential equations for the radial functions. These coupled equations form in general an infinite set and truncation is necessary. The truncation error is being investigated by varying the number of harmonics to be used in the expansion of the wave function. The resulting truncated sets of coupled differential equations are being solved numerically by starting at the origin (where the radial variable vanishes) and integrating radially outward.

Although the method is conceived for application especially to scattering problems, it is being applied first toward the solution of bound-state problems. Methods for matching boundary conditions and for converging to an energy eigenvalue have been developed.

The method can be generalized to an arbitrary number of particles, and the separation of terms in the Hamiltonian has been partially carried out. However, a particular choice for the internal angular coordinates has not been made.

A THREE-NUCLEON INTERACTION[1]

D. R. Harrington[2]

A contribution to the long-range part of the three-nucleon potential arising from the interaction of virtual pions with the cloud of *s*-wave two-pion resonances around a nucleon is investigated. Crude estimates are made for the effect of this potential in nuclear matter and in the triton. In nuclear matter the corresponding effective two-nucleon interaction at small distances is repulsive and strong enough to dominate the one-pion-exchange potential. The contribution to the triton binding energy is about 1.1 Mev.

[1]Abstract of paper to be published in the *Physical Review*.

[2]Summer faculty member from Rutgers – The State University, New Brunswick, N.J.

A STUDY OF THE HARTREE-FOCK APPROXIMATION AS APPLIED TO FINITE NUCLEI[1]

K. T. R. Davies S. J. Krieger[2] M. Baranger[2]

Hartree-Fock calculations have been performed for the closed-shell nuclei ^{16}O, ^{40}Ca, and ^{80}Zr, and, with certain simple approximations, for the open-shell nuclei ^{12}C, ^{28}Si, and ^{60}Zn. The velocity-dependent two-body force acts in relative s states only. The force saturates nuclear matter at the correct energy and density and yields small second-order perturbation corrections, but has too large a range to be in good agreement with the two-body data. However, the choice of this simple force enables us to study the Hartree-Fock approximation in detail, which is the main purpose of this paper. We calculate wave functions, energy levels, binding energies, and density distributions for the six nuclei and obtain rough agreement with the experimental results. A discussion is given of the nonlocal Hartree-Fock potential.

[1]Abstract of paper to be submitted to *Nuclear Physics*.

[2]Carnegie Institute of Technology, Pittsburgh, Pa.

OSCILLATOR BRACKETS FOR HARTREE-FOCK CALCULATIONS[1]

M. Baranger[2] K. T. R. Davies

Some explicit formulas are derived for the oscillator brackets occurring in the calculation of nuclear two-body matrix elements. These formulas are especially adapted to the calculation of brackets with low relative angular momentum *l*. There are no restrictions on the radial quantum numbers, which makes this method particularly useful for Hartree-Fock calculations. Estimates are given for the computing time.

[1]Abstract of paper to be published in *Nuclear Physics*.

[2]Consultant to the Oak Ridge National Laboratory from Carnegie Institute of Technology, Pittsburgh, Pa.

NUCLEAR GROUND-STATE PROPERTIES OF ^{16}O BY AN EXTENSION OF THE EDEN-EMERY METHOD[1]

A. D. MacKellar[2] R. L. Becker

The Bethe-Goldstone equation is solved for the case in which the two-nucleon interaction is the Brueckner-Gammel-Thaler or the Hamada-Johnston potential, and the single-particle potential is that of a harmonic oscillator. The Eden-Emery approximation to the Pauli exclusion operator is used. In this context the tensor force is treated exactly by solving coupled radial equations. Approximate satisfaction of the Brueckner-Hartree-Fock self-consistency conditions is achieved by variation of state-dependent constants in the

[1]Abstract of published paper: *Phys. Letters* 18, 308 (1965).

[2]Oak Ridge Graduate Fellow from Texas A and M University.

single-particle potential and of the range parameter of this potential. The single-particle energy levels, $p_{1/2}$-$p_{3/2}$ splitting, total binding energy per nucleon, and rms radius of the ground-state configuration of ^{16}O are computed and compared with experiment and with calculations using reaction matrix elements appropriate to infinite nuclear matter.

NUCLEAR GROUND-STATE PROPERTIES OF ^{16}O BY AN EXTENSION OF THE EDEN-EMERY METHOD[1]

A. D. MacKellar[2]

A Brueckner theory calculation of the nuclear ground-state properties of ^{16}O is performed. The method employed is an extension of the calculations of Eden and Emery, and Eden, Emery, and Sampanthar.

The Bethe-Goldstone equation is solved using harmonic oscillator unperturbed single-particle wave functions and the Eden-Emery approximation of the effect of the exclusion principle. The Eden-Emery method for uncoupling the Bethe-Goldstone equations is found inadequate in the presence of a strong tensor force, and in the present calculation a correct treatment is made of the coupling between the $l = j - 1$ and $l = j + 1$ equations. The coupled integro-differential equations are written in a form in which the exclusion principle operator becomes a separable kernel and the equations are reduced to a finite set of coupled differential equations.

Explicit equations are derived for the Brueckner-Hartree-Fock single-particle potential and ground-state binding energy for doubly closed-shell nuclei using the transformation properties of harmonic oscillator functions from single-particle to relative and center-of-mass coordinates. However, in the numerical calculation for ^{16}O, the Eden-Emery-Sampanthar approximation to self-consistency is kept, which adds an adjustable state-dependent constant to the harmonic oscillator potential and employs an approximate variational calculation to determine the harmonic oscillator range parameter. This compromise in the accuracy of the calculation is necessary in order to keep the computer time within bounds.

The two-nucleon interactions studied are the standard hard-core potential of Moszkowski and Scott (SHC), the Brueckner-Gammel-Thaler potential (BGT), the Hamada-Johnston potential (HJ), and the Yale potential. The resulting calculated binding energy per nucleon for ^{16}O is −5.1 Mev for SHC, −9.2 Mev for BGT, −8.0 Mev for HJ, and −5.1 Mev for Yale. The difference between the results for the HJ and Yale potentials, which are quite similar interactions, indicates the extreme sensitivity of this calculation to the form of the interaction close to the hard-core radius. Single-particle levels are calculated and in general are more tightly bound than the levels calculated by Brueckner, Lockett, and Rotenberg applying the "local density" approximation to nuclear matter t-matrix elements. The calculated $p_{1/2}$-$p_{3/2}$ splitting is found to be larger and the model rms radius smaller than the experimental values for all cases.

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[1]Abstract of Ph.D. thesis, Texas A and M University; ORNL-TM-1374.

[2]Oak Ridge Graduate Fellow from Texas A and M University.

SHELL-MODEL STUDIES OF NUCLEI IN THE REGION $A = 90$

R. M. Tarbutton[1] J. B. McGrory W. T. Pinkston[2]

Hughes, Snow, and Pinkston[3] have made least-squares fits of the strength parameters of a $T = 1$ central plus tensor interaction for nuclei treated as two particles outside a closed shell. They found a potential which fits well both ^{18}O and ^{210}Po and which has some of the properties of the free two-nucleon potential; however, their treatment of ^{86}Sr and ^{90}Zr using an ^{88}Sr core gave a rather poor fit and an interaction which is rather unrealistic. Assuming that ^{88}Sr is not a good core, we have treated several nuclei as consisting of a core of 50 neutrons and 28 protons, with protons in the $1f_{5/2}$, $2p_{3/2}$, $2p_{1/2}$, and $1g_{9/2}$ shells interacting through the ^{18}O-^{210}Po potential. These calculations, including as many as four $g_{9/2}$ particles, were performed using a shell-model program written for the IBM 7090 computer.[4] Starting with an estimate based on first-order perturbation theory, the single-particle energies were varied to give a good fit to the known energy levels of ^{87}Rb, ^{88}Sr, ^{89}Y, and ^{90}Zr.

[1]Graduate student from Vanderbilt University.

[2]Summer faculty member from Vanderbilt University.

[3]T. A. Hughes, R. Snow, and W. T. Pinkston, unpublished.

[4]S. S. M. Wong, E. C. Halbert, and J. B. McGrory, *Bull. Am. Phys. Soc.* 10, 487 (1965).

POLARIZATION-ASYMMETRY EQUALITY AND THE MEASUREMENT OF SPIN-FLIP IN INELASTIC SCATTERING FROM NUCLEI[1]

G. R. Satchler

It is shown that the difference between polarization and asymmetry measurements of inelastic scattering can provide a measure of the interference between the transition amplitudes with and without spin transfer to the nucleus.

[1]Abstract of paper submitted for publication in *Physics Letters*.

INELASTIC SCATTERING AND THE NUCLEAR SHELL MODEL[1]

G. R. Satchler

The application of a previously derived formalism to a microscopic description of the inelastic and charge-exchange scattering of various projectiles by nuclei is discussed. The problem is reduced to the evaluation of certain nuclear form factors. The model appropriate for low energies assumes a central but spin- and isospin-dependent two-body force between the projectile and each target nucleon. The high-energy impulse approximation is also discussed. The nuclear wave functions are treated in an independent-particle (shell model) representation. Particular attention is paid to selection rules which may be imposed by assumptions about the nuclear structure.

[1]Abstract of paper submitted for publication in *Nuclear Physics*.

SHELL-MODEL FORM FACTORS FOR THE $^{90}Zr(p,p')$ REACTION[1]

M. B. Johnson[2] L. W. Owen[3] G. R. Satchler

The application of the shell model to the $^{90}Zr(p,p')$ reaction is described. The nuclear matrix elements, and particularly the radial form factors, are discussed. Interactions of Gaussian and Yukawa form between projectile and target nucleons are used. They are assumed to be central, but spin and isospin dependence is included. The shell-model orbitals are calculated for a potential of the Woods-Saxon shape. The effects of parameter variations and corrections such as may be due to nonlocality of the potentials are studied in some detail. It is shown how the data for the $^{90}Zr(p,p')$ reaction favors a Yukawa interaction with a range of about 1 fermi.

[1]Abstract of paper submitted for publication in the *Physical Review*.

[2]Virginia Polytechnic Institute.

[3]Physics Department, University of Tennessee.

ANALYSIS OF THE SCATTERING OF 40-Mev PROTONS[1]

M. P. Fricke[2] G. R. Satchler

Elastic and inelastic scattering of unpolarized 40-Mev protons from ^{12}C, ^{54}Fe, ^{56}Fe, ^{58}Ni, ^{60}Ni, and ^{208}Pb have been analyzed using the optical-model potential and its collective-model extension in the distorted-wave approximation. Fits to the inelastic scattering from ^{24}Mg and to the elastic scattering from ^{27}Al, ^{65}Cu, Sn, and ^{181}Ta also are included. The Woods-Saxon shape parameters for the potential differ from those suggested for scattering at lower energies, and either surface or volume forms of the imaginary part produce good agreement with the data. To describe the inelastic scattering best, it is found necessary to deform the imaginary (as well as the real) part of the central potential. The deformation parameters obtained are in reasonable agreement with those found by other methods.

[1]Abstract of published paper: *Phys. Rev.* 139, B567 (1965).

[2]ORAU Graduate Student from University of Minnesota; Electronuclear Division.

ADIABATIC MODEL FOR A DEUTERON OPTICAL POTENTIAL

M. B. Johnson[1]

A code was written to calculate the optical potential for deuterons implied by assuming it is the sum of a neutron and proton potential averaged over the internal motion of the dueteron,

$$U_d(r) = \int d\mathbf{s}\, [U_n(\mathbf{r}_n) + U_p(\mathbf{r}_p)]\, \phi_d^2(s)\ ,$$

where $s = |\mathbf{r}_n - \mathbf{r}_p|$, $r = \frac{1}{2}\, |\mathbf{r}_n + \mathbf{r}_p|$ and we take a Hulthén function for ϕ_d,

[1]Physics Department, Virginia Polytechnic Institute.

$$\phi_d(s) = N_d \frac{e^{-\alpha s} - e^{-\beta s}}{s}, \quad N_d = \left[\frac{\alpha\beta(\alpha+\beta)}{2\pi(\beta-\alpha)^2}\right]^{1/2}.$$

A Saxon shape with surface absorption was taken for U_n, U_p:

$$U_{n,p}(r) = -\frac{V}{e^x + 1} + 4iW_D \frac{d}{dx'}\left(\frac{1}{e^{x'} + 1}\right),$$

with $x = (r - r_0 A^{1/3})/a$, $x' = (r - r_0' A^{1/3})/a'$.

Preliminary calculations for $8 \leqq A \leqq 200$ were made using $r_0 = r_0' = 1.25$, $a = 0.65$, $a' = 0.47$. The resulting shapes Re $[U_d(r)]$ are only approximately like those of a Saxon potential; however, there is a clear trend for the parameters of roughly equivalent Saxon shapes. The equivalent radius $\bar{r}_0$ increases with A roughly like $\bar{r}_0 \approx 1.17 + 0.01A^{1/3}$ for $60 \leqq A \leqq 200$, with the equivalent surface diffuseness roughly constant at $\bar{a} \approx 0.88$ in the same region. Of course, the well depth $\bar{V}$ is of order 100 Mev. For lighter nuclei it is less easy to identify an equivalent Saxon well, but the same trends are maintained. It is intended to use these computed potentials to calculate the elastic scattering and compare with experiment. The imaginary parts predicted are peaked around $r_0 = 1.25$ and somewhat broader than those for nucleons. It is clear this is an inadequate model for Im $[U_d(r)]$, so one may use the predicted real parts and attempt to vary the imaginary parts in order to fit the observed deuteron scattering.

It is interesting to contrast these results with those obtained by assuming a Gaussian form for both $U_{n,p}(r)$ and $\phi_d(s)$.[2] The latter can be computed analytically, and results in a Gaussian for U_d of *larger* "radius."

[2]G. R. Satchler, *Nucl. Phys.* **21**, 116 (1960).

LOCAL ENERGY APPROXIMATION FOR FINITE RANGE IN STRIPPING REACTIONS[1]

J. K. Dickens[2] R. M. Drisko[3] F. G. Perey[2] G. R. Satchler

A numerical comparison is made of the local energy approximation with exact calculations of finite-range effects in typical stripping reactions. The approximation is found to be very accurate.

[1]Abstract of published paper: *Phys. Letters* **15**, 337 (1965).

[2]Neutron Physics Division.

[3]Electronuclear Division.

OPTICAL-MODEL ANALYSIS OF THE SCATTERING OF 24.7-Mev ALPHA PARTICLES[1]

Lynne McFadden[2] G. R. Satchler

The measured elastic scattering of 24.7-Mev alpha particles from the nuclei O, Mg, Al, Si, Ca, Mn, Ni, Co, Cu, Ge, Zr, Ag, In, Sn, Hf, W, Au, Bi, and U has been analyzed using the optical model. Fits were obtained using a four-parameter Woods-Saxon potential. No marked improvement was found by using a more general potential. The fits for medium and heavy nuclei are good, but those for the lighter nuclei are

[1]Abstract of paper submitted for publication in *Nuclear Physics*.

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noticeably poorer. Potential ambiguities were studied in some detail for Ni and Mg, and potentials with depths of about 150 and 200 Mev were obtained for all the nuclei in addition to a more shallow potential. The medium-weight nuclei show a preference for the deep potentials, the light nuclei for the shallow ones. The behavior of the predicted scattering matrix elements is discussed also.

DEPENDENCE OF ANGULAR DISTRIBUTION IN THE (α,p) REACTION ON THE TOTAL ANGULAR-MOMENTUM TRANSFER[1]

L. L. Lee, Jr.[2] A. Marinov[3] C. Mayer-Boricke[4] J. P. Schiffer[3]
R. H. Bassel[5] R. M. Drisko[5] G. R. Satchler

It is shown that the j dependence of the differential cross sections for (α,p) reactions can be explained by spin-orbit coupling effects in the elastic proton channel.

[1]Abstract of published paper: *Phys. Rev. Letters* 14, B533 (1965).

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ANALYSES OF THE SCATTERING OF NUCLEAR PARTICLES BY COLLECTIVE NUCLEI IN TERMS OF THE COUPLED-CHANNEL CALCULATION[1]

T. Tamura

The formalism of the coupled-channel analysis of the scattering of nuclear projectiles by nuclei is presented in detail. Since the necessity for coupled-channel calculations increases with the degree of collectivity exhibited by the target nucleus, the presentation is particularly suited to collective nuclei, with the target states described by phenomenological collective coordinates. Within this restriction the formalism given here is quite general, so that the following cases can be considered: The target can be any (collective) nucleus, even-A or odd-A, vibrational or rotational; the projectile can be either charged or uncharged, and can have any spin; either or both the projectile and the target can be polarized; finally, the energy of the projectile can be very low, since the contribution of the compound-state formation to the cross section can be included. Using a computer program which was written following the above formalism (which can be used to do any of the calculations enumerated above), scattering cross sections for several typical cases were obtained and are presented to show their contrasting behavior when different targets (and different coupling schemes)

[1]Abstract of published paper: *Rev. Mod. Phys.* 37, 679 (1965).

and different projectiles are chosen. Realistic calculations were also made in order to fit a large number of existing experimental data. Good fits were obtained in most cases, which indicates that the coupled-channel calculation is a very powerful tool in explaining various complicated scattering data, and, further, in extracting useful spectroscopic information about the target nucleus. Possible future developments of the present analyses are discussed.

EXCITATION OF THE UNNATURAL-PARITY 3^+ STATE IN ^{24}Mg IN THE INELASTIC SCATTERING OF ALPHA PARTICLES[1]

T. Tamura

As an example of the excitation of unnatural-parity states in even nuclei by the inelastic scattering of alpha particles, an analysis is made of data of $^{24}Mg(\alpha,\alpha')^{24}Mg^*$ processes for $E_\alpha = 28.5$ Mev. The theoretical cross sections are obtained through the coupled-channel calculation, in which 0^+, 2^+, 4^+, 6^+, 2^+, and 3^+ states are coupled together, where the first four states are assumed as members of the $K = 0$ ground band, while the last two as members of the $K = 2$ γ-vibrational band. Reasonably good agreement with experiment was obtained, allowing one to conclude that the multiple-excitation processes can account for the excitation of the unnatural-parity states.

[1]Abstract of published paper: *Nucl. Phys.* 73, 241 (1965).

COUPLED-CHANNEL CALCULATION OF THE PHASE VARIATION IN THE SCATTERING OF ALPHA PARTICLES BY NICKEL ISOTOPES[1]

T. Tamura

It is shown that coupled-channel calculations can fit very well the recent data by Meriwether *et al.* of the scattering of alpha particles of 25 to 100 Mev by nickel isotopes. It is shown in particular that the energy variation of the phase of the inelastic scattering cross section relative to that of the elastic cross section is reasonably explained in this way.

[1]Abstract of published paper: *Nucl. Phys.* 73, 81 (1965).

STATIC QUADRUPOLE MOMENT OF THE FIRST EXCITED 2^+ STATE OF ^{114}Cd[1]

T. Tamura T. Udagawa[2]

It is shown that the very large magnitude, recently found experimentally, of the static quadrupole moment of the first excited 2^+ state of ^{114}Cd can well be accounted for by considering a very simplified model in which the amplitudes of the first and the second 2^+ states are written as linear combinations of those of the one- and two-phonon states. Both phenomenological and microscopic models are considered.

[1]Abstract of published paper: *Phys. Rev. Letters* 15, 765 (1965).

[2]Tokyo Institute of Technology, Tokyo, Japan.

FORTRAN PROGRAMS FOR THE CLEBSCH-GORDAN AND RACAH COEFFICIENTS AND THE 9-*j* SYMBOL[1]

T. Tamura

FORTRAN programs for the Clebsch-Gordan and Racah coefficients and 9-*j* symbol are presented. They are written in a way rather compact and easy to understand. Optimization of the speed of computation was made in these routines. These routines allow for treating the case in which the arguments of these coefficients are very large, and thus can be used, for example, in the analysis of the nuclear reactions of heavy and high-energy projectiles.

[1]Abstract of unpublished paper: ORNL-3877 revised (November 1965).

THE NUCLEON-NUCLEON INTERACTION FROM NUCLEON-NUCLEUS SCATTERING

R. M. Haybron

The inelastic scattering of 100- to 200-Mev protons on nuclei can be expressed in terms of the free, two-nucleon scattering matrix. Since the momentum-transfer dependence of this quantity is determined by the nucleon-nucleon phase shifts, one gets different predictions for the nucleon-nucleus scattering for each phase-shift set. Hence, in principle, the nucleon-nucleus data could provide information about the nucleon-nucleon interaction in this energy range. This possibility is being investigated using several sets of phase shifts and data on nuclei from ^{12}C through ^{40}Ca. Preliminary results indicate that the combined uncertainties in the calculations and experiments for the nucleon-nucleon system preclude a choice of a preferred phase-shift set.

REFRACTION EFFECTS IN DWIA PROTON SCATTERING

R. M. Haybron

The inelastic scattering of high-energy protons by nuclei can be described in the distorted-wave impulse approximation (DWIA), in which the proton-nucleus interaction is expressed in terms of the free, two-nucleon scattering matrix. These calculations are usually performed by evaluating the scattering matrix using the "asymptotic" momenta of the scattering proton. On the other hand it is known that since the proton is moving in a refractive medium, the "local" momenta characterizing the inelastic scattering can be quite different from the asymptotic values. In effect the momentum transfer characterizing the inelastic event is not sharp, and hence the scattering matrix must be averaged over a range of values.

This effect is not especially important at high energies (E_0 = 100 Mev) except for $E0$ and $M1$ transitions. However, it becomes more pronounced for all transitions as the bombarding energy is lowered, and if this type of calculation is to be performed in the 50-to-100-Mev domain, due allowance must be made for it. A code has been written which performs the momentum-transfer averaging for a variety of types of interaction, including the full two-nuclear scattering matrix. Refraction effects are currently being investigated in the energy range 50 to 200 Mev for a variety of cases.

EXCITATION OF QUADRUPOLE AND OCTUPOLE LEVELS OF ^{12}C, ^{16}O, AND ^{40}Ca BY 156-Mev PROTONS[1]

R. M. Haybron[2] H. McManus[3]

The inelastic cross sections and polarizations for the excitation of some observed 2^+ and 3^- levels of ^{12}C, ^{16}O, and ^{40}Ca by 156-Mev protons were calculated in the distorted-wave impulse approximation, using the particle-hole transition densities of Gillet and collaborators. The results were compared with available experimental data, and good qualitative agreement was obtained; in particular the particle-hole densities provided the necessary enhancements of the cross sections. Fits were also attempted using the theory of collective excitations. These provide reasonable fits to the cross-section data, but not to the polarization.

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[1]Abstract of published paper: *Phys. Rev.* **140**, B638 (1965).

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INELASTIC SCATTERING OF HIGH-ENERGY PROTONS IN THE COLLECTIVE THEORY OF EXCITATIONS[1]

R. M. Haybron[2]

The cross section for the inelastic scattering of 156-Mev protons from several light, even-even nuclei has been calculated for the excitation of some strongly excited low-lying states using the collective theory of excitations. Comparison with experiment produces deformation parameters which are in reasonable agreement with those obtained by other means, provided both the real and imaginary portions of the appropriate volume absorbing optical potential are deformed. Similar treatment of surface absorbing potentials yields cross sections which compare closely in shape to the results for volume potentials, but require unreasonably large deformations. Deformation of only the real part of either type of potential does not yield satisfactory fits.

[1]Abstract of paper to be published in *Nuclear Physics*.
[2]Formerly from Michigan State University.

HIGH-ENERGY INELASTIC SCATTERING OF NUCLEONS; THE DISTORTED-WAVE IMPULSE APPROXIMATION[1]

R. M. Haybron[2] H. McManus[3]

The effects of distorted waves on the high-energy inelastic scattering of protons by ^{12}C were investigated using the distorted-wave impulse approximation. It was found that except for electric monopole transitions, the use of distorted waves results in a reduction of the peak differential cross section by a factor of 2 or 3, with little effect on the location or shape of the curve. It was also found that the presence of spin-orbit coupling in the distorting potential has a non-negligible effect on the proton polarization at some angles. The 2^+ level of ^{12}C at 4.43 Mev was treated in some detail in *L-S* and *j-j* coupling extremes to look at the relative effects of distortions on non-spin-flip and spin-flip matrix elements.

[1]Abstract of published paper: *Phys. Rev.* **136**, B1730 (1964).
[2]Formerly from Michigan State University.
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NUCLEAR FORM FACTORS FROM INELASTIC ELECTRON SCATTERING

R. M. Haybron M. B. Johnson R. J. Metzger

The inelastic scattering of high-energy electrons from light nuclei can be satisfactorily described using plane waves, wherein the longitudinal contributions to the cross section are simply related to the Fourier transform of the transition charge density. The longitudinal part of the interaction dominates in the excitation of predominantly collective states, so that in such cases the electron

data should provide a straightforward and relatively complete description of the overlap of excited nuclear state with the ground state.

The computer code QFIT has been written to develop a chi-squared fit to such data. The calculation proceeds as follows:

1. The inelastic form factor $f(q)$ is expanded in terms of a polynomial in the momentum transfer of $e^{-\beta q^2}$.
2. The form factor, $f(q)$, is squared, appropriately normalized, and chi-squared is computed using the input electron data.
3. The coefficients in the expansion of $f(q)$ are varied to obtain a minimum chi-squared fit. (The range parameter β which is initially chosen from the elastic electron data may also be varied if desired.)
4. The Fourier transform of $f(q)$ is then computed. This of course requires a knowledge of the multipolarity of the transition being considered.

This code provides the inelastic form factor or its configuration-space representative. Both of the quantities are useful in a variety of ways, in particular for comparison to the predictions of structure calculations. In addition the reduced matrix element for a given transition is trivially obtained.

THE ^{90}Zr(p,p') REACTION AT 18.8 Mev AND THE NUCLEAR SHELL MODEL[1]

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NUCLEAR REACTIONS. ^{90}Zr(p,p), (p,p'), E = 18.8 Mev. Measured $\sigma(E_p, \theta)$. ^{90}Zr deduced levels, l, β.

The elastic and inelastic scattering of 18.8-Mev protons from ^{90}Zr has been studied. Angular distributions for the elastic and 17 inelastic groups were measured. An optical-model analysis of the elastic scattering was performed. The inelastic scattering was compared with the predictions of the shell model, using a simple two-body interaction between the incident and target nucleons. A Yukawa potential with a range of about 1 fermi and a strength of about 200 Mev give a good fit to the excitation of the states of the $g^2_{9/2}$ configuration. Excitation of the other states is discussed in terms of the shell-model configurations expected to contribute. Arguments are given for the spin-flip strength being small.

[1]Abstract of paper submitted for publication in the *Physical Review*.

[2]University of Michigan.

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PROTON EXCITATION OF VIBRATIONAL STATES OF ^{126}Te[1]

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G. R. Satchler

The differential cross sections for the elastic and inelastic scattering of 12-Mev protons by ^{126}Te have been measured. The results are interpreted in terms of the collective model, using both the distorted-wave and coupled-channel methods.

[1]Abstract of published paper: *Nucl. Phys.* **61**, 448 (1965).

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The quadrupole and octupole vibrational states are identified at 0.67 and 2.395 Mev respectively. Levels at 1.36 and 1.42 Mev are interpreted as due to two quadrupole phonons. Scattering to some of the group of states just above 2 Mev is in agreement with the predictions for the excitation of three quadrupole phonons.

THE ^{40}Ca(d,d), (d,d'), AND (d,p) REACTIONS WITH 12.8-Mev DEUTERONS[1]

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G. R. Satchler

NUCLEAR REACTIONS. ^{40}Ca(d,d'), ^{40}Ca(d,p), E = 12.8 Mev; measured $\sigma(E_{d'}, \theta)$, $\sigma(E_p, \theta)$. ^{40}Ca deduced deformation parameters; ^{41}Ca deduced spectroscopic factors.

Differential cross sections were measured for the ^{40}Ca(d,d), (d,d'), and (d,p) reactions initiated by 12.8-Mev deuterons. Inelastic scattering to the 3.35-Mev (0^+), 3.73-Mev (3^-), and 4.48-Mev (5^-) levels of ^{40}Ca, and (d,p) reactions feeding the ground ($\frac{7}{2}^-$), 1.97-Mev ($\frac{3}{2}^-$), and 2.47-Mev ($\frac{3}{2}^-$) levels of ^{41}Ca were observed. An optical-model analysis of the elastic scattering was made, and the potentials obtained were used in a distorted-wave study of the reactions. The collective model gave a good fit to the inelastic excitation of the 3^- and 5^- levels; it was necessary to use the complex form of interaction in order to obtain reasonable values of the deformation parameters. The effects of finite range and nonlocality were included in the deuteron stripping analysis and yield reasonable agreement with the observed cross sections. The spectroscopic factors extracted when spin-orbit coupling is included in the deuteron optical potential are significantly less than the value unity expected.

[1]Abstract of paper submitted for publication in the *Physical Review*.

[2]Institute of Nuclear Physics, Cracow, Poland, and Institute of Physics, Jagellonian University, Cracow, Poland.

STUDY OF THE ^{40}Ca(d,p)^{41}Ca GROUND-STATE REACTION AT E_d = 14.3 Mev[1]

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The proton polarization from the ^{40}Ca(d,p)^{41}Ca ground-state (g.s.) reaction has been measured in the angular range from 15 to 90° at a mean deuteron energy of 14.3 Mev. The ^{40}Ca(d,d)^{40}Ca and the ^{40}Ca(d,p)^{41}Ca g.s. differential cross sections were determined at the same bombarding energy and within the same angular range. A preliminary analysis of the data in terms of the distorted-wave Born approximation theory is presented. Most calculations were performed in the zero-range approximation with local optical potentials but including the effects of nonlocality in the approximation of Perey. The inclusion of finite range improved the fit to the (d,p) cross sections but had little effect on the polarization. Although a good fit to the polarization data has not been obtained, it is clear that a spin-orbit term is needed in the deuteron optical potential, and furthermore, the indications are that the imaginary part of the spin-orbit potential has to be positive or zero.

[1]Abstract of published paper: *Phys. Rev.* **138**, B1425 (1965).

[2]University of Pittsburgh.

DEUTERON EXCITATION OF TWO-PHONON STATES IN ^{60}Ni[1]

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Scattering cross sections of 15-Mev deuterons by ^{60}Ni to various excited states were measured and fitted theoretically with good agreement in terms of the coupled-channel calculation. It is emphasized that the differential cross section to the two-phonon 0^+ state has a markedly different structure from the differential cross sections to the two-phonon 2^+ and 4^+ states and thus that the (d,d') process is a very useful method in identifying the two-phonon 0^+ states.

[1]Abstract of published paper: *Phys. Letters* **18**, 295 (1965).

[2]Florida State University.

INELASTIC SCATTERING OF DEUTERONS FROM ^{60}Ni AND ^{114}Cd[1]

J. K. Dickens[2] F. G. Perey[2] G. R. Satchler

NUCLEAR REACTIONS. ^{60}Ni(d,d'), E = 9.89, 10.86, 11.92, and 13.56 Mev; ^{114}Cd(d,d'), E = 8, 9, 10, 11, 12, 13, 14, 15 Mev. Measured $\sigma(E_{d'}, \theta)$. Enriched targets.

Differential cross sections for inelastic scattering of deuterons from the first excited states of ^{114}Cd and ^{60}Ni were measured for deuteron bombarding energies between 8 and 15 Mev for ^{114}Cd, and between 9.9 and 13.6 Mev for ^{60}Ni. The data were analyzed by the distorted-wave method, using the collective model of excitation. Good agreement with experiment for all cases is obtained, but only by deforming both real and imaginary parts of the optical potential and including Coulomb excitation. Real coupling alone considerably underestimates the magnitude of the cross sections, even though for nickel it reproduces slightly better the experimental angular distributions. At the lower energies there are large contributions from Coulomb excitation and its interference with the nuclear excitation.

[1]Abstract of paper submitted for publication in *Nuclear Physics*.

[2]Neutron Physics Division.

THE ELASTIC SCATTERING OF 5.5- TO 10.0-Mev ^{3}He PARTICLES BY ^{27}Al NUCLEI[1]

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NUCLEAR REACTIONS. ^{27}Al$(^3$He$,^3$He$)^{27}$Al, $E_{^3\mathrm{He}}$ = 5.5 to 10.0 Mev; measured $\sigma(\theta)$. Natural target.

Angular distributions for the elastic scattering of 5.5-, 7.0-, 8.0-, 9.0-, and 10.0-Mev ^{3}He particles by ^{27}Al nuclei have been measured for scattering angles between 15 and 165° in the laboratory system. The 5.5-Mev results are significantly different from those published by Parry *et al.*[3]

The data have been analyzed, using conventional optical-model potentials.

[1]Abstract of published paper: *Nucl. Phys.* **67**, 417 (1965).

[2]Research School of Physical Sciences, Australian National University, Canberra.

[3]G. Parry, H. D. Scott, and S. Swierszczewski, *Proc. Phys. Soc. (London)* **77**, 230 (1961).

GRAVITATIONAL ACCELERATION OF FREE NEUTRONS[1]

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H. Horstmann[3]

The gravitational acceleration of free neutrons from the Oak Ridge Research Reactor has been measured in the evacuated 180-m flight path at Oak Ridge National Laboratory. The transmission edges associated with the (100) and (002) lattice spacings in a polycrystalline beryllium filter have been used to define particular neutron velocities $v_{hkl} = h/2md(hkl)$ in the "slow beam." Boral filters permitted the selection of a "fast beam" which did not fall appreciably. The differences between the vertical positions of the slit image formed by the "fast beam" and of the two transmission edges (12.7 and 15.5 cm lower) have been determined with the aid of least-squares fits to theoretical curves. An x-ray examination of the beryllium filter established the values for $2d(hkl)$. We find the acceleration of free neutrons due to gravity to be $g = 975.4 \pm 3$ cm/sec^2 (100 planes) and $g = 973.1 \pm 7$ cm/sec^2 (002 planes). These may be compared with the local value, $g = 979.74$ cm/sec^2, and McReynolds's early result, $g = 935 \pm 70$ cm/sec^2. A recent suggestion of Spitzer that there might be a difference in g for the two vertical neutron spin projections $\pm\frac{1}{2}$ does not appear to be confirmed. No splitting greater than a few percent of g is found.

[1]Abstract of published paper: *Phys. Rev.* **139**, B756 (1965).

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ELECTRIC DIPOLE MOMENT OF THE NEUTRON

P. D. Miller J. K. Baird[1] W. Dress[2]
N. F. Ramsey[3]

Prior to the suggestion of parity nonconservation by Lee and Yang[4] in 1957, it was generally accepted that elementary particles could not possess an electric dipole moment. It had been pointed out, however, as early as 1950[5] that parity conservation and the presence or absence of electric dipole moments of elementary particles must rest ultimately on experiment. After Wu *et al.*[6] showed that parity conservation was violated in the weak interactions, it was pointed out by Landau[7] that time-reversal invariance, together with *TCP* invariance, still did not permit elementary particles to possess electric dipole moments correlated with their spin angular momentum. The experiment of Christenson *et al.*[8] on the decay $K_2^0 \rightarrow 2\pi$ has been interpreted as a failure of *CP* and hence time-reversal invariance if *TCP* is still to be invariant. It has also been pointed out by Schiff[9] and by Meister and Rhada[10] that an electric dipole moment of a neutron, eD, could be as large as $D = 2 \times 10^{-21}$ cm without violating the upper

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[3]Harvard University.

[4]T. D. Lee and C. N. Yang, *Phys. Rev.* **105**, 1671 (1957).

[5]E. M. Purcell and N. F. Ramsey, *Phys. Rev.* **78**, 807 (1950).

[6]C. S. Wu *et al.*, *Phys. Rev.* **105**, 1413 (1957).

[7]L. Landau, *Zh. Eksperim. i Teor. Fiz.* **32**, 405 (1957); *Soviet Phys. JETP (English Transl.)* **5**, 336 (1957).

[8]J. H. Christenson *et al.*, *Phys. Rev. Letters* **13**, 138 (1964).

[9]L. Schiff, *Phys. Rev.* **132**, 2194 (1963).

[10]N. L. Meister and T. K. Rhada, *Phys. Rev.* **135**, B769 (1964).

limit of T invariance set by angular correlation experiments in the decay of polarized neutrons.[11,12] A recent analysis by Boulware[13] indicates that if there is a weak T violation, then different models predict neutron electric dipole moments in the range $D = 10^{-23}$ to 10^{-19} cm. Boulware points out also that if the T violation occurs only in the leptonic, or strangeness-changing, interactions, then we could only have an electric dipole moment $D \sim 10^{-28}$ cm.

The most recent experiment to establish an upper limit to an electric dipole moment is that of Hofstadter.[14] He showed that the electric dipole moment of the electron is less than $D = 3.5 \times 10^{-16}$ cm. The most sensitive electric-dipole-moment measurements can be done on neutral particles, and the most sensitive experiment to date is that of Smith, Ramsey, and Purcell.[15] They showed, by means of a magnetic resonance experiment with a thermal-neutron beam in a strong electrostatic field, that for the neutron $D < 5 \times 10^{-20}$ cm.

The apparatus for the present experiment will be a split-coil magnetic resonance spectrometer as developed by Ramsey.[16] In the uniform magnetic field region between the rf coils, a strong parallel electrostatic field will be applied. If an electric dipole moment exists, the Hamiltonian in this region is given by

$$\mathcal{H} = \vec{\mu} \cdot \vec{B} + \vec{p} \cdot \vec{E} \, .$$

Thus if there exists an electric dipole moment of the neutron, $\vec{p}$, correlated with its spin, we should see a small shift in the resonant frequency given by

$$\delta\nu_{EDM} = \frac{eDE}{h} \, .$$

The sensitivity of the experiment is strongly enhanced by making the magnetic resonance as narrow as possible. The natural width of the resonance is determined by the uncertainty principle to be approximately

$$h \, \Delta\nu = \frac{h}{\Delta t} \, ,$$

where Δt is the transit time of the neutrons through the apparatus. Thus this width $\Delta\nu$ can be minimized by making the apparatus long and by using very slow neutrons.

The source of neutrons will be the HB-2 beam hole of the LITR, which has a thermal flux of 3×10^{13} neutrons cm^{-2} sec^{-1} at the inside end. A bent, neutron-conducting tube[17] of the type developed by Maier-Leibnitz[18] will be used to bring out a beam of the coldest neutrons from the Maxwell-Boltzmann distribution. Neutrons coming out of the tube will be polarized by reflection from an iron-cobalt magnetic mirror. The average velocity of the spectrum after polarization is calculated to be about 50 m/sec, and the intensity of neutrons passing through the apparatus should be $\sim$1000 to 10,000/sec. The calculated spectrum of neutrons reaching the detector is shown in Fig. 1. The

[11] M. A. Clark and J. M. Robson, *Can. J. Phys.* **38**, 693 (1960).

[12] M. T. Burgy *et al.*, *Phys. Rev.* **120**, 1829 (1960).

[13] D. G. Boulware, *Nuovo Cimento* **50A**, 1041 (1965).

[14] R. Hofstadter, report at the 1964 Dubna Conference on High Energy Physics.

[15] J. H. Smith, N. F. Ramsey, and E. M. Purcell, *Phys. Rev.* **108**, 120 (1957).

[16] See, for example, N. F. Ramsey, *Molecular Beams*, Oxford Univ. Press, London, 1956.

[17] P. D. Miller, *A Low Pass Filter for Cold Neutrons to Be Used in a Search for a Neutron Electric Dipole Moment*, ORNL-TM-1149 (1965).

[18] See, for example, H. Maier-Leibnitz and T. Springer, *J. Nucl. Energy: Pt. A & B* **17**, 217 (1963).

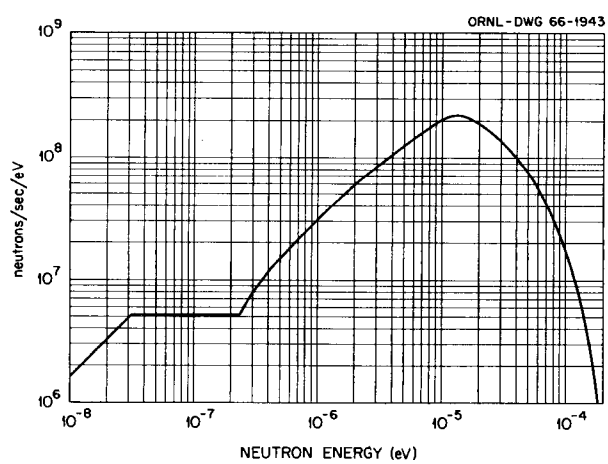

Fig. 1. Spectrum of Neutrons Reaching Detector After Passing Through a Nickel Totally Reflecting Low-Pass Filter with Radius of Curvature of 100 cm, and Being Reflected from an Iron-Cobalt Magnetic Mirror at an Angle of 4°.

magnetic resonance spectrometer will be about 2 m long. It will have a magnetic field of about 10 gauss provided by permanent magnets, and the electrostatic field will be about 150 to 200 kv/cm. After passing through the magnetic resonance spectrometer, the neutron spins will be analyzed by reflection from another iron-cobalt magnetic mirror, and they will then be detected by an ^{6}Li-loaded glass scintillator.

The colder neutron spectrum, longer apparatus, higher intensity, improved neutron polarizing and analyzing mirrors, and higher electrostatic field should provide a sensitivity of about $D = 10^{-23}$ cm.

The current (as of February 1, 1966) status of the experiment is as follows:

1. The beam hole liner for the HB-2 beam hole of the LITR is under construction. Installation at the reactor is expected to take place in April.
2. The design engineering is completed on the magnetic resonance spectrometer, and a fabricator is being sought.
3. Most of the designs of smaller components such as the low-pass filter section of the neutron-conducting tube, the polarizing and analyzing magnets, and the detector are completed.

A LOW-PASS FILTER FOR COLD NEUTRONS TO BE USED IN A SEARCH FOR A NEUTRON ELECTRIC DIPOLE MOMENT[1]

P. D. Miller

An experiment to detect or set a new upper limit on the electric dipole moment of the neutron is being planned. Central to the apparatus is a bent neutron-conducting tube to be installed at the HB-2 beam hole of the LITR. The dependence on various design parameters of the cold neutron spectrum from such a tube is investigated.

[1]Abstract of ORNL-TM-1149.

STRONG *p*-WAVE NEUTRON RESONANCES IN ^{120}Sn, ^{118}Sn, AND ^{124}Sn

J. A. Harvey Toyojiro Fuketa[1]

NUCLEAR REACTIONS. ^{120}Sn, ^{118}Sn, ^{124}Sn; measured σ_T. ^{121}Sn, ^{119}Sn, ^{125}Sn deduced levels, π, J. Enriched target.

In the study of the spectra of the gamma rays from neutron capture in individual resonances of the isotopes of tin, several strong high-energy gamma rays[2] were observed to the ground and low-lying excited states which have low spin and even parity. If these capturing states were formed by *s*-wave neutrons, these transitions would most likely be *M*1 transitions. If they are *M*1 transitions, their strengths would be from ~10 to 100 times those expected from the summary by Bartholomew.[3] However, if the resonances were *p*-wave resonances, these high-energy gamma rays could be *E*1 transitions, and their strengths would be consistent with those summarized by Bartholomew. Several of these resonances have sufficiently large neutron

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[2]J. A. Harvey *et al.*, *Phys. Div. Ann. Progr. Rept. Dec. 31, 1963*, ORNL-3582, p. 62.

[3]G. A. Bartholomew, *Ann. Rev. Nucl. Sci.* 11, 259 (1961).

widths (~1 to ~50% scattering) that it is possible to look for the interference between resonance and potential scattering to determine whether the resonances are *s*- or *p*-wave resonances.

Neutron transmission measurements have been made with the ORR fast-chopper time-of-flight neutron spectrometer on 10-cm-thick metal samples of ^{120}Sn (200 g, 98%) and ^{118}Sn (160 g, 97%). Measurements were made with BF_3 proportional counters at the 45-m flight station with a resolution of 60 nsec/m and at the 180-m station with a resolution of 15 nsec/m. The open-beam counting rate at the 45-m flight station was ~13 counts per 0.64-μsec channel per minute. The open-beam background was ~3%, and the sample-in background ~1% of the open-beam rate. The transmission of the 10-cm sample was only 0.15, and runs of several days' duration were required to obtain transmission points with statistical accuracies of ~2%. The open-beam counting rate at 180 m was ~1.5 counts per 0.64-μsec channel per minute. The open-beam background was ~13%, and the sample-in background ~10% of the open-beam rate. Runs of several days' duration were required to obtain transmission points with statistical accuracies of ~6%.

The resonances have been analyzed with the area and shape analysis programs,[4] which include Doppler and resolution broadening. The resonances in ^{120}Sn at 922, 3200, and 9200 ev show considerable interference between resonance and potential scattering and are definitely *s*-wave resonances. The resonances at 426 and 1720 ev with ~20 and ~70% scattering, respectively, do not exhibit the asymmetry computed for *s*-wave resonances. Hence, both these resonances must be *p*-wave resonances. Figure 1 shows the comparison of theoretical curves, including Doppler and resolution broadening, with the experimental transmission points for $l = 0$ and $l \neq 0$ for these two resonances. Strong gamma-ray transitions[2] had been observed from neutron capture in this 426-ev resonance to the ground state and low-lying excited states.

The large resonances in ^{118}Sn at 359, 770, 1580, 2960, 3450, and 7400 ev are obviously *s*-wave resonances from the interference observed. Several of these resonances were already known to be *s*-wave resonances from the earlier transmission measurements of Fuketa *et al.*,[5] using a 2.5-cm-thick sample. The resonance at 45.8 ev is probably a *p*-wave resonance; however, it is difficult to make a definite assignment since Γ_n/Γ for this

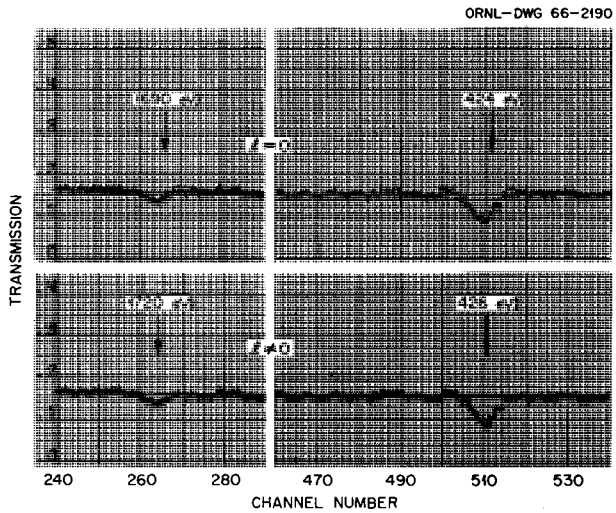

Fig. 1. Experimental Data and the Theoretical Fits for the Two Resonances at 426 and 1720 ev, Assuming $l = 0$ and $l \neq 0$.

resonance is only ~0.6%. Strong gamma-ray transitions[2] had been observed from neutron capture in this 45.8-ev resonance to the $\frac{1}{2}^+$ ground state and/or the $\frac{3}{2}^+$ excited state at 25 kev, and the $\frac{3}{2}$ or $\frac{5}{2}^+$ state at 1090 kev. If the 45.8-ev resonance were an *s*-wave resonance, these high-energy gamma transitions would have *M*1 strengths ~50 times the average value[3] for *M*1 transitions for other nuclides in this mass region.

From the transmission measurements[5] with a 2.5-cm-thick sample of ^{124}Sn (35 g, 93%), it was determined that the 62.0-ev resonance with 10% scattering was definitely a *p*-wave resonance. Strong gamma-ray transitions[2] had also been observed from neutron capture in this resonance to the low-lying $\frac{3}{2}^+$ and $\frac{1}{2}^+$ excited states.

Assuming a *p*-wave strength function of 4×10^{-4}, a nuclear radius of 0.62×10^{-12} cm, and that the level spacing does not depend on parity, the 62.0-ev resonance in ^{124}Sn is ~80 times stronger than expected for an average *p*-wave resonance. The

[4] S. E. Atta and J. A. Harvey, ORNL-3205 (1961) and *Addendum; Phys. Div. Ann. Progr. Rept. Jan. 31, 1963*, ORNL-3425, p. 46.

[5] T. Fuketa, F. A. Khan, and J. A. Harvey, *Phys. Div. Ann. Progr. Rept. Jan. 31, 1963*, ORNL-3425, p. 36.

p-wave resonances at 426 and 1720 ev in ^{120}Sn and at 45.8 ev in ^{118}Sn are ~20 times stronger than expected for average p-wave resonances in these nuclides. These strong p-wave resonances have reduced neutron widths which are comparable to those of some of the three-quasi-particle $\frac{1}{2}^+$ states computed by Shakin.[6] These p-wave resonances are suggestive of p-wave "doorway" states because of their strengths and their strong $E1$ transitions to low-lying states.

[6]C. Shakin, *Ann. Phys. (N.Y.)* **22**, 373 (1963).

LEVEL SPACING AND s-WAVE NEUTRON STRENGTH FUNCTION OF THE ODD-Z, ODD-N NUCLIDE ^{138}La

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NUCLEAR REACTIONS. ^{138}La; measured σ_{nT}. Deduced resonance parameters, E_0, $2g\Gamma_n^\circ$, Γ_γ; level density and $\overline{\Gamma_n^\circ}/D$. Enriched target.

Although a vast amount of information is available on the level spacings and s-wave neutron strength functions of heavy nuclides, little is known about the neutron cross sections of the heavy odd-Z, odd-N target nuclides. There are only a few stable odd-Z, odd-N isotopes; and these occur in nature in very low abundance compared to the odd-Z, even-N isotopes. Enriched samples are needed in order to be able to assign resonances to these odd-Z, odd-N nuclides. Often more resonances in a low-abundance isotope can be observed with a small enriched sample than with a large sample of natural enrichment. In natural lanthanum, ^{138}La is abundant to only 0.089%. The enriched sample available for these neutron transmission measurements was a 1.17-g sample of La_2O_3 enriched to 7.03% in ^{138}La. The oxide powder was packed into a small sample holder with a cross section 0.050 × 1.063 in., which resulted in a sample thickness of 0.01220×10^{24} atoms of lanthanum per square centimeter.

Transmission measurements from 0.2 to 2000 ev in four different energy ranges were made with the ORR fast-chopper time-of-flight neutron spectrometer using BF_3 proportional counters at the 45-m flight station. The energy resolution varied from 1 to 2% in energy below 50 ev and was 60 nsec/m above 50 ev. The open-beam counting rate was 0.5 count/min per 0.5-μsec channel, and the room background was ~10% above 50 ev and less below 50 ev. The backgrounds were determined by the technique of "blacked-out resonances," such as the 132-ev cobalt resonance. The sample was alternated with the background sample in about a 1-hr cycle, with each transmission measurement requiring a few days to obtain sufficient counts. Transmission data vs time of flight obtained with 0.5-μsec channel widths are shown in Fig. 1 from

Table 1. Parameters of Resonances of ^{138}La

E_0 (ev)	$2g\Gamma_n^\circ$ (mv)[a]
3.08 ± 0.03	0.73 ± 0.03
21.1 ± 0.1	0.96 ± 0.05
67.1 ± 0.3	1.9 ± 0.1
90.0 ± 0.4	2.0 ± 0.1
131.2 ± 0.7	4.6 ± 0.3
220 ± 1	9.5 ± 1.0
240 ± 2	20 ± 2
261 ± 2	22 ± 2
306 ± 3	36 ± 3
356 ± 3	12 ± 2

[a]$2g\Gamma_n^\circ = 2g\Gamma_n/\sqrt{E_0 \text{ (in ev)}}$.

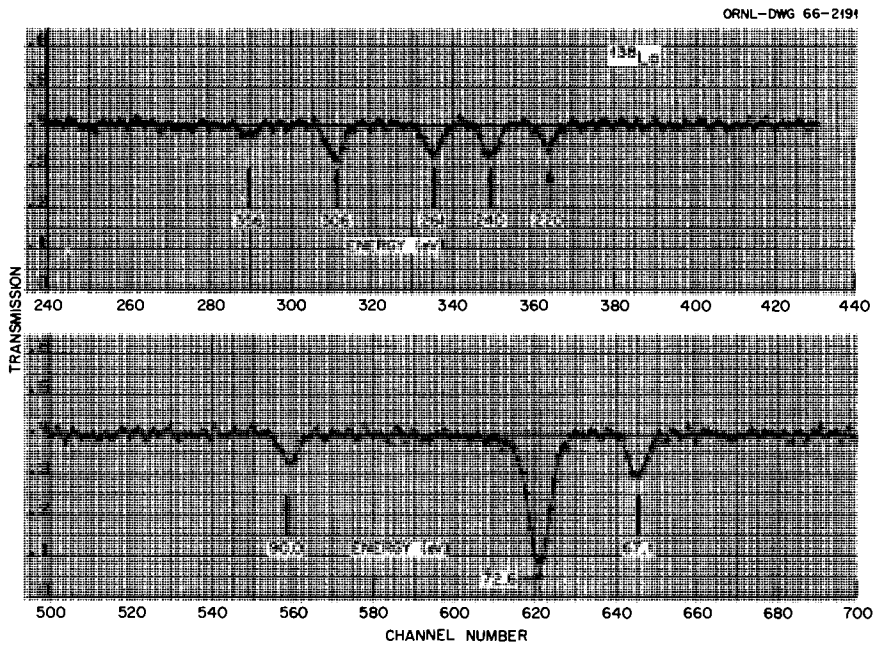

Fig. 1. Theoretical Fit to the Experimental Transmission of an La_2O_3 Sample Enriched to 7.03% in ^{138}La.

450 to 160 ev and from 110 to 60 ev. The statistical accuracies of the transmission points are ~1.5%, and the resolution is ~4.1 channels. The transmission data have been analyzed, using the area analysis program,[1] with a value for Γ_γ of 0.10 ev. The parameters for the ten resonances assigned to ^{138}La are listed in Table 1. These resonances have also been observed in capture cross-section measurements.[2] The large resonance in Fig. 1 at 72.6 ev and another resonance at 1200 ev are due to ^{139}La. The resonances at 3.08 and 21.1 ev have been reported previously[3] from measurements with an ^{138}La sample enriched to only 0.597%.

From the parameters of the resonances up to 160 ev and a 40% correction[4] for "missed" resonances, a value of 46 ± 15 ev was obtained for the average level spacing per spin state. Since the spin of ^{138}La is 5^-, the average level spacing refers to the spacings of levels with spins $^9/_2$ and $^{11}/_2$ with odd parity. From the parameters of the eight resonances up to 280 ev and a 16% correction[4] for "missed" resonances, a value of $(1.3 \pm 0.6) \times 10^{-4}$ was obtained for the *s*-wave neutron strength function. This value is somewhat lower than theoretical predictions,[5] which range from 2 to 3×10^{-4} for this mass number.

The radiation width of the 3.08-ev resonance was determined to be 0.099 ± 0.006 ev from shape analysis of the transmission data of the ^{138}La sample. The error includes contributions due to the uncertainties in the resolution and the Doppler broadening. This value of Γ_γ is in good agreement with the value of 0.11 ± 0.01 ev obtained using a natural lanthanum sample.

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[1] S. E. Atta and J. A. Harvey, ORNL-3205 (1961) and *Addendum; Phys. Div. Ann. Progr. Rept. Jan. 31, 1963*, ORNL-3425, p. 46.

[2] R. C. Block, H. W. Hockenbury, and J. E. Russell, *Reports to NCSAG (June 1964)*, WASH-1048, p. 71.

[3] R. C. Block, G. G. Slaughter, and J. A. Harvey, *Phys. Div. Ann. Progr. Rept. Mar. 10, 1959*, ORNL-2718, p. 26.

[4] T. Fuketa and J. A. Harvey, *Nucl. Instr. Methods* **33**, 107 (1965).

[5] D. M. Chase, L. Wilets, and A. R. Edmonds, *Phys. Rev.* **110**, 1080 (1958); F. Perey and B. Buck, *Nucl. Phys.* **32**, 353 (1962).

PARAMETERS OF NEUTRON RESONANCES IN ^{180}W

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NUCLEAR REACTIONS. ^{180}W; measured σ_{nT}. Deduced resonance parameters, E_0, Γ_n, Γ_n°; level density and $\overline{\Gamma_n^\circ}/D$. Enriched and natural targets.

Transmission measurements have been made with the ORNL fast-chopper time-of-flight spectrometer upon a sample of natural tungsten and upon a 10.05-g sample of $^{180}WO_3$ enriched to 6.93%. The contents of the other isotopes were as follows: ^{182}W (43.7%), ^{183}W (11.8%), ^{184}W (18.8%), and ^{186}W (18.7%). The measurements were made, using BF_3 proportional counters, at the 45-m station with a resolution of 1 to 2% from 0.1 to 100 ev and 50 nsec/m from 100 to 400 ev.

The sample was packed into four standard chopper sample holders with a cross-sectional area of 0.050 × 1.063 in. This resulted in an average sample thickness of 0.0194×10^{24} atoms of W per square centimeter.

The transmission data have been analyzed, using the area analysis program,[2] assuming a radiation width of 0.060 ev. Parameters have been obtained for five resonances assigned to ^{180}W and are listed in Table 1. The resonances at 15.9 and 75 ev were observed previously by Bollinger *et al.*[3] from gamma-ray spectra measurements and were assigned to either ^{180}W or ^{182}W.

From these parameters the average level spacing, D, is ~20 ev, which is a factor of 3 to 5 smaller than those of the other three even-even target nuclides.[4] The s-wave neutron strength function $(\overline{\Gamma_n^\circ}/D)$ is $\sim 1 \times 10^{-4}$, which is a factor of ~2 smaller than those of the other tungsten isotopes; but this may not be significant, since the number of resonances assigned to ^{180}W is so small.

[1]Visitor from Kiel University, Kiel, Germany.

[2]S. E. Atta and J. A. Harvey, *Numerical Analysis of Neutron Resonances*, ORNL-3205 (1961) and *Addendum; Phys. Div. Ann. Progr. Rept. Jan. 31, 1963*, ORNL-3425, p. 46.

[3]L. M. Bollinger *et al.*, *Phys. Rev.* **132**, 1640 (1963).

[4]R. C. Block, J. E. Russell, and R. W. Hockenbury, *Phys. Div. Ann. Progr. Rept. Dec. 31, 1964*, ORNL-3778, pp. 59–61.

Table 1. Parameters of Resonances in ^{180}W

E_0 (ev)	Γ_n (ev)	Γ_n° (ev)[a]
	$\times 10^{-3}$	$\times 10^{-3}$
15.9 ± 0.1	12.5 ± 1.5	3.0
49.3 ± 0.1	6.2 ± 0.7	0.88
62.7 ± 0.2	1.4 ± 0.2	0.18
75.2 ± 0.2	35 ± 2	4.0
87.4 ± 0.3	7.3 ± 0.5	0.78

[a]$\Gamma_n^\circ = \Gamma_n/\sqrt{E_0 \text{ (in ev)}}$.

THE PARAMETERS OF THE NEUTRON RESONANCES IN ^{182}W, ^{183}W, ^{184}W, AND ^{186}W

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NUCLEAR REACTIONS. ^{182}W, ^{183}W, ^{184}W, ^{186}W; measured $\sigma_{nT}(E)$, $\sigma_{n\gamma}(E)$. Deduced resonance parameters, E_0, Γ_n, Γ_γ, J; level densities and $\bar{\Gamma}_n^0/D$ for isotopes. Enriched targets.

Neutron capture and transmission measurements were reported last year[3] for separated samples of ^{182}W, ^{183}W, ^{184}W, and ^{186}W, but at that time only the capture data had been reduced to cross sections. All of the data have now been reduced, and resonance parameters have been obtained for the tungsten resonances up to approximately 2 kev. These parameters are presented in Tables 1 through 4 for the resonances in ^{182}W, ^{183}W, ^{184}W, and ^{186}W respectively (parameters for the low-energy resonances were taken from BNL-325, second edition).

For convenience, the results for the even-even tungsten isotopes (Tables 1, 3, and 4) will be discussed first. The neutron resonance energies as determined by the high-resolution capture measurements are listed in column 1. The transmission data were analyzed for neutron widths with the aid of the Harvey-Atta Area Code and the IBM 7090 computer. A constant radiation width of 70 mv was assumed for all the even-even tungsten resonances, and the resultant neutron widths are listed in column 2. The errors in column 2 are standard deviations based on counting statistics. In order to analyze the capture data, a Monte Carlo code was prepared by J. G. Sullivan of the Mathematics Division to include the effects of multiple neutron scattering in calculating the neutron capture in the tungsten resonances. With the aid of this Monte Carlo code, the area under a capture resonance can be reduced to a functional relationship between the neutron and radiation widths, which together can account for this area. Similarly, the area under the resonance in the transmission measurement can also be reduced to a different functional relationship between the neutron and radiation widths. By plotting these two relationships (i.e., a plot of radiation width vs neutron width), the intersection of the transmission and capture curves uniquely gives the neutron and radiation width of the resonance. These results are listed in columns 3 and 4 for the radiation and neutron widths respectively. For the cases where the neutron width is much smaller than the radiation width, a radiation width of 70 mv was assumed. (It is interesting to note the extreme sensitivity of the capture detector to detect small resonances which were essentially "missed" by the transmission detector.) The errors (standard deviation) quoted for the parameters in columns 3 and 4 are composed of errors due to counting statistics, determination of the capture detector efficiency, and determination of the neutron flux incident upon the tungsten samples. The reduced neutron widths, assuming that all of the resonances are due to s-wave neutrons, are listed in column 5.

Twenty-six resonances were observed in ^{182}W below 1200 ev. However, 11 of these resonances have a reduced neutron width (column 5) of less than 5% of the average reduced neutron width for all 26 resonances. A Porter-Thomas distribution of s-wave resonances predicts that only 4 resonances out of 26 should have a reduced neutron width less than 5% of the average reduced width. Thus, there appears to be an "excess" of approximately 7 resonances. Similarly, of the 24 resonances observed in ^{184}W below 2000 ev, 7 resonances have a reduced width less than 5% of the average reduced width, whereas only approximately 4 resonances are predicted from a Porter-Thomas distribution to have reduced widths of less than 5% of the average. For ^{186}W, of the 27 resonances observed below 2200 ev, 8 resonances

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[3]R. C. Block, R. W. Hockenbury, and J. E. Russell, *Phys. Div. Ann. Progr. Rept. Dec. 31, 1964*, ORNL-3778, p. 53.

have a reduced neutron width of less than 5% of the average reduced widths, whereas a Porter-Thomas distribution predicts only approximately 5 such resonances. This excess of small resonances is attributed to the inclusion of small *p*-wave resonances. Such *p*-wave resonances will have quite small neutron widths at these low energies. The average level spacing for *s*-wave resonances in the even-even tungsten isotopes can then be estimated by correcting for this excess of small resonances and then dividing the remaining number of resonances into the energy

Table 1. Resonance Parameters of ^{182}W

E_0 (ev)	Γ_n (ev)	Γ_γ (ev)	Γ_n (ev)	Γ_n° (ev)
				$\times 10^{-3}$
4.14[a]			1.45×10^{-3}[a]	0.71[a]
21.2[a]			37×10^{-3}[a]	8.0[a]
98	$<10^{-3}$	0.07[b]	0.01×10^{-3}	0.001
114.7	0.29 ± 0.02	(0.065 ± 0.006)	0.29 ± 0.02	27
[130.5][c]	$<10^{-3}$		$<10^{-3}$	[<0.1][c]
214	$(3 \pm 1) \times 10^{-3}$	0.07[b]	$(2.8 \pm 0.3) \times 10^{-3}$	0.19
250	1.1 ± 0.1	0.064 ± 0.006	1.1 ± 0.1	70
283	$(2.9 \pm 1.4) \times 10^{-3}$	0.07[b]	$(1.1 \pm 0.1) \times 10^{-3}$	0.065
[303][c]	$<10^{-3}$	0.07[b]	$(0.15 \pm 0.04) \times 10^{-3}$	[0.009][c]
343	$(6 \pm 2) \times 10^{-3}$	0.07[b]	$(8.4 \pm 0.8) \times 10^{-3}$	0.045
378	0.13 ± 0.03	0.065 ± 0.013	0.13 ± 0.03	6.7
410	$<10^{-3}$	0.07[b]	$(0.2 \pm 0.1) \times 10^{-3}$	0.01
430	0.28 ± 0.04	0.055 ± 0.007	0.28 ± 0.04	14
486	0.50 ± 0.07	0.049 ± 0.007	0.50 ± 0.07	23
580	0.30 ± 0.07	0.057 ± 0.007	0.30 ± 0.07	12
616	$<10 \times 10^{-3}$	0.07[b]	$(1.4 \pm 0.3) \times 10^{-3}$	0.056
658	0.16 ± 0.05	0.059 ± 0.007	0.16 ± 0.05	6.2
673	$<10 \times 10^{-3}$	0.07[b]	$(0.6 \pm 0.3) \times 10^{-3}$	0.023
762	$(69 \pm 25) \times 10^{-3}$	0.074 ± 0.027	0.069 ± 0.025	2.5
785	$<40 \times 10^{-3}$	0.07[b]	$(14 \pm 2) \times 10^{-3}$	0.50
866	$<40 \times 10^{-3}$	0.07[b]	$(21 \pm 3) \times 10^{-3}$	0.72
922	0.40 ± 0.13	(0.078 ± 0.012)	0.40 ± 0.13	13
951	2.2 ± 0.2	(0.077 ± 0.016)	2.2 ± 0.2	71
1010	0.49 ± 0.19	0.070 ± 0.011	0.49 ± 0.19	16
1100	1.6 ± 0.2	0.069 ± 0.008	1.6 ± 0.2	48
1170	0.48 ± 0.20	0.058 ± 0.008	0.48 ± 0.20	14

[a]From BNL-325, 2d ed.
[b]Assumed value.
[c]Very weak, *if* real resonance.

span over which they were observed. This leads to average level spacings of (63 ± 10) ev, (95 ± 14) ev, and (92 ± 13) ev for ^{182}W, ^{184}W, and ^{186}W respectively.

Although the average level spacing is severely affected by the inclusion or exclusion of small resonances, the *s*-wave strength function (Γ_n^o/D) is only slightly affected. The strength functions for ^{182}W, ^{184}W, and ^{186}W are $(2.9 \pm 0.9) \times 10^{-4}$, $(2.6 \pm 0.8) \times 10^{-4}$, and $(1.8 \pm 0.5) \times 10^{-4}$ respectively. These *s*-wave strength functions agree within the stated errors with strength functions of other nuclides in this mass region.

The parameters of the ^{183}W resonances are listed in Table 2. Column 1 lists the resonance energies from the capture measurements, and columns 2 and 3 list the neutron widths from the Harvey-Atta area analysis. Column 2 is for the assumption of spin 0 resonances ($g = 1/4$) and column 3 for the assumption of spin 1 resonances

Table 2. Resonance Parameters of ^{183}W

E_0 (ev)	Γ_n ($g = 1/4$) (ev)	Γ_n ($g = 3/4$) (ev)	Γ_γ ($g = 1/4$) (ev)	Γ_n ($g = 1/4$) (ev)	Γ_γ ($g = 3/4$) (ev)	Γ_n ($g = 3/4$) (ev)	J	Γ_n^o (ev)
								$\times 10^{-3}$
7.62[a]								0.7[a]
27.1[a]								7.5[a]
40.7[a]			[0.08][b]	$(9.4 \pm 1.2) \times 10^{-3}$	[0.08][b]	$(3.0 \pm 0.4) \times 10^{-3}$		0.97
46.2[a]							1	22.6[a]
47.9[a]							0	17.8[a]
65.5[a]						$(2.5 \pm 0.3) \times 10^{-3}$		0.17[a]
101.3	0.22 ± 0.03	0.095 ± 0.010			0.098 ± 0.016	0.098 ± 0.010	1	9.7
104.1	$(5.8 \pm 1.2) \times 10^{-3}$	$(1.9 \pm 0.4) \times 10^{-3}$	[0.08][b]	$(9 \pm 0.9) \times 10^{-3}$	[0.08][b]	$(3 \pm 0.3) \times 10^{-3}$		0.59
138.3	$(17 \pm 3) \times 10^{-3}$	$(5.5 \pm 0.9) \times 10^{-3}$	[0.08][b]	$(15 \pm 2) \times 10^{-3}$	[0.08][b]	$(4.2 \pm 0.5) \times 10^{-3}$		0.82
144.6	0.095 ± 0.009	0.032 ± 0.003	0.09 ± 0.02	0.095 ± 0.009			0	7.9
154.9	0.41 ± 0.05	0.20 ± 0.03	~0.08	0.410[a]			0	32.0[a]
157.3	0.15 ± 0.01	0.050 ± 0.004			~0.08	0.067[a]	1	5.3[a]
174.3	0.15 ± 0.01	0.053 ± 0.004			(0.09 ± 0.03)	(0.053 ± 0.004)	1	4.0
192.6	0.10 ± 0.01	0.035 ± 0.004			(0.07 ± 0.03)	(0.035 ± 0.004)	1	2.5
203.8			[0.08][b]	$(5.2 \pm 0.8) \times 10^{-3}$	[0.08][b]	$(1.7 \pm 0.3) \times 10^{-3}$		0.24
220.8			[0.08][b]	$(8 \pm 1) \times 10^{-3}$	[0.08][b]	$(2.6 \pm 0.3) \times 10^{-3}$		0.36
228	$(15 \pm 7) \times 10^{-3}$	$(5 \pm 2) \times 10^{-3}$	[0.08][b]	$(2.2 \pm 0.3) \times 10^{-3}$	[0.08][b]	$(0.73 \pm 0.11) \times 10^{-3}$		0.10
236	$(21 \pm 7) \times 10^{-3}$	$(7 \pm 2) \times 10^{-3}$	[0.08][b]	$(30 \pm 10) \times 10^{-3}$	[0.08][b]	$(8 \pm 2) \times 10^{-3}$		1.2
241	$(25 \pm 8) \times 10^{-3}$	$(8 \pm 3) \times 10^{-3}$	[0.08][b]	$(90 \pm 30) \times 10^{-3}$	[0.08][b]	$(17 \pm 5) \times 10^{-3}$		3.4
244			[0.08][b]	$(14 \pm 2) \times 10^{-3}$	[0.08][b]	$(5 \pm 1) \times 10^{-3}$		0.61
259	0.15 ± 0.02	0.050 ± 0.007			(0.10 ± 0.04)	(0.050 ± 0.007)	1	3.1
280	0.46 ± 0.05	0.20 ± 0.02			(0.073 ± 0.010)	(0.21 ± 0.023)	1	12.5
289	$(30 \pm 15) \times 10^{-3}$	$(10 \pm 5) \times 10^{-3}$	[0.08][b]	$(11 \pm 3) \times 10^{-3}$	[0.08][b]	$(4 \pm 1) \times 10^{-3}$		0.44
297	0.10 ± 0.02	0.038 ± 0.007			(0.099 ± 0.032)	(0.039 ± 0.007)	1	2.3
323	0.23 ± 0.03	0.08 ± 0.01			(0.098 ± 0.026)	(0.082 ± 0.012)	1	4.6
338	$(16 \pm 16) \times 10^{-3}$	$(6 \pm 6) \times 10^{-3}$	[0.08][b]	$(33 \pm 4) \times 10^{-3}$	[0.08][b]	$(9 \pm 1) \times 10^{-3}$		1.1
349	(0.39 ± 0.06)	(0.14 ± 0.02)			(0.095 ± 0.019)	(0.140 ± 0.028)	1	7.5
354			[0.08][b]	$(8 \pm 4) \times 10^{-3}$	[0.08][b]	$(2.6 \pm 1.3) \times 10^{-3}$		0.28
361	(0.10 ± 0.03)	(0.035 ± 0.010)			(0.070 ± 0.021)	(0.035 ± 0.010)	1	1.8
379	(0.22 ± 0.04)	(0.074 ± 0.015)			(0.078 ± 0.023)	(0.074 ± 0.015)	1	3.8
392	(0.06 ± 0.03)	(0.02 ± 0.01)	[0.08][b]	7.6	[0.08][b]	(0.048 ± 0.010)		2.4

[a]From BNL-325, 2d ed.
[b]Assumed value.

($g = 3/4$). The combined results of transmission and capture area analysis for spin 0 and spin 1 resonances are listed in columns 4 and 5 and columns 6 and 7. In columns 4 and 5, or 6 and 7, a blank space means that the data could not be fitted by that spin assignment. Column 8 lists the spin assignments of the resonances as measured in this experiment. These assignments were made on the basis of the radiation widths obtained from the capture and transmission analysis; if the assumption of one spin produced a radiation width which deviated greatly from the average radiation width for ^{183}W resonances, then this spin assignment was ruled out. Column 9 lists the reduced neutron widths. For those resonances where a spin was not assigned, the average reduced width is listed (i.e., for the assumption of $g = 1/2$).

Table 3. Resonance Parameters of ^{184}W

E_0 (ev)	Γ_n (ev)	Γ_γ (ev)	Γ_n (ev)	Γ_n° (ev)
				$\times 10^{-3}$
102.1	$(4.1 \pm 0.7) \times 10^{-3}$	0.07[a]	$(3.5 \pm 0.4) \times 10^{-3}$	0.35
184.7	1.2 ± 0.1	0.078 ± 0.011	1.2 ± 0.1	88
244	$(2.3 \pm 1.8) \times 10^{-3}$	0.07[a]	$(2.4 \pm 0.3) \times 10^{-3}$	0.15
311	$(75 \pm 15) \times 10^{-3}$	0.051 ± 0.009	0.075 ± 0.015	4.3
424	$(40 \pm 10) \times 10^{-3}$	0.069 ± 0.014	0.042 ± 0.10	1.9
[595][b]	$<8 \times 10^{-3}$	0.07[a]	$(1.0 \pm 0.3) \times 10^{-3}$	[0.041][b]
684	0.68 ± 0.11	0.078 ± 0.008	0.68 ± 0.11	26
705	$<10 \times 10^{-3}$	0.07[a]	$(6.6 \pm 1.0) \times 10^{-3}$	0.25
787	$(60 \pm 40) \times 10^{-3}$	0.07[a]	$(26 \pm 4) \times 10^{-3}$	0.93
802	1.6 ± 0.2	0.079 ± 0.008	1.6 ± 0.2	56
961	1.6 ± 0.3	0.11 ± 0.01	1.6 ± 0.3	52
1000	0.14 ± 0.07	0.055 ± 0.007	0.14 ± 0.07	4.4
1090	3.4 ± 0.3	0.095 ± 0.010	3.4 ± 0.3	103
1140	0.34 ± 0.13	0.060 ± 0.007	0.34 ± 0.13	10
1270	1.2 ± 0.2	0.063 ± 0.007	1.2 ± 0.2	34
1340	<0.1	0.07[a]	$(21 \pm 3) \times 10^{-3}$	0.57
1410	2.7 ± 0.4	0.076 ± 0.008	2.7 ± 0.4	72
1430	0.25 ± 0.15	0.079 ± 0.010	0.25 ± 0.15	6.6
1520	1.3 ± 0.4	0.058 ± 0.010	1.3 ± 0.4	33
1560	<0.15	0.07[a]	$(68 \pm 7) \times 10^{-3}$	1.7
1660	<0.1	(0.080 ± 0.015)	$\gtrsim 0.25$	$\gtrsim 2$
1800	1.1 ± 0.4	0.065 ± 0.010	1.1 ± 0.4	26
1880	<0.1	0.07[a]	$(30 \pm 4) \times 10^{-3}$	0.69
1930	<0.1	(0.075 ± 0.015)	$\gtrsim 0.25$	$\gtrsim 2$

[a]Assumed value.

[b]Very weak, *if* real resonance.

Because of the mixture of spin 0 and spin 1 resonances in ^{183}W, it is perhaps not meaningful to discuss average reduced widths and level spacings. However, if it is assumed that the s-wave strength function is approximately the same for the two spin states, then an average strength function can be extracted. For the resonances below 400 ev, this strength function is $(2.0 \pm 0.4) \times 10^{-4}$ per spin state, in agreement with the strength functions of the even-even tungsten isotopes.

Table 4. Resonance Parameters of ^{186}W

E_0 (ev)	Γ_n (ev)	Γ_γ (ev)	Γ_n (ev)	Γ_n° (ev)
				$\times 10^{-3}$
18.8[a]	0.266[a]	(0.053 ± 0.005)	0.266[a]	62[a]
111.3	$<10^{-3}$	0.07[b]	$(0.04 \pm 0.01) \times 10^{-3}$	0.004
171.5	$(27 \pm 3) \times 10^{-3}$	0.075 ± 0.025	0.027 ± 0.003	2.6
197.6	$(0.4 \pm 0.2) \times 10^{-3}$	0.07[b]	$(0.6 \pm 0.1) \times 10^{-3}$	0.043
218	0.53 ± 0.04	0.062 ± 0.006	0.53 ± 0.04	36
245	$<2 \times 10^{-3}$	0.07[b]	$(0.2 \pm 0.1) \times 10^{-3}$	0.013
288	$(26 \pm 5) \times 10^{-3}$	0.07[b]	0.026 ± 0.006	1.5
407	$(75 \pm 15) \times 10^{-3}$	0.062 ± 0.015	0.075 ± 0.015	3.7
458	$<2 \times 10^{-3}$	0.07[b]	$(0.8 \pm 0.2) \times 10^{-3}$	0.037
512	$(56 \pm 23) \times 10^{-3}$	0.049 ± 0.012	0.065 ± 0.024	2.9
543	0.50 ± 0.07	0.065 ± 0.008	0.50 ± 0.07	22
666	0.75 ± 0.12	0.085 ± 0.012	0.75 ± 0.12	29
732	2.1 ± 0.2	0.092 ± 0.013	2.1 ± 0.2	81
774	$<6 \times 10^{-3}$	0.07[b]	$(6 \pm 2) \times 10^{-3}$	0.21
835	$(17 \pm 8) \times 10^{-3}$	0.07[b]	$(20 \pm 3) \times 10^{-3}$	0.69
858	$<4 \times 10^{-3}$	0.07[b]	$(2 \pm 1) \times 10^{-3}$	0.068
968	1.1 ± 0.2	0.072 ± 0.010	1.1 ± 0.2	35
1080	0.65 ± 0.20	0.061 ± 0.007	0.65 ± 0.20	20
1130	0.45 ± 0.15	0.062 ± 0.012	0.45 ± 0.15	13
1190	0.77 ± 0.15	0.055 ± 0.007	0.77 ± 0.15	22
1420	0.25 ± 0.15	(0.090 ± 0.025)	0.25 ± 0.15	6.6
1510	1.2 ± 0.2	0.068 ± 0.009	1.2 ± 0.2	31
1550	$<20 \times 10^{-3}$	0.07[b]	$(4.6 \pm 1.5) \times 10^{-3}$	0.12
1800	0.10 ± 0.09	0.065 ± 0.015	0.10 ± 0.09	2.4
1940	0.55 ± 0.23	0.060 ± 0.011	0.55 ± 0.23	12
2040	0.40 ± 0.24	0.067 ± 0.013	0.40 ± 0.24	8.8
2120	0.11 ± 0.09	0.067 ± 0.013	0.11 ± 0.09	2.4

[a]From BNL-325, 2d ed.

[b]Assumed value.

LEVEL STRUCTURE OF ^{183}W, ^{185}W, AND ^{187}W FROM THERMAL-NEUTRON CAPTURE GAMMA RAYS

M. J. Martin[1] J. A. Harvey G. G. Slaughter

NUCLEAR REACTIONS. ^{182,183,184,186}W(n,γ), E = thermal; measured $\sigma(E_\gamma)$, I_γ. Enriched targets.

The energies and intensities of the gamma rays emitted following thermal-neutron capture in 5-g samples of tungsten enriched in ^{182}W (94.4%), ^{183}W (86.2%), ^{184}W (94.3%), and ^{186}W (97.2%) have been measured with a 6-cm^3 lithium-drifted germanium crystal. For each isotope, an energy range from 50 kev to the neutron binding energy was covered with a resolution of 5 kev at the low energies increasing to 10 kev at the high energies.

A preliminary list of the low-energy transitions is contained in Table 1. These gamma-ray energies and intensities (intensities not given here) are being used in conjunction with the (d,p) results of Erskine[2] to study the level structure of ^{183}W, ^{185}W, and ^{187}W. Many new levels have been found, including the $J = \frac{1}{2}$ member of the $\frac{1}{2}$ [510] band in ^{185}W (at $\approx$15 kev) and ^{187}W (at 147 kev). The structure of these levels, in terms of Nilsson single-particle states and the rotational model, is being investigated. Table 2 contains the gamma rays seen in the decay of ^{187}W following the ^{186}W(n,γ) reaction.

[1]Director's Division.

[2]J. R. Erskine, *Phys. Rev.* **138**, B66 (1965).

Table 1. Energies (in Mev) of Gamma Rays from Thermal-Neutron Capture

^{183}W	^{184}W	^{185}W	^{187}W
0.0995	0.111	0.134	0.127
0.108	0.124	0.163	0.147
0.141	0.159	0.173	0.157
0.163	0.162	0.234	0.202
0.204	0.182	0.266	0.266
0.210	0.200	0.272	0.273
0.246	0.215	0.278	0.285
0.260	0.226	0.290	0.289
0.2915	0.253	0.325	0.302

Table 1 (continued)

^{183}W	^{184}W	^{185}W	^{187}W
0.313	0.272	0.352	0.310
0.354	0.294	0.418	0.355
0.367	0.317	0.450	0.376
0.386	0.334	0.497	0.424
0.400	0.340	0.531	0.500
0.559	0.361	0.568	0.530
	0.383	0.577	0.576
0.652	0.420	0.594	0.657
0.695	0.440	0.614	0.692
0.845		0.637	0.705
0.888	0.641	0.661	0.780
0.927	0.678	0.705	0.787
0.938	0.710	0.741	0.833
0.979	0.724	0.755	0.840
	0.742	0.821	0.866
	0.757	0.866	
	0.762	0.887	
	0.767	0.910	
	0.779	0.941	
	0.791	0.979	
	0.894		
	0.904		
	0.944		

Table 2. Energies (in Mev) of Gamma Rays from ^{187}W Decay

0.135
0.480
0.551
0.588
0.617
0.625
0.684
0.772

HIGH-RESOLUTION MEASUREMENTS OF GAMMA RAYS FROM THERMAL- AND RESONANCE-NEUTRON CAPTURE IN THE ISOTOPES OF TIN

J. A. Harvey G. G. Slaughter M. J. Martin[1]

NUCLEAR REACTIONS. ^{116,117,118,119,120,122,124}Sn(n,γ), E = thermal and resonance neutrons; measured $\sigma(E_\gamma)$, I_γ. Deduced levels ^{117,118,119,120,121,123,125}Sn. Enriched targets.

High-resolution measurements of the gamma-ray spectra from thermal- and resonance-neutron capture in the isotopes of tin have been made with lithium-drifted germanium detectors. A beam of pure thermal neutrons was obtained by double reflection from Inconel mirrors of a reactor beam from the Oak Ridge Research Reactor. A cadmium-filtered or ^{10}B-filtered reactor beam served as the source of resonance-energy neutrons. Earlier measurements[2] of the gamma rays from the isotopes of tin with an NaI spectrometer had demonstrated the value of using both thermal- and resonance-energy neutrons and the need for higher resolution of the gamma rays. Lithium-drifted germanium crystals with volumes of 1.9 and 6 cm^3 were furnished by R. J. Fox, Instrumentation and Controls Division. For high-energy gamma rays ($>\sim$3000 kev), the pair production process with the subsequent escape of both annihilation quanta is the predominant process. Above 4000 kev the energy resolution was 10 to 15 kev for runs of several days duration, and the energies of the lines may be measured to $\sim$5 kev absolutely and $\sim$3 kev relatively. For low-energy gamma rays ($<\sim$1500 kev), the energy resolution was $\sim$5 kev, and the energies can be measured to an absolute accuracy of 1 to 2 kev. The relative efficiencies of both detectors vs gamma-ray energy have been determined for both the double-escape peak and the full-energy peak. In the energy region around $\sim$1500 kev deposited in the crystal, there is some ambiguity as to whether a weak peak is a full-energy or a double-escape peak.

The metal samples of the enriched tin isotopes were available in quantities from 1 to 200 g and enrichments from 29.1 to 98.4%. Specifications of the samples are given in Table 1. The gamma-ray spectra from the small, low-enrichment samples must be corrected for contributions from other isotopes.

The gamma-ray spectra obtained with the 1.9-cm^3 crystal from the capture of thermal- and resonance-energy neutrons in the 35-g sample of ^{117}Sn are shown in Fig. 1. The peaks are all double-escape peaks, and the energies of the gamma rays are labeled above the peaks. Table 2 summarizes the energies and intensities of the gamma rays from neutron capture in ^{117}Sn. The absolute intensities of the high-energy gamma rays were obtained by normalization to the intensity of the ground-state transition, which had been measured previously with an NaI spectrometer.[2] Figure 2 shows the energy-level diagram of ^{118}Sn deduced from the gamma-ray energies listed in the table, assuming the high-energy transitions originated at the capturing state. The excited state at 1225 is a 2^+ state; and the states at 1750, 2040, and 2480 kev with spins of 0^+ or 1^+ are known from (d,p) studies.[3] The states at 1675 and 2020 kev and at higher energies have not been reported previously. The transition to the state at 1750 kev was observed only from resonance capture, and the transition to the state at 2020 kev was observed only from thermal capture. Low-energy gamma rays with energies of 1224, 448, 531, and 812 kev from thermal capture can be fitted to the level diagram as shown.

The gamma-ray spectra obtained with the 6-cm^3 crystal from the capture of thermal- and resonance-energy neutrons in the 55-g ^{119}Sn sample have been analyzed in a similar manner.

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[1]Director's Division.

[2]J. A. Harvey *et al.*, *Phys. Div. Ann. Progr. Rept. Dec. 31, 1963*, ORNL-3582, p. 62.

[3]L. R. Norris and C. F. Moore, *Phys. Rev.* **136**, B40 (1964); B. L. Cohen and R. E. Price, *Phys. Rev.* **118**, 1582 (1960); B. L. Cohen and R. E. Price, *Phys. Rev.* **121**, 1441 (1961); C. L. Nealy and R. K. Sheline, *Phys. Rev.* **135**, B325 (1964).

Table 1. Specifications of Tin Samples

Isotope \ Sample and Weight in Grams	^{112}Sn 3.3	^{114}Sn 2.5	^{115}Sn 1	^{116}Sn 40	^{117}Sn 35	^{118}Sn 160	^{119}Sn 55	^{120}Sn 200	^{122}Sn 45	^{124}Sn 45
^{112}Sn	70.05%	1.21%	0.876%	<0.01%	0.08%	<0.03%	<0.03%	0.1%	<0.02%	<0.02%
^{114}Sn	0.71%	56.85%	1.67%	0.03%	0.04%	<0.03%	<0.03%	0.1%	<0.02%	0.03%
^{115}Sn	0.27%	0.73%	29.112%	0.06%	0.06%	<0.03%	<0.03%	0.1%	<0.02%	0.03%
^{116}Sn	5.19%	10.62%	32.58%	95.74	2.34%	0.39%	0.65	0.2%	1.01%	0.99%
^{117}Sn	2.42%	3.98%	8.192%	1.02%	89.2%	0.4%	0.63%	0.1%	0.58%	0.54%
^{118}Sn	7.01%	9.59%	10.88%	1.49%	4.5%	97.15%	3.01%	0.5%	1.91%	1.75%
^{119}Sn	2.41%	3.05%	3.1%	0.32%	1.12%	0.64%	89.8%	0.6%	0.77%	0.64%
^{120}Sn	8.82%	10.52%	9.964%	1.06%	2.16%	1.2%	5.34%	97.9%	3.75%	2.49%
^{122}Sn	1.27%	1.60%	1.5%	0.13%	0.26%	0.1%	0.28%	0.3%	90.8%	0.75%
^{124}Sn	1.85%	1.86%	1.734%	0.15%	0.28%	0.12%	0.27%	0.1%	1.16%	92.8%

High-energy gamma rays have been observed to the ground state and to states at 1170, 1870, 2070, and 2090 kev and low-energy gammas of energies 1170, 703, 925, and 987 can be fitted to the level diagram. Many of the other gamma rays do not correspond to transitions between states known from (d,p) work.[3] The analysis of the ^{115}Sn spectra is incomplete; however, a very strong gamma ray of 1293 kev was observed from thermal-neutron capture, which corresponds to a transition[4] from the first 2^+ state to ground.

Table 3 summarizes the energies and intensities of the gamma rays obtained with the 6-cm^3 crystal from neutron capture in the 160-g sample of ^{118}Sn. Again the intensities are relative to the sum of the intensities of the ground-state and the first-excited-state transitions, which was determined from measurements with an NaI spectrometer.[2] The ground-state transition was not observed from thermal-neutron capture. Excited states at 0.024, 0.77, 0.921, 1.08, and 1.34 Mev are known from radioactive decay, (d,p),[3] and Coulomb excitation studies.[5] The fact that the transition from the 1090-kev state is observed to only the 24-kev excited state and not to the ground state favors the $5/2^+$ assignment to this state. Four low-energy gamma rays can be fitted to the known levels, as indicated in the comments in Table 3.

The type of results obtained from thermal and resonance capture in the other even-even target nuclides ^{116}Sn, ^{120}Sn, ^{122}Sn, and ^{124}Sn is similar to that obtained for ^{118}Sn. The capture of resonance-energy neutrons gives strong high-energy gamma rays to the low-lying $s^+_{1/2}$ and $d^+_{3/2}$ states and a few weaker gamma rays to higher excited states. Figure 3 shows a plot of the difference in energy between these $d_{3/2}$ and $s_{1/2}$ states as a function of mass number. The capture of thermal neutrons gives weak high-energy gamma rays to the low-lying $1/2^+$ and $3/2^+$ states, and many lower-energy gamma rays were observed. A few of the low-energy gamma rays can be fitted into the level schemes; however, many do not correspond to transitions between known levels.

[4] H. H. Bolotin, *Phys. Rev.* **136**, B1566 (1964).

[5] P. H. Stelson *et al.*, *Bull. Am. Phys. Soc.* **9**, 484 (1964); R. L. Robinson and P. H. Stelson, *Bull. Am. Phys. Soc.* **10**, 245 (1965).

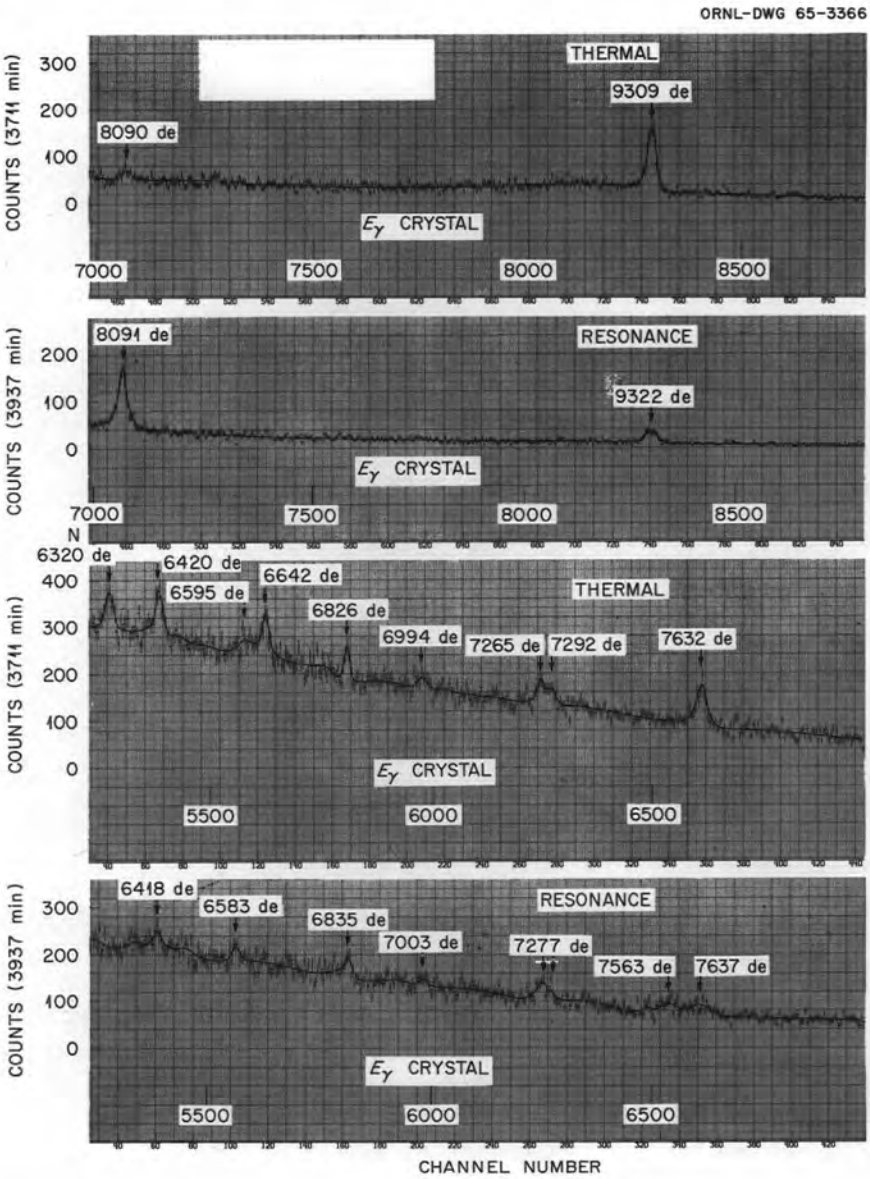

Fig. 1. Gamma-Ray Spectra Obtained with the 1.9-cm^3 Crystal from Thermal and Resonance Capture in ^{117}Sn.

In resonance capture, the angular distribution of the high-energy gamma rays to the low-lying $\frac{1}{2}^+$ and $\frac{3}{2}^+$ states provides a useful technique in determining the spin of low-energy *p*-wave neutron resonances. If *p*-wave neutrons are captured to form a $\frac{3}{2}^-$ state, the angular distribution of the transition to the low-lying $\frac{1}{2}^+$ state will be peaked at 90° while the transition to the low-lying $\frac{3}{2}^+$ state will have a minimum at 90°. The ratio of the intensities of these two high-energy gamma rays will change by a factor of 2 (assuming pure *E*1 transitions) from 90 to 135°. The ratios have been measured for ^{118}Sn and ^{122}Sn, and values of 1.5 ± 0.2 and 1.5 ± 0.3 have been obtained. Since *s*-wave capture, and *p*-wave capture to form a $\frac{1}{2}^-$ state, must be isotropic, there must be reso-

Table 2. Energies and Intensities of Gamma Rays from Neutron Capture in ^{117}Sn

Thermal		Resonance		Comments
E_γ (kev)	Intensity (%)	E_γ (kev)	Intensity (%)	
9309	2.8	9322	1.5	To ground state
8090	0.4	8091	6	To 1225 kev 2^+ state
7632	1.6	7637	2	To 1675 kev state
		7563	2	To 1750 kev $(0, 1)^+$ state
7292	0.5	7277	2	To 2020 kev
7265	0.7			To 2040 kev $(0, 1)^+$ state
6994(?)	0.4	7003(?)	0.9	
6826	0.6	6835	1.1	To 2480 kev $(0, 1)^+$ state
6642	0.9			
6595	0.2	6583	1.4	
6420	1.2	6418	1.8	
6112	1.1	6124	2.5	
6062	0.6	6062	5	
5972	0.7			
5565	0.9			
5212	1.9	5214	3	
5194	1.5			
4552	2.3			
4414	0.7			
3700	1.8			
	Relative Intensity			
1224	100	1227		From 1225 2^+ state to ground
1177	11			
1099	21			
812	14			From 2040 to 1225 kev state
531	6			From 1750 to 1225 kev state
448	2.5			From 1675 to 1225 kev state
361	0.9			
340	1.6			
254	0.4			
245	0.45			
233	0.4			
210	0.4			

nance capture by $\frac{3}{2}^-$ states in both ^{118}Sn and ^{122}Sn. For ^{118}Sn about half of the resonance capture is in the 45.8-ev resonance and about half in the 359-ev resonance, which is *s*-wave. Hence, the 45.8-ev resonance must be *p*-wave with spin $\frac{3}{2}^-$. For ^{122}Sn resonance capture is due principally to the 107- and 260-ev resonances, and we can conclude only that one of these resonances is *p*-wave with spin $\frac{3}{2}^-$. For ^{124}Sn the ratio of the two gamma rays did not change with angle, which agrees with results of McNeill *et al.*[6] Since the resonance capture is mainly from the 62-ev resonance, which is known to be a *p*-wave resonance, the capturing state must be $\frac{1}{2}^-$.

[6]McNeill, McConnell, and Firk, *Can. J. Phys.* 43, 2156 (1965).

Table 3. Energies and Intensities of Gamma Rays from Neutron Capture in ^{118}Sn

Thermal		Resonance		
E_γ (kev)	Intensity (%)	E_γ (kev)	Intensity (%)	Comments
6488	<0.1	6494	8	To ground state
6464	0.6	6469	13	To 24 kev $\frac{3}{2}^+$ state
6026	0.4	6027	3	
5926	0.3	5933	5	
		5917	2	
		5571	3	To 921 $\frac{3}{2}^+$ state
5401	0.3	5400	3	To 1090 $(\frac{3}{2}, \frac{5}{2})^+$ state
		5235	2	
5009	0.1			
4793	0.2			
4541	0.2			
4500	0.2			
3904	0.3			
3813	0.8			
3775	0.3			
3476	0.8			
3296	0.4			
	Relative Intensity			
1249	25			
1229	25	1235		
1164	25			
1065	35			From 1090 kev $(\frac{3}{2}, \frac{5}{2})^+$ state to 24 kev state
921	65			From 921 kev $\frac{3}{2}^+$ state to ground
897	55			From 921 kev $\frac{3}{2}^+$ state to 24 kev state
765	25			From 770 kev state to ground
652	5			
560	3			

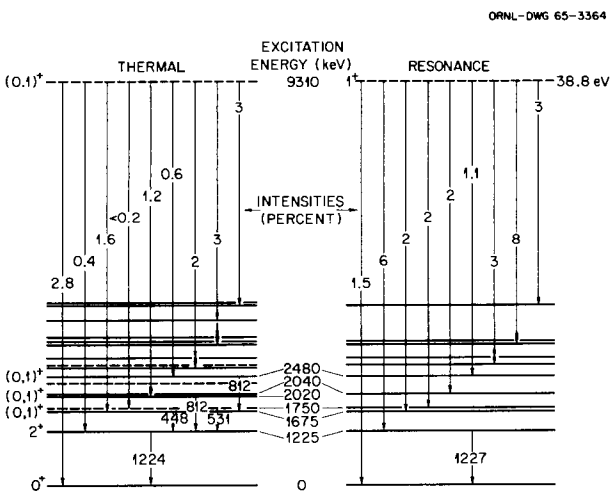

Fig. 2. Energy-Level Diagram Obtained for ^{118}Sn from Thermal and Resonance Capture in ^{117}Sn.

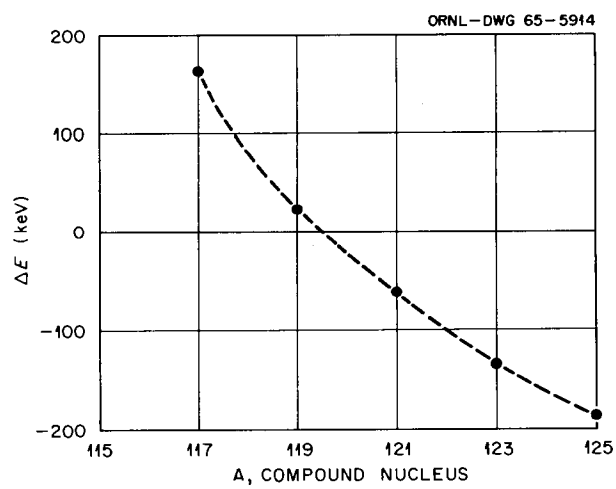

Fig. 3. Difference in Energy Between the Low-Lying $d_{3/2}$ and $s_{1/2}$ States in ^{117}Sn, ^{119}Sn, ^{121}Sn, ^{123}Sn, and ^{125}Sn.

TOTAL CROSS SECTIONS FOR KILOVOLT NEUTRONS OF EVEN-ODD NUCLEI IN THE REGION OF THE 3s STRENGTH-FUNCTION RESONANCES[1]

W. M. Good D. Paya[2] R. Wagner[3] T. Tamura

NUCLEAR REACTIONS. ^{43}Ca, ^{47}Ti, ^{49}Ti, ^{53}Cr, ^{57}Fe, ^{63}Cu, ^{65}Cu, measured $\sigma_T(E)$, $E \leq 60$ kev. ^{44}Ca, ^{48}Ti, ^{50}Ti, ^{54}Cr, ^{58}Fe, ^{64}Cu, ^{66}Cu, deduced levels, Γ, level density, resonances, resonance parameters, Γ_n^o/D. Enriched targets.

The 3s strength-function resonance has its maximum value in nuclei for which the major 28-neutron shell is near closure or just beyond. In view of this fact, it seemed desirable to investigate this mass region more extensively, and to do so we have studied the even-even compound nuclei which lie in the region of the 3s strength-function resonance. We find that the resonances in ^{53}Cr, and to a certain extent in ^{57}Fe, show an uncommon tendency to cluster. The result is that for ^{53}Cr the strength function below 10 kev has a relatively large value of about 12×10^{-4}, whereas in the energy interval 3 to 60 kev the value is about 5×10^{-4}, in accord with the optical-model prediction. This situation suggests that the relatively large peak values of about 10×10^{-4}, which certain experiments show for the 3s strength-function resonance, may result from a tendency for several nuclides in the vicinity of ^{53}Cr to have rather large "local" strengths in a manner similar to ^{53}Cr. This means that the maximum value of the 3s strength function is actually about 4.5×10^{-4}. A quasi-particle calculation is made to try to understand the spacings observed. Except for ^{53}Cr, the calculations showed good agreement with experiment that the observed levels are predominantly of the four-quasi-particle type, since two-quasi-particle types are so relatively few in number as to likely not be seen.

[1]Abstract of paper to be published.

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[3]Permanent address: Physikalisches Institut der Universität Basel, Basel, Switzerland.

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s-WAVE NEUTRON STRENGTH FUNCTIONS OF ISOTOPES IN THE 3s RESONANCE REGION $40 < A < 70$[1]

R. Wagner[2] W. M. Good D. Paya[3]

NUCLEAR REACTIONS. ^{43}Ca, ^{47}Ti, ^{49}Ti, ^{53}Cr, ^{57}Fe, ^{63}Cu, ^{65}Cu, measured $\sigma_T(E)$, $E \leq 60$ kev. ^{44}Ca, ^{48}Ti, ^{50}Ti, ^{54}Cr, ^{58}Fe, ^{64}Cu, ^{66}Cu, deduced levels, Γ, level density, resonances, resonance parameters, Γ_n^o/D. Enriched targets.

We have measured the total neutron cross sections of ^{43}Ca, ^{47,49}Ti, ^{53}Cr, ^{57}Fe, ^{61}Ni, and ^{63,65}Cu in the kev region using a pulsed-beam time-of-flight technique. The energy resolution was 1 to 2%, which was in general not sufficient to determine the angular momenta of the observed compound states. Seth's area analysis was used

[1]Abstract of paper presented at International Conference on the Study of Nuclear Structure with Neutrons, Antwerp, Belgium, July 19–23, 1965.

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to determine the neutron widths of the observed resonances.[4] Except for these states for which angular momentum could be determined, the statistical factor $g = (2J + 1)/2(2I + 1)$ was assumed to be $\frac{1}{2}$. The *s*-wave strength functions obtained are in general agreement with the predictions of the optical models.[5] A variation in the general appearance of the resonance structure is observed as the strength function maximum is crossed. Chromium-53 has a large strength of about 14×10^{-4} if measurements extend up to only 20 kev; $(5.1 \pm 2.6) \times 10^{-4}$ is its strength, however, in energy range up to 40 kev, which would suggest the existence of a "local" strength.

[4]K. K. Seth, *Ann. Phys.* **8**, 223 (1959).

[5]B. Buck and F. Perey, *Phys. Rev. Letters* **8**, 444 (1962).

NEUTRON RESONANCE STRUCTURE AND *s*-WAVE STRENGTH FUNCTION OF THE EVEN ISOTOPES OF ZIRCONIUM[1]

J. A. Biggerstaff W. M. Good H. Kim

NUCLEAR REACTIONS. ^{90}Zr, ^{92}Zr, ^{94}Zr, ^{96}Zr, measured $\sigma_T(E)$, $E \leq 60$ kev. ^{91}Zr, ^{93}Zr, ^{95}Zr, ^{97}Zr, deduced levels, level density, resonances, resonance parameters, Γ_n^o/D. Enriched targets.

Beginning at about mass 90, the *s*-wave strength function is anomalously small compared with the optical-model prediction. First studies of the neutron resonances in the even isotopes of zirconium[2] indicated a rise in the average cross section which was most consistent with a predominantly *p*-wave interaction. A small *s*-wave contribution did not seem surprising based upon the behavior of slightly heavier nuclei. However, subsequently, more refined measurements[3,4] have indicated that the resonances at least to an energy of about 25 kev are *s*-wave with a strength function of about 1×10^{-4}. Data taken up to 60 kev now show an average cross section which rises more rapidly than $\sqrt{E}$, contributed by resonances not sufficiently well resolved to permit distinguishing those of *s*-wave character. Unless the *p*-wave strength function can attain values of 10×10^{-4}, these results indicate an *s*-wave strength function below 25 kev $\approx 1 \times 10^{-4}$, which increases with energy in the interval 40 to 60 kev.

[1]Abstract of paper presented at International Conference on the Study of Nuclear Structure with Neutrons, Antwerp, Belgium, July 19–23, 1965.

[2]H. W. Newson *et al.*, *Ann. Phys.* **8**, 218 (1959).

[3]J. A. Biggerstaff, W. M. Good, and H. J. Kim, *Bull. Am. Phys. Soc.* **9**, 167 (1964).

[4]S. S. Moskalev, H. V. Muradian, and Yu. V. Adamchuk, *Nucl. Phys.* **53**, 667 (1964).

TOTAL CROSS SECTIONS OF EVEN ISOTOPES OF ZIRCONIUM[1]

W. M. Good H. Kim

NUCLEAR REACTIONS. ^{90}Zr, ^{92}Zr, ^{94}Zr, ^{96}Zr, measured $\sigma_T(E)$, E = 60 kev. ^{91}Zr, ^{93}Zr, ^{95}Zr, ^{97}Zr, deduced levels, level density, resonances, resonance parameters, Γ_n^o/D. Enriched targets.

The zirconium nuclei are located at the beginning of the region of masses, namely about 90 to 130, in which the strength functions are anomalously small, as far as the optical model is concerned. We have examined the resonance structure of ^{90,92,94,96}Zr in the energy region 2 kev $< E_n <$ 60 kev, and we find that the s-wave strength function, in the region in which the s waves can be identified, has a mean value for all nuclides of $(1.2 \pm 0.4) \times 10^{-4}$. At energies roughly above 25 kev, the effective s-wave strength function rises to a value of $(2.5 \pm 0.6) \times 10^{-4}$, which cannot be uniquely interpreted for lack of s-wave identification and in view of the possibility of some energy dependence in the s-wave strength function. Level densities for nuclides with neutron numbers in the vicinity of the magic number 50 are considered.

[1]Abstract of paper to be published.

A STUDY OF THE RESONANCES IN NEUTRON BOMBARDMENT OF ^{206}Pb AND ^{207}Pb[1]

J. R. Bird[2] J. A. Biggerstaff J. H. Gibbons
W. M. Good R. L. Macklin

NUCLEAR REACTIONS. ^{206}Pb(n,γ), ^{207}Pb(n,γ), E_n = 12 to 80 kev; measured $\sigma(E;n,n)$, $\sigma(E,n\gamma)$, γ-ray spectra. ^{207}Pb, ^{208}Pb E_r, Γ_n, Γ_γ, Γ_{γ_i}. Enriched targets.

In the light nuclei and in the neighborhood of closed shells, level spacings are of the order of a kilovolt or more. For such nuclei the pulsed Van de Graaff is a useful instrument for neutron investigations. In transmission, small samples can be studied with less than 2% energy resolution. By means of a three-parameter analyzer, capture gamma-ray spectra vs neutron energy have been obtained. The nuclei ^{206}Pb and ^{207}Pb have been studied, and information has been obtained on E_0, Γ_n, Γ_γ, and Γ_{γ_i}. The result of the investigation has been to locate new bound and unbound states in ^{207}Pb, locate new unbound states in ^{208}Pb, establish the predominantly p-wave character of the states in ^{207}Pb and ^{208}Pb near neutron dissociation, obtain information on electric and magnetic radiation reduced widths, and possibly also information on direct capture.

[1]Abstract of paper presented at International Conference on the Study of Nuclear Structure with Neutrons, Antwerp, Belgium, July 19–23, 1965.

[2]Visiting scientist from Atomic Energy Research Establishment, Harwell, England.

STUDY OF THE GAMMA-RAY SPECTRA EMITTED IN THE RESONANCE CAPTURE OF NEUTRONS BY ^{19}F[1]

J. R. Bird[2] J. A. Biggerstaff J. H. Gibbons W. M. Good

NUCLEAR REACTIONS. ^{19}F(n,γ), E_n = 27 and 49 kev; measured E_γ, I_γ. Deduced radiation widths.

Gamma-ray spectra have been measured at the 27-kev (2^-) and the 49-kev (1^-) resonances of ^{19}F$(n,\gamma)^{20}$F. The $E1$ transition to ground is virtually absent at both resonances, while the other $E1$'s have strengths that appear normal when compared with heavier nuclei in which the radiation widths are proportional to level spacing. A description is given of the two-parameter instrument by means of which it is possible to measure simultaneously the neutron energy (flight time) and gamma-ray pulse-height spectra for radiative neutron capture.

[1]Abstract of published paper: *Phys. Rev.* **138**, B20 (1965).

[2]Australian Atomic Energy Commission, Sutherland, New South Wales, Australia.

NEUTRON RESONANCE CAPTURE IN 2*s*1*d* SHELL NUCLEI[1]

I. Bergqvist[2] J. A. Biggerstaff
J. H. Gibbons W. M. Good

NUCLEAR REACTIONS. $^{19}F(n,\gamma)$, ^{27}Al(n,γ), ^{24}Mg(n,γ), ^{32}S(n,γ), E_n = 12 to 80 kev; measured $\sigma(E;n,\gamma)$, γ-ray spectrum; ^{20}F, ^{28}Al, ^{25}Mg, ^{33}S deduced $M1/E1$.

A pulsed Van de Graaff has been used to measure gamma-ray spectra from neutron resonance capture in nuclei in the 2*s*1*d* shell. A number of previously known neutron resonances in the kev region were studied. In many cases the emitted gamma-ray spectrum has a rather simple composition, with transitions to low-lying levels with known spins and parities. It is found that $M1$ transitions from capturing states to low-lying levels of even parity are especially strong in odd-Z nuclei and relatively weak in even-Z nuclei. The results from thermal-neutron capture experiments show the same systematic behavior. No strong $M1$ transitions from capturing states of negative parity have been identified. The existence of $M1$ giant resonance states close to the neutron binding energy in the odd-Z nuclei might explain the enhancement of the $M1$ transitions found in these nuclei. A valid 2*s*1*d* shell systematics could sometimes permit, for such nuclei, gamma-ray spectral determination of both resonance spin and parity, as examples will show.

[1]Abstract of paper presented at International Conference on the Study of Nuclear Structure with Neutrons, Antwerp, Belgium, July 19–23, 1965.

[2]Visiting scientist from Research Institute of National Defense, Stockholm, Sweden.

NEUTRON RESONANCE CAPTURE IN 2s1d SHELL NUCLEI[1]

I. Bergqvist[2] J. A. Biggerstaff
J. H. Gibbons W. M. Good

NUCLEAR REACTIONS. (n,γ) on targets mass 19–40, E_n = 20 to 120 kev; measured E_γ, I_γ. Deduced radiation widths.

A neutron resonance capture gamma-ray spectrum measurement has been made on nuclei in the 2s1*d* shell using 20- to 120-kev neutrons. Systematics of deduced ratios of transition strengths ($M1/E1$) suggest that this ratio is enhanced by ~10 times for *odd-odd* compound nuclei in this shell relative to the ratio expected and observed for odd-even nuclei.

[1]Abstract of published paper: *Phys. Letters* **18**, 323 (1965).

[2]Research Institute of National Defense, Stockholm, Sweden.

FAST-NEUTRON CAPTURE GAMMA-RAY SPECTRUM FROM $^{238}U(n,\gamma)^{239}U$[1]

I. Bergqvist[2]

NUCLEAR REACTIONS. $^{238}U(n,\gamma)$; E_n = 30 kev; measured γ-ray spectrum; ^{239}U deduced $M1/E1$. Enriched target.

The gamma-ray spectrum from the capture of 30-kev neutrons in ^{238}U has been measured using a 9 × 12 in. NaI(Tl) spectrometer. Agreement with a statistically calculated spectrum is obtained. Evidence is given for a $K^\pi = \frac{1}{2}^+$ band in ^{239}U at an excitation energy of 0.13 Mev, which can be identified as the [631] $\frac{1}{2}^+$ band. The number of levels below an excitation energy of about 1 Mev found in other experiments is compatible with the experimental gamma-ray spectrum.

[1]Abstract of paper presented at International Conference on the Study of Nuclear Structure with Neutrons, Antwerp, Belgium, July 19–23, 1965.

[2]Visiting scientist from the Research Institute of National Defense, Stockholm, Sweden.

NEUTRON CAPTURE CROSS SECTIONS FROM 5 TO 100 kev[1]

R. L. Macklin J. H. Gibbons

Recent results and advances in technique for 5- to 100-kev neutron capture cross-section measurements are reviewed.

[1]Abstract of paper to be published in the Proceedings of International Conference on the Study of Nuclear Structure with Neutrons, Antwerp, Belgium, July 19–23, 1965.

ABSOLUTE VALUE AND ENERGY DEPENDENCE OF THE ^{3}He(n,p)T REACTION[1]

R. L. Macklin J. H. Gibbons

NUCLEAR REACTIONS. T(p,n)^{3}He, E_{th}–1.4 Mev, deduced ^{3}He(n,p)T by reciprocity, $5 < E_n$ (kev) < 300.

The absolute total yield from T(p,n)^{3}He has been carefully measured from threshold up to E_p = 1.4 Mev. The absolute cross section for ^{3}He(n,p)T was obtained by reciprocity over the energy interval corresponding to $5 < E_n$ (kev) $<$ 300. The results indicate that the cross section becomes non-($1/v$) for $E_n \gtrsim 5$ kev. This departure from $1/v$ may be accounted for by assuming the existence of an excited state in ^{4}He near 20.1 Mev or perhaps by a final-state (p-T) interaction.

[1]Abstract of paper to be published in the Proceedings of International Conference on the Study of Nuclear Structure with Neutrons, Antwerp, Belgium, July 19–23, 1965.

ENERGY DEPENDENCE OF THE ^{10}B(n,α)/^{10}B($n,\alpha\gamma$) CROSS-SECTION RATIO[1]

R. L. Macklin J. H. Gibbons

NUCLEAR REACTIONS. ^{10}B(n,α)/^{10}B($n,\alpha\gamma$), thermal, 30, 110, 160 kev.

The alpha-particle and lithium-ion recoils from this reaction were observed in coincidence in face-to-face surface-barrier silicon detectors, using 0.1 atm of $^{10}B_2H_6$ as sample. Neutrons were provided by the ORNL 3-Mv pulsed Van de Graaff, using the ^{7}Li(p,n) reaction. Cross-section ratios, (n,α_0)/(n,α_1), of 0.084 ± 0.005 (160 kev), 0.077 ± 0.004 (110 kev), 0.072 ± 0.003 (30 kev), and 0.067 ± 0.002 (thermal neutrons) were found. These results indicate a small monotonic variation in the ratio, in good agreement with earlier measurements at higher energies.

[1]Abstract of published paper: *Phys. Rev.* **140**, B324 (1965).

METHOD FOR OBTAINING BURSTS OF POLARIZED NEUTRONS OF ENERGY 10 TO 700 kev

J. W. T. Dabbs J. A. Harvey

The proposed method (use of right-left asymmetry in scattering of the ORELA neutron spectrum through ~90° lab angle, followed by energy moderation in a graphite block) was reported, along with Monte

Carlo intensity calculations, in the last annual report.[1] At that time, calculations of the polarization were in progress, but were incomplete.

These calculations have been completed. The polarization of neutrons escaping into a number of energy bins was determined, using the Wolfenstein formulation[2] with the parameters calculated from the phase-shift formulas of Giamati and Thaler.[3] The phase-shift differences were pessimistically chosen to be somewhat larger than the correct differences by using a slower variation with energy than expected in extrapolating the known values to the lower energies. The phase shift for s wave and the differences for p and d waves were taken to be $\delta_0 = -77\sqrt{E}$, $\Delta\delta_1 = -1.5E$, and $\Delta\delta_2 = +1.5E^2$ respectively; here E is in Mev and the values are in degrees. It should be noted that a coordinate transformation was required both before and after each collision to utilize the Wolfenstein formulation. For 1000 neutrons, the results are given in Table 1, in which P is the portion of the polarization remaining. The agreement of the intensities and effective lengths with the first calculation[1] is gratifying. The loss in polarization is seen to be negligible; indeed, no appreciable depolarization occurs at any energy according to the calculation.

The results of Table 1 indicate that the polarization change is quite small and that the original supposition was correct; thus the method appears feasible.

An 18-in.-diam vertical access port has been incorporated into the design of the ORELA target room (1) to permit simpler installation of Dewars for the liquid-helium scatterer and (2) to allow access for special maintenance or for other special target configuration.

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[1] ORNL-3778, p. 83.

[2] L. Wolfenstein, *Ann. Rev. Nucl. Sci.* **6**, 43 (1956).

[3] C. C. Giamati and R. M. Thaler, *Nucl. Phys.* **59**, 159 (1964).

Table 1. Moderated Neutron Polarization; Monte Carlo Calculations Based on 1000 Neutrons

Graphite, 10 × 10 × 8 cm

ΔE (kev)	$N(\Delta E)$[a]	$\bar{L}$ (cm)[b]	ΔL (cm)[c]	P	Number Collisions in ΔE
700–100	0.977	5.7	3.7	0.998 ± 0.001	13
100–10	0.022	12.4	4.5	0.993 ± 0.003	14
10–1	0.0010	14.6	4.3	0.988 ± 0.006	14
1–0.1	0.00005	15.2	4.2	0.983 ± 0.008	14

[a] $N(\Delta E)$ is fraction of neutrons escaping within ΔE.

[b] $\bar{L}$ is effective source distance behind exit face of moderator.

[c] $\Delta\bar{L}$ is standard deviation in $\bar{L}$.

n-d SCATTERING – VECTOR POLARIZATION OF RECOIL DEUTERONS FROM A POLARIZED NEUTRON BEAM[1]

H. B. Willard S. T. Thornton[2] C. M. Jones

In *n-d* scattering, two sets of scattering lengths are consistent with the low-energy data: set I, a_2 = 0.8 fm, a_4 = 6.4 fm; set II, a_2 = 8.3 fm, a_4 = 2.6 fm, where a_2 and a_4 are the doublet and quartet lengths respectively. Although current theoretical calculations are converging on set I, there does not appear to be any unambiguous experimental evidence for either choice. We have calculated the vector polarization of the scattered neutron and recoil deuteron for incident beams of completely polarized neutrons. Low-energy (slow) neutrons produce scattered neutrons with polarizations of 66% (set I) and 65% (set II). On the other hand the vector polarizations of the recoil deuterons are +50 and −33% respectively. At 350 kev neutron energy the neutron polarizations are +51% (set I) and +49% (set II), while the deuteron vector polarizations are +38% (set I) and −21% (set II). Therefore a determination of the deuteron vector polarization in a triple-scattering experiment provides a sensitive test for the proper scattering lengths. Detailed calculations of the pertinent parameters using the ^{7}Li(*p*,*n*)^{7}Be reaction as the polarized neutron source and possible deuteron vector polarization analyzers have been carried out.

[1]Abstract of paper to be published in Proceedings of International Conference on Polarization Phenomena of Nucleons, Karlsruhe, Germany, Sept. 6–10, 1965.

[2]Oak Ridge Graduate Fellow from the University of Tennessee, under appointment from the Oak Ridge Associated Universities.

INTERACTION OF 350-kev POLARIZED NEUTRONS WITH ORIENTED ^{165}Ho NUCLEI[1]

R. Wagner[2] P. D. Miller T. Tamura H. Marshak[3]

The interaction of polarized and unpolarized 350-kev neutrons with oriented and unoriented ^{165}Ho nuclei was investigated in order to study the effect of nuclear deformation and to search for a possible spin-spin interaction. The ORNL 3-Mv pulsed and bunched Van de Graaff proton beam was used in conjunction with a time-of-flight spectrometer. The ^{7}Li(*p*,*n*) reaction, at a laboratory angle of 51°, provided a source of 55% polarized 350-kev neutrons. Using the NBS transportable ^{3}He refrigerator, a single crystal of ^{165}Ho metal was cooled to 0.34°K, and a nuclear polarization of approximately 15% was obtained with a superconducting split solenoid. The differential cross section for unpolarized 350-kev neutrons, elastically scattered from unoriented ^{165}Ho nuclei, was measured in a cylindrical geometry and is in good agreement with the results of a coupled-channel calculation. The total cross section of unoriented ^{165}Ho was measured between 300 and 400 kev. A coupled-channel calculation of the total cross section using the same optical-model parameters as those which fitted the angular distribution is found to agree very well with these data. To investigate the spin-spin interaction, measurements were made of the transmitted intensities with the target nuclei polarized alternately parallel and antiparallel to the direction of neutron polarization. The observed change in intensity, (−0.11 ± 0.32)%, and the observed total cross section of 7.94 barns imply a change in cross section of +30 ± 85 mb, where the plus sign corresponds to a larger cross section for the parallel orientation. Comparison of this result with that of the coupled-channel calculation

[1]Abstract of published paper: *Phys. Rev.* **139**, 29B (1965).

[2]Permanent address: University of Basel, Switzerland.

[3]National Bureau of Standards, Washington, D.C.

indicates that if the spin-spin interaction in the optical-model potential is written as $-V_{ss}(\sigma \cdot I)$ times a Saxon form factor, then V_{ss} lies between −130 and +280 kev. Since the ^{165}Ho nucleus is highly deformed, a transmission measurement was made to determine the change in cross section between a highly oriented and a nearly unoriented target. The transmission of the target decreased by (1.3 ± 0.4)% for the higher orientation value, which corresponds to a cross-section increase of 360 ± 100 mb. This deformation effect on the total cross section is also in good agreement with that derived from the coupled-channel calculation. The deformation parameter β used in the optical-model potential was +0.3, in agreement with other measurements.

TOTAL CROSS SECTION FOR 14-Mev NEUTRONS USING ALIGNED ^{165}Ho NUCLEI[1]

H. Marshak[2] A. C. B. Richardson[2] T. Tamura

NUCLEAR REACTIONS. ^{165}Ho (aligned), σ_T, 14 Mev.

Total cross sections of 14-Mev neutrons, produced from the ^{3}H$(d,n)^4$He reaction, by unoriented and oriented ^{165}Ho are measured, and analyzed by the coupled-channel calculations with good agreement. It is found that the orientation effect is nearly twice as large as is expected from the black-nucleus model, indicating that 14 Mev is not yet high enough so that the latter model can be used.

[1]Abstract of published paper: *Phys. Rev. Letters* **16**, 194 (1966).

[2]National Bureau of Standards, Washington, D.C.

DIFFERENTIAL NEUTRON SCATTERING FROM NITROGEN

C. H. Johnson J. L. Fowler R. L. Kernell[1]

NUCLEAR REACTIONS. ^{14}N(n,n), E_n = 1.779–3.207 Mev, measured $\sigma(\theta)$; ^{15}N, deduced resonance parameters.

In 1955 Fowler and Johnson[2] published a paper, "Differential Elastic Scattering Cross Section for Neutrons on Nitrogen," in which they made angular momentum and parity assignments for some six resonances. Bartholomew *et al.*,[3] in studying gamma-ray angular distributions from the ^{14}C(p,γ) ^{15}N reaction, assigned even parity for the 1.401- and 1.595-Mev resonances, in disagreement with the assignment from the neutron scattering experiment. Since apparatus had already been developed at the Oak Ridge National Laboratory to measure

[1]Oak Ridge Graduate Fellow from the University of Tennessee.

[2]J. L. Fowler and C. H. Johnson, *Phys. Rev.* **98**, 728 (1955).

[3]G. A. Bartholomew *et al.*, *Can. J. Phys.* **33**, 441 (1955).

differential scattering from liquid oxygen,[4] we decided to remeasure the differential scattering from nitrogen and extend the results to higher energies. In a shielded neutron scattering chamber, neutrons from the T(*p*,*n*) reaction produced by bombarding tritium gas in a cell with protons from the 5.5-Mv Van de Graaff are collimated by a double-tapered slot through a paraffin shield. These neutrons are incident upon a liquid scattering sample contained in a Dewar flask. We detect scattered neutrons with a stilbene crystal from which pulses due to gamma rays are suppressed by pulse shape discrimination. Since we calibrated the detecting crystal in the incident neutron flux at 0°, we can calculate the absolute differential cross section.

We have measured differential cross sections at nine energies between 1.595 and 3.207 Mev. Figure 1 shows our new results at 1.595 Mev. Here we plot the center-of-mass differential cross sections as a function of the cosine of the center-of-mass angle. The curve is calculated from the phase shifts and resonance parameters given in the earlier paper[2] and listed in the upper right-hand corner. It is corrected for the energy resolution of this work. We have assumed that the *s* and *p* potential phase shifts are the same in the two-channel spin states. As can be seen, there is rather good agreement, particularly since there is no normalization – the differential cross sections are absolute. If this were a $J = 5/2^+$ resonance the theoretical curve would peak in both the forward and backward directions, as is indicated in Fig. 2, which is reproduced from ref. 2. In Fig. 2 the arrows indicate the energy at which the measurements were made relative to the resonances in the total cross section of nitrogen. Above 1.54

[4] J. L. Fowler and C. H. Johnson, *Bull. Am. Phys. Soc.* **10**, 261 (1965).

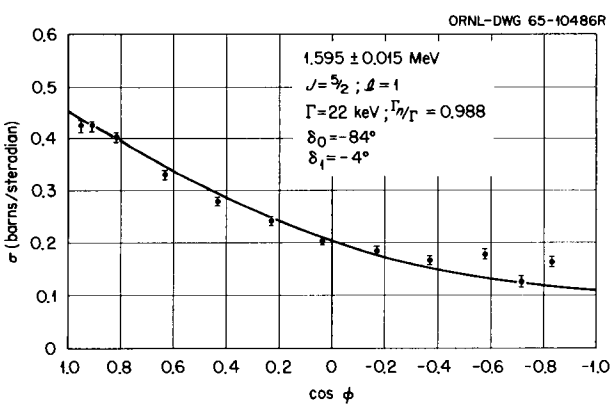

Fig. 1. Differential Cross Section of Neutrons Scattered from Nitrogen at 1.595 Mev. Solid line calculated from phase shifts and resonance parameters listed in figure.

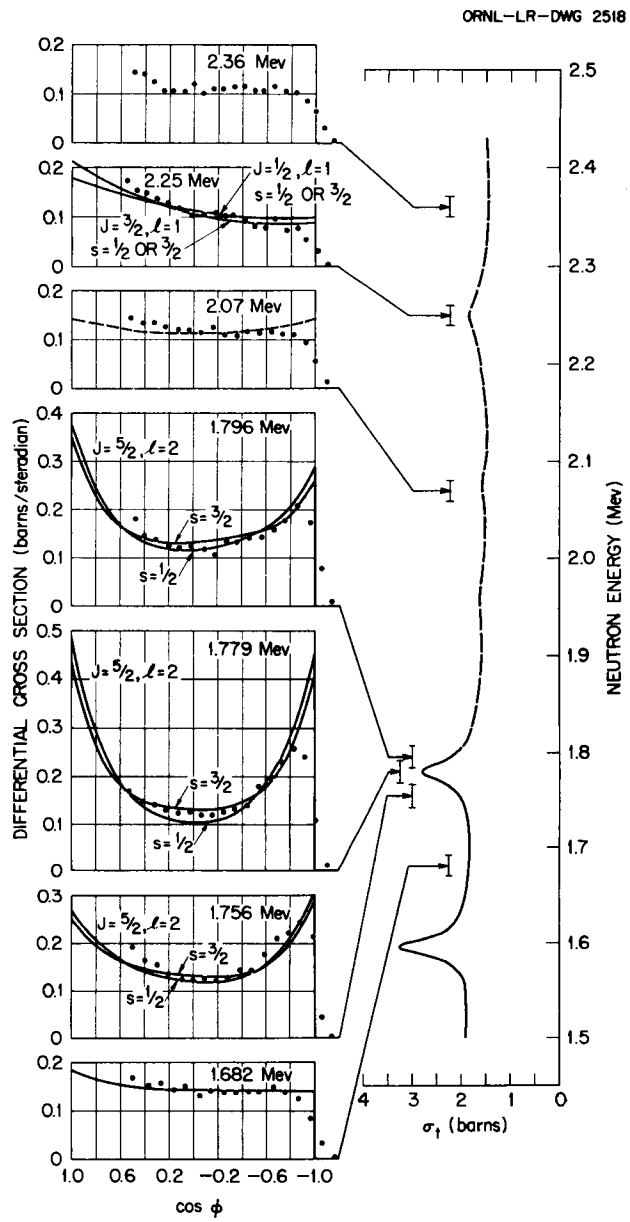

Fig. 2. Differential Cross Sections of Neutrons Scattered from Nitrogen at 1.682 to 2.360 Mev.

Mev the differential scattering reported in ref. 2 was measured by observing the nitrogen nuclear recoil spectra obtained with a carefully designed proportional counter. At the nonresonant energy of 1.68 Mev, Fig. 3, the differential cross sections are in agreement with those shown in Fig. 2.

Figure 4 shows our recent measurements on the differential cross sections at 1.779 Mev. Here, too, we agree with the 1955 assignment that this is a *d* resonance. The difference between even-parity levels and odd-parity ones, as is evidenced by the curves at 1.779 and 2.25 Mev (Fig. 2), is so marked that it is extremely difficult to see how we can be mistaken with regard to parity assignments.

Figure 5 shows the nonresonant angular distribution at 2.00 Mev with a least-squares Legendre polynomial fit which includes terms up through P_5. At 2.25 Mev (Fig. 2) there is a 70-kev-wide resonance with large (n,p) and (n,α) widths. The new experimental angular distribution (Fig. 6) measured with ±15 kev resolution is also in agreement with the 1955 results, showing that this is an odd-parity level.

Furthermore, measurements on the $^{11}B(\alpha,p)^{14}C$ reactions confirm several of our assignments. Lee and Schiffer[5] have measured the angular distribution of protons at a number of resonance levels of ^{15}N. Their angular distributions at somewhat higher excitation than that corresponding to our

[5] L. L. Lee and J. P. Schiffer, *Phys. Rev.* **115**, 160 (1959).

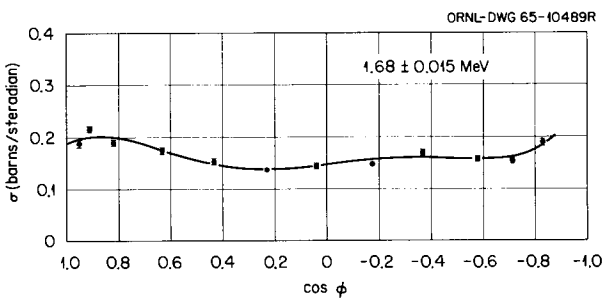

Fig. 3. Differential Cross Section of Neutrons Scattered from Nitrogen at 1.68 Mev.

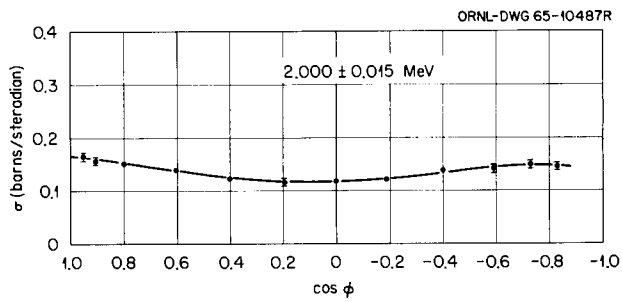

Fig. 5. Differential Cross Section of Neutrons Scattered from Nitrogen at 2.00 Mev.

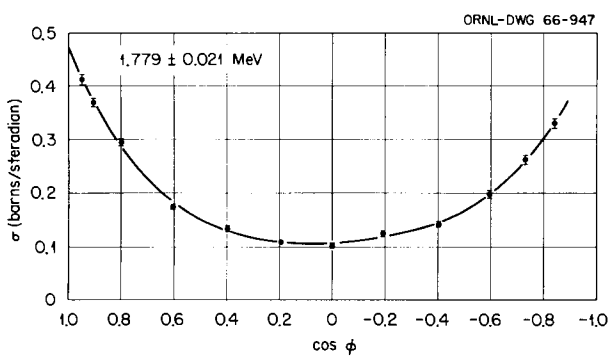

Fig. 4. Differential Cross Section of Neutrons Scattered from Nitrogen at 1.779 Mev.

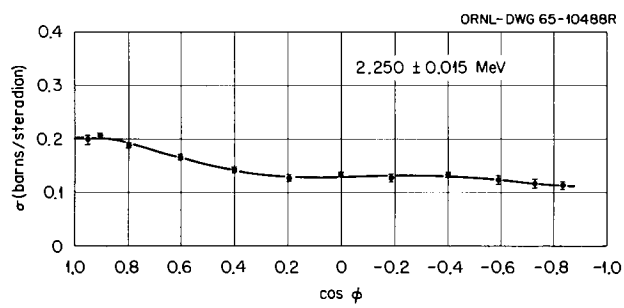

Fig. 6. Differential Cross Section of Neutrons Scattered from Nitrogen at 2.250 Mev.

1.595-Mev state show interference effects consistent with our $5/2^-$ assignment for this state. The analysis of Lee and Schiffer agrees with our assignment of $5/2^+$ for the 1.779-Mev resonance and $3/2^-$ for the 2.25-Mev one.

We have extended our differential cross-section measurements to 3.20 Mev neutron energy, and have found two more resonances, one less than 20 kev wide at 2.95 Mev (Fig. 7) and another of the order of 70 kev wide at 3.20 Mev (Fig. 8). Both are characterized by forward and back scattering of neutrons, indicating even parity. The lower one is very likely the $5/2^+$ resonance seen by Lee and Schiffer in the $^{11}B(\alpha,p)^{14}C$ reaction.[5] Figures 9 and 10 show the differential cross sections at two nonresonant energies. For Figs. 3–10 the solid lines are the results of a least-squares Legendre polynomial fit, including terms up through P_5.

Since our more careful recent angular distributions confirm the earlier neutron scattering measurements,[2] and since in every case in which Lee and Schiffer[5] look at the same resonance we do with the $^{11}B(\alpha,p)^{14}C$ reaction they agree with our assignment, we feel that the Chalk River $^{14}C(p,\gamma)^{15}N$ assignments must be in error.

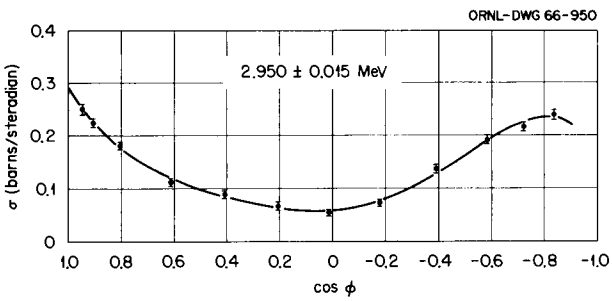

Fig. 7. Differential Cross Section of Neutrons Scattered from Nitrogen at 2.950 Mev.

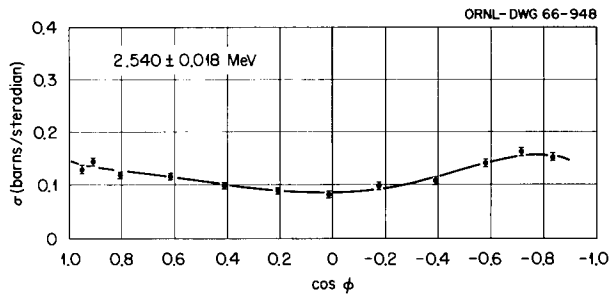

Fig. 9. Differential Cross Section of Neutrons Scattered from Nitrogen at 2.54 Mev.

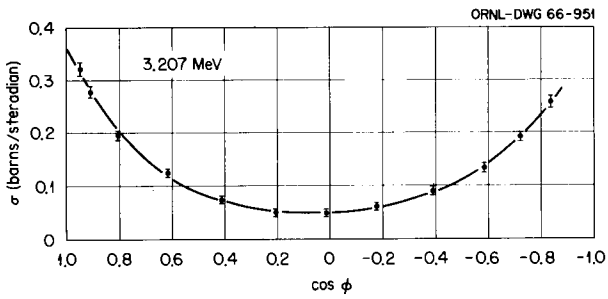

Fig. 8. Differential Cross Section of Neutrons Scattered from Nitrogen at 3.207 Mev.

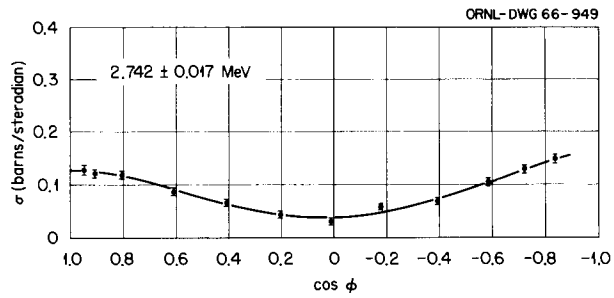

Fig. 10. Differential Cross Section of Neutrons Scattered from Nitrogen at 2.74 Mev.

DIFFERENTIAL SCATTERING OF NEUTRONS FROM ^{208}Pb AT RESONANT ENERGIES[1]

J. L. Fowler

NUCLEAR REACTIONS. ^{208}Pb$(n,n)^{208}$Pb, E_n = 0.715–1.761 Mev, measured $\sigma(\theta)$, deduced resonance parameters ^{209}Pb.

Measurements are reported on differential elastic scattering of neutrons of a few kev energy spread from 99.75% ^{208}Pb in the energy region 0.715 to 1.761 Mev. The results include absolute differential cross sections at 20 resonant and 9 nonresonant energies. A least-squares phase-shift analysis provides the resonance parameters and reduced widths of 21 resonances. The observed $s_{1/2}$ potential-scattering phase shifts are in agreement with those expected from a type of phenomenological potential which reproduces the single-particle bound states of ^{209}Pb. Parity assignments of the J = 1/2 resonances are in disagreement with the prediction for six intermediate states arising from two-particle one-hole neutron excitations. There are, however, a number of resonances with widths corresponding to several percent of the single-particle limits which are likely candidates for some sort of intermediate states.

[1]Abstract of a paper submitted to the *Physical Review*.

NEUTRON INELASTIC SCATTERING PROGRAM

J. A. Biggerstaff
Y. Cassagnou[1]
W. E. Kinney[2]
M. V. Harlow, Jr.[2]
J. M. McConnell[3]
F. G. Perey[2]
P. H. Stelson

Development of experimental equipment and procedures for measuring fast-neutron inelastic scattering cross sections by the flight-timing method is essentially complete and is reviewed below. A summary of recent results is given in an accompanying paper,[4] and a few examples are presented.

We wish to measure $\sigma(E_n, E_n', \theta)$; E_n is determined by the kinematics of the D(d,n) reaction which is used to produce the primary neutrons. Since either the 3- or the 5.5-Mv pulsed Van de Graaff accelerator may be used, we can obtain 3.8 Mev < E_n < 8.5 Mev. A deuterium gas target has been designed which minimizes the effect of occluded deuterium. The energy E_n' is measured by measuring the time of arrival of the scattered neutrons relative to the time of production of the primary neutrons. Scattered neutrons are detected in a liquid organic scintillator (NE-213); gamma-ray-induced pulses are rejected by pulse shape analysis, and pulse height and flight time for each event are recorded in a 16 × 256 array. The retention of pulse height information enables subsequent data reduction programs to correct for time slowing in the electronics as a function of pulse height. A block diagram of the electronics is shown in Fig. 1. The detector is enclosed in a massive shield and is mounted on a polar coordinate system which enables positioning of the detector at

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[2]Neutron Physics Division.

[3]Instrumentation and Controls Division.

[4]Abstract: *Fast Neutron Scattering Using Time-of-Flight Techniques*, by M. V. Harlow, Jr., *et al.*, to be presented at American Physical Society Meeting, Washington, D.C., Apr. 25–28, 1966.

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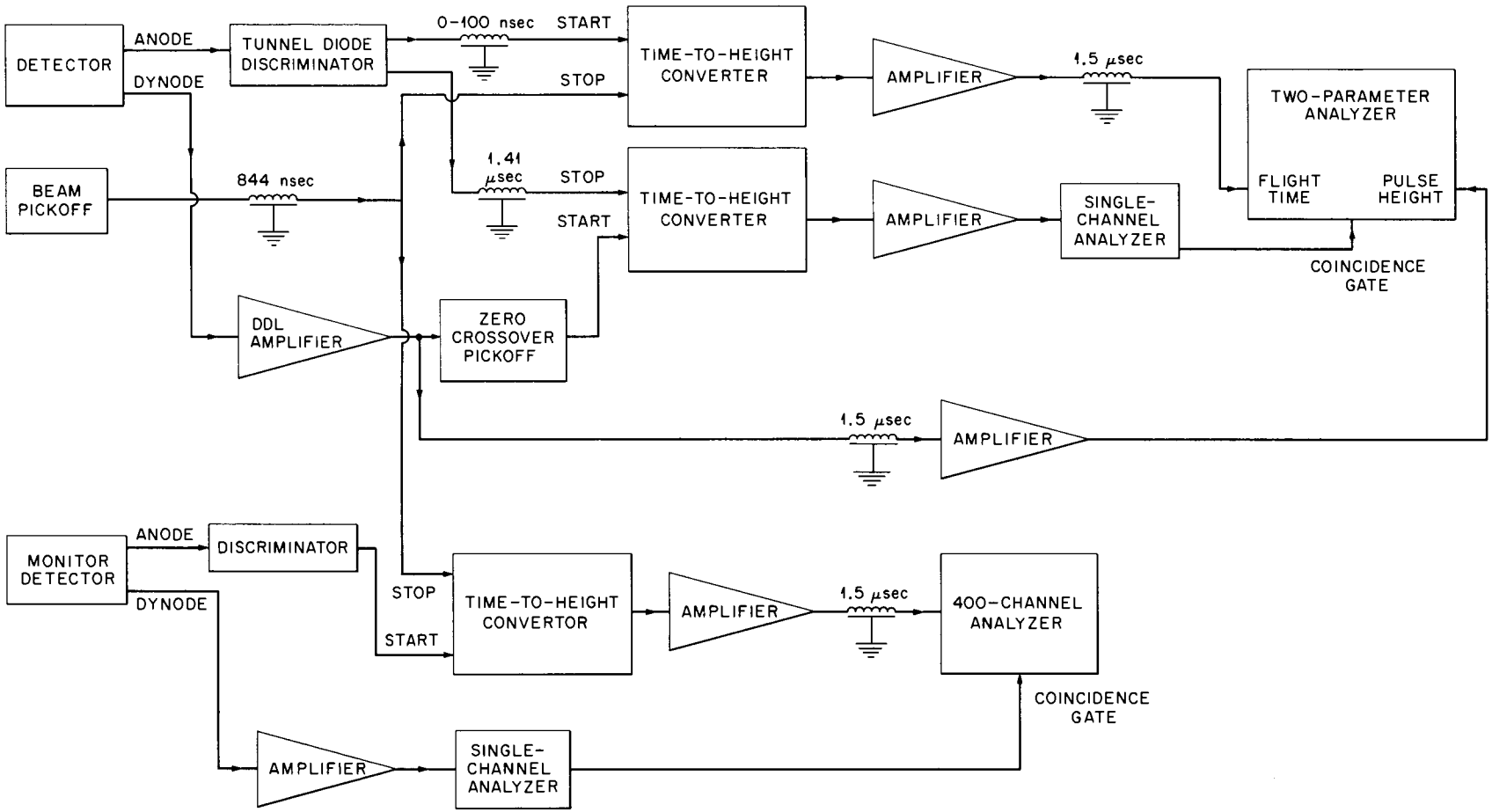

Fig. 1. Flight-Time Electronics, Showing (γ,n) Discrimination by Pulse-Shape Analysis and Accumulation of Pulse Height and Flight Time in a Two-Parameter Array.

distances up to 6 m from the scatterer and at angles from 0 to 140°.

Sample flight-time spectra are shown in Figs. 2–4. These spectra have been corrected for background and for time slowing and then have been summed over the pulse height distribution. Note that flight time increases to the *left* so that the energy scale has the usual sense, although it is, of course, not linear. These data were taken with a 4-m flight path and with a time resolution varying from ~2 nsec for the highest-energy neutrons to ~4 nsec for the lowest energies shown.

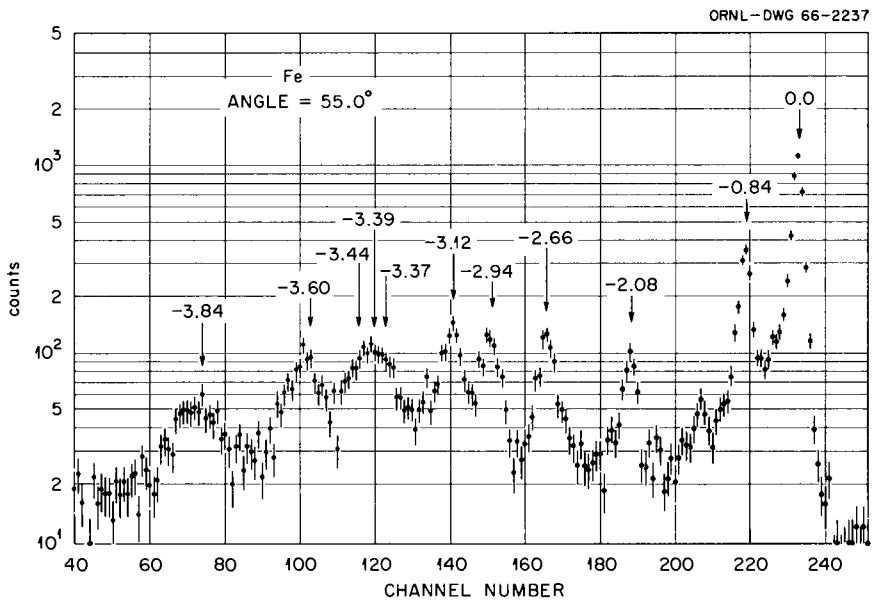

Fig. 2. Inelastic Scattering from ^{NAT}Fe at E_n = 5 Mev. Numbers above each peak are Q values for the (n,n') reaction.

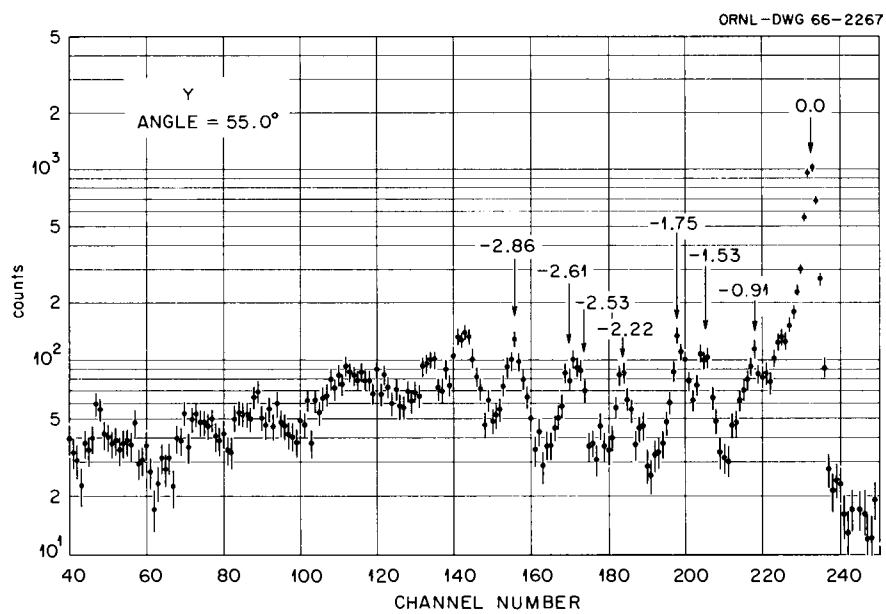

Fig. 3. Inelastic Scattering from ^{89}Y at E_n = 5 Mev. Numbers above each peak are Q values for the (n,n') reaction.

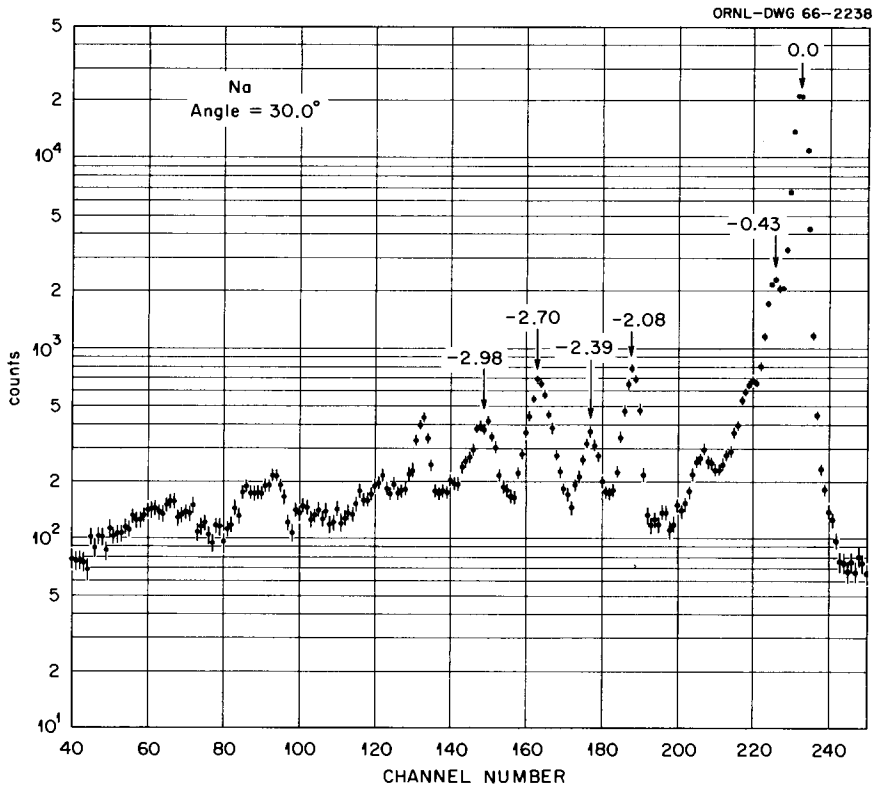

Fig. 4. Inelastic Scattering from ^{23}Na at E_n = 5 Mev. Numbers above each peak are Q values for the (n,n') reaction.

LACK OF STRUCTURE IN ^{235}U FISSION CROSS SECTION IN THE NEUTRON ENERGY RANGE FROM 150 TO 335 kev[1]

R. L. Macklin J. H. Gibbons

NUCLEAR FISSION. ^{235}U, E_n = 150–335 kev, σ_f.

We have not found previously claimed structure (of 30- to 40-kev width and 40- to 90-kev spacing) in the ^{235}U fission cross section.

[1]Abstract of published paper: *Phys. Rev. Letters* **16**, 248 (1966).

FISSION FRAGMENT ENERGY CORRELATION MEASUREMENTS FOR ^{239}Pu AND ^{241}Pu THERMAL-NEUTRON-INDUCED FISSION

J. H. Neiler F. J. Walter H. W. Schmitt

NUCLEAR FISSION. ^{239}Pu and ^{241}Pu, measured correlated fragment energies, deduced mass and energy distributions, mass-energy correlations.

Introduction

Fission fragment energy correlation experiments (more properly called pulse-height correlation experiments) have been carried out for the thermal-neutron-induced fission of ^{239}Pu and ^{241}Pu. Silicon surface-barrier detectors were used to detect the fragments.

These experiments are part of a series of such experiments which have been carried out to study the mass and energy distributions and mass-energy correlations for low-excitation fission; particular attention has been given to the determination of absolute fragment energies. A previous publication[1] gives results for ^{252}Cf spontaneous fission and ^{235}U thermal-neutron-induced fission.

In ref. 1 we have given a description of the experiments and a development of the analysis of such experiments in some detail. Since these apply in all respects to the particular measurements reported here, the experimental method will be outlined only briefly; we refer entirely to ref. 1 for details of the analysis and for other details of the experiments. Table 1, reproduced from ref. 1, gives a list of definitions and symbols used in these discussions.

Previous energy measurements of fragments from thermal-neutron-induced fission of plutonium include (1) ionization chamber measurements, for example, earlier double-chamber measurements by Brunton and Thompson[2] and more recent measurements by Apalin *et al.*,[3] and (2) time-of-flight measurements, including early single- and double-velocity measurements by Leachman[4] and Stein,[5] respectively, and recent double-velocity measurements by Milton and Fraser.[6] Previous studies of plutonium thermal-neutron fission involving solid-state detectors have been reported by Gibson *et al.*[7] and by Walter *et al.*,[8] although in these cases only partial results were reported. Mass distributions have been obtained from some of the kinetic measurements; those obtained from the double-velocity measurements are pre-neutron-emission mass distributions. Post-neutron-emission mass distributions have in general been obtained from radiochemical and mass spectrometric measurements; surveys have been compiled by Katcoff[9] and Walker.[10]

In a comparison of results of the present experiment with those of the most recent double-velocity experiments, small but significant discrepancies of several percent have been observed in fragment kinetic energies. These discrepancies are now understood and have led to improved fragment kinetic energy values, as discussed below.

Method and Apparatus

The target consisted of a thin fissile deposit on a thin backing foil in which the fragment energy loss was less than ~5 Mev. In the case of ^{239}Pu, the deposit consisted of ~20 μg/cm^2 of PuO_2, vacuum evaporated onto a nickel backing ~70

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[1] H. W. Schmitt, J. H. Neiler, and F. J. Walter, *Phys. Rev.* **141**, 1146 (1966). A preliminary report was included in *Phys. Div. Ann. Progr. Rept. Dec. 31, 1964*, ORNL-3778.

[2] D. C. Brunton and W. B. Thompson, *Can. J. Res.* **28A**, 498 (1950).

[3] V. F. Apalin *et al.*, *Nucl. Phys.* **71**, 553 (1965).

[4] R. B. Leachman, *Phys. Rev.* **87**, 444 (1952).

[5] W. E. Stein, *Phys. Rev.* **108**, 94 (1957).

[6] J. C. D. Milton and J. S. Fraser, *Can. J. Phys.* **40**, 1626 (1962); *Phys. Rev. Letters* **7**, 67 (1961).

[7] W. M. Gibson, T. D. Thomas, and G. L. Miller, *Phys. Rev. Letters* **7**, 65 (1961).

[8] F. J. Walter, H. W. Schmitt, and J. H. Neiler, *Phys. Rev.* **133**, B1500 (1964).

[9] S. Katcoff, *Nucleonics* **18**, 201 (1960).

[10] W. H. Walker, Chalk River Report CRRP-913 (1960).

$\mu g/cm^2$ thick. The ^{241}Pu was prepared in the form PuF_4; a deposit ~20 $\mu g/cm^2$ thick was vacuum evaporated onto a carbon film about 20 $\mu g/cm^2$ thick. In each case, the thin foils spanned an aperture 2 cm in diameter; the neutron beam was collimated to a diameter slightly less than 1 cm, so that it was not incident on the mounting frame or any other part inside the vacuum chamber.

Table 1. Notation

*	Denotes quantities for pre-neutron-emission fragments
$\langle\ \rangle$ or $\bar{}$	Denotes average quantities, as indicated
A	Mass of fissioning nucleus
a_i, a_i', b_i, b_i'	Constants in energy calibration equation for silicon solid-state detectors
B_{ni}	Binding energy of nth neutron emitted from ith fragment
E^*_{ki}	Pre-neutron-emission kinetic energy of ith fragment
E_{ki}	Post-neutron-emission kinetic energy of ith fragment
E^*_K	Total pre-neutron-emission fragment kinetic energy
E_K	Total post-neutron-emission fragment kinetic energy
E_{Ri}	Center-of-mass recoil energy of neutron-emitting fragment
E^*_{xi}	Pre-neutron-emission excitation of ith fragment
E^*_{xT}	Total pre-neutron-emission fragment excitation energy
$E_{\gamma i}$	Gamma decay energy for ith fragment
$E_{\gamma T}$	Total fragment gamma decay energy
FWHM	Full width at half maximum
H	Subscript indicating heavy fragment
i	$i = 1, 2$; subscript index indicating first or second fragment, corresponding to first or second detector
J	Jacobian, used in transformations of variables
L	Subscript indicating light fragment
m^*_i	Pre-neutron-emission mass of ith fragment
m_i	Post-neutron-emission mass of ith fragment
N	Number of events or counts
Q	Total energy available for nuclear reaction (fission)
x_i	Channel number for ith fragment, corresponding to ith detector
Z, N	Proton, neutron number for nucleus
η_i	Average center-of-mass kinetic energy of neutrons emitted from ith fragment
μ_i	Provisional mass of ith fragment, defined by $\mu_i = AE_j/(E_i + E_j)$ $(i, j = 1, 2;\ i \neq j)$
ν_i	Number of neutrons emitted from ith fragment
ν_T	Total number of neutrons emitted from fragments
σ	rms width, square root of second central moment; variable is indicated in subscript

Contributions from thermally fissionable impurities in the sample were less than 0.8% in both cases; no corrections for impurity contributions have been made.

Two surface-barrier detectors were mounted face-to-face on opposite sides of the target, as indicated in Fig. 1 of ref. 1. The detectors were fabricated from *n*-type silicon of nominal resistivity 500 ohm-cm and were 4 cm^2 in area. The fragment collimators were $^1/_{16}$-in.-thick aluminum, and the apertures were rounded to minimize scattering and low-energy tailing. The detectors were operated in the "saturation region" of the pulse-height-vs-bias curve, and their performances were similar to those reported for the detectors of ref. 1.

Details of the electronic system used in these experiments are given in a previous publication;[11] particular attention was given to the reduction or elimination of pileup pulses, including fission-on-fission and alpha-on-fission events. Data were accumulated event-by-event on punched paper tape in 128 × 128 channels. Each of the experiments reported here contains $\sim 10^6$ events, although a number of similar runs were made to check various experimental effects and to establish optimum conditions for the experiments.

Results for ^{239}Pu Thermal-Neutron Fission

The pulse-height correlation data array $N(x_1, x_2)$ is shown in Fig. 1. Data were obtained in 128 × 128 channels, and a total of $\sim 10^6$ events are included. The numbers labeling the contours indicate the number of events per cell (1 channel × 1 channel). Lines of constant total kinetic energy E_K and of constant provisional mass μ_1 or μ_2 are included. (See Table 1 for notation and definitions.) A transformation to the array $N(\mu_1, E_K)$ was carried out; this array is shown in Fig. 2. Numbers labeling the contours in this figure indicate the number of events per Mev per amu. In both Fig. 1 and Fig. 2, the numbers of events per cell have been entered outside the "10" contours in order to show the locations of rarer events.

Complete two-dimensional data giving ν as a function of fragment mass and kinetic energy would be required to construct lines of constant m_1^* or E_K^* in the above arrays or to construct the array $N(m_1^*, E_K^*)$. Such data are being obtained;[12] however, for general application to these and other energy correlation experiments, we have taken the approach indicated in ref. 1; that is, we derive the parameters and functions of interest from the $N(\mu_1; E_K)$ array and account for the effects of neutron emission in a separate step. The relation between μ_1 and m_1^*, based on the average-neutron-emission data of Apalin *et al.*,[3] is given in Fig. 3c.

The fragment mass distribution obtained from the present experiment is shown in Fig. 3*a*. For comparison, both the provisional mass distribution $N(\mu)$ and the pre-neutron-emission mass distribution $N(m^*)$ are shown; the latter is obtained from $N(\mu)$ and $\nu(m^*)$ as indicated in ref. 1. No resolution corrections are included in these curves. Similarly, the average total kinetic energy $\langle E_K(\mu) \rangle$, based on the provisional masses, is shown in Fig. 3*b* together with the total pre-neutron-emission kinetic energy $\langle E_K^*(m^*) \rangle$. The quantities $N(\mu)$ and $\langle E_K(\mu) \rangle$ are obtained directly from transformation of the data array together with an abolute energy calibration[13] based on a direct comparison of pulse-height spectra for fragments from ^{239}Pu thermal-neutron fission and ^{252}Cf spontaneous fission; thus these quantities are independent of any neutron-emission data.

In Fig. 4*a* we show the resolution-corrected pre-neutron-emission mass distribution for ^{239}Pu from the present experiment, compared with post-neutron-emission mass distribution determined from radiochemical and mass spectrometric measurements.[9] The differences in the two curves of Fig. 4*a* are readily understood in terms of the increase in $\nu(m^*)$ in each fragment group, as discussed previously, especially by Terrell[14] for this and other cases of low-excitation fission.

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[11] C. W. Williams *et al.*, *Nucl. Instr. Methods* **29**, 205 (1964).

[12] J. C. D. Milton and J. S. Fraser, private communication (1965); data for ^{235}U and ^{233}U have been published in *Proc. IAEA Symp. Phys. Chem. Fission*, vol. II, in press.

[13] H. W. Schmitt, W. E. Kiker, and C. W. Williams, *Phys. Rev.* **137**, B837 (1965). The method of calibration is contained in Appendix II of this paper. Further discussions of response and energy calibration of solid-state detectors based on comparisons of fission-fragment and heavy-ion measurements have been reported; see Schmitt *et al.*, *Proc. IAEA Symp. Phys. Chem. Fission*, vol. I, p. 531, 1965.

[14] J. Terrell, *Phys. Rev.* **127**, 880 (1962).

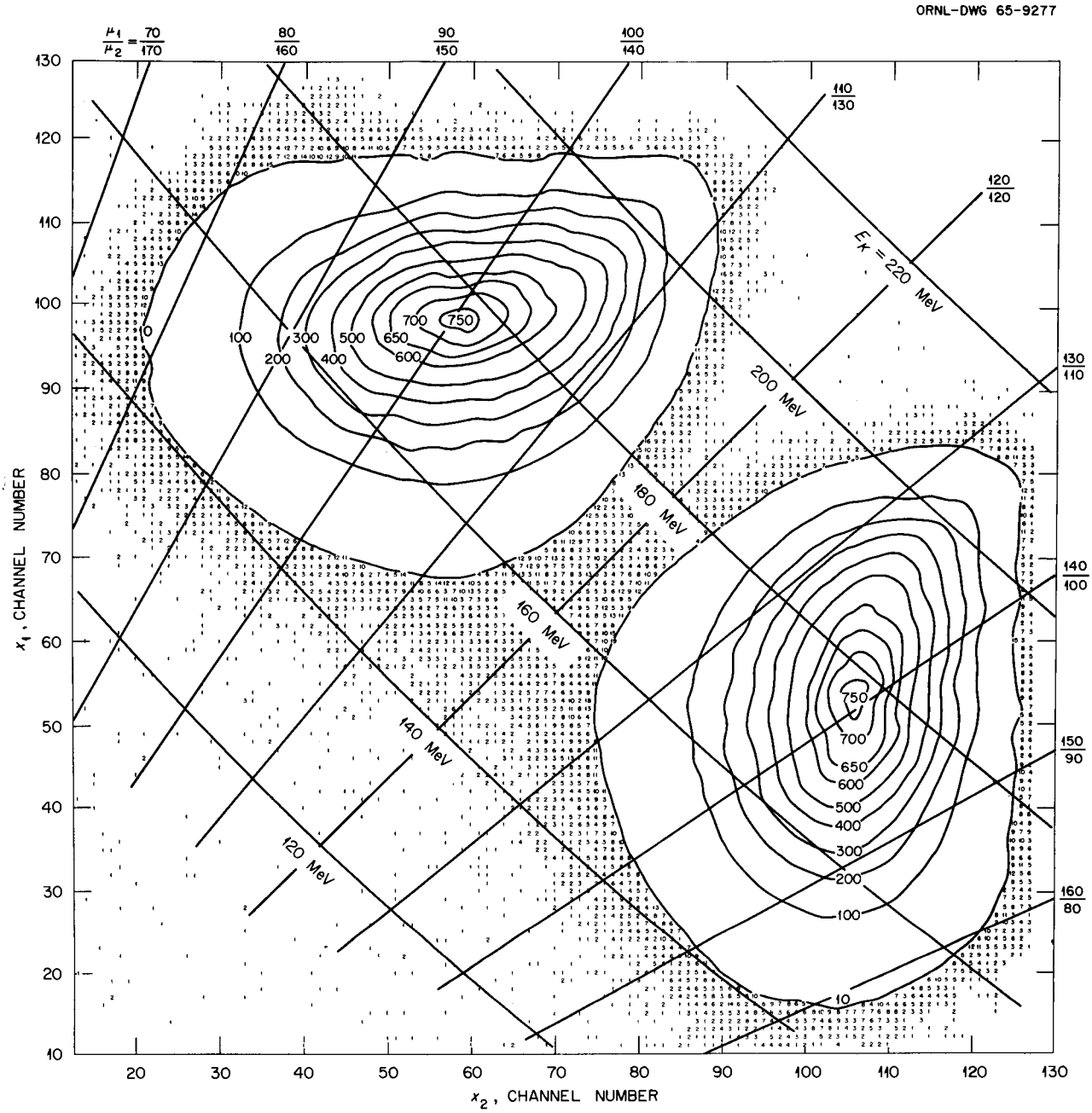

Fig. 1. Pulse-Height Correlation Data Array $N(x_1, x_2)$ for ^{239}Pu Thermal-Neutron-Induced Fission. This array contains 0.97×10^6 events. The numbers labeling the contours and those outside the 10 contours indicate the number of events per cell (1 channel × 1 channel). Lines of constant μ_1/μ_2 and E_K are shown.

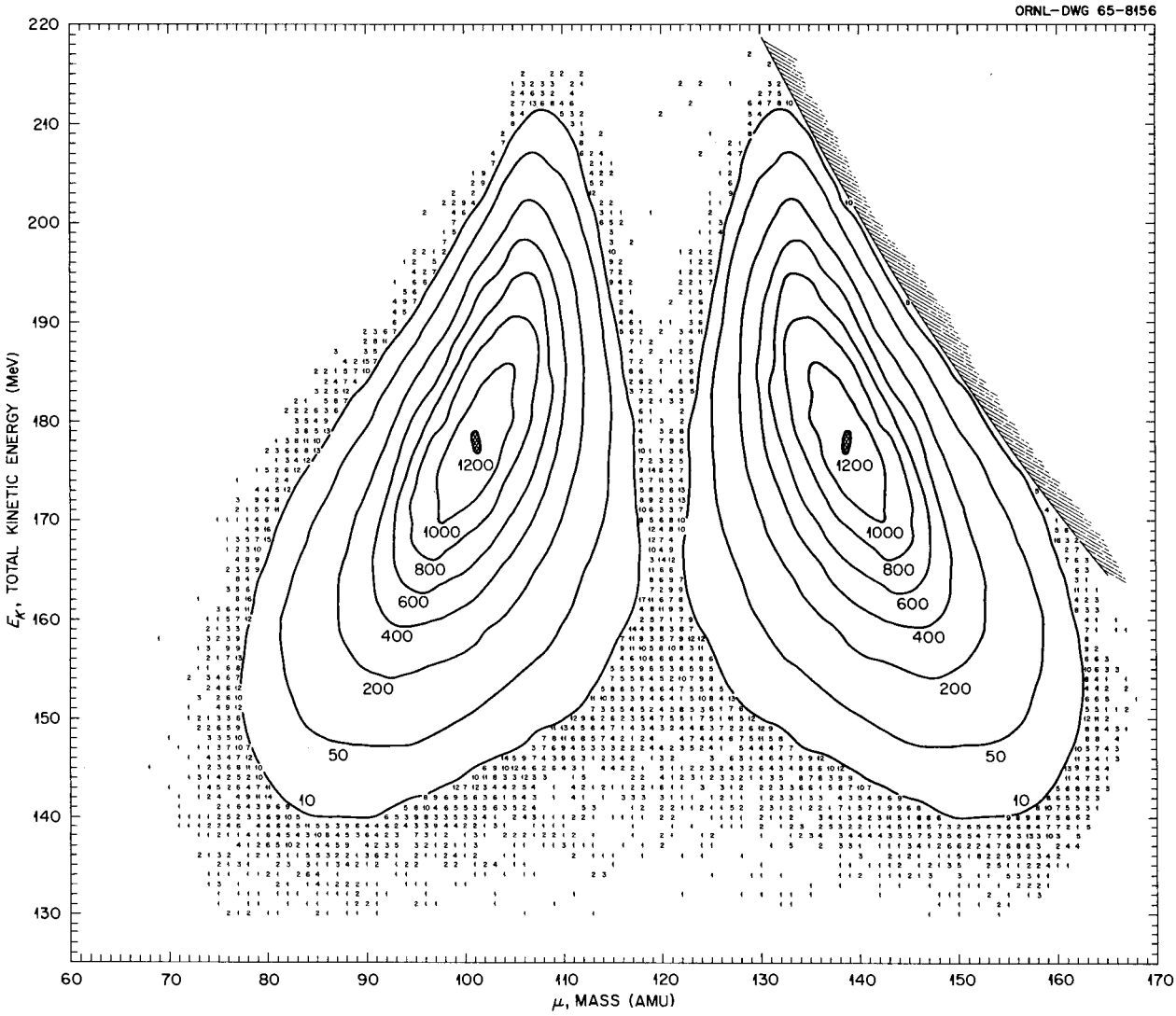

Fig. 2. Provisional Mass vs Total Kinetic Energy Array $N(\mu_1, E_K)$ for ^{239}Pu Thermal-Neutron Fission. Numbers labeling the contours and those entered outside the 10 contours indicate the number of events per cell (1 amu × 1 Mev). The curve in the upper right-hand portion of the array corresponds to the vertical line x_2 = channel 127 in Fig. 1, and represents the upper limit of data acquisition in x_2.

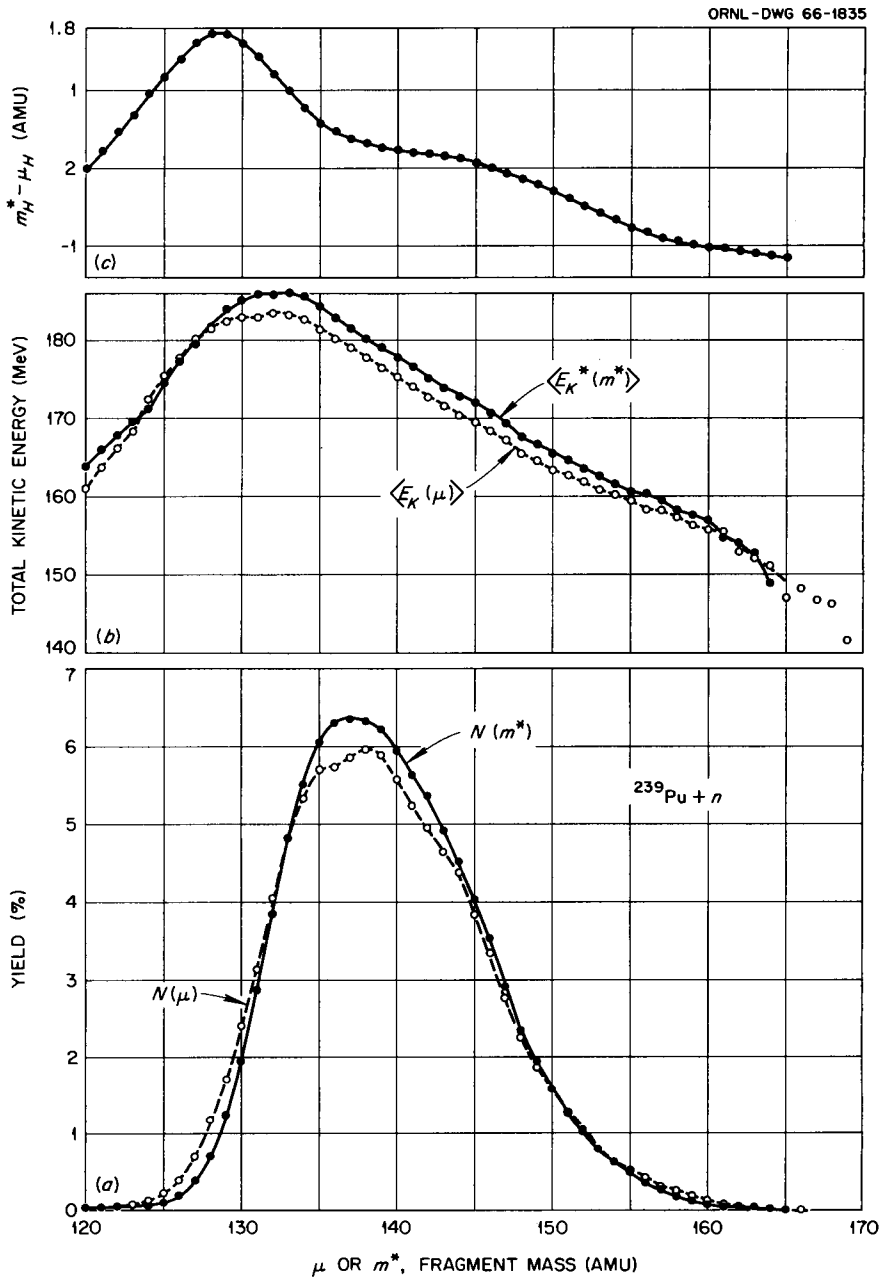

Fig. 3. Interim Results for ^{239}Pu Thermal-Neutron Fission. (*a*) Provisional mass distribution $N(\mu)$ and pre-neutron-emission mass distribution $N(m^*)$. No corrections for resolution have been included. (*b*) $\left\langle E_K(\mu)\right\rangle$ and $\left\langle E_K^*(m^*)\right\rangle$. (*c*) $m_H^* - \mu_H$ vs m_H^*.

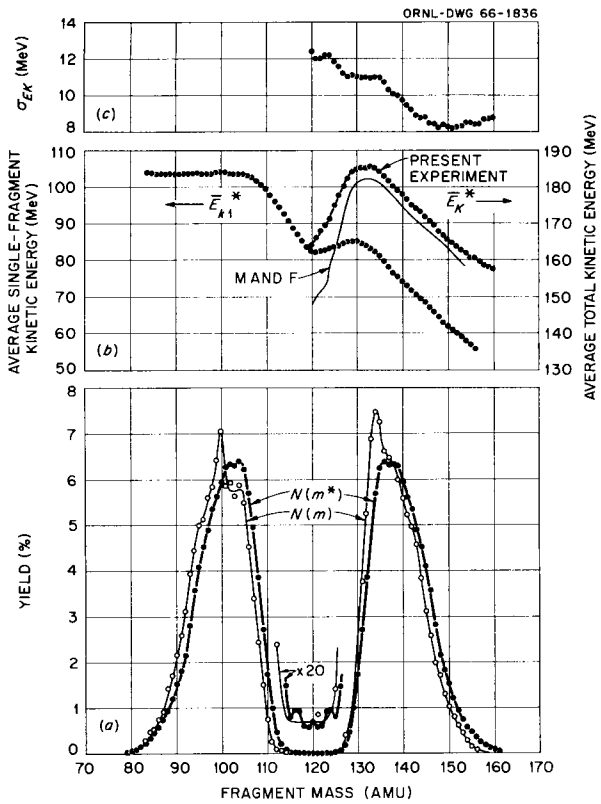

Fig. 4. Results for ^{239}Pu Thermal-Neutron Fission. (*a*) Pre-neutron-emission mass distribution corrected for resolution; the post-neutron-emission mass distribution is from the survey of Katcoff.[9] (*b*) Average single-fragment and total pre-neutron-emission kinetic energy as a function of fragment mass. The curve of Milton and Fraser[6] is shown for comparison; see text for discussion. (c) Root-mean-square width of total kinetic energy distribution as a function of fragment mass.

The average single-fragment pre-neutron-emission energy is shown as a function of fragment mass in Fig. 4*b*; also the average total pre-neutron-emission kinetic energy is plotted as a function of fragment mass. The total kinetic energy curve of Milton and Fraser[6] is shown for comparison. The discrepancy is 2 to 4 Mev over most of the mass range, increasing to ~17 Mev at symmetry, and is now understood in terms of the effect of fragment scattering from the walls of the flight tubes in the double-velocity experiment.[15] The possible effects of scattering were discussed in ref. 6, but the surprisingly large magnitude of the probability for fragment scattering at small angles to a surface was only recently found explicitly in the measurements of Engelkemeier.[16] Such scattering produces tailing toward lower velocities and energies, and thus somewhat broadens the derived mass distributions and alters the average total kinetic energies, that is, decreases them over most of the mass range. It should be noted, however, that the general shape of the kinetic energy curve of Milton and Fraser is not qualitatively different from that of the present curve; therefore many of the conclusions and points of discussion made by these authors on the basis of the qualitative trends remain unchanged.

The rms width σ_{E_K} of the total kinetic energy distribution as a function of fragment mass is plotted in Fig. 4c. The variation in ν as a function of total kinetic energy for a given mass division was neglected in computing this quantity. That is, the quantity $\sigma^2_{E_K}$, where

$$\sigma^2_{E_K} = \langle E_K^2 \rangle - \langle E_K \rangle^2 ,$$

was calculated as a function of μ, from the $N(\mu_1, E_K)$ array. The value of μ_1 corresponding to an integral value of m_1^* was found, and $\sigma^2_{E_K}$ at this value was obtained by interpolation. The square root of this value of $\sigma^2_{E_K}$ is plotted as a function of m_1^* in Fig. 4c.

A list of average fragment masses and energies and of widths of some of the distributions associated with the entire fragment spectrum is being prepared. Studies of the energy balance in ^{239}Pu thermal-neutron fission, similar to those carried out in ref. 1 for ^{252}Cf and ^{235}U, are being made and will be included in a publication of this work.

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[15] This effect was also discussed in ref. 1 in connection with the ^{252}Cf and ^{235}U results. Discussions with J. S. Fraser and J. C. D. Milton on this point are again gratefully acknowledged.

[16] D. Engelkemeier and G. N. Walton, Report AERE-R-4716 (1964); also private communication, 1965.

Results for ^{241}Pu Thermal-Neutron Fission

The pulse-height correlation data array $N(x_1, x_2)$ is shown in Fig. 5. Data were obtained in 128 × 128 channels, and a total of $\sim 10^6$ events are included in this array. The numbers labeling the contours indicate the number of events per cell (1 channel × 1 channel), and lines of constant total kinetic energy E_K and of constant provisional mass μ_1 or μ_2 are included. A transformation to

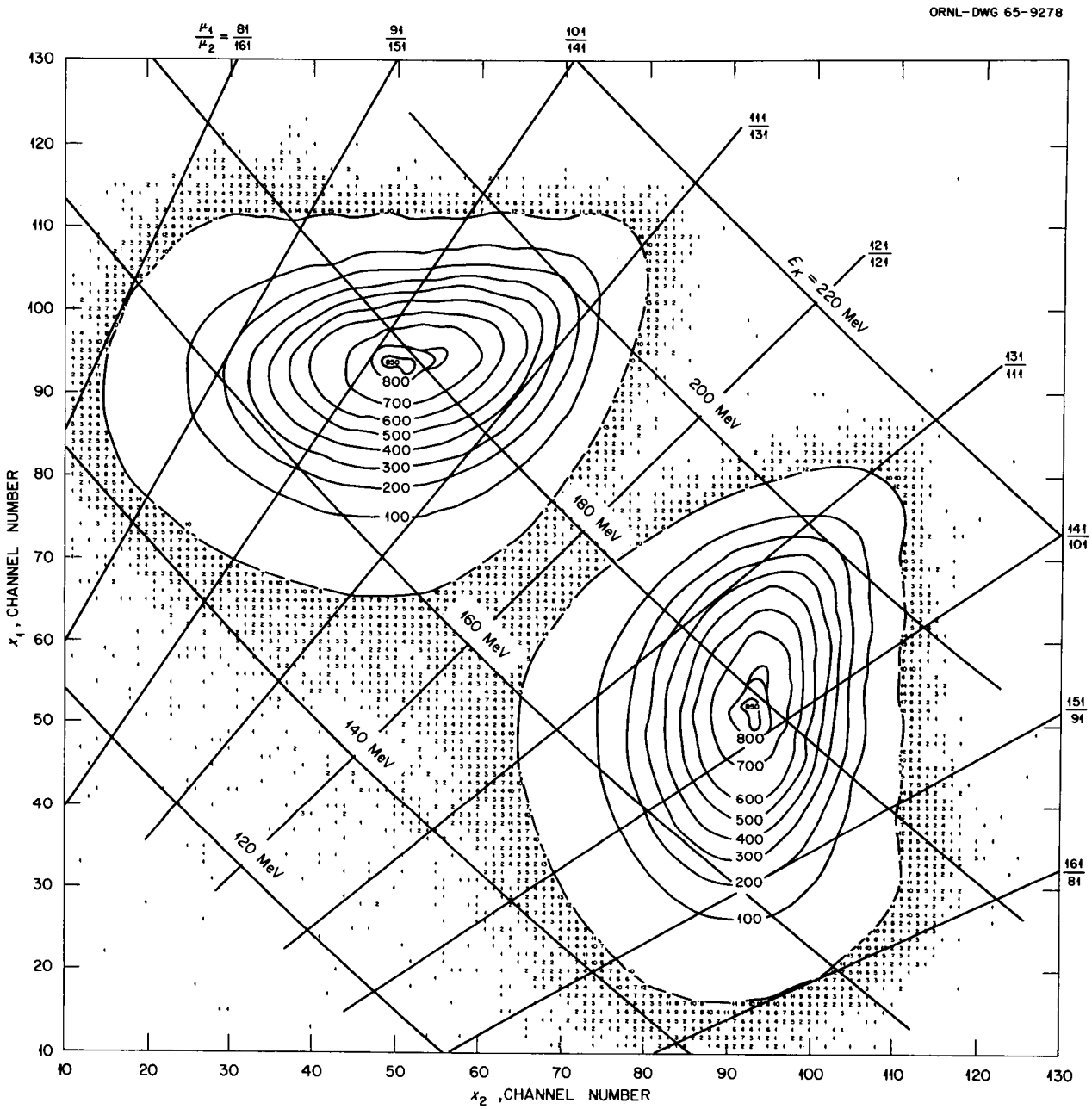

Fig. 5. Pulse-Height Correlation Data Array $N(x_1, x_2)$ for ^{241}Pu Thermal-Neutron-Induced Fission. This array contains 0.97×10^6 events. The numbers labeling the contours and those outside the 10 contours indicate the number of events per cell (1 channel × 1 channel). Lines of constant μ_1/μ_2 and E_K are shown.

the array $N(\mu_1, E_K)$ was carried out; this array is shown in Fig. 6. Numbers labeling the contours in this figure indicate the number of events per Mev per amu. In both Fig. 5 and Fig. 6, the actual numbers of events per cell have been entered outside the "10" contours in order to show the locations of rarer events.

As in the case of ^{239}Pu, we first derive the parameters and functions of interest from the $N(\mu_1, E_K)$ array, then account for the effects of neutron emission in a separate step. To our knowledge, however, there are no experimental neutron-emission data for ^{241}Pu thermal-neutron fission. Therefore, we have examined the function we require, that is, $\nu(m^*)$, as experimentally determined for other target nuclei and attempted to derive by interpolation a reasonable function $\nu(m^*)$ for ^{241}Pu. The data involved in this procedure and the resulting $\nu(m^*)$ assumed in the present analysis for ^{241}Pu are shown in Fig. 7. The ^{235}U and ^{239}Pu data are those of Apalin *et al.*[3] and the ^{252}Cf data are those of Bowman *et al.*[17]

[17] H. R. Bowman *et al.*, *Phys. Rev.* **129**, 2133 (1963).

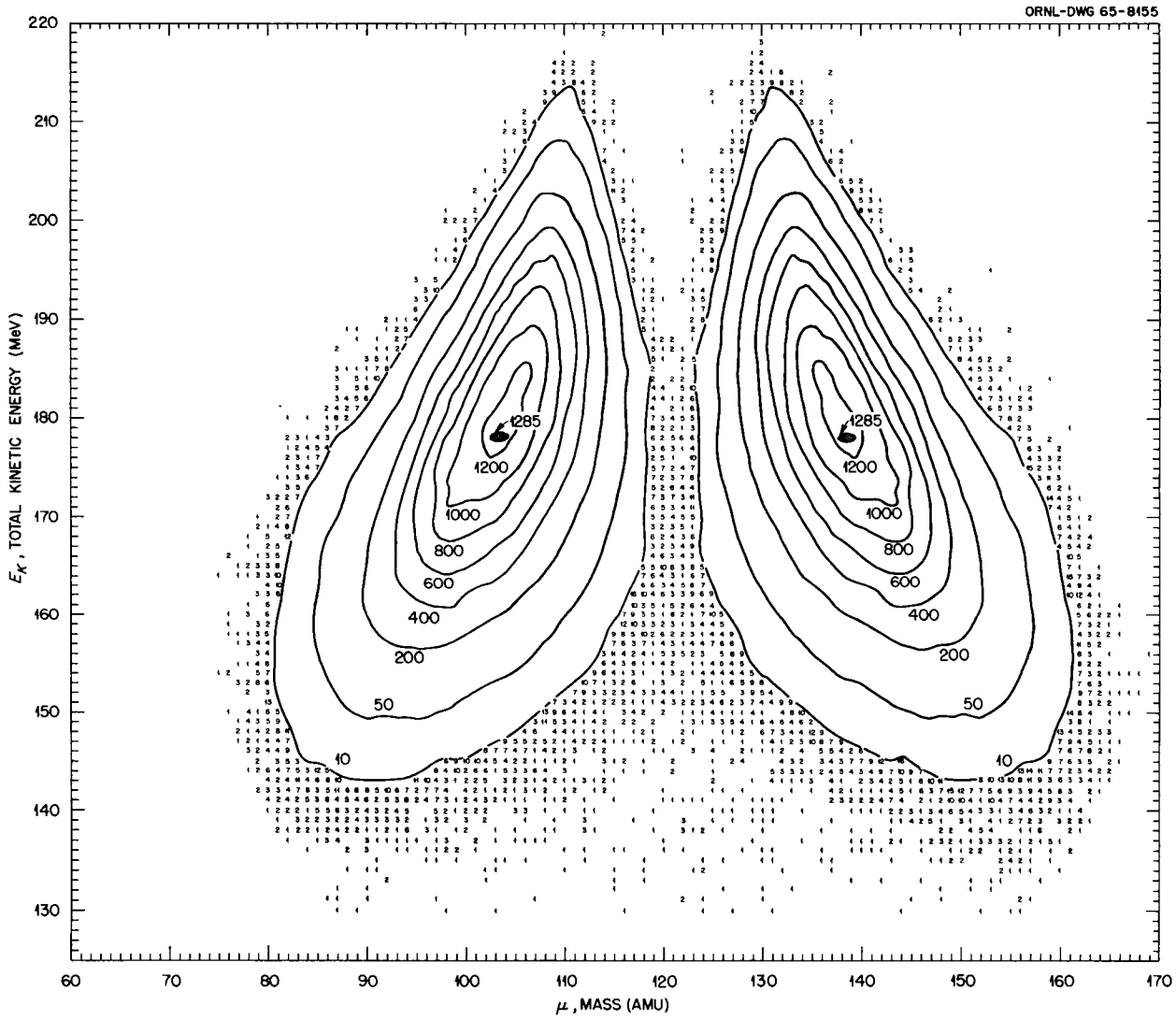

Fig. 6. Provisional Mass vs Total Kinetic Energy Array $N(\mu_1, E_K)$ for ^{241}Pu Thermal-Neutron Fission. Numbers labeling the contours and those entered outside the 10 contours indicate the number of events per cell (1 amu × 1 Mev).

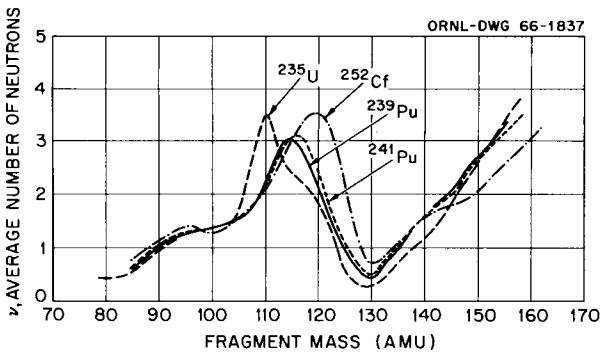

Fig. 7. Average Number of Neutrons $\nu(m^*)$ Emitted as a Function of Fragment Mass for Several Isotopes. Smooth curves are drawn for the thermal-neutron fission of ^{235}U and ^{239}Pu from the data of ref. 3, and for ^{252}Cf spontaneous fission from the data of ref. 17. The curve labeled ^{241}Pu is an estimate and is used in our derivations of $N(m^*)$ and $\langle E_K^*(m^*)\rangle$ from $N(\mu)$ and $\langle E_K(\mu)\rangle$.

The deviations in our assumed $\nu(m^*)$ for ^{241}Pu relative to the ^{239}Pu experimental data are small over most of the mass range. The relationship between μ_1 and m_1^* based on this assumed $\nu(m^*)$ is shown in Fig. 8c.

In Fig. 8*a* the provisional mass distribution $N(\mu)$ and the deduced pre-neutron-emission mass distribution $N(m^*)$ are shown; no resolution corrections are included in these curves. Similarly the quantities $\langle E_K(\mu)\rangle$ and $\langle E_K^*(m^*)\rangle$ are shown in Fig. 8*b*. The absolute energy calibration was based on direct comparison measurements of pulse-height spectra for ^{252}Cf spontaneous fission fragments and ^{241}Pu thermal-neutron fission fragments; the calibration constants were those of ref. 13.

The mass-energy results for ^{241}Pu are summarized in Fig. 9. The resolution-corrected pre-neutron-emission mass distribution from the present experiment is shown in Fig. 9*a* together with existing radiochemical and mass spectrometric yields. The relationship between $N(m)$ and $N(m^*)$ in this case is clearly similar to that observed for ^{235}U and ^{239}Pu, and is understood in terms of the increase in $\nu(m^*)$ in each fragment group, as discussed by Terrell[14] and as indicated above.

The average total and single-fragment pre-neutron-emission kinetic energies as functions of fragment mass $\langle E_K^*(m^*)\rangle$ and $\langle E_{K1}^*(m^*)\rangle$ are shown in Fig. 9*b*. The rms width σ_{E_K} of the total kinetic energy distribution as a function of fragment mass is plotted in Fig. 9c. This quantity is calculated by the method used to calculate σ_{E_K} for ^{239}Pu, above.

A list of average fragment masses and energies and of widths of some of the distributions associated with the entire fragment spectrum is being prepared. Studies of the energy balance in ^{241}Pu fission, similar to those carried out in ref. 1 for ^{252}Cf and ^{235}U, are being made and will be included in a publication of this work.

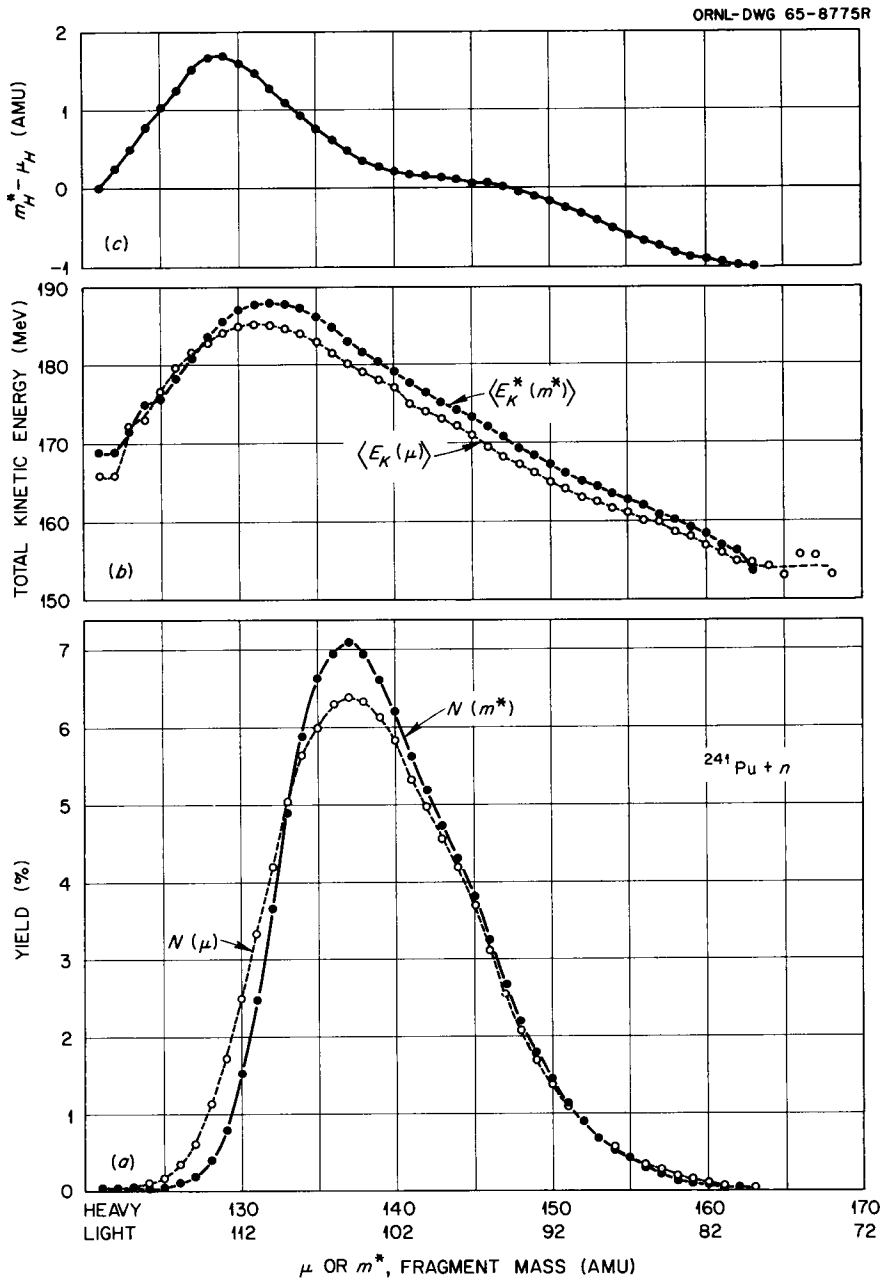

Fig. 8. Interim Results for ^{241}Pu Thermal-Neutron Fission. (*a*) Provisional mass distribution $N(\mu)$ and pre-neutron-emission mass distribution $N(m^*)$. No corrections for resolution have been included. (*b*) $\langle E_K(\mu) \rangle$ and $\langle E_K^*(m^*) \rangle$. (c) $m_H^* - \mu_H$ vs m_H^*.

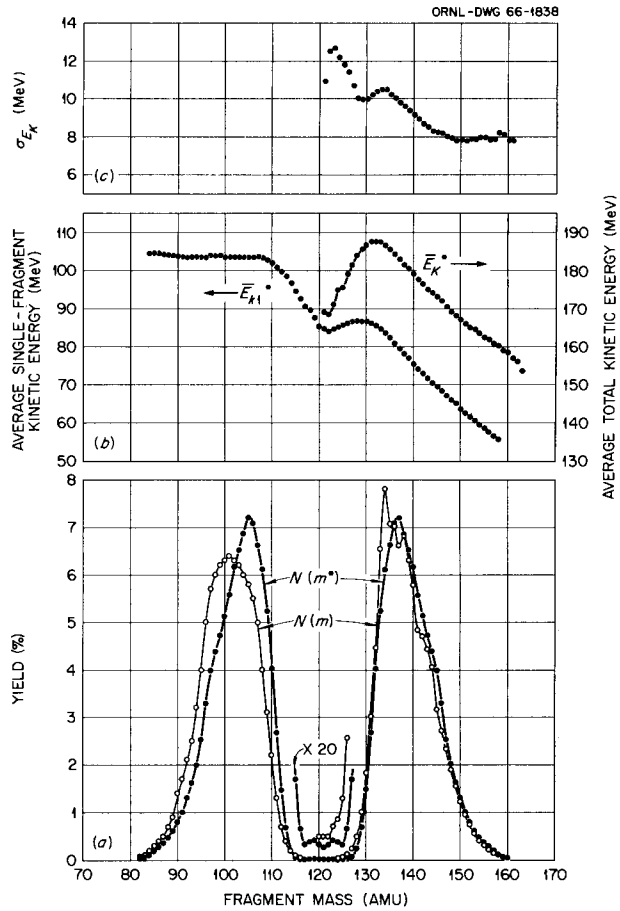

Fig. 9. Results for ^{241}Pu Thermal-Neutron Fission. (*a*) Pre-neutron-emission mass distribution corrected for resolution. (*b*) Average single-fragment and total pre-neutron-emission kinetic energy as a function of fragment mass. (c) Root-mean-square width of total kinetic energy distribution as a function of fragment.

PROMPT NEUTRON EMISSION IN ^{252}Cf SPONTANEOUS FISSION

H. W. Schmitt Frances Pleasonton R. W. Lide[1]

NUCLEAR FISSION. ^{252}Cf, measured correlated fragment energies and one velocity, deduced fragment neutron-emission characteristics, pre- and post-neutron-emission mass and energy distributions, velocity distribution.

Introduction

Detailed study of the excitation energies of fission fragments is required as one of several essential ingredients in the study of the mechanism of fission. About three-fourths of the excitation energy of the fragments is released in neutron emission; the remainder is released in gamma decay.

Direct measurements have been carried out at other laboratories to determine the neutron-emission

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properties of fragments formed in the spontaneous fission of ^{252}Cf[2,3] and also of fragments formed in thermal-neutron-induced fission.[4,5] In all of these experiments, direct correlation was obtained between the neutrons and fragments, so that, for example, the average number of neutrons $\nu(m^*)$ emitted as a function of prompt fragment mass was obtained. Such experiments are generally extremely difficult or impractical for medium- or high-excitation fission because of the high backgrounds and low intensities characteristic of such experiments at particle accelerators.

Thus it is attractive to consider obtaining neutron-emission properties of the fragments from measurements of the kinetic parameters of the fragments only, without direct measurement of the neutrons. A minimum of three parameters is required in such an experiment, and two possibilities suggest themselves: (1) measurement of the velocities of both fragments and the energy of one of them, and (2) measurement of the energies of both fragments and the velocity of one. Both types of experiments make use of the fact that if neutron emission from a fragment is symmetric about 90° in the fragment center-of-mass system, the average final velocity is equal to the initial velocity (within <0.1%). It can similarly be shown that the ratio of the average final energy to the initial energy is essentially equal to the ratio of final mass to initial mass. These principles, together with conservation of linear momentum for the initial (pre-neutron-emission) fragments and conservation of mass (nucleons), constitute the bases for analysis of such experiments to obtain the number of neutrons emitted by the fragments.

Clearly the energies and angles of emission of the neutrons are not obtained; however, the number of neutrons emitted by a single fragment or by both fragments may be obtained as functions of mass and kinetic energy, or as functions of other fragment parameters. Where fragment kinetics are concerned, such experiments are particularly desirable since the results include a consistent set of pre-neutron-emission and post-neutron-emission mass and energy distributions and mass-energy correlations.

An experiment of the first type (measurement of both fragment velocities and one fragment energy) has been carried out by Stein[6] for ^{252}Cf spontaneous fission. The experiment reported here is of the second type and involves determinations of both fragment energies and one fragment velocity. There does not appear to be any strong advantage in principle favoring one or the other of these types of experiments. For possible application to medium- or high-excitation fission, there may be a slight practical advantage in favor of the second type, where there is no risk of missing noncollinear events and where detection efficiencies are not expected to vary with fragment mass or energy.

The experiment reported here was carried out for ^{252}Cf spontaneous fission, and serves to test the method of three-parameter, energy-energy-time measurement for obtaining the neutron emission properties of fission fragments. The observation of fine structure in $\nu(m^*)$ from the present experiment is discussed.

Method and Apparatus

A block diagram of the apparatus is shown in Fig. 1.

The ^{252}Cf source gave about 3×10^5 fissions/min and was made by self-transfer onto a thin nickel backing in which the energy loss for fission fragments was $\lesssim 4$ Mev.

The detectors were silicon surface-barrier detectors about 4 cm^2 in area and were fabricated from ~825 ohm-cm silicon. Detector selection was in accordance with standards of evaluation developed at this laboratory[7] for detectors to be used in fission experiments.

The flight distance for fragment 1 (source to detector 1) was 101.4 cm; detector 2 was at a distance of 3.01 cm from the source. The ^{252}Cf deposit faced detector 1. Fragment collimators were located along the flight path to prevent detection of fission fragments which were scattered from the walls of the flight tube. In addition,

[2] S. L. Whetstone, Jr., *Phys. Rev.* **114**, 581 (1959).

[3] H. R. Bowman *et al.*, *Phys. Rev.* **126**, 2120 (1962); **129**, 2133 (1963).

[4] V. F. Apalin *et al.*, *Nucl. Phys.* **71**, 553 (1965).

[5] J. C. D. Milton and J. S. Fraser, *Proc. IAEA Symp. Phys. Chem. Fission, Salzburg, Austria*, 1965.

[6] W. E. Stein, *Proc. IAEA Symp. Phys. Chem. Fission, Salzburg, Austria*, 1965.

[7] H. W. Schmitt and F. Pleasonton, *Nucl. Instr. Methods* (in press).

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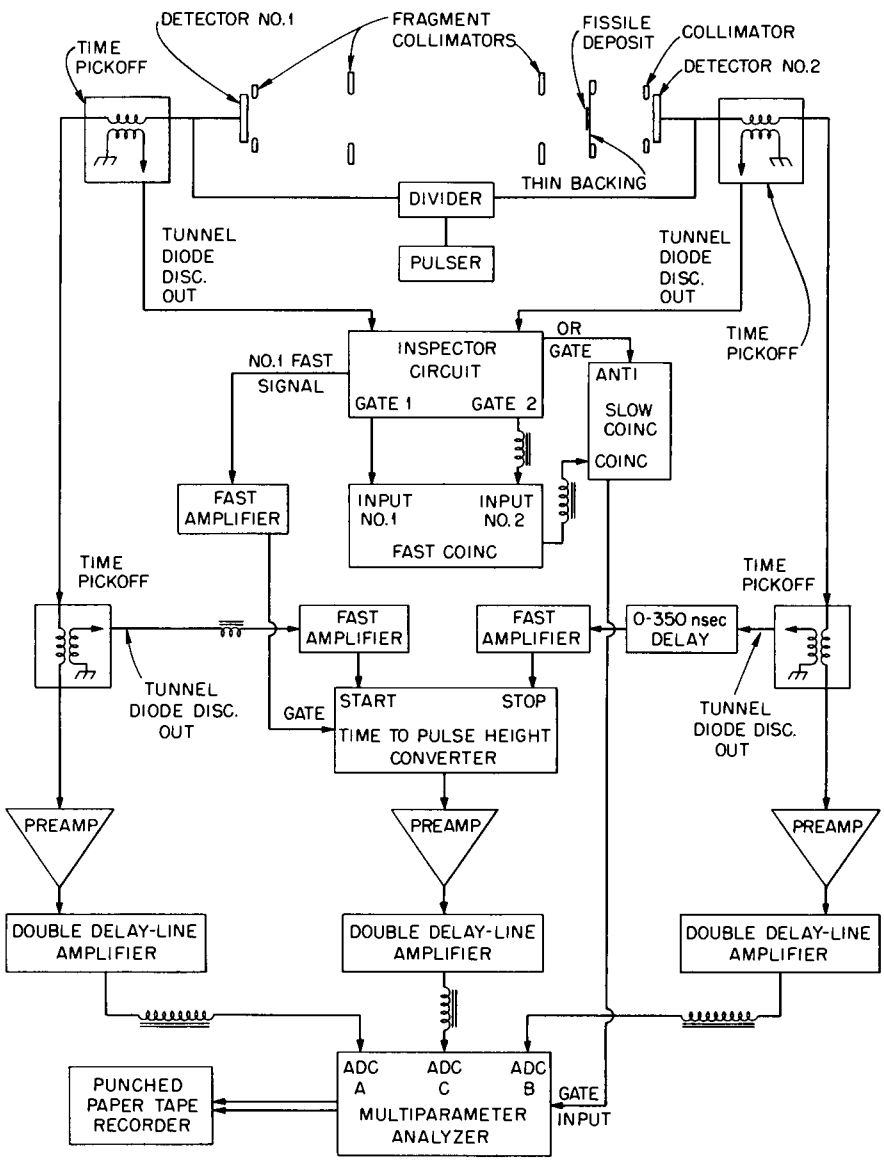

Fig. 1. Schematic Diagram of Experimental Arrangement.

rounded plastic collimators were placed directly in front of the detectors to eliminate edge effects in the detectors.

Two time pick-off units were used in series with each of the fragment detectors. In each side, one of the units was used to provide a timing signal, the other to provide signals for pileup inspection and rejection. As shown in Fig. 1, the first time pick-off unit on each side provides for inspection. The tunnel diode bias is set below the level of natural alpha particles, so that if a natural alpha particle and a fission fragment (or two fission fragments or two alpha particles) occur with a time separation of 20 nsec to 2 μsec, an "OR gate" pulse is generated which then prevents recording of either of the pulses.

The second time pick-off in each side is used for timing. The variable delay in side 2 permitted linearity determinations and stability checks; for data acquisition in the experiment, this delay was

set at 199.2 nsec, so that the stop pulses into the time-to-pulse-height converter occurred after the start pulses corresponding to the slowest fragments.

Standard charge-sensitive preamplifiers and amplifiers were used for amplification of the linear signals from the detectors. Data were recorded event-by-event onto punched paper tape. Two hundred fifty-six channels were used in each of the three parameters.

Analysis

The time sequence of events following the occurrence of the fission is shown in Fig. 2. Fragment 2 impinges on detector 2 at time t_2 and, a time t_{r2} later, the pulse thereby created in the time pick-off unit crosses the tunnel diode discriminator level, thus generating a timing pulse. This pulse is delayed a known fixed time t_D, then enters the "STOP" side of the time-to-pulse-height converter (TPHC) at time t_{2D}. Fragment 1, similarly, impinges on detector 1 at time t_1 and generates a timing pulse after a short rise-time interval t_{r1}; this pulse enters the "START" side of the TPHC directly.

Thus the measured time t_m is as indicated in the figure, and the time of flight of fragment 1 is given by

$$t_1 = t_D - t_m - t_{r1} + t_{r2} + t_2 \ , \qquad (1)$$

where the last three terms are small compared to the difference of the first two terms. There are also minor delays in other parts of the circuit; these are generally fixed and are accounted for by γ in the time calibration equation

$$t_m = \alpha x_3^2 + \beta x_3 + \gamma \ , \qquad (2)$$

where α, β, and γ are calibration constants determined in auxiliary experiments and x_3 is the channel number for the "time" pulses. Because the timing system is quite linear, α is small and the first term of Eq. (2) amounts to less than 1% of t_1.

A subsidiary experiment was carried out to ascertain the form of the rise-time correction terms t_{r1} and t_{r2}. It was found that an expression of the form

$$t_{ri} = c_i/(x_i + \sigma_i) \ , \quad i = 1, 2 \ , \qquad (3)$$

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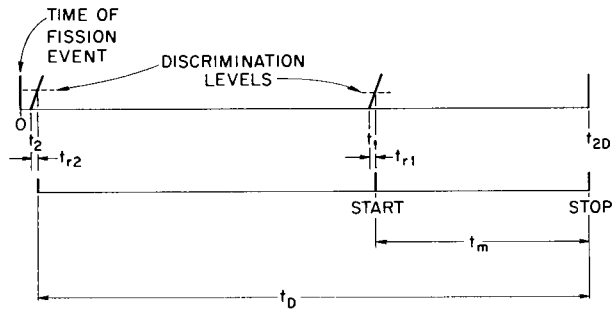

Fig. 2. Time Sequence of Events. The measured time interval is t_m; time-of-flight of fragment 1 is t_1.

where c_i and σ_i ($i = 1, 2$) are calibration constants, suffices to describe these terms. In this form, the denominator is proportional to the linear pulse amplitude for detector i; x_1 and x_2 are the channel numbers for the linear signals from detectors 1 and 2. The constants c_i and σ_i were determined in auxiliary experiments with the detectors and electronic equipment used in the main experiment.

A relationship for t_2 in terms of t_1 may be established from conservation of linear momentum of the fragments. Since $t_2 \ll t_1$, a sufficiently accurate determination of t_2 is obtained if the post-neutron-emission masses and velocities are used in the momentum conservation equation. Then

$$t_2 = t_1(m_2 D_2/m_1 D_1) \ , \qquad (4)$$

where m_2 may be approximated to sufficient accuracy by the quantity $A - \overline{\nu}_T - m_1$. Equations (2), (3), and (4) are used in (1) to obtain the flight time of fragment 1. The energy of fragment 1 is given by

$$E_1 = m_1 D_1^2/2t_1^2 \qquad (5)$$

and is experimentally determined through the relation[8]

$$E_1 = k\,[(a_1 + a_1' m_1)\, x_1 + b_1 + b_1' m_1] \ , \qquad (6)$$

[8]H. W. Schmitt, W. E. Kiker, and C. W. Williams, *Phys. Rev.* **137**, B837 (1965).

where k is a units conversion factor and a_1, a_1', b_1, and b_1' are the energy calibration constants for detector 1. If we combine Eqs. (1) through (6) and define

$$T = t_D - (x_3^2 + \beta x_3 + \gamma) - \frac{c_1}{x_1 + \sigma_1} + \frac{c_2}{x_2 + \sigma_2} , \quad (7)$$

we obtain the post-neutron-emission mass m_1 in terms of the experimental quantities:

$$m_1 = \frac{\mathcal{B} + \sqrt{\mathcal{B}^2 - 4\mathcal{A}\mathcal{C}}}{2} , \quad (8)$$

where

$$\mathcal{A} = (D_1 + D_2)^2/2T^2 - k(a_1' x_1 + b_1') ,$$

$$\mathcal{B} = D_2(D_1 + D_2)(A - \nu_T)/T^2 + k(a_1 x_1 + b_1) , \quad (9)$$

$$\mathcal{C} = D_2^2(A - \nu_T)^2/2T^2 .$$

In processing the data from event-by-event records of channel combinations x_1, x_2, x_3, we avoid grid fluctuations (i.e., effects of recording data only at discrete values of x_1, x_2, x_3) by adding a random number between −0.5 and +0.5 to each channel number before any computations are made. The new combination of three channel numbers is then used in the above equations to calculate m_1 and m_1^2. Then, in effect, three two-parameter arrays are constructed; these are $\overline{m}_1(x_1, x_2)$, $m_1^2(x_1, x_2)$ and $N(x_1, x_2)$. The first and third of these arrays are used in subsequent calculations; the three arrays are used together to compute $\sigma_{m1}(x_1, x_2)$, the standard deviation of the mass distribution for each x_1, x_2 combination. The equation is

$$\sigma_{m1} = \frac{N}{N-1} (\overline{m_1^2} - \overline{m}_1^2)^{1/2} . \quad (10)$$

The remainder of the analysis may now be carried out from the $\overline{m}_1(x_1, x_2)$ and $N(x_1, x_2)$ arrays. First, we note that on the average, if neutron emission occurs from the fragments with an angular distribution which is symmetric about 90° in the fragment center-of-mass system, the final fragment kinetic energy E_i is given with good accuracy in terms of the initial fragment energy E_i^* by the relation

$$E_i = \frac{m_i^*}{m_i} E_i^* \quad (i = 1, 2) , \quad (11)$$

where m_i^* and m_i are the pre-neutron-emission and post-neutron-emission masses respectively, and $i = 1, 2$ refers to fragment 1 or 2. From these equations, together with the momentum conservation equation for fragments before neutron emission ($m_1^* E_1^* = m_2^* E_2^*$), it is easily shown that m_1^* is given in terms of the post-neutron-emission quantities by the relation

$$m_1^* = \frac{A}{1 + (m_2 E_1 / m_1 E_2)^{1/2}} , \quad (12)$$

where A is the mass of the fissioning nucleus.

Consider now a point A in the $\overline{m}_1(x_1, x_2)$ array at which the coordinates are x_{1A} and x_{2A}, and at which $\overline{m}_1 = \overline{m}_{1A}$. The energy E_{1A} at this point is then given by Eq. (7). To find m_{1A}^* from Eq. (12), we must still determine m_{2A} and E_{2A}. For this we use a "method of complementary points," as follows: The energy E_2 is given in terms of m_2 and x_2 by Eq. (6) if all subscripts 1 are replaced by subscripts 2. To find the value of m_{2A}, we define a point B which is complementary to A; that is,

$$E_{1B} = E_{2A} ; \quad E_{2B} = E_{1A} . \quad (13)$$

Then, because of the symmetries involved, we have

$$\overline{m}_{2A} = \overline{m}_{1B} ; \quad \overline{m}_{1A} = \overline{m}_{2B} , \quad (14)$$

and it remains only to locate the coordinates x_{1B} and x_{2B}.

The coordinate x_{2B} is obtained directly from the energy calibration equation for detector 2, where the known values of E_{1A} and $\overline{m}_{1A}$ are used in place of E_{2B} and m_{2B} respectively. A first approximation to x_{1B} must be made, wherein we use the relation $\overline{m}_{2A} = A - \overline{\nu}_T - \overline{m}_{1A}$ to calculate a first approximation to E_{2A}; then these values of $\overline{m}_{2A}$ and E_{2A} are used in the energy calibration equation for detector 1 to determine the first approximation to x_{1B}. The value of $\overline{m}_{1B}$ at the point x_{1B}, x_{2B} may now be obtained directly from the $\overline{m}_1(x_1, x_2)$ array, and this new value may be used for m_{2A} in the energy calibration equation

for detector 2 to obtain a new approximation for E_{2A}. The procedure is repeated and, after two or three such iterations, should converge with sufficient accuracy.

Thus we now have, for any point A in x_1, x_2 coordinates, the values of $\overline{m}_1$, $\overline{m}_2$, E_1, and E_2. The pre-neutron-emission mass m_1^* is then given by Eq. (12), and the pre-neutron-emission kinetic energies E_i^* are given by Eqs. (11). The following quantities are then calculated:

$$\overline{\nu}_T = A - \overline{m}_1 - \overline{m}_2 \ , \tag{15}$$

$$\overline{\nu}_1 = m_1^* - \overline{m}_1 \ , \tag{16}$$

$$E_K^* = E_1^* + E_2^* \ . \tag{17}$$

Combining these results with the $N(x_1, x_2)$ array, employing a "sub-boxing" technique, we construct the final arrays of interest: $\nu_T(m_1^*, E_K^*)$, $\nu_1(m_1^*, E_K^*)$, and $N(m_1^*, E_K^*)$. From these arrays, we may study the variations in ν_1 and ν_T as functions of fragment mass and total kinetic energy release, and we may also obtain the usual relations giving average number of neutrons emitted from one or both fragments as functions of fragment mass, that is, $\nu_1(m_1^*)$ or $\nu_T(m_1^*)$. In addition to these neutron results, the pre- and post-neutron-emission kinetic parameters are obtained, and we generate (in principle) a self-consistent set of results including the neutron-emission parameters described above together with $N(m^*)$, $N(m)$, $\overline{E}_K^*(m^*)$, $N(E_K^*)$, $N(E_1)$, $N(\nu_1)$, etc.

It is frequently useful to examine interim results in a somewhat different form. For example, arrays with E_1 and E_2 as coordinates permit detailed examination of complementary points; also any structure or special features of the arrays in m_1^*, E_K coordinates may be examined in E_1, E_2 space. Accordingly, after the $\overline{m}_1(x_1, x_2)$ and $N(x_1, x_2)$ arrays have been constructed, the method of complementary points as described above was used to determine $\overline{m}_2$ and $\overline{E}_2$ along with $\overline{m}_1$ and $\overline{E}_1$ for each point in x_1, x_2 space. A "sub-box" transformation was then carried out to obtain $\overline{m}_1(E_1, E_2)$ and $N(E_1, E_2)$ arrays, and from these together with Eqs. (12), (15), and (16), we obtain the $\nu_1(E_1, E_2)$ and $\nu_T(E_1, E_2)$ arrays.

Results

Only a portion of the possible results of the present experiment have been obtained to date. In Fig. 3 are shown the pre- and post-neutron-emission fragment mass distributions. The smooth curve drawn through the post-neutron-emission mass distribution points was obtained from the data of ref. 8; the smooth curve drawn through the pre-neutron-emission mass distribution points was obtained from the data of Whetstone[9] and is almost indistinguishable from the results of an earlier energy-correlation experiment at this Laboratory.[10]

The single-fragment velocity and energy distributions are more directly related to the measured quantities and are shown in Fig. 4. The velocity distribution is in essential agreement with those of refs. 8 and 9. The average light-fragment velocity is found to be 1.377 cm/nsec, compared with 1.375 cm/nsec from ref. 9 and 1.383 cm/nsec from ref. 8; and the average heavy-fragment velocity is found to be 1.037 cm/nsec, compared with 1.036 cm/nsec from both refs. 8 and 9.

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[9] S. L. Whetstone, Jr., *Phys. Rev.* 131, 1232 (1963).

[10] H. W. Schmitt, J. H. Neiler, and F. J. Walter, *Phys. Rev.* 141, 1146 (1966).

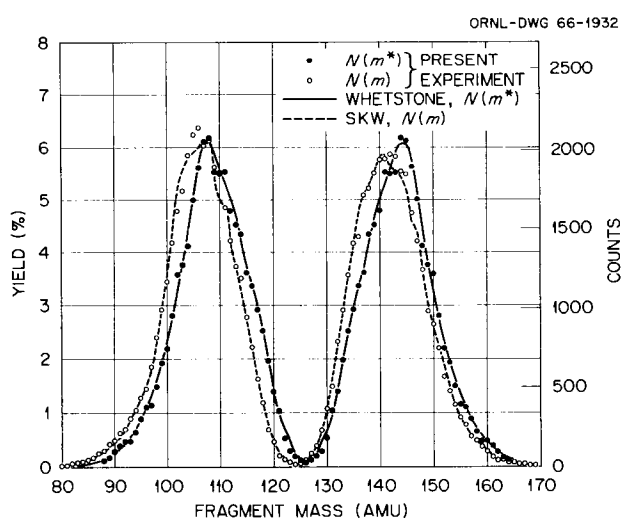

Fig. 3. Pre- and Post-Neutron-Emission Fragment Mass Distributions. Points are from the present experiment; smooth curves are from refs. 8 and 7 respectively.

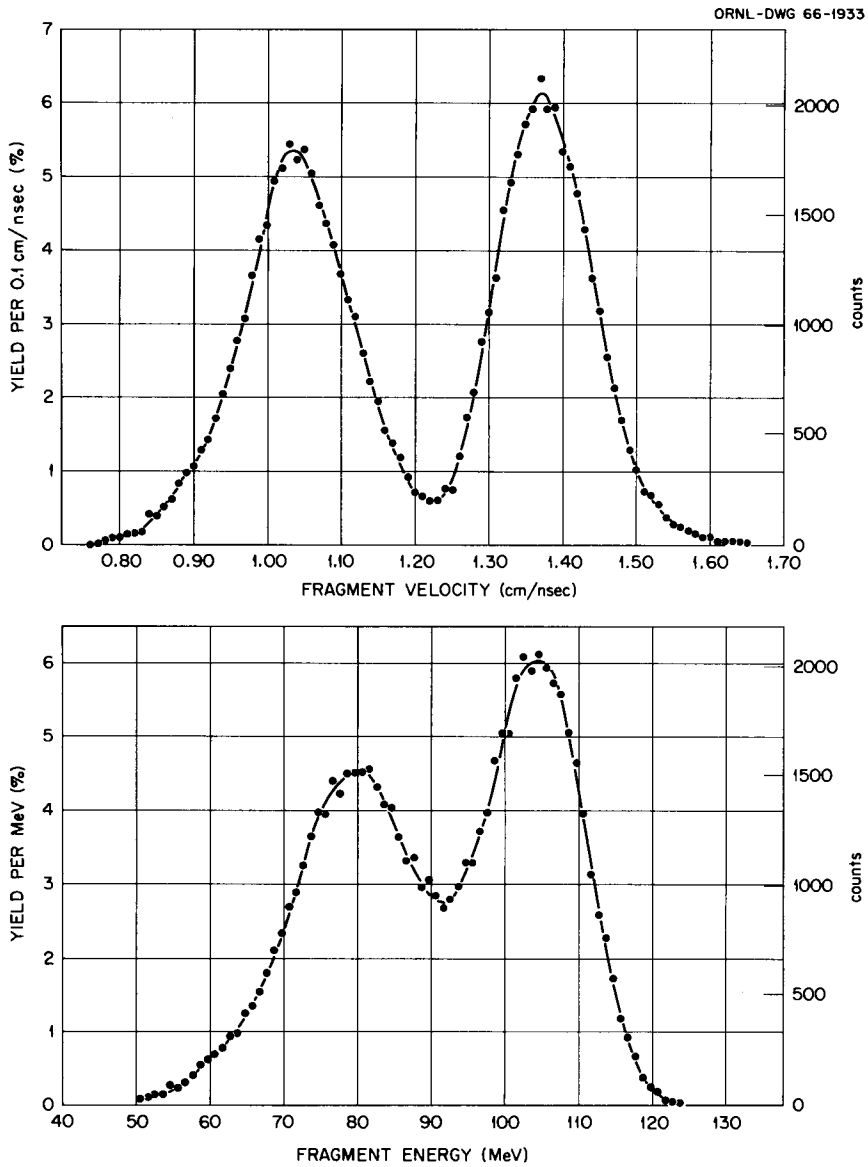

Fig. 4. Single-Fragment Velocity and Energy Distributions.

The energy distribution shown in Fig. 4 is in excellent agreement with that of ref. 8. The average energies obtained here are 103.9 and 79.1 Mev for the light and heavy fragments respectively, compared with the values 103.8 and 79.4 Mev from ref. 8.

Figure 5 shows the average number of neutrons emitted as a function of prompt fragment mass. The smooth curves have been drawn through the data of Bowman *et al.*[3] and through the data of Whetstone[2] corrected for dispersion effects by Terrell.[11] The results of the present experiment have been corrected for dispersion.

[11] J. Terrell, *Phys. Rev.* **127**, 880 (1962).

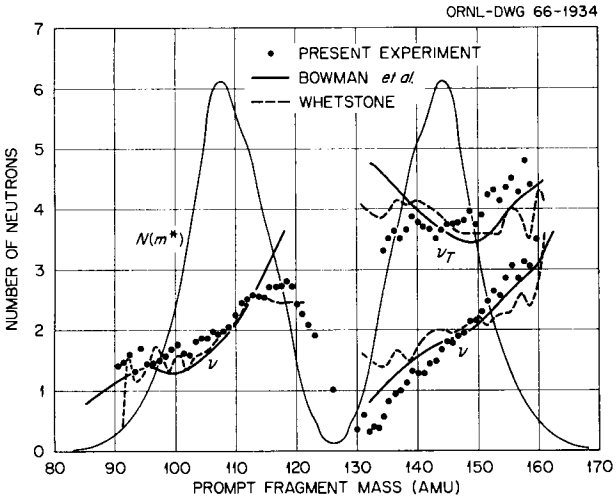

Fig. 5. Average Number of Neutrons Emitted as a Function of Fragment Mass. Points are from present work and may be compared with smooth curves drawn through the results of Whetstone[2] and Bowman *et al.*[3] The pre-neutron-emission mass distribution is reproduced for reference.

The fine structure observed in Fig. 5, particularly in $\nu_T(m^*)$, is especially interesting. The fine-structure maxima coincide with the maxima of the even-even "parabolas" in the curves of total available energy vs fragment mass and charge, as indeed do the fine-structure maxima in $\langle E_K^*(m^*)\rangle$. (See, e.g., ref. 12, also Fig. 10 of ref. 10.) Thus fragments with even-even proton-neutron configurations are seen to have both larger excitation energies and larger kinetic energies than those of other configurations. We note that the structure in $\nu(m^*)$ appears to be more prominent in the heavy-fragment group than in the light-fragment group; studies are in progress to determine whether this is the result of differences in dispersion effects in the two groups or whether a real difference exists.

Although the quantitative results presented here are preliminary and may be subject to small changes due to refinements in analysis, the method has been shown to be useful to determine qualitative trends in $\nu(m^*)$, and even to determine quantitative values of ν within $\sim$0.5 amu. A note of caution must be injected, however: The recent measurements of Milton and Fraser[5] indicate that the angular distribution of neutrons emitted in thermal-neutron fission may be described in terms of components which are isotropic in the center-of-mass systems of the fragments and a component which is isotropic in the laboratory system. This last component is indicated to be large, that is, $\sim$20%. The effect of such a result on the present method of determination of ν must be studied.

Experiments are in progress to attempt to obtain $\nu(m^*)$ for cases of higher-excitation fission by this method.

[12]T. D. Thomas and R. Vandenbosch, *Phys. Rev.* **133**, B976 (1964).

FRAGMENT ENERGY CORRELATION MEASUREMENTS FOR ^{252}Cf SPONTANEOUS FISSION AND ^{235}U THERMAL-NEUTRON FISSION[1]

H. W. Schmitt J. H. Neiler[2] F. J. Walter[2]

Fission fragment mass and energy distributions and mass-vs-energy correlations have been obtained for ^{252}Cf spontaneous fission and ^{235}U thermal-neutron-induced fission. Silicon surface-barrier detectors were used in energy correlation measurements; absolute fragment energies were obtained by means of the mass-dependent energy calibration developed recently at this laboratory. Average total fragment kinetic energies before

[1]Abstract of published paper: *Phys. Rev.* **141**, 1146 (1966).

[2]Oak Ridge Technical Enterprises Corporation, Oak Ridge, Tenn.

neutron emission are found to be 186.5 ± 1.2 Mev for ^{252}Cf and 171.9 ± 1.4 Mev for ^{235}U. Detailed experimental results are given and compared with those of other experiments. Observed fine structure in the fragment mass distribution and in the average total fragment kinetic energy as a function of mass is correlated with the energetically preferred even-even nucleon configurations in the fragments. New determinations of the rms width of the total kinetic energy distribution as a function of mass show structure which is also correlated with the energetically preferred even-even fragment configurations. Fission-neutron and gamma-ray data of other experiments are used with the new fragment kinetic energies presented here to examine the total energy balance for fission for the two cases studied.

CORRELATED FRAGMENT ENERGY MEASUREMENTS AND MASS-vs-ANGLE CORRELATIONS IN ^{226}Ra + p FISSION[1]

H. W. Schmitt J. W. T. Dabbs P. D. Miller

Fission-fragment mass and energy distributions and mass-vs-energy correlations have been obtained from energy correlation measurements of fragments from the proton-induced fission of ^{226}Ra. The mass distribution was observed to be triple peaked, and the symmetric part was found to increase relative to the asymmetric parts as the proton energy was increased from 11.0 to 12.0 and to 13.5 Mev. The fragment center-of-mass angle θ was 90°; protons were obtained from the Oak Ridge tandem accelerator. In studies of fragment total kinetic energy vs mass, a separation into three rather distinct areas of occurrence was found. The results indicate that a two-mode hypothesis may indeed be valid for ^{226}Ra + p fission, and that the "symmetric" mode is describable in terms of the nonviscous-liquid-drop-model calculations of Nix and Swiatecki. The kinetic energies associated with the "asymmetric" mode are consistent with those of the predominantly asymmetric fission of heavier elements at low excitation energy, when the reduced Coulomb repulsion of the fragments in the present case is taken into account. The results of a search for fragment mass-vs-angle correlations at E_p = 13.5 Mev show a small (~5%) effect which may, however, be explained in terms of the small probability for second-chance fission at this energy.

[1]Abstract of paper to be published in the *Physical Review*.

EVALUATION OF SEMICONDUCTOR DETECTORS FOR FISSION-FRAGMENT ENERGY MEASUREMENTS[1]

H. W. Schmitt Frances Pleasonton

A practical guide for the evaluation of silicon semiconductor detectors for fission-fragment energy measurements is given. The evaluation is based on shape parameters associated with the pulse-amplitude spectrum for ^{252}Cf spontaneous fission fragments. Reasonable limits for these parameters are suggested, and the significance of each is discussed. Measurements of similar parameters for the ^{235}U thermal-neutron fission-fragment pulse-amplitude spectrum are reported. A method for computer determination of the spectrum parameters is outlined.

[1]Abstract of paper to be published in *Nuclear Instruments and Methods*.

RESPONSE OF SILICON FISSION DETECTORS TO CHANNELED ^{127}I AND ^{40}Ar IONS

C. D. Moak J. W. T. Dabbs W. W. Walker[1]

A phenomenon called ionization defect, wherein particle energy is lost in the recoil of atoms rather than in production of electron-ion pairs, has been known for many years for the case of heavy ions in gases.[2-4] It was not surprising that a similar effect might occur in solid-state detectors; however, the possibility of a new complication was recognized. Along with any ionization defect which might occur in these detectors, it was recognized that the high ionization density along a heavy-ion track in such a detector might be great enough to depress the local electric fields so much that electron-hole pairs could be lost by recombination before escaping from the vicinity of the track. At the Asheville conference on semiconductor nuclear particle detectors, it was suggested that the term "pulse-height defect" be used to describe the nonlinearities reported as being observed for fission fragments in silicon detectors.[5] It was understood that the pulse-height vs energy graph for heavy ions was reasonably linear but extrapolated to approximately 10 to 20 Mev on the energy axis. In more recent work, lower values in the range 2 to 5 Mev have been reported for the pulse-height defect in both silicon and germanium.[6] Britt and Wegner[7] found that, at least for some detectors, pulse-height response was dependent on the electric field in the detector, and this indicated that field saturation effects in the dense track of a heavy ion might be responsible for the pulse-height detect.[8] F. J. Walter showed that it is possible to construct a surface-barrier detector whose pulse-height response to heavy ions is independent of field over a wide range of field strengths in the detector.[9] The fact that response could be made field-independent redirected attention to the so-called end-of-range effects as being responsible for heavy-ion nonlinearities. Lindhard and Nielsen[10] and Haines and Whitehead[11] derived predictions of the effect of nuclear stopping upon the response of solid-state detectors. The purpose of the experiment reported here was to eliminate atomic collisions if possible and to see whether any detector nonlinearities remained. By directing heavy ions down the crystalline channels of a detector, we hoped that some of the particles would be constrained to avoid close encounters with lattice atoms and go on making electron-hole pairs to the end of their range.

Experimental Arrangement

The accelerator procedures used to obtain a multicomponent beam of ^{127}I ions have been described elsewhere.[12] A new procedure is the use of argon gas rather than oxygen as the stripper gas in the accelerator; ions from this gas provide yet another spectrum in the magnetic analyzer, and they provide useful information about detector response for lighter ions. The angular divergence of the beam, as defined by the detector, was approximately 0.02°. The detector mounting arrangement is shown in Fig. 1. Silicon fission detectors[13] were mounted on goniometer heads, and x-ray diffraction procedures were used to orient their principal axes. After orientation, the detectors on the goniometer heads were transferred

[1]Summer research participant from the University of Alabama.

[2]H. W. Schmitt and R. B. Leachman, *Phys. Rev.* **102**, 183 (1955).

[3]L. O. Herwig and G. H. Miller, *Phys. Rev.* **95**, 413 (1954).

[4]J. K. Knipp and R. C. Ling, *Phys. Rev.* **82**, 30 (1951).

[5]J. W. T. Dabbs and F. J. Walter, eds., "Semiconductor Particle Detectors," *Natl. Acad. Sci.–Nat. Res. Council Publ. 871*, 1961.

[6]F. J. Walter *et al.*, *Bull. Am. Phys. Soc.* **8**, 39 (1963); W. W. Walker, C. D. Moak, and J. W. T. Dabbs, *Bull. Am. Phys. Soc.* **10**, 515 (1965).

[7]H. C. Britt and H. E. Wegner, *Rev. Sci. Instr.* **34**, 274 (1963).

[8]H. Flicker, *Rev. Sci. Instr.* **34**, 822 (1963).

[9]F. J. Walter, *IEEE Trans. Nucl. Sci.* **NS-11**(3), 232 (1964).

[10]J. Lindhard and V. Nielsen, *Phys. Letters* **2**, 209 (1962).

[11]E. L. Haines and A. B. Whitehead, *Rev. Sci. Instr.* **36**, 1385 (1965).

[12]C. D. Moak *et al.*, *Rev. Sci. Instr.* **34**, 853 (1963).

[13]Oak Ridge Technical Enterprises Corp., Oak Ridge, Tenn.

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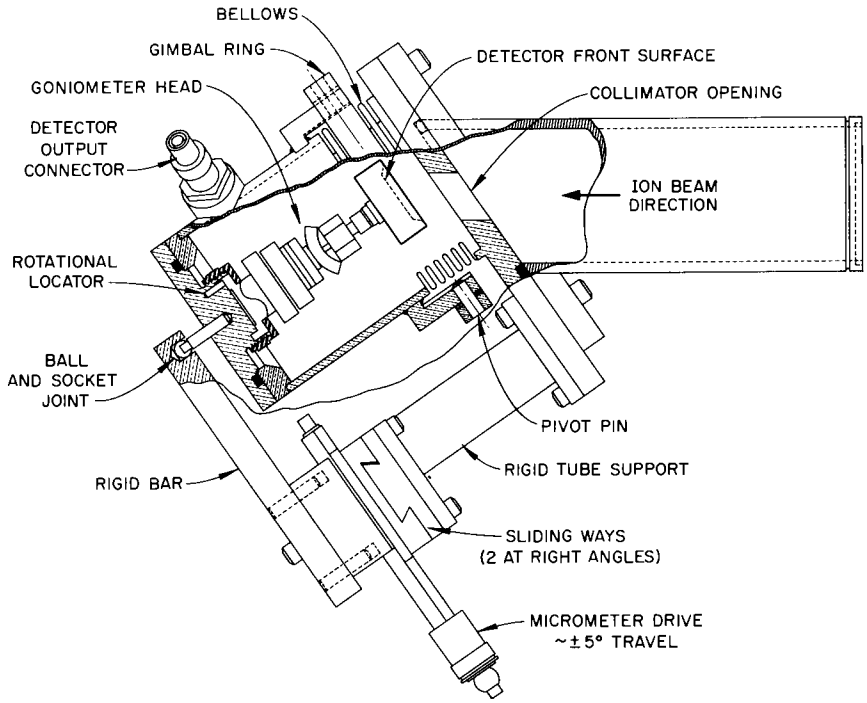

Fig. 1. Detector Mounting Arrangement.

to the target apparatus (Fig. 1) for bombardment. Alpha particles from ^{241}Am were used to calibrate a precision pulser with attenuator. With the attenuator (×20) removed, the pulser was left in the circuit and was set for 120 Mev to provide continuous amplifier gain calibration. Two perpendicular adjustments were provided for small-angle tilts about the approximately preset orientation. Later it was known that the preset angle was within 1 or 2° of the required channel direction. The built-in angle (35° 16′) of the apparatus was designed to bring the [110] crystal axis near alignment with the beam. Along the 10-m path from the accelerator analyzer to the detector station, thin collimators were used to shield the detectors from scattered heavy ions.

Results

The series of pulse-height spectra shown in Fig. 2 is illustrative of the results obtained. The upper spectrum was taken with the detector 7.6° away from the [110] direction. For each run two angles are given; the first angle is measured in the plane toward the [111] axis from the [110] axis, and the second angle is perpendicular to the first. The total misorientation is the vector sum of the two angles given. The upper spectrum contains four peaks due to argon ions in addition to the peaks due to iodine ions. Several contaminant peaks remain unidentified; these are presumed to be due to light ions. The iodine pulse-height spectrum is typical of a "good" fission detector; the peaks are reasonably symmetric, the valleys are deep, and there is no evidence for charge multiplication. Biases ranging from 40 to 150 v did not alter this spectrum. Detector resistivity was ~500 ohm-cm. The middle three runs in Fig. 2 are examples of many taken between the initial (upper) and final (lower) runs. In all runs the original peaks remained fixed, and new features were added to the spectra depending upon the angular position; the low-energy side of the off-channel peaks remained undisturbed. Part of the particles gave pulses of larger than usual size for angles near the channel direction, and finally at the [110] direction these particles formed a new

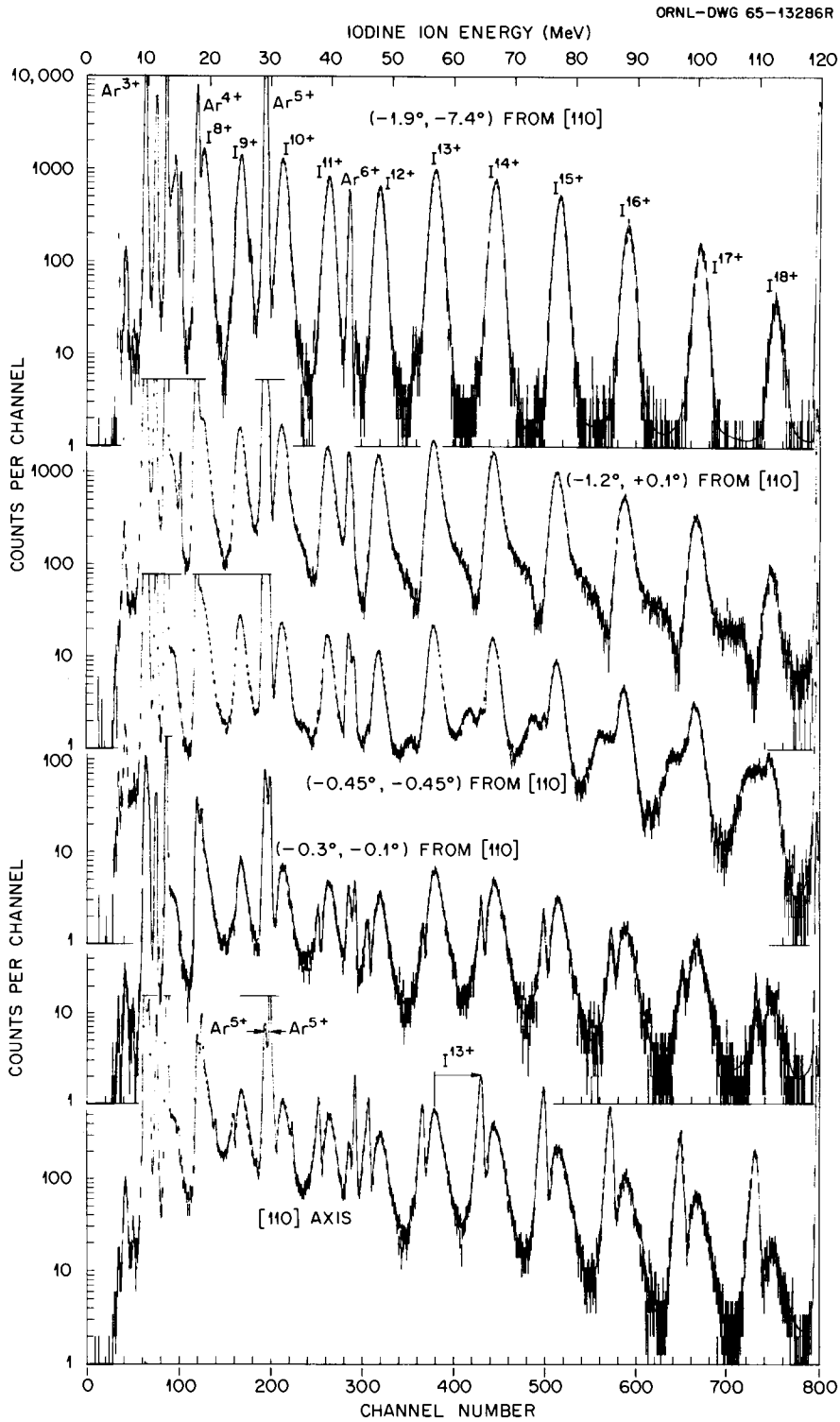

Fig. 2. Silicon Detector Response to Iodine and Argon Ions Entering the Crystal Near Its [110] Axis.

set of peaks, as seen in the bottom spectrum of Fig. 2. The results shown were reproducible and were observed on two detectors as a check against any possible detector malfunction. Careful examination of the spectra gave the following information:

1. Both argon and iodine ions show channeling effects.
2. A larger fraction of argon ions shifted to the channeled condition than was the case for iodine ions.
3. The fraction of iodine ions appearing in the new peaks increased slowly from 0.3 at 38 Mev to 0.5 at 109 Mev.
4. The channeled-ion peaks were not symmetric, being sharper on the high-energy side.
5. If the high-energy sides of the new peaks are used as a measure of resolution (i.e., the upper half-width at half maximum), then the 0.1- to 0.3-Mev values derived were more than three times better than those for the usual (unchanneled) peaks.
6. Pulse-height shifts for iodine ions were much larger than those for argon ions.
7. Small changes in detector bias voltage ranging from 80 to 110 v produced no effect upon these spectra; larger bias changes were not attempted.

Analysis

The original questions concerning pulse-height defect and resolution can be answered with the response curves shown in Fig. 3. The open circles pertain to channeled particles and the closed circles to unchanneled particles. Clearly the channeled particles gave approximately full pulse height since they follow the extrapolated alpha-particle line very closely. The data points appear to show almost zero pulse-height defect. A curious discrepancy occurs when the data points are corrected for energy loss in the gold front electrode layer of the detector. When each point is shifted downward in energy to allow for energy loss, the graph for channeled particles falls *above* the alpha-particle line and also exhibits a negative pulse-height defect. Since correction for energy loss in the gold produced these rather unlikely conclusions, one of the detectors was subjected to further study. The gold layer was removed along with an evaporated carbon superstratum and examined under an electron microscope.[14] As shown in Fig. 4, many small white areas indicate the absence of gold on parts of the detector surface. The uneven texture of the gold,

[14]The authors are indebted to T. S. Noggle for the analysis of the texture of the detector gold layer.

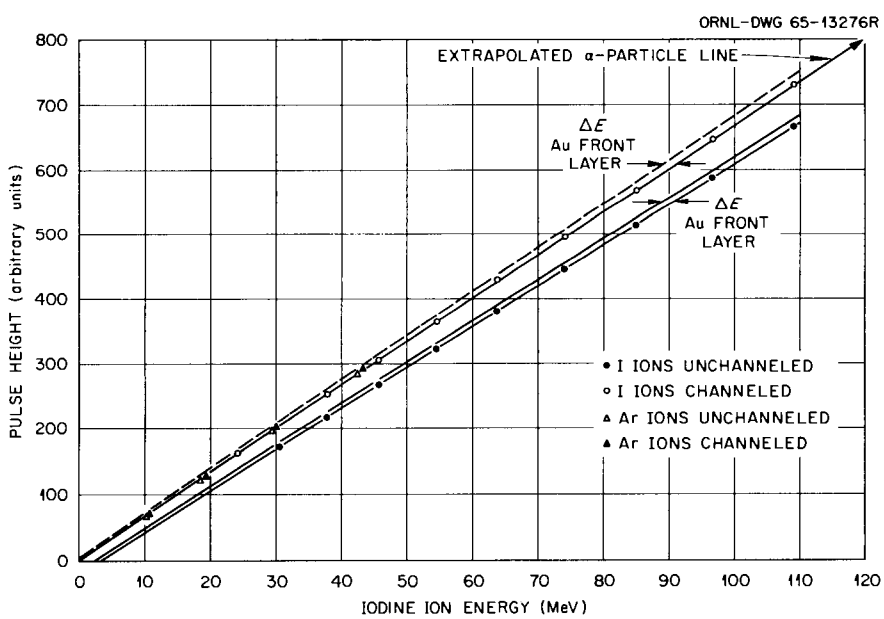

Fig. 3. Silicon Fission Detector, Ion Beam Along [110] Axis.

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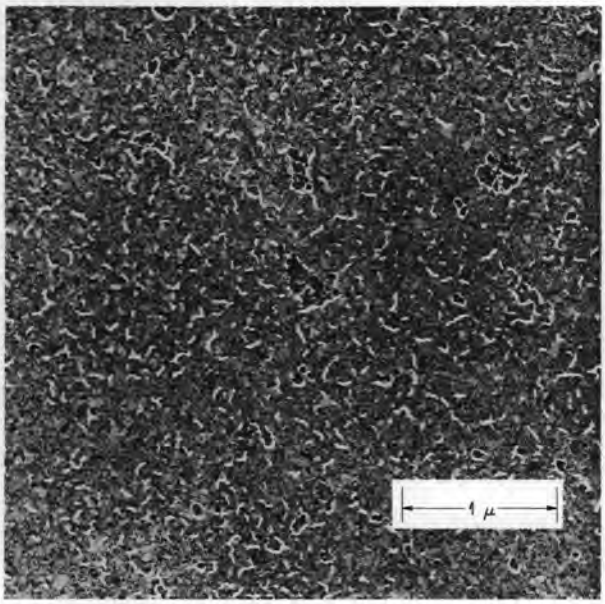

Fig. 4. Electron Micrograph of Au Front Layer Stripped from an Si Fission Detector.

apparently unavoidable for thicknesses $\lesssim 100$ A, now accounts for several observations. Apparently the very largest detector pulses for a given energy did not pass through a gold layer at all. Thus the upper graph in Fig. 3 should not be adjusted for an energy loss due to the gold front layer, since the open circles were derived from the peak position of the channeled-particle pulse distribution. The less steep low-energy side of the sharp peaks seems to be due to particles which passed through various thicknesses of gold but were not scattered out of the channel acceptance angle of the crystal. Those particles which were scattered beyond the channel acceptance angle would account for the pulses which remained in the unchanneled peak. Corroboration but not proof of this picture is found in the fact that the fraction of particles in the sharp peaks increases rather than decreases with energy. Channel acceptance angles are known to decrease with energy; however, Rutherford scattering in the gold layer would fall rapidly with energy, and this latter would then seem to dominate in determining the fraction of particles remaining within the channeled group. The lighter argon ions show a larger fraction in the upper pulse-height groups, and this too would be expected on the basis of a dominant effect due to scattering in the gold layer. The data points for argon ions are included in Fig. 3; again only the points corresponding to the unchanneled groups are corrected for gold layer energy loss. Finally a rough calculation of the cross section for scattering beyond the channel acceptance angle indicates that more than 30% of the particles would be lost from the channeled group, in approximate agreement with what is observed.[15]

Interpretation

The results reported here seem to indicate that the pulse-height defect of silicon fission detectors is due to the onset of atomic collision processes near the end of the particle range and that their poor resolution may be due to statistical uncertainty in the energy lost in such collisions. The results fit the predictions of Haines and Whitehead[11] quite well. It is concluded that channeled iodine and argon ions give linear pulse-height response very nearly equal to alpha-particle response with pulse-height defects <0.2 Mev. At present, it appears that scattering effects due to the gold front layer of the detector are the principal obstacle to producing clean spectra with even higher pulse-height resolution.

It should be noted that approximate but inexact orientation of the incoming particles along a principal detector crystal axis can produce a mixed response which could cause considerable difficulty. If the alignment is not exact or if the particles are not well collimated, it appears advisable to orient the detector well away from a channel direction.

Acknowledgments

The authors wish to thank T. S. Noggle for his analysis of the gold surface texture of the detectors, S. Datz and H. Lutz for valuable discussions, R. M. Steele for x-ray orientation analyses, and G. F. Wells and the operators of the Oak Ridge tandem accelerator for their valuable assistance.

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[15]H. Lutz and S. Datz, private communication.

AN INVESTIGATION OF THE $^{9}Be(^{3}He,p)^{11}B$ REACTION AT LOW ENERGIES[1]

W. R. Coker[2] M. M. Duncan[2] J. L. Duggan[3] P. D. Miller

NUCLEAR REACTIONS. $^{9}Be(^{3}He,p)^{11}B$, E_p = 1–3 Mev, $\sigma(\theta)$ measured for p to ^{11}B states at 4.46, 5.03, 7.30, 8.57, and 8.93 Mev.

Angular distributions and excitation functions have been measured for proton groups from the 4.46-, 5.03-, 7.30-, 8.57-, and 8.93-Mev excited states of ^{11}B using ^{3}He particles in the energy range from 1 to 3 Mev. The experimental measurements are analyzed in terms of two-particle plane-wave stripping formalism and the distorted-wave Born approximation (DWBA). Results of both approaches seem consistent with investigations which have been made for this reaction at higher energies.

[1]Abstract of paper submitted for publication in *Nuclear Physics*.

[2]University of Georgia.

[3]Oak Ridge Associated Universities.

SCATTERING AND REACTIONS INDUCED BY THE PROTON BOMBARDMENT OF ^{14}N

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NUCLEAR REACTIONS. $^{14}N(p,p)^{14}N$, $^{14}N(p,p_1)^{14}N^*$, E_p = 4–5.6 Mev, $\sigma(\theta)$ measured.

The new precision gas scattering chamber has been used to measure the spectra of reaction products produced by the proton bombardment of nitrogen from about 4 to 5.6 Mev bombarding proton energy. The proton beam was obtained from the 5.5-Mv Van de Graaff accelerator. The chamber was operated in the differentially pumped mode. We observed not only the elastically scattered protons and those inelastically scattered from the first and the second excited states but also, at the higher energies, alpha particles from the p-α reaction. Good-resolution yield curves were obtained at 6 scattering angles, and detailed angular distributions were measured at 11 selected energies. These data have now been arranged on magnetic tape in a form suitable for processing on the large computer and are now being analyzed.

[1]Oak Ridge Graduate Fellow from the University of Tennessee under appointment from the Oak Ridge Associated Universities.

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TOTAL NEUTRON YIELD FROM THE REACTION $^{14}C(\alpha,n)^{17}O$[1]

J. K. Bair J. L. C. Ford, Jr. C. M. Jones

NUCLEAR REACTIONS. $^{14}C(\alpha,n)$, measured $\sigma(E)$ 2.5 Mev $\leqq E \leqq$ 5.1 Mev, deduced ^{18}O level E, Γ, alpha-particle strength function.

The total neutron yield of the reaction $^{14}C(\alpha,n)^{17}O$ has been measured in the alpha-particle bombarding energy range 2.5 to 5.1 Mev. Six new anomalies were observed in the yield curve at alpha-particle energies of 4.030 ± 0.015, 4.07 ± 0.04, 4.17 ± 0.04, 4.434 ± 0.010, 4.70 ± 0.04, and 5.004 ± 0.010 Mev. These would correspond to excitation energies in the ^{18}O compound nucleus of 9.361, 9.39, 9.47, 9.675, 9.88, and 10.119 Mev. The experimental widths vary from 21 to 200 kev. An approximate value of the average alpha-particle strength function was obtained.

[1]Abstract of paper to be published in the *Physical Review*.

$^{51}V(p,n)^{51}Cr$ CROSS SECTION FROM THRESHOLD TO 2.25 Mev[1]

J. H. Gibbons R. L. Macklin

NUCLEAR REACTIONS. $^{51}V(p,n)^{51}Cr$, E_{th}–2.25 Mev, $\sigma(4\pi)$ absolute.

The absolute (p,n) total cross section for $^{51}V(p,n)$ has been measured from threshold to 2.25 Mev with an accuracy of 5%. The cross section measured with an ~15-kev-thick target fluctuates appreciably despite the ~1-kev level spacing observed using a thin target. The small change of neutron energy with emission angle makes this reaction a good 4π monoenergetic source.

[1]Abstract of paper to be published in *Nuclear Instruments and Methods* (letter to the editor).

AN INVESTIGATION OF (p,n) REACTION MECHANISM VIA ISOSPIN ANALOG RESONANCES

H. J. Kim R. L. Robinson

NUCLEAR REACTIONS. $^{88}Sr(p,n)^{88}Y$ g.s., $^{89}Y(p,n)^{89}Zr$ g.s., $^{89}Y(p,n)^{89}Zr^*$ ($\frac{1}{2}^-$, 590 kev), time-of-flight spectra.

The excitation functions and the angular distributions of neutrons produced by the reactions $^{88}Sr(p,n)^{88}Y$, $^{89}Y(p,n)^{89}Zr$, and $^{89}Y(p,n)^{89}Zr^*$ ($\frac{1}{2}^-$, 590-kev state) in the vicinity of well-established d-wave resonances in the compound systems, which are isospin analogs of low-lying

$d_{5/2}$ neutron single-particle states, were investigated in detail. Neutrons from the (p,n) reactions were detected by the time-of-flight method. The pulsed proton beam was provided by the ORNL 5.5-Mv Van de Graaff accelerator. The excitation functions show a characteristic asymmetric energy dependence[1] about the resonance energy, and the neutron angular distributions measured on resonance as well as off resonance are symmetric about 90°. Two features make it possible to study some aspects of the reaction mechanism in detail: (1) the *d*-wave resonances are well isolated and are superimposed on a smoothly varying nonresonant cross section and (2) selective enhancements of the neutron partial cross sections are brought about by the decay of the analog states. The experimental angular dependences of the enhanced cross sections are compared to the theoretical results which are calculated from the isospin resonance theory of Robson[1] and generalized Hauser-Feshbach theory with an appropriate set of optical-model potentials. The results show that the statistical compound nucleus gives a good description of the reaction mechanism. The investigation to study the properties (namely spin and parity) of low-lying states of odd antimony and indium isotopes is under way via (p,n) reaction on tin and cadmium targets, utilizing the selective enhancement of neutron partial cross section induced by the isospin analog resonance.

[1]D. Robson, *Phys. Rev.* 137, B535 (1965).

CROSS SECTIONS FOR ANALOG RESONANCES IN ^{75}As, ^{111}Cd, AND ^{113}Cd(p,n) REACTIONS[1]

R. L. Kernell[2] C. H. Johnson

NUCLEAR REACTIONS. ^{75}As(p,n), ^{111}Cd(p,n), ^{113}Cd(p,n), E = 2.7 to 5.6 Mev; measured $\sigma(E)$; deduced widths of analog resonances. Enriched targets.

Total (p,n) cross sections have been measured to an accuracy of ±10% near analog resonances for targets of ^{75}As, ^{111}Cd, and ^{113}Cd; target thicknesses were, respectively, 5, 26, and 13 kev. Resonances observed at bombarding energies of 3057 ± 6 kev and 3097 ± 6 kev for ^{75}As are interpreted as the analogs of the 2^- ground state and of a previously unreported 39-kev state of ^{76}As. The cross sections at resonance are 13 and 15 mb; the off-resonance cross section is 8 mb. Each resonance has a natural width of 11 kev. Resonances observed at 4022 ± 20 kev for ^{111}Cd and at 4300 ± 8 kev for ^{113}Cd are identified as the analogs of the ground states of ^{112}Cd and ^{114}Cd. The ^{111}Cd resonance has a natural width of 25 kev and a maximum cross section of 4.6 mb; the corresponding values for ^{113}Cd are 28 kev and 10.6 mb. The cross sections at resonance for ^{111}Cd and ^{113}Cd are 1.5 and 1.6 of the nonresonant cross sections. Analogs of the first excited 2^+ states of ^{112}Cd and ^{114}Cd are observed as weak resonances at 4639 ± 20 kev for ^{111}Cd and at 4857 ± 12 kev for ^{113}Cd. These resonances have a width of about 35 kev and are approximately 10% of the nonresonant cross section.

[1]Abstract of paper to be published in proceedings of APS Topical Conference on "Isobaric Spin in Nuclear Physics," Tallahassee, Fla., Mar. 17–19, 1966.

[2]Oak Ridge Graduate Fellow from the University of Tennessee under appointment from the Oak Ridge Associated Universities.

PROTON STRENGTH FUNCTIONS FOR $89 < A < 130$

C. H. Johnson R. L. Kernell[1]

NUCLEAR REACTIONS. ^{93}Nb(p,n), ^{103}Rh(p,n), ^{105}Pd(p,n), ^{109}Ag(p,n), ^{111}Cd(p,n), ^{115}In(p,n), ^{119}Sn(p,n), ^{125}Te(p,n), E = 3.0 to 5.8 Mev; measured $\sigma(E)$. Enriched targets.

The complex nuclear potential, by virtue of its imaginary part, predicts a cross section σ_c for compound nuclear formation for incident protons. Generally σ_c is difficult to measure; however, if the proton energy is well below the top of the Coulomb barrier and yet well above the threshold for neutron emission, σ_c becomes nearly equal to the (p,n) cross section, which is relatively easy to measure. The external Coulomb field of the nucleus causes the (p,n) excitation functions to vary strongly with both proton energy and atomic number, but Coulomb corrections can be made in order to reduce these functions to proton strength functions, which vary only slowly with proton energy and atomic weight. Hopefully, these slow variations as well as the magnitudes of the strength functions can be described by a reasonable complex potential. Measurements at several laboratories have shown a proton strength function maximum near $A = 75$ which is attributed to an s-wave resonance. Predictions for 5-Mev protons, based on Perey's[2] optical-model parameters, give a minimum in the strength function near $A = 90$ and a maximum due to p- and f-wave resonances near $A = 125$.

The present work is concerned with (p,n) cross sections for 3.0- to 5.8-Mev protons on nuclei with $A = 89$ to 130. Monoenergetic protons impinged on thin targets of either enriched or naturally pure isotopes, and the neutrons were counted by a 4π flat-response graphite-sphere detector. Twenty-five nuclei in this mass region have been studied, and preliminary results were given in earlier reports.[3–6] It has become apparent, however, that the variations in the strength functions are so small, the order of 20%, that these older results might not be accurate enough for meaningful comparisons to the theory. Errors in the cross sections could have arisen for two main reasons. First, the targets of separated isotopes, which were prepared from limited quantities of material, could have been nonuniform and thus of uncertain areal density. Second, very small contaminants of lighter elements could have caused a significant spurious neutron yield for proton energies below 4 Mev. Corrections had already been made for ^{37}Cl, which was easily detected by the appearance of neutrons at its (p,n) threshold below 2 Mev; however, corrections had not been made for yields from possible contaminants of ^{65}Cu and ^{11}B. Our more recent work has shown that copper is a common contaminant in the separated isotopes and that boron was present in some target backings. For these reasons, we submitted[7] the used targets for various types of analyses and also made some new cross-section measurements.

Only a few details will be given here. In Fig. 1, which summarizes some of the more important results, the solid points show the natural Pd, Ag, Cd, Sn, and Te cross sections relative, in each case, to the smooth-curve cross sections for the heaviest isotope of each element. (This presentation is simply an easy way to remove the dominant Coulomb effects.) The open points give the weighted sums of the isotopic cross sections, which have now been corrected for impurities and

[1]Oak Ridge Graduate Fellow from the University of Tennessee under appointment from the Oak Ridge Associated Universities.

[2]F. G. Perey, *Phys. Rev.* 131, 745 (1963).

[3]C. H. Johnson, A. Galonsky, and C. N. Inskeep, *Phys. Div. Semiann. Progr. Rept. Mar. 10, 1958*, ORNL-2501, p. 29.

[4]C. H. Johnson, A. Galonsky, and C. N. Inskeep, *Phys. Div. Ann. Progr. Rept. Mar. 25, 1960*, ORNL-2910, p. 25.

[5]R. L. Kernell and C. H. Johnson, *Phys. Div. Ann. Progr. Rept. Dec. 31, 1964*, ORNL-3778, p. 95.

[6]C. H. Johnson and R. L. Kernell, *Phys. Div. Ann. Progr. Rept. Dec. 31, 1964*, ORNL-3778, p. 97.

[7]We are indebted to several members of the Analytical Chemistry Division for making the target analyses.

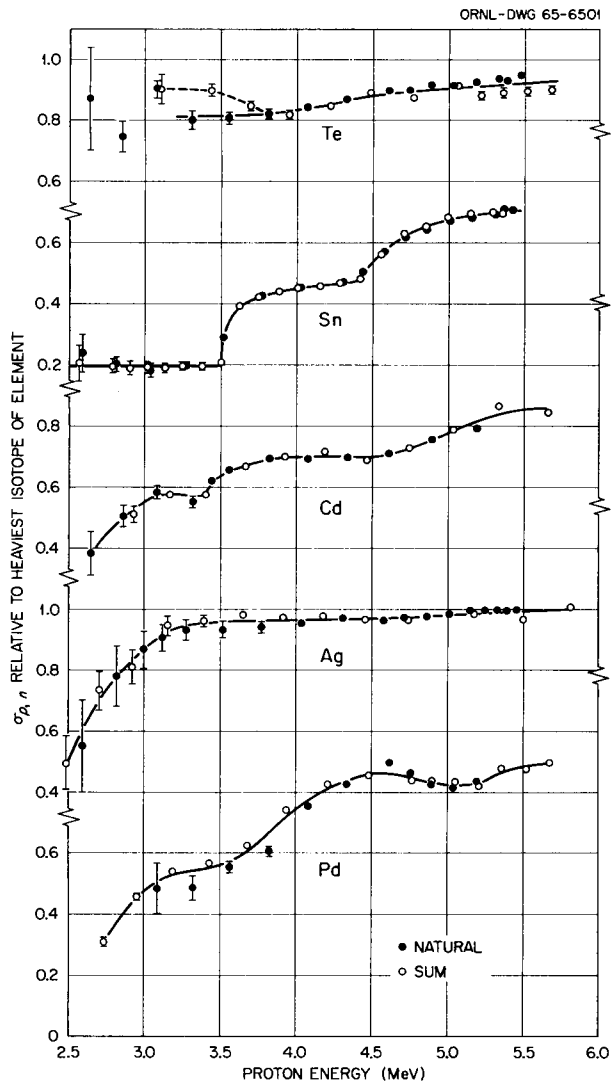

Fig. 1. Comparisons of the (*p,n*) Cross Sections for Natural Elements and the Weighted Sums of the Isotopic Cross Sections.

for nonuniformities in the targets. At the higher proton energies, the sums include small contributions from isotopic cross sections which were not measured but were estimated with little uncertainty. The figure shows generally good agreement between the sums and the natural-target cross sections. For tellurium there is a negligible disagreement of about 4% above 5.1 Mev but a serious disagreement below 3.7 Mev; for this reason the data below 3.7 Mev were discarded. For palladium there is about a 5% disagreement below 4 Mev; an examination of the various isotopic yields indicates that this can be attributed to a ^{11}B contaminant in the ^{110}Pd.

We also measured the thick-target excitation functions for Ag, Cd, In, and Sn and compared them to the corresponding thin-target yields in order to determine the atomic stopping powers, and then we used these stopping powers in order to derive cross sections from thick-target yields for ^{93}Nb, ^{103}Rh, and palladium. We used our own stopping powers, rather than published values, in order to ensure internal consistency in our measurements. The purpose was to establish the ^{93}Nb cross section, which was determined only with thick targets, and to give additional measurements on the ^{103}Rh and palladium cross sections. The resulting palladium cross sections averaged about 5% less than those from the thin target; our final values represent weighted averages for the thick and thin targets.

Our final cross sections generally have uncertainties of ±5%; however, some uncertainties, notably those of the tellurium and palladium isotopes, are as large as ±10%. Clearly, we must give less significance to some targets when we make our final comparison of the strength functions with predictions of the optical model.

From these cross sections we have derived strength functions,[8] that is, the ratios to the "black nucleus" values, and we have compared these with predictions from the optical model for Perey's geometry[2] with various real and imaginary well depths. This parameter search is not yet complete, but it has already shown systematic trends in the strength functions which are not described by a simple resonance behavior. Figure 2 shows some of the results. (All data were taken with poor resolution, and no search was made for the analogue state resonance, whose expected energies are indicated by arrows. The fact that the ^{93}Nb curve shows the effect of analogue resonances is rather striking, since these data were obtained with thick targets with effective resolutions of about 200 kev.) The smooth curves are the optical-model predictions for parameters which have been chosen, rather arbitrarily, to give a good fit to ^{115}In. These parameters are W_0 = 12.5 Mev for the imaginary surface potential and $V = 58.75 - 0.5E$ for the real well depth, where E is the proton energy.

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[8] C. H. Johnson, A. Galonsky, and J. P. Ulrich, *Phys. Rev.* **109**, 1243 (1958).

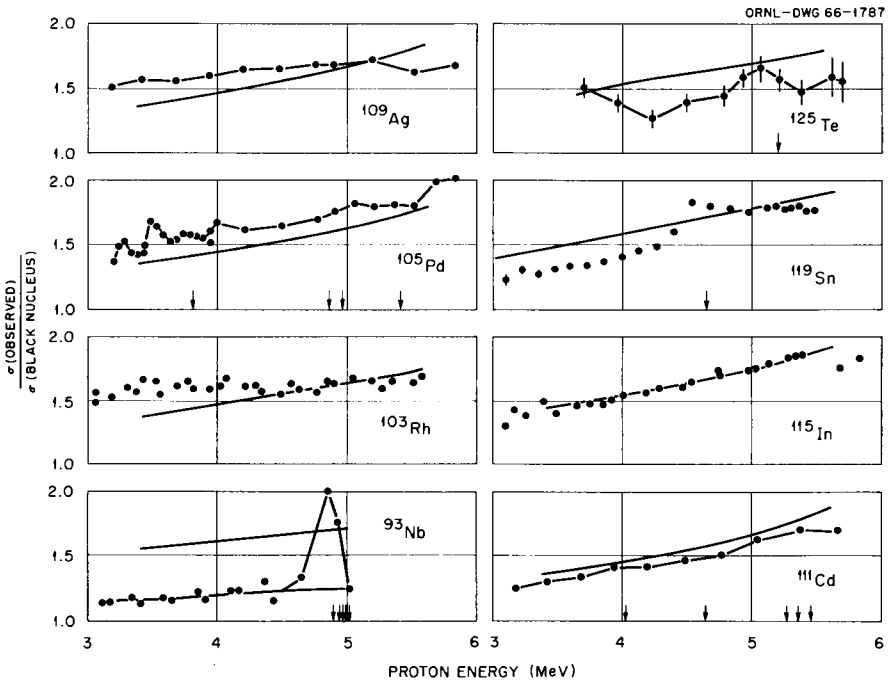


Fig. 2. Proton Strength Functions. The ordinate is the ratio of the cross section to the "black nucleus" value. The smooth solid curves are predictions for an opticol model. Arrows indicate positions of expected analogue resonances.

With these parameters, the optical model predicts all of the strength functions to about ±10% except for ^{93}Nb, whose observed values are about 75% of the predicted values. We found this same low trend for the ^{89}Y cross section;[6] however, we questioned these results because measurements at 5 Mev are too near the neutron threshold for the (p,n) cross section to be equal to the compound-nucleus cross sections. We have now made a fairly reliable correction of 25% based on a Hauser-Feshbach calculation[9] including width fluctuations,[10] and still find that the ^{89}Y strength function is only 60% of the predicted value for 5-Mev protons.

One might suspect that these low strength functions near A = 90 could be accounted for by an appropriate adjustment of the real well depth, but in fact the well depth chosen for Fig. 2 already predicts a minimum here. The most reasonable approach seems to be to choose W_0 of about 6 Mev in order to fit the data for ^{89}Y and ^{93}Nb. It is clear that such a small imaginary potential will not fit the other curves in Fig. 2 because it predicts a strong resonance behavior both as a function of A and of proton energy. In fact, the small energy dependences for the ^{103}Rh and ^{109}Ag strength functions can be fitted only for imaginary potentials which are made larger than 12.5 Mev in order to minimize the resonant behavior. It appears that the imaginary potential must be varied with A in order to reduce the absorption near A = 90 and to decrease the resonance behavior near A = 105. Perey found evidence that the imaginary potential should be modified in order to account for the possible deformation of the target nucleus. Our results may be related to the fact that the deformation parameter β^2, as determined by Coulomb excitation, is only about 0.1 near A = 90 but is about 0.25 near A = 103.

[9]The Hauser-Feshbach code was loaned by Wilmore at Harwell.

[10]P. A. Moldauer, *Phys. Rev.* **123**, 968 (1961).

SCATTERING OF PROTONS FROM Kr IN THE VICINITY OF LOW-LYING ISOSPIN ANALOG STATES

H. J. Kim C. M. Jones H. B. Willard J. K. Bair

NUCLEAR REACTIONS. Kr(p,p)Kr, E_p = 3–6 Mev, $\sigma(\theta)$ for elastic and inelastic scattering.

The systematics of isospin analog resonances observed[1] in the mass region ~90 indicate that the low-lying neutron single-particle states of ^{85}Kr may be investigated by proton scattering from ^{84}Kr in the incident energy range 3 to 6 Mev. We have investigated differential cross sections for elastic and inelastic proton scattering from krypton gas targets of normal isotopic composition (56.9% ^{84}Kr, 17.4% ^{86}Kr, 11.6% ^{83}Kr, 11.6% ^{82}Kr). The investigation was done using the 5.5-Mv Van de Graaff and the recently completed precision gas scattering chamber. Excitation functions at six backward angles were measured over the bombarding energy range 3.6 to 5.4 Mev. A portion of the excitation functions is shown in Fig. 1. The excitation functions are smooth, and there are no observed anomalies below 4.9 Mev.

The size and the shape of the anomalies indicate that they are due to resonance scattering of *d*-wave and *s*-wave protons by ^{84}Kr. Tentative energies and the widths of the resonances are E_{lab} = 5.00 ± 0.03 Mev, $\Gamma \cong$ 25 kev; and E_{lab} = 5.28 ± 0.03 Mev, $\Gamma \cong$ 42 kev. These resonances are also seen in the excitation functions of in-

[1]C. F. Moore *et al.*, *Phys. Rev.* 141, B1166 (1966).

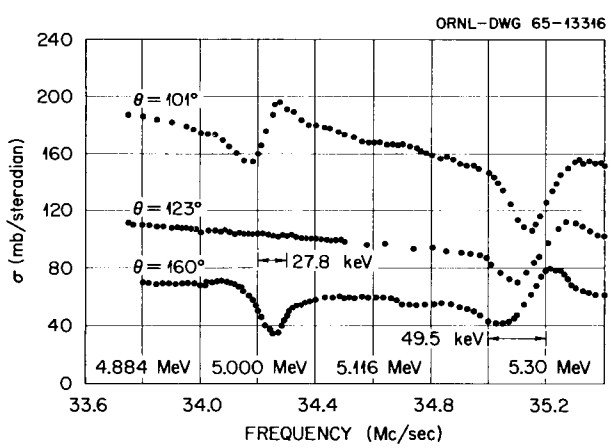


Fig. 1. Excitation Functions of ^{84}Kr(p,p)^{84}Kr. The angles are in the laboratory frame of reference. $\sigma(\theta)$'s have been corrected for the isotopic abundance.

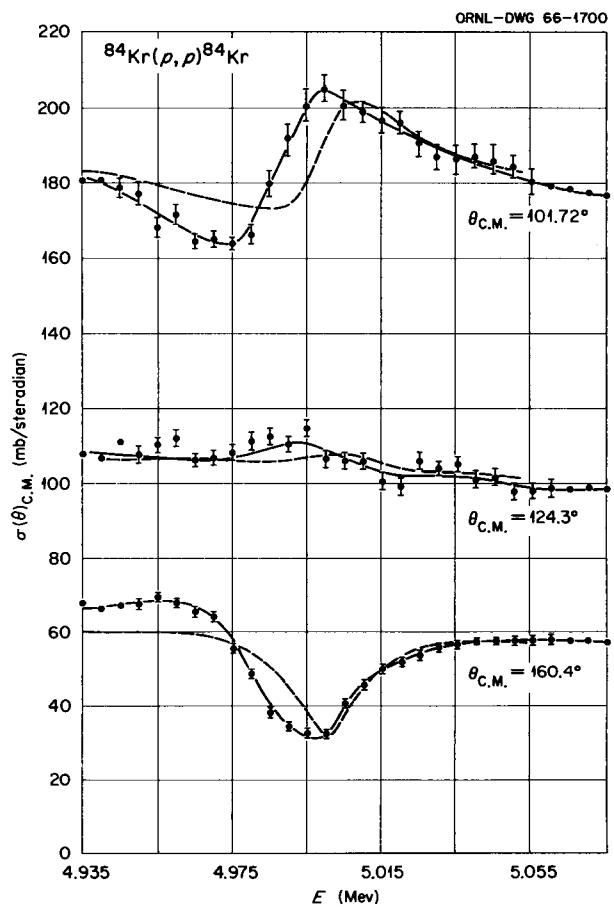


Fig. 2. Result of Four-Parameter Fit. The optical-model parameters are V = 58.41 Mev, r_v = 1.245 fermis, a_v = 0.657 fermi, W = 6.343 Mev, r_w = 1.010 fermis, a_w = 0.9229 fermi, and V_{so} = 7.00 Mev. The best-fit resonance parameters are $E_{R(c.m.)}$ = 4.9431 Mev, Γ = 26.60 kev, Γ_p = 1.75 kev, and relative resonance phase shift = 222°.

elastic proton scattering from the 2^+, 880-kev state of ^{84}Kr. Although the resonance orbital angular momenta are readily determined by comparing the experimental excitation functions with the theoretical ones calculated using an optical model (model parameters are obtained by fitting off-resonance angular distribution measured at E_{lab} = 4.87 Mev) and the Breit-Wigner single-level resonance formula, the experimental cross sections deviate from the calculated values. Figure 2 shows the comparison for the *d*-wave resonance. Investigation is in progress to see whether or not the deviation from the Breit-Wigner formula is due to the isospin analog nature of the resonance.

ELASTIC AND INELASTIC PROTON SCATTERING FROM ^{106}Pd AND ^{108}Pd[1]

R. L. Robinson J. L. C. Ford, Jr.
P. H. Stelson G. R. Satchler

NUCLEAR REACTIONS. ^{106,108}Pd(p,p'), E_p = 12, 13 Mev; measured $\sigma(\theta)$. ^{106,108}Pd deduced levels, β_2, β_3. Enriched targets.

Angular distributions of elastically and inelastically scattered 12- and 13-Mev protons from ^{106}Pd and ^{108}Pd have been measured for angles between 24 and 165°. Quadrupole and octupole deformation parameters, β_2 and β_3, were extracted from the experimental cross sections by means of the distorted-wave direct interaction theory. They are β_2 = 0.25 and β_3 = 0.15 for ^{106}Pd, and β_2 = 0.23 and β_3 = 0.14 for ^{108}Pd. These are consistent with values obtained through Coulomb excitation studies. The octupole states were observed at 2.07 Mev in ^{106}Pd and at 2.03 Mev in ^{108}Pd. Differential cross sections of the two-quadrupole phonon states have been compared with the predictions of the coupled-channels theory as extended by Tamura. To achieve reasonable agreement between experiment and theory for excitation of the second 2^+ level, it was necessary to admix the one- and two-quadrupole phonon states. Energies and cross sections at one angle for a number of other levels below 3.2 Mev are also reported.

[1]Abstract of paper submitted for publication in the *Physical Review*.

ELASTIC AND INELASTIC SCATTERING OF 13-Mev PROTONS FROM ^{107}Ag AND ^{112}Cd

J. L. C. Ford, Jr. P. H. Stelson R. L. Robinson

NUCLEAR REACTIONS. ^{107}Ag, ^{112}Cd(p,p'), enriched targets, E_p = 12.94, 13 Mev; measured $\sigma(\theta)$. ^{107}Ag, ^{112}Cd deduced levels, β_2, β_3.

The investigation of the levels of vibrational nuclei by direct inelastic scattering has been continued. Measurements for ^{106}Pd and ^{108}Pd were reported previously.[1] The results for the elastic and inelastic scattering of 13-Mev protons from ^{107}Ag and ^{112}Cd will be discussed here.

The experiment was performed on the ORNL tandem accelerator using an 18-in.-diam scattering chamber in which the counters can be remotely

[1]R. L. Robinson *et al.*, *Phys. Div. Ann. Progr. Rept. May 1965*, ORNL-3778, p. 101.

positioned by rotating the top. The targets were ~1 mg/cm^2 metallic foils of the separated isotopes, enriched to 98.8% in ^{107}Ag and ^{112}Cd. Scattered particles were detected in two surface-barrier silicon semiconductor detectors placed 7 in. from the target and subtending a solid angle of 2.7×10^{-4} steradian. Data were normalized to the number of elastically scattered protons observed in a detector fixed at 90° relative to the incident beam, and the magnitude of the elastic cross section was then treated as a free parameter during the optical-model analysis.

The pulse-height spectrum for 13-Mev protons scattered from ^{112}Cd at 47° is shown in Fig. 1. Proton groups were observed which correspond to excitation of the first 2^+ state, the two-phonon states, and the octupole state. These states are identified in the figure by the spin assignments. In Fig. 2 the levels excited by inelastic scattering

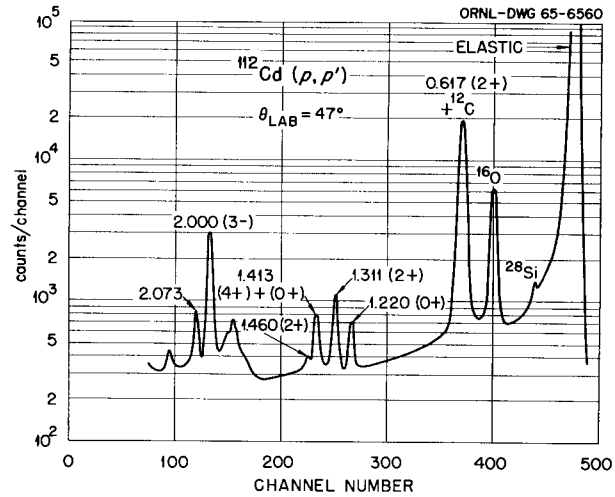


Fig. 1. Spectra of 13-Mev Protons Scattered from a ^{112}Cd Target Through an Angle of 47°.

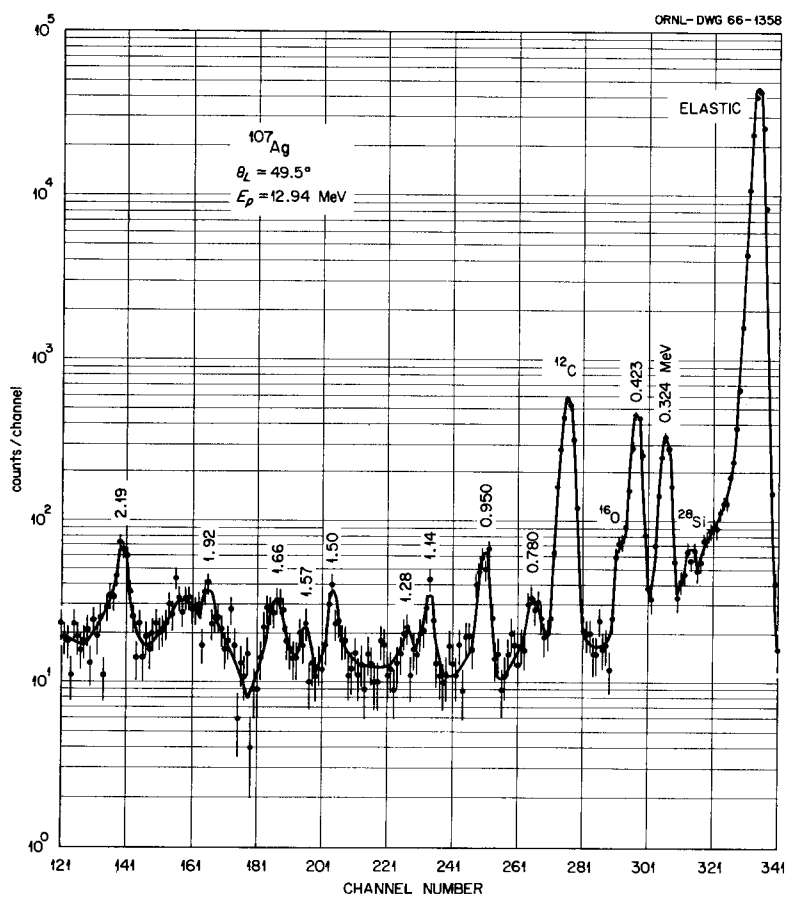


Fig. 2. Spectra of 12.94-Mev Protons Scattered from an ^{107}Ag Target Through an Angle of 49.5°.

of 12.94-Mev protons from ^{107}Ag are displayed, and are identified by their respective excitation energies.

The elastic differential cross sections divided by the Rutherford cross section are shown in Figs. 3 and 4. The optical-model potential used to obtain the curves drawn through the data points contained a real potential, an imaginary potential with surface absorption but no volume absorption, a spin orbit term, and the Coulomb potential. The geometrical parameters used in the fits shown were r_0 = 1.2 fermis and a = 0.7 fermi for the radius and diffuseness of the real potential, and r_0' = 1.25 fermis and a' = 0.7 fermi for the imaginary potential. Similar parameters were determined previously for ^{106}Pd and ^{108}Pd. The values for the depth of the real and imaginary wells were V = 55.7 Mev and W = 9.5 Mev for ^{112}Cd, and V = 55.0 Mev and W = 9.6 Mev for ^{107}Ag. Somewhat lower values for χ^2 were obtained in the search routine if the geometrical parameters were slightly varied for each nucleus.

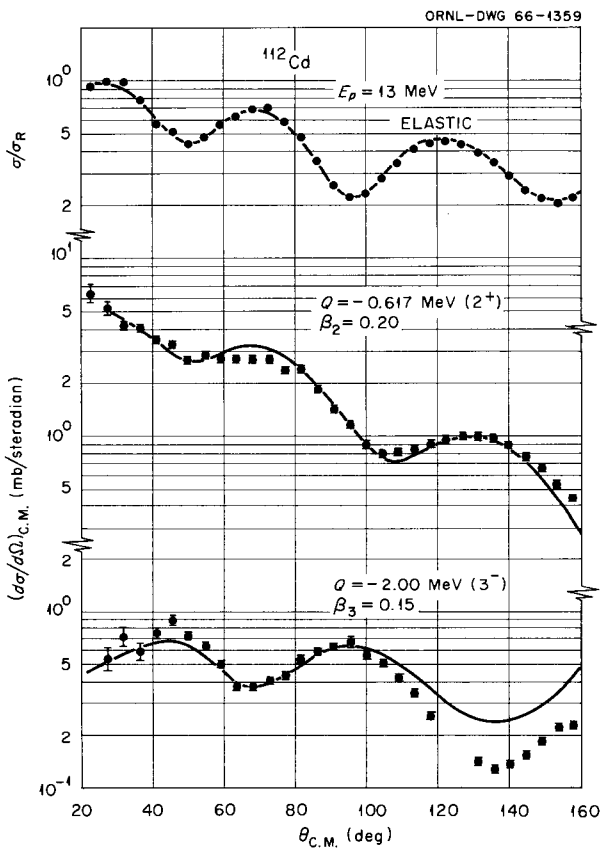


Fig. 3. The ^{112}Cd Differential Cross Section for Elastic Scattering Divided by the Rutherford Cross Section; Differential Cross Sections for Excitation of the 0.618-Mev Quadrupole and 2.00-Mev Octupole States in ^{112}Cd by Inelastic Proton Scattering. The solid lines are fits obtained from the distorted-wave approximation.

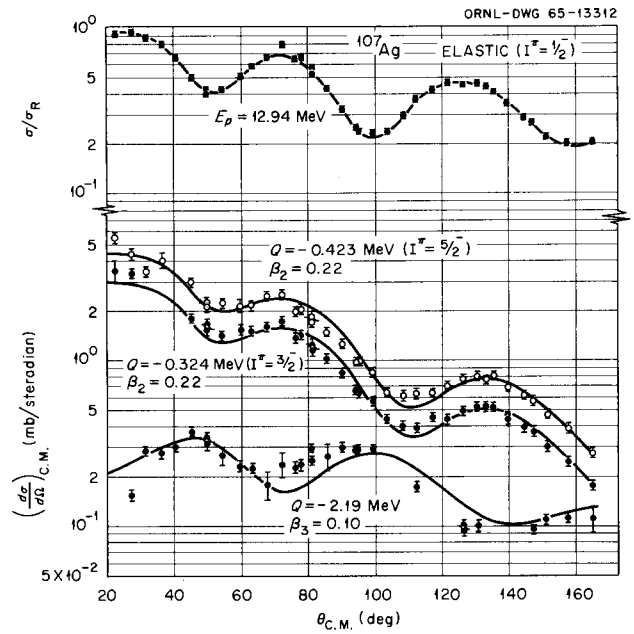


Fig. 4. The ^{107}Ag Differential Cross Section for Elastic Scattering Divided by the Rutherford Cross Section; Differential Cross Sections for Excitation of the 0.324-, 0.423-, and 2.19-Mev States in ^{107}Ag by Inelastic Proton Scattering. The solid lines are fits obtained from the distorted-wave approximation.

The differential cross sections for protons inelastically scattered from the one-phonon quadrupole and octupole states of ^{112}Cd are shown in Fig. 3. The curves are the result of distorted-wave calculations. Adjustment of the magnitude of the theoretical cross section, which is proportional to the square of the deformation parameter β_λ, to the experimental data yields 0.20 and 0.15 for the quadrupole and octupole deformations, respectively, with errors of about 5%. The values obtained from Coulomb excitation are β_2 = 0.186 and β_3 = 0.146.[2,3]

[2]P. H. Stelson and L. Grodzins, *Nucl. Data* **1**, 21 (1965).

[3]F. K. McGowan *et al.*, *Nucl. Phys.* **66**, 97 (1965).

In the case of ^{112}Cd, four states, rather than three, are observed in the region of the two-phonon states. The angular distributions for these states are displayed in Fig. 5. Since excitation of the two-phonon levels cannot be treated by the first-order distorted-wave approximation, the fitting of these cross sections will require a coupled-channels calculation. It is interesting to note that the cross sections of the second and third 2^+ states are proportional to the $B(E2)$'s of the gamma rays between these states and the first 2^+ state.

The properties of ^{107}Ag may be compared with those predicted by the single-particle core-coupling model. In this model an odd-A nucleus can be interpreted as an odd particle coupled to an even-even core.[4,5] The ground state of the odd nucleus then has spin I_0, equal to the angular momentum of the odd nucleon. Collective oscillations of the core can be excited just as they are in the neighboring even-even nucleus, but they will couple with the angular momentum of the odd nucleon to produce a nearly degenerate multiplet. The inelastic cross section for excitation of the member of an excited-state multiplet with spin I is just $(2I + 1)/(2I_0 + 1)(2I_c + 1)$ times the cross section for excitation of the state of spin I_c in the even core nucleus. The model further predicts that the angular momentum transfer to the target nucleus should equal the spin I_c of the core state, resulting in a similar angular distribution as for the excitation of the corresponding state in the neighboring even-even nucleus. In this model the low-lying levels of ^{107}Ag are considered to arise from the coupling of the $p_{1/2}$ particle or hole to the neighboring even-even nuclei ^{106}Pd and ^{108}Pd.

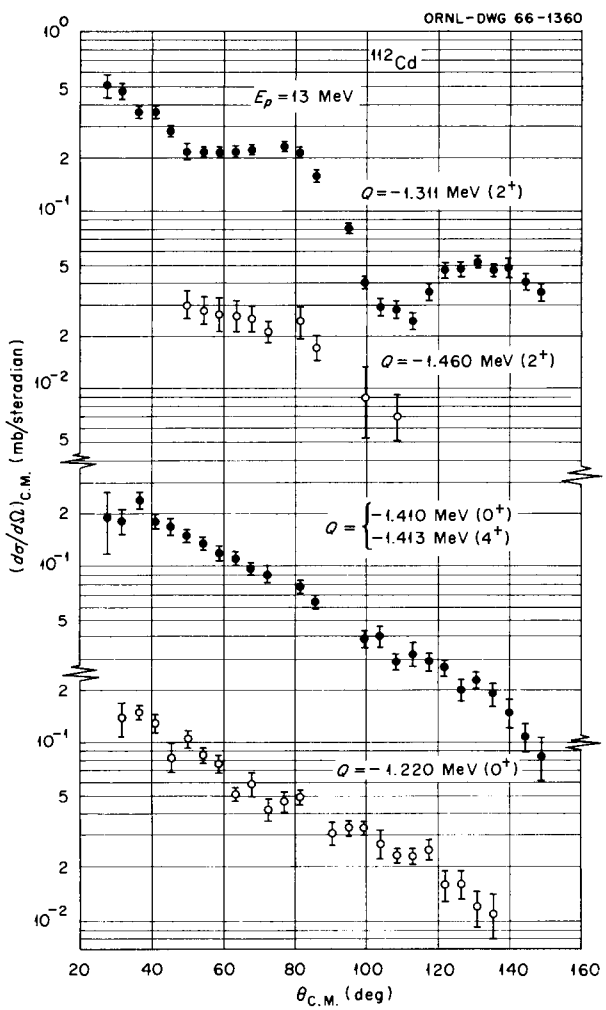


Fig. 5. Inelastic Differential Cross Sections for Excitation of the Four States Observed in the Energy Region of the Two-Phonon States of ^{112}Cd.

The inelastic differential cross sections for the 0.324-, 0.423-, and 2.19-Mev states in ^{107}Ag are shown in Fig. 4. The 0.324- and 0.423-Mev states can be fitted with the experimental curve for the first 2^+ state in ^{106}Pd, while the shape of the angular distribution of the 2.19-Mev state is similar to that of the 3^- states of ^{106}Pd and ^{108}Pd. This suggests that these levels result from the coupling of the odd particle to the excited states of the even-even core. However, the 2.19-Mev state is the only strongly excited level with the shape predicted for the octupole state.

The "partial deformation" for exciting the level with spin I is[6]

$$\beta_\lambda^{p^2}(I) = \frac{2I + 1}{(2I_0 + 1)(2I_c + 1)}\,\beta_\lambda^2,$$

where β_λ is the total deformation and equals that of the even-even core if the core excitation model is valid. The curves fitted to the inelastic angular distributions in Fig. 4 were obtained from distorted-wave calculations. The partial deformations extracted from these fits are 0.14 ± 0.01 and 0.17 ±

[4] R. D. Lawson and J. L. Uretsky, *Phys. Rev.* **108**, 1300 (1957).

[5] A. de-Shalit, *Phys. Rev.* **122**, 1530 (1961).

[6] P. H. Stelson *et al.*, *Nucl. Phys.* **68**, 97 (1965).

0.01 for the 0.324- and 0.423-Mev levels, respectively, yielding a total deformation of 0.22. For the 2.19-Mev level the partial deformation is 0.10. Coulomb excitation experiments have furnished spin assignments of $3/2^-$ and $5/2^-$ for the 0.324- and 0.423-Mev states of ^{107}Ag, as well as $B(E2)$ measurements.[7,8] The $B(E2)$ values correspond to partial deformations of 0.13 and 0.16 for the 0.324- and 0.423-Mev levels.

The ratio of the cross section of the 0.423-Mev state to that for excitation of the 0.324-Mev state is 1.50, which is the value obtained from the core excitation intensity rule using the above values for the spins. Furthermore, since the β_2 values for ^{106}Pd and ^{108}Pd are 0.25 and 0.23, the sum of the cross sections for the 0.324- and 0.423-Mev states in ^{107}Ag is 70 and 90% of the cross section for excitation of the first 2^+ state in ^{106}Pd and ^{108}Pd respectively. These measurements then tend to support the core excitation model. However, since the octupole deformations of ^{106}Pd and ^{108}Pd are 0.15 and 0.14, the 2.19-Mev level has only half the octupole strength found in the palladium isotopes. One wonders where the rest of the octupole strength is.

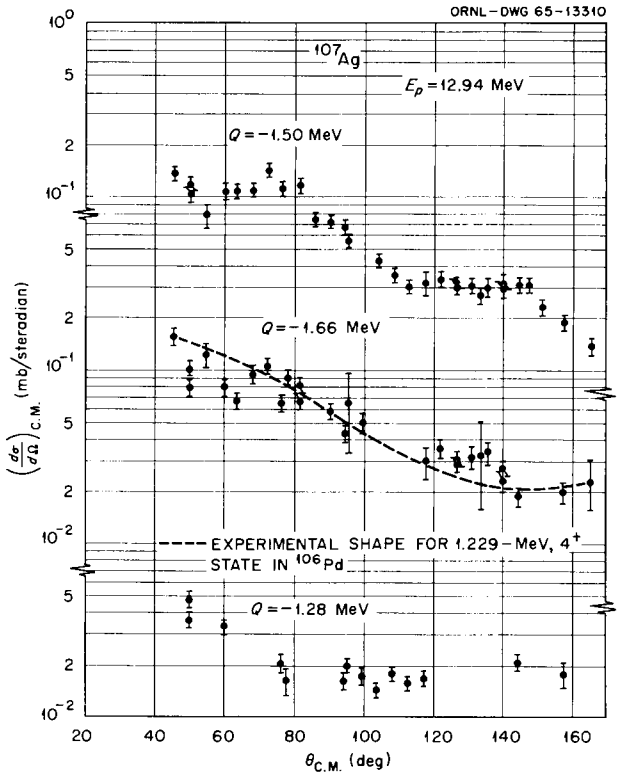


Fig. 7. Differential Cross Sections for Excitation of the 1.28-, 1.50-, and 1.66-Mev States in ^{107}Ag by Inelastic Proton Scattering.

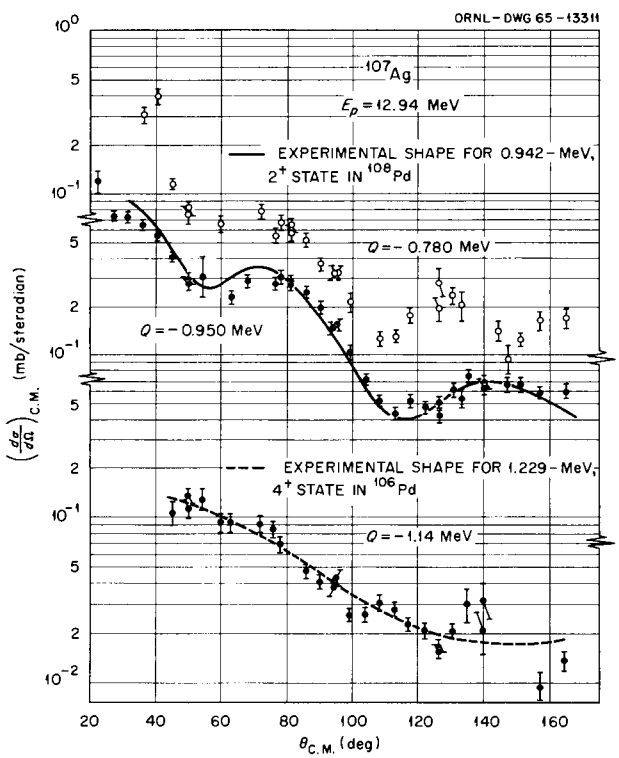


Fig. 6. Differential Cross Sections for Excitation of the 0.780-, 0.950-, and 1.14-Mev States in ^{107}Ag by Inelastic Proton Scattering.

The differential cross section of the 0.950-Mev state resembles that of the second 2^+ state in ^{108}Pd, as seen in Fig. 6. Furthermore, the cross section of the 0.950-Mev state alone is approximately equal to that of the ^{108}Pd level.

The cross sections of the 1.14- and 1.66-Mev states can be fitted with the shape of the differential cross section of the 4^+ ^{106}Pd state (Figs. 6 and 7). Once again the sum of the two cross sections equals σ_{4^+} in ^{106}Pd. The spin of the state with the smaller cross section, the one at 1.14 Mev, is expected to have spin 7/2, and that with the larger cross section, the 1.66-Mev state, spin 9/2. The ratio of the cross sec-

[7] F. K. McGowan and P. H. Stelson, *Phys. Rev.* **99**, 127 (1955).

[8] F. K. McGowan and P. H. Stelson, *Phys. Rev.* **109**, 901 (1958).

tions for these states agrees well with that predicted by the core excitation intensity rule using these spin values. Decay-scheme work assigns the 1.14-Mev level a spin of $5/2^-$ or $7/2^-$.[9] However, in that investigation a spin of $5/2^-$ was favored, and the 0.950- and 1.142-Mev states were interpreted as arising from the coupling of the odd proton to the second 2^+ state of the core.

The shape of the angular distribution of the 1.50-Mev state is also similar to that of the second 2^+ state of ^{108}Pd, while the weak 1.28-Mev level does not particularly resemble any of the palladium cross sections. Fitting the observed ^{107}Ag differential cross sections with the coupled-channels theory should further clarify the nature of the states in the two-phonon region.

[9]N. L. Lark *et al.*, *Nucl. Phys.* **35**, 582 (1962).

COULOMB EXCITATION[1]

R. L. Robinson

Methods by which the Coulomb excitation process contribute to spin and parity assignments are reviewed. These can be divided into the two groups: (1) determination of the relative spin and parity of the ground state and excited state from a study of the Coulomb excitation cross section and (2) determination of the properties of gamma rays and conversion electrons resulting from Coulomb excitation.

[1]Abstract of paper to be published in the Proceedings of the Conference on Bases for Nuclear Spin-Parity Assignments.

COULOMB EXCITATION OF STATES IN THE CHROMIUM NUCLEI

F. K. McGowan P. H. Stelson R. L. Robinson
W. T. Milner J. L. C. Ford, Jr.

NUCLEAR REACTIONS. ^{50,52,53,54}Cr(^{16}O, ^{16}O$'\gamma$), ^{50,52,53,54}Cr($\alpha, \alpha'\gamma$), enriched targets, E = 30–39 Mev, E_α = 4–5.6 Mev; measured γ, $\gamma\gamma$ spectra, E_γ, $\gamma(\theta)$. ^{50,52,53,54}Cr, deduced levels, J, π, $B(E2)$, $B(M1)$.

The possibility of describing some excited states of nondeformed odd-mass nuclei in terms of excitations of the even-even core, proposed by de-Shalit,[1] has met with moderate success. If the core states J_c in an odd-mass nucleus are identified with the corresponding core states $J_c = 0$ and 2 in the neighboring even-mass nucleus, the situation is particularly simple. The core multiplet has states with spins $|j - J_c| < J < j + J_c$, where the odd nucleon is in a state j. The $B(E2)$'s for $E2$ transitions proceeding from the various members of a multiplet to the ground state are equal. Furthermore, these $B(E2)$'s should be equal to $B(E2, 2 \rightarrow 0)$ for the $2 \rightarrow 0$ transitions in neighboring even-mass nuclei.

The information on possible core multiplets in nuclei with ground-state spin $j = 3/2$ is not as

[1]A. de-Shalit, *Phys. Rev.* **122**, 1530 (1961).

extensive as for nuclei with ground-state spin $j = 1/2$. Experimental information on the properties of the $J = 3/2$ member of the multiplet is lacking in most examples studied to date.

Information on several states in $^{53}_{24}Cr_{29}$, whose ground-state spin is 3/2, has been obtained from Coulomb excitation with ^{4}He and ^{16}O ions. The measurements included gamma-ray yields, coincidence spectroscopy, and gamma-ray angular distributions. Figure 1 shows a direct gamma-ray spectrum of the gamma rays from Coulomb excitation of ^{53}Cr with 33-Mev ^{16}O ions. The excitation functions for the 565-, 1010-, and 1290-kev gamma rays establish that these transitions result from direct $E2$ excitation of states at these energies in ^{53}Cr. The distribution of the 565-kev gamma rays is isotropic, which is consistent with a spin assignment of 1/2 or 3/2 for the 565-kev state. The empirical evidence[2] for the J dependence of the angular distributions of the (d,p) reaction favors a spin assignment $J = 1/2$ [deep minimum at $\theta = 140°$ in the (d,p) angular distribution[3]]. This assignment is also in agreement with the results from $^{52}Cr(n,\gamma)^{53}Cr$ gamma-ray directional correlations.[4]

Table 1 summarizes our best values of the $B(E2)$'s for excitation of states in the chromium nuclei and the spin assignments deduced from the gamma-ray angular distributions. Strongly enhanced $E2$ transitions to the ground state are observed from states with spins 1/2 and 7/2 and are comparable with the $E2$ transitions $2 \rightarrow 0$ in ^{52}Cr and ^{54}Cr. As noted for other nuclei (^{63}Cu and ^{65}Cu) with ground-state spin 3/2, the $E2$ transition probability from any excited state with $J = 3/2$ below 2 Mev is small. A possible candidate for the $J = 3/2$ member of the core-excitation multiplet is the 2.32-Mev state, which is known to have spin 3/2.[3,4] The thick-target yield of gamma rays for 33-Mev ^{16}O ions exciting a state in ^{53}Cr at this energy and for an $E2$ enhancement of 13 would be about 33 times smaller than

[2] L. L. Lee, Jr., and J. P. Schiffer, *Phys. Rev.* **136**, B405 (1964).

[3] See, for instance, P. T. Andrews *et al.*, *Nucl. Phys.* **56**, 465 (1964).

[4] G. A. Bartholomew and M. R. Gunye, *Can. J. Phys.* **43**, 1128 (1965).

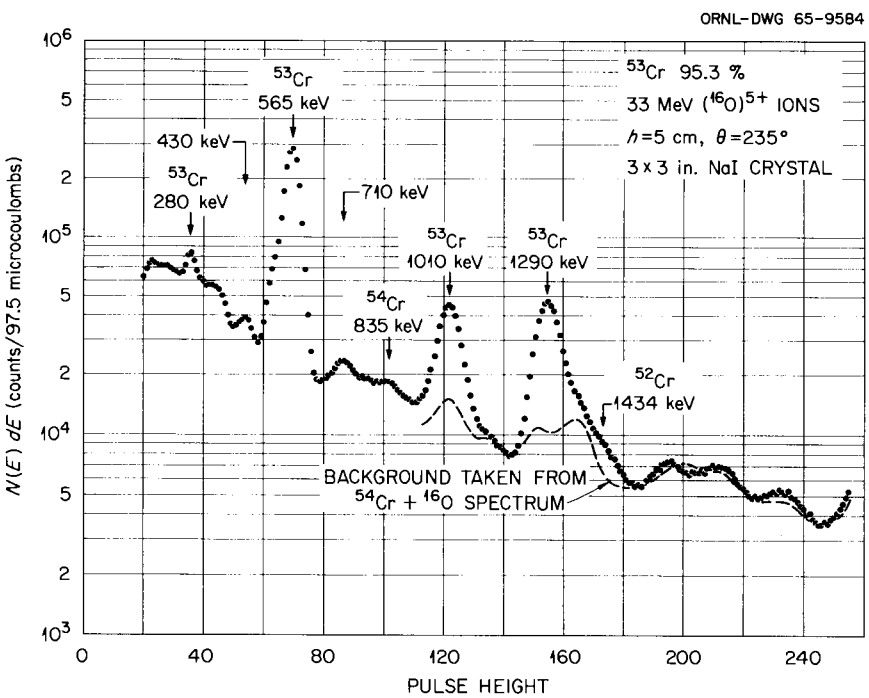


Fig. 1. Direct Pulse-Height Spectrum of the Gamma Rays for ^{16}O Ions on ^{53}Cr.

Table 1. Summary of Our Best Values of the $B(E2)$'s for Excitation of States in the Chromium Nuclei

The column headed $B(E2)_d/B(E2)_{sp}$ contains the ratio of observed decay rate to that for a single-particle transition. The quantity β_2 is the root-mean-square quadrupole distortion deduced from the observed $B(E2)$'s for excitation of the first 2^+ state.

Nucleus	E_{level} (kev)	$B(E2, J_i \to J_f)$ (10^{-50} cm^{4}e^2)	Absolute Error (%)	$J_i \to J_f$	$B(E2)_d/B(E2)_{sp}$	$T_{1/2}$ (sec)	β_2
^{50}Cr	783 ± 1	11.5	±10	0 → 2	21	8.4×10^{-12}	0.303
^{52}Cr	1434 ± 10	7.2	±12	0 → 2	12.7	6.5×10^{-13}	0.236
^{54}Cr	835 ± 1	10.0	±10	0 → 2	17.5	6.8×10^{-12}	0.277
^{53}Cr	565 ± 1	1.15	±10	3/2 → 1/2	19.5		
	1010 ± 1	0.72	±12	3/2 → 5/2	4.0	(1.8×10^{-12})	
	1290 ± 1	3.0	±12	3/2 → 7/2	12.7	1.05×10^{-12}	

the yield of gamma rays from excitation of the 1.29-Mev state.

The $B(M1)$'s for the 280-kev transition 7/2 → 5/2 and the 1010-kev transition 5/2 → 3/2 are 10^{-1} $B(M1)_{sp}$ and 2×10^{-2} $B(M1)_{sp}$ respectively.

In addition to the first 2^+ states in ^{50,52,54}Cr, states at 1878 ± 10 and 1828 ± 10 kev are also excited in ^{50}Cr and ^{54}Cr respectively. If these states are interpreted to be the result of double $E2$ excitation of a 4^+ state, the values obtained for the ratio $B(E2, 4 \to 2)/B(E2, 2 \to 0)$ are 1.80 ± 0.29 and 2.16 ± 0.35 for ^{50}Cr and ^{54}Cr. Data[5] from radioactive decay and the nuclear reactions (n,γ) and (d,p) favor the 4^+ assignment. A 0^+ assignment seems quite unlikely because the data yield $B(E2, 0' \to 2)/B(E2, 2 \to 0) = 13$.

[5]See, for instance, K. Way *et al.*, *Nuclear Data Sheets.*

COULOMB EXCITATION OF ^{106,108,110}Pd

R. L. Robinson F. K. McGowan
P. H. Stelson W. T. Milner
J. L. C. Ford, Jr.

NUCLEAR REACTIONS. ^{106,108,110}Pd(^{16}O, ^{16}O$'\gamma$), E = 42–49 Mev, ^{106,108,110}Pd ($\alpha, \alpha'\gamma$), E = 9–10 Mev, measured I_γ, E_γ, $\gamma\gamma$-coincidence; deduced $B(E2)$'s, $B(E3)$'s. Enriched targets.

In a continuing effort to understand the character of the low-lying levels in even, medium-weight nuclei, we have studied gamma radiation resulting from Coulomb excitation of ^{106,108,110}Pd. Coulomb excitation was effected with 42- to 49-Mev oxygen ions obtained from the Tandem Van de Graaff accelerator and with 9- and 10-Mev alpha particles obtained from the 5.5-Mv Van de Graaff accelerator. Thick targets enriched to 82% in ^{106}Pd, 94% in ^{108}Pd, and 91% in ^{110}Pd were used.

Singles gamma-ray spectra and spectra in coincidence with transitions from the first 2^+ state to the

ground state were measured by means of 3 × 3 in. NaI crystals. Representative spectra are shown in Figs. 1 to 4. Singles spectra were also measured with a lithium-drifted germanium detector. Energies were determined to about 1 kev from these spectra for transitions from the "two-phonon" states by using the 2 → 0 transitions as internal calibrations. Examples of these spectra are given in Figs. 5 and 6.

The gamma-ray yields were deduced from the spectra taken with the NaI crystals; from these yields the $B(E\lambda)$'s were calculated by methods outlined in a previous paper.[1] The $B(E\lambda)$'s are summarized in Fig. 7; they are given in units of $10^{-25\lambda}\, e^2 cm^{2\lambda}$ throughout the paper. Corrections have been applied for (1) internal conversion of the transitions, (2) isotopic abundance, (3) double excitation of the second 2^+ (2′) state resulting from alpha-particle bombardment, and (4) angular correlation of the coincident gamma rays following direct excitation of the 2 state with alpha particles. The theoretical correlation between gamma rays preceded by double excitation is not yet available.

With 9- and 10-Mev alpha-particle bombardment, 96 to 99% of the population of the second 2^+ state is by direct Coulomb excitation. Thus, $B(E2;\ 2' \to 2)$ and $B(E2;\ 2' \to 0)$ can be determined from these studies if the branching ratio of the cascade to crossover gamma rays, R, from this state and the $E2/M1$ admixture, δ^2, of the $2' \to 2$ transition are known. Radioactivity studies[2] have established R as 2.09 ± 0.25 and δ^2 as >200 for ^{106}Pd. In the present work the 440-kev cascade transition of ^{110}Pd and the 811-kev crossover transition were both observed. From their intensities a value of 3.1 ± 0.6 was deduced for R. The $B(E2)$'s given for the two transitions in Fig. 7 are for an assumed value of $\delta^2 > 10$. Since the crossover transition for ^{108}Pd is not detected, only a lower limit of 5 can be placed on R.

From the values of $B(E2;\ 2 \to 0)$, $B(E2;\ 2' \to 2)$, and $B(E2;\ 2' \to 0)$, one can calculate the gamma-ray

[1] F. K. McGowan *et al.*, *Nucl. Phys.* **66**, 97 (1965).

[2] R. L. Robinson, F. K. McGowan, and W. G. Smith, *Phys. Rev.* **119**, 1692 (1960).

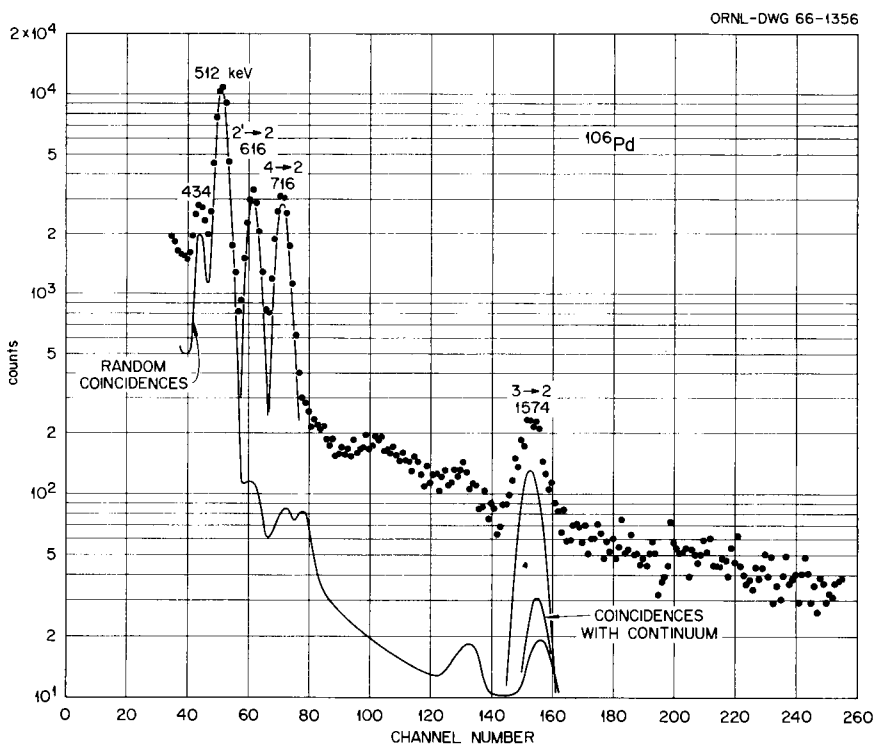


Fig. 1. ^{106}Pd Gamma-Ray Spectrum in Coincidence with the 512-kev Gamma Ray. The bombarding particles were 45.5-Mev oxygen ions.

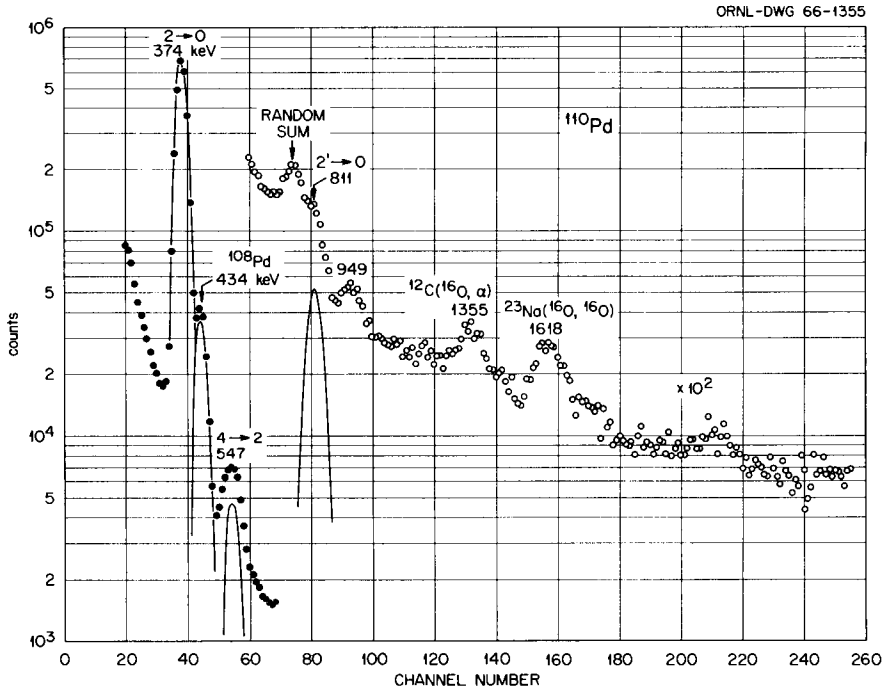


Fig. 2. Gamma-Ray Spectrum for 45.5-Mev Oxygen Ions on ^{110}Pd.

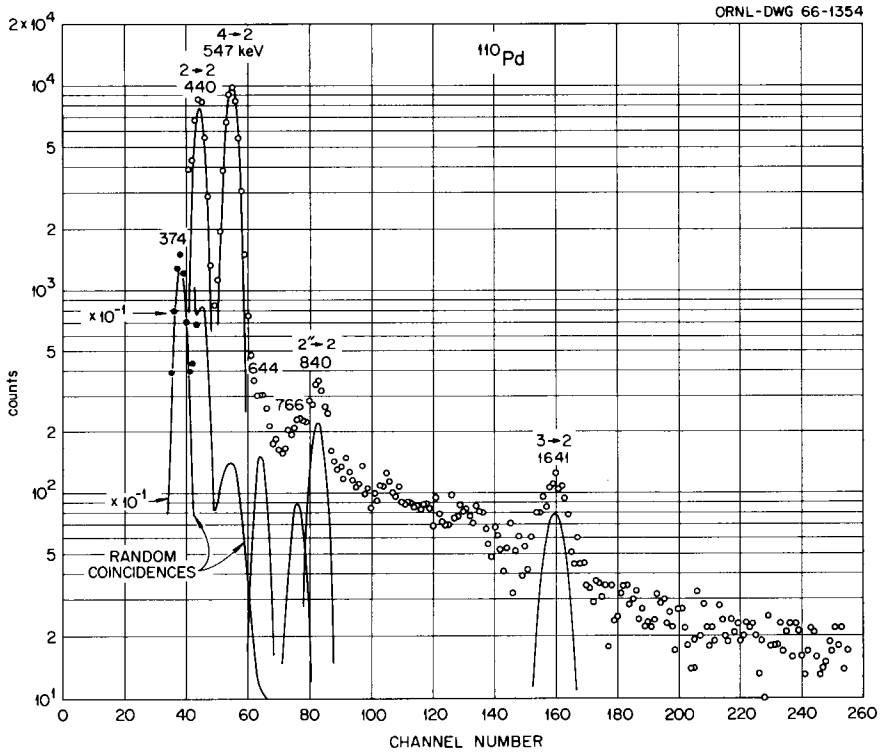


Fig. 3. ^{110}Pd Gamma-Ray Spectrum in Coincidence with the 374-kev Gamma Ray. The bombarding particles were 45.5-Mev oxygen ions.

yields expected for direct and double Coulomb excitation following oxygen ion bombardment. These yields are compared with the experimental yields for ^{106}Pd and ^{110}Pd in Table 1. The yields deduced from the 616-kev peak in the spectra of ^{106}Pd were corrected for an ~14% contribution due to the $0' \rightarrow 2$ transition. Deviation of the ratio of the experimental to the theoretical yields could result from the interference between the direct and double $E2$ processes or from the interaction of the static quadrupole moment of the excited state with the projectile.

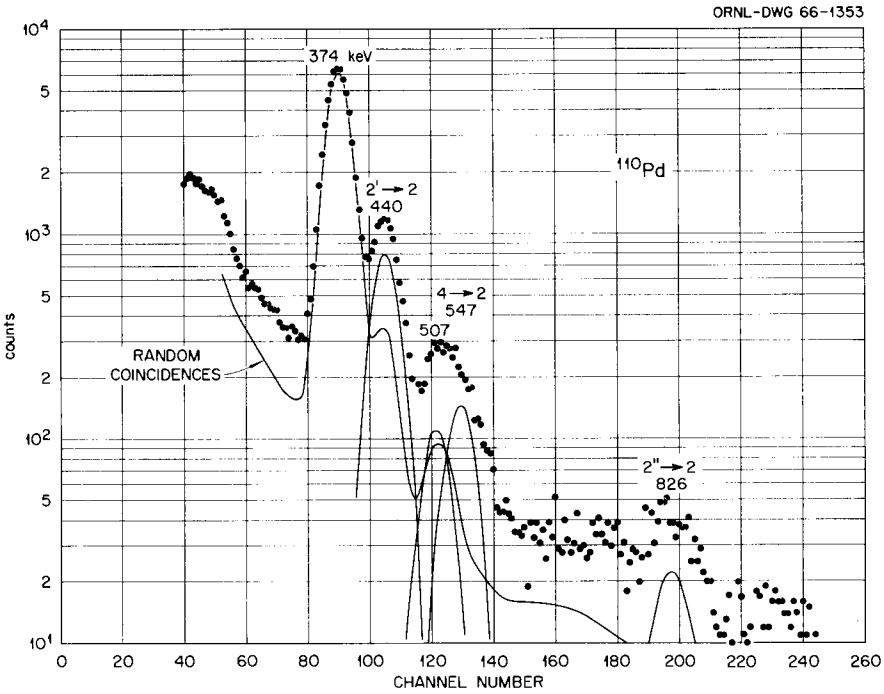


Fig. 4. ^{110}Pd Gamma-Ray Spectrum in Coincidence with the 374-kev Gamma Ray. The bombarding particles were 10-Mev ^{4}He ions.

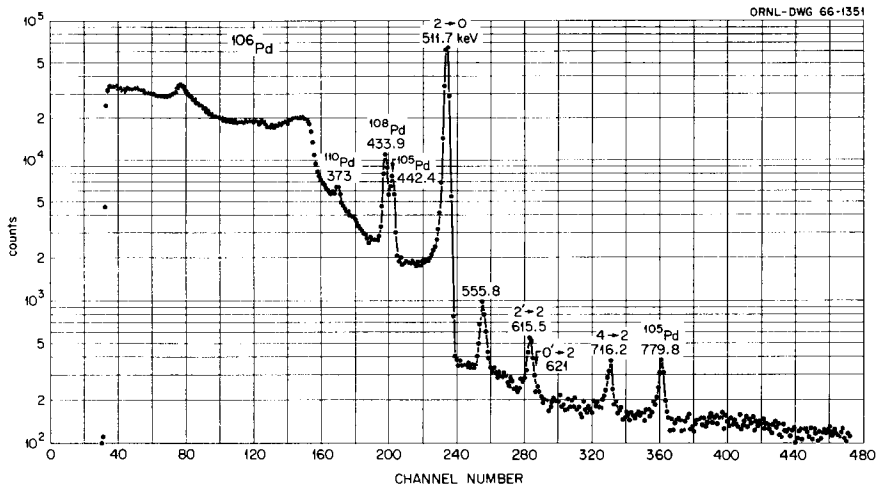


Fig. 5. Gamma-Ray Spectrum for 45.5-Mev Oxygen Ions on ^{106}Pd as Measured with a Lithium-Drifted Ge Detector.

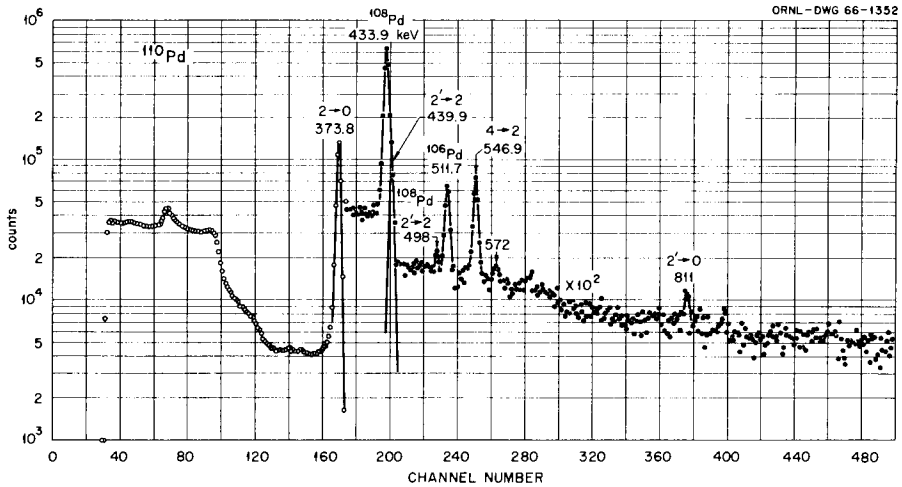
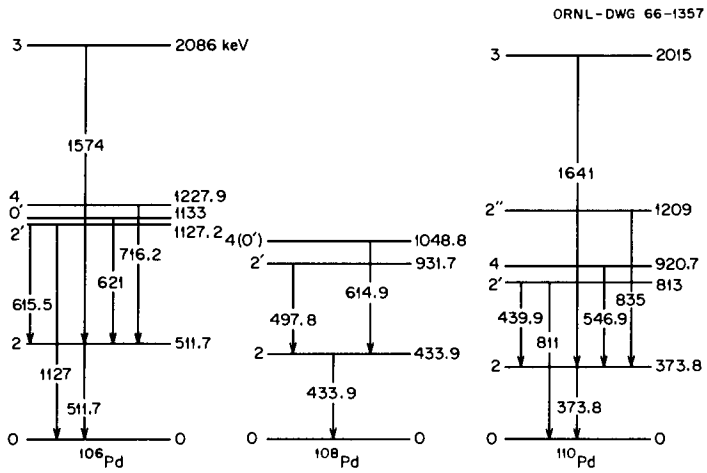


Fig. 6. Gamma-Ray Spectrum for 45.5-Mev Oxygen Ions on ^{110}Pd as Measured with a Lithium-Drifted Ge Detector.



	^{106}Pd	^{108}Pd	^{110}Pd
$B(E2;2\to0)$	12.9 ± 0.9	14.8 ± 1.0	17.2 ± 1.2
$\frac{B(E2;2\to0)}{B(E2)_{sp}}$	43	48	55
$B(E2;2'\to0)$	0.30 ± 0.04	0.14 ± 0.03/ϵ	0.24 ± 0.02
$\frac{B(E2;2'\to0)}{B(E2)_{sp}}$	1.0		0.8
$\frac{B(E2;0'\to2)}{B(E2;2'\to0)}$	0.8 ± 0.4		
$\frac{B(E2;2'\to2)}{B(E2;2\to0)}$	1.01 ± 0.19		0.91 ± 0.21
$\frac{B(E2;4\to2)}{B(E2;2\to0)}$	1.65 ± 0.26	2.05 ± 0.31	1.88 ± 0.26
$B(E3;3\to0)$	15 ± 3		11 ± 2
$\frac{B(E3;3\to0)}{B(E2)_{sp}}$	23		16

Fig. 7. Coulomb-Excited States of ^{106,108,110}Pd and a Summary of the Reduced Transition Probabilities. The $B(E2;\ 2\to0)$'s are from P. H. Stelson and F. K. McGowan, *Phys. Rev.* 110, 489 (1958), and the $B(E2;\ 2'\to0)$ of ^{108}Pd is from P. H. Stelson and F. K. McGowan, *Phys. Rev.* 121, 209 (1961). ϵ is the ratio of cascade to cascade and crossover gamma rays.

Table 1. Comparison of Yields of Cascade Gamma Rays from the 2′ States of ^{106,110}Pd with Those Predicted for Direct and Double $E2$ Coulomb Excitation[a]

Nucleus	E_{16_0} (Mev)	I_{E2}	I_{E2E2}	I_{exp}	$\frac{I_{exp}}{I_{E2}+I_{E2E2}}$
^{106}Pd	42.0	2.3 ± 0.4	0.74 ± 0.16	2.9 ± 0.4	0.95 ± 0.19
	45.5	4.0 ± 0.6	1.5 ± 0.3	5.9 ± 1.0	1.07 ± 0.23
^{110}Pd	42.0	5.8 ± 0.8	2.9 ± 0.7	9.5 ± 1.0	1.09 ± 0.17
	45.5	8.8 ± 1.1	5.3 ± 1.3	15.8 ± 1.6	1.12 ± 0.18
	49.0	12.7 ± 1.7	8.9 ± 2.1	25.6 ± 2.3	1.19 ± 0.19

[a]Yields are given in units of 10^4 per microcoulomb of charge 6 oxygen ions.

In the case of ^{108}Pd, $B(E2;\ 2' \to 2)$ and $B(E2;\ 2' \to 0)$ could not be estimated because of the unknown gamma-ray branching ratio. However, if the ratio $I_{exp}/(I_{E2} + I_{E2E2})$ were known, these $B(E2)$'s as well as R could be determined by combining results obtained from Coulomb excitation with oxygen ions and alpha particles. For an assumed value of 1.10 ± 0.10 for this ratio, which appears typical of the cadmium nuclei[1] and the other two palladium nuclei, $B(E2;\ 2' \to 2)/B(E2;\ 2 \to 0) = 1.7 \pm 0.4$, $B(E2;\ 2' \to 0) = 0.16 \pm 0.02$, and $R = 7.0 \pm 1.9$. The last is consistent with our lower limit of 5 for R.

A careful study of the line shape for the 615.5-kev peak in the spectra of ^{106}Pd taken with a germanium detector (see Fig. 5) suggests that there is an unresolved peak at the position expected for the $0' \to 2$ transition which contributes (14 ± 7)% of the total intensity. This gives the value for $B(E2;\ 0' \to 2)$ contained in Fig. 7. The $0'$ state in ^{108}Pd has been reported to have essentially the same energy as the 4^+ state.[3] There was no indication of the 614.9-kev peak attributed to the $4 \to 2$ transition in ^{108}Pd being broadened in the spectra measured by means of the germanium detector. The $B(E2;\ 4 \to 2)$ given in Fig. 7 is based on the total intensity of the 615-kev gamma ray and is therefore expected to be about 10% high.

The $0'$ level in ^{110}Pd has not been located. Possibly the unexplained gamma ray at 572 kev observed with the germanium detector is from the $0'$ state. The value of $B(E2;\ 0' \to 2)/B(E2;\ 2 \to 0)$ would then be 0.8 ± 0.2. If this explanation is correct, the 572-kev transition will be coincident with the $2 \to 0$ transition. The 547-kev peak in the coincidence spectra as measured with the NaI scintillation spectrometer did appear ~7% wider than expected for a single gamma ray.

The excitation of the presumed 3^- states in ^{106}Pd and ^{110}Pd was detected by observing the $3^- \to 2^+$ transitions. These are the peaks at 1574 ± 16 and 1641 ± 16 kev in Figs. 1 and 3. The enhancements over the single-particle estimate, as given in Fig. 7, are similar to those found for other octupole transitions. The higher background associated with our ^{108}Pd target precluded observation of a $3^- \to 2^+$ transition.

Since an 0.83-Mev gamma ray was observed in coincidence with the 374-kev transition when Coulomb excitation of ^{110}Pd was effected with both alpha particles and oxygen ions (Figs. 3 and 4), it is attributed to de-excitation of a third 2^+ state at 1209 ± 15 kev. If the excitation is all by the direct $E2$ process, $B(E2;\ 2'' \to 0)$ obtained with the alpha-particle bombardment is $(0.23 \pm 0.07)/\epsilon'$ and with the oxygen ion bombardment is $(0.21 \pm 0.03)/\epsilon'$. The quantity ϵ' is the ratio of cascade gamma rays to the sum of the cascade and crossover gamma rays.

The vibrational model predicts that $B(E2;\ I \to 2)/B(E2;\ 2 \to 0) = 2$, where I is the spin of the two-phonon state. The $B(E2;\ 4 \to 2)$'s are in agreement with this prediction, but the $B(E2;\ 2' \to 2)$'s are about a factor of 2 smaller. This is consistent with experimental results obtained with other

[3]*Nuclear Data Sheets*, Nuclear Data Group, Oak Ridge National Laboratory.

vibrational nuclei. One explanation for this reduction is that the 2^+ two-phonon state is mixed with the neighboring 2^+ states. The 4^+ state is not mixed, since there are no other 4^+ states nearby. This explanation is supported by inelastic proton scattering studies.[4] To fit the shape of the differential cross section of proton scattering to the $2'$ state, it was necessary to admix the one- and two-phonon states. However, the shape of the differential cross section to the 4^+ state was fitted without any admixture.

[4]R. L. Robinson, J. L. C. Ford, Jr., P. H. Stelson, and G. R. Satchler, to be published.

INFORMATION ON CONVERSION COEFFICIENTS FROM COULOMB EXCITATION AND LIFETIME MEASUREMENTS[1]

P. H. Stelson

Several papers have pointed out that information on total internal-conversion coefficients for $E2$ transitions can be obtained from the comparison of $B(E2)$'s found from lifetime measurements with those obtained from Coulomb excitation results (either inelastic scattering cross sections or gamma-ray yields). From such a comparison of ten rare-earth nuclei, Fossan and Herskind[2] concluded that the experimental α's differed from the theoretical α's by an average of 12 to 14%. Bernstein[3] has suggested that the deviations from theory exhibit an N/Z dependence.

In the course of compiling a list of $B(E2)$ values for nuclei,[4] we have once again studied the problem of total $E2$ conversion coefficients, since it is desirable to use the large amount of precise information available from lifetime measurements to supplement the Coulomb excitation results. Taking all the available information on 23 even-even rare-earth nuclei, we conclude that the average deviation of the experimental and theoretical α's is only about 1%. Sliv's theoretical values are used for α_K and α_L, and we take the contribution from higher shells to be $0.33\alpha_L$. A statistical analysis suggests that the observed fluctuations in the individual values of $\alpha_{exp}/\alpha_{theor}$ are what one would expect from the errors assigned to the experimental measurements.

[1]Abstract of paper to be published in *Internal Conversion Processes.*

[2]D. B. Fossan and B. Herskind, *Nucl. Phys.* **40**, 24 (1963).

[3]E. M. Bernstein, *Phys. Rev. Letters* **8**, 100 (1962).

[4]P. H. Stelson and L. Grodzins, *Nucl. Data* **1**, 21 (1965).

NUCLEAR TRANSITION PROBABILITY, $B(E2)$, FOR $0^+_{g.s.} \rightarrow 2^+_{first}$ TRANSITIONS AND DEFORMATION PARAMETERS, β_2[1]

P. H. Stelson L. Grodzins[2]

Adopted values for the reduced electromagnetic transition probability, $B(E2)_{ex}$, from the ground to the first-excited 2^+ state of even-even nuclei are given in Table 1. Values of β_2, the quadrupole deformation parameter, and of τ, the mean life of the 2^+ state, are also listed there.

[1]Abstract of published paper: *Nucl. Data* **1**, 21 (1965).

[2]Massachusetts Institute of Technology, Cambridge.

Table 2 presents the data on which Table 1 is based, namely, the experimental results for $B(E2)_{ex}$ values with quoted errors. The literature has been covered to January 1965.

The ratio of the value of β_2 to values expected from the single-particle model is presented graphically as a function of neutron number. As an indication of the extent of collective features in nuclear structure, this ratio seems a better measure than the value of β_2 itself.

GAMMA-RAY ENERGIES DETERMINED WITH A LITHIUM-DRIFTED GERMANIUM DETECTOR[1]

R. L. Robinson P. H. Stelson F. K. McGowan
J. L. C. Ford, Jr. W. T. Milner

RADIOACTIVITY. ^{7}Be, ^{22}Na, ^{51}Cr, ^{54}Mn, ^{60}Co, ^{65}Zn, ^{88}Y, ^{137}Cs, ^{198}Au, ^{203}Hg, ^{207}Bi; measured E_γ. ^{102,106}Rh, measured E_γ, I_γ.

NUCLEAR REACTIONS. ^{48}Ti, ^{50}Cr, ^{56}Fe, ^{64,66,68,70}Zn, ^{70,72,74,76}Ge, ^{75}As, ^{76,78,80,82}Se, ^{79}Br, ^{94,96,98,100}Mo, ^{96,100,104}Ru, ^{104,106,108,110}Pd, ^{106,108,110,112,114,116}Cd, ^{116,117,118,120,122,124}Sn, ^{121,123}Sb, ^{122,124,126,128,130}Te, ^{195}Pt($\alpha,\alpha'\gamma$), E = 6–9 Mev; measured E_γ. ^{77}Se, ^{119}Sn($\alpha,\alpha'\gamma$), E = 6–9 Mev; measured E_γ, I_γ. ^{18}O($\alpha,n\gamma$) ^{21}Ne, E = 6–9 Mev; measured E_γ. ^{21}Ne deduced level. Enriched targets.

The energies of gamma rays from about 60 nuclides have been determined to within a few tenths of a kev by means of a lithium-drifted germanium detector. They include values for the transitions resulting from the decay of ^{51}Cr, ^{7}Be, ^{207}Bi, ^{54}Mn, ^{88}Y, ^{65}Zn, and ^{22}Na, which are frequently used as calibration standards. The majority of energies are for transitions following Coulomb excitation. Previously unresolved gamma-ray doublets have been observed in the decay of the radioactive nuclei ^{102}Rh and ^{106}Rh and in Coulomb-excited ^{75}As, ^{77}Se, ^{117}Sn, and ^{119}Sn. From the relative intensities of the members of the ^{77}Se doublet, new estimates have been made for the $B(E2)_{ex}$ of the 239.3- and 250.1-kev states. They are, respectively, 1770 ± 160 and 94 ± 26 e^2 fm^4.

[1]Abstract of published paper: *Nucl. Phys.* **74**, 281 (1964).

OBSERVATION OF RECOILLESS EMISSION OF GAMMA RAYS FOLLOWING COULOMB EXCITATION[1]

D. Seyboth[2] F. E. Obenshain[3] Gordon Czjzek[4]

We have observed the recoilless emission of gamma rays from ^{61}Ni after the 67.4-kev energy level of this nucleus was populated by Coulomb excitation. The projectiles used for the excitation were 25-Mev oxygen ions from the ORNL Tandem Van de Graaff. The Mössbauer effect observed by

[1]Abstract of published paper: *Phys. Rev. Letters* **14**, 954 (1965).

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[4]Metals and Ceramics Division.

this method for ^{61}Ni was compared with previous measurements[5] using the radioactive source

$$^{61}\mathrm{Co} \xrightarrow[99\ \mathrm{min}]{\beta-} {}^{61}\mathrm{Ni}^{*} .$$

The total Mössbauer absorption measured in the present experiment is equal to that observed previously, but the spectrum is wider, and the absorption at zero velocity is (74 ± 6)% of the expected value. This experiment establishes the feasibility of Mössbauer measurements using gamma rays from Coulomb excitation. Since this method is applicable to all stable nuclei with low-lying energy levels, it can be an important tool both in nuclear and solid-state physics.

[5]F. Obenshain and H. Wegener, *Phys. Rev.* **121**, 1344 (1961).

OBSERVATION OF THE MÖSSBAUER EFFECT FOLLOWING COULOMB EXCITATION OF ^{73}Ge[1]

Gordon Czjzek[2] J. L. C. Ford, Jr. F. E. Obenshain[3] Dietrich Seyboth[4]

The Mössbauer effect in ^{73}Ge has been observed after the 67.0-kev level of this nucleus was populated by Coulomb excitation. A target, enriched to 84% in ^{73}Ge, and a single-crystal absorber of natural germanium, both at liquid-nitrogen temperature, were used. The measured Mössbauer spectrum was fitted with a single line of Lorentz shape. The resulting parameters were: line position (0.11 ± 0.14) mm/sec, maximum absorption (0.64 ± 0.04)%, and line width (4.4 ± 0.6) mm/sec. The position is consistent with vanishing isomer shift. The recoilless fraction, as deduced from the Debye temperature of germanium, θ_d = 360°K, at T = 80°K, is f = 0.125. Assuming this to be the recoilless fraction of the absorber, a value for the recoilless fraction of our target f_s = 0.011 ± 0.004 is obtained. This small value for the recoilless fraction can be explained either by the assumption that the excited nuclei end in positions with a weak binding energy, or that the heat generated in the slowing-down process of these nuclei leads to a high effective temperature of their environment.

[1]Abstract of paper presented at the Autumn Meeting of the American Physical Society, Chicago, October 28–30, 1965; also abstract of paper to be submitted for publication in *Physics Letters*.

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[3]Present address: Kernforschungszentrum Karlsruhe, Karlsruhe, Germany.

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MÖSSBAUER MEASUREMENTS OF THE ^{57}Fe HYPERFINE STRUCTURE COUPLING IN FeRh ALLOYS NEAR 50 at. % RHODIUM

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F. E. Obenshain H. Wegener[3]

Previous studies have shown that FeRh alloys with a concentration between 48 and 55 at. % Rh have a critical temperature T_1 below which there is antiferromagnetic ordering and above which

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there is ferromagnetic ordering up to the Curie temperature T_C.[4–7] At this transition the lattice expands approximately 1% in volume in going to the higher-temperature phase. In this range of composition, the transition temperature T_1 and the Curie temperature T_C depend sensitively on the rhodium concentration and on the presence of impurity atoms.[8] Kouvel and Hartelius[7] have made a detailed study of the temperature dependence of the magnetization in the ferromagnetic region for an alloy containing 52 at. % rhodium. Recent Mössbauer measurements[9–11] in these alloys of the ^{57}Fe hyperfine structure spectra (hfs) show a small decrease in the effective magnetic field H_{eff} at the nucleus when an alloy in this concentration range changes from ferromagnetic to antiferromagnetic ordering at T_1. On the other hand, neutron diffraction measurements[12,13] suggest that the magnetic moment on the iron atom increases somewhat while the magnetic moment on the Rh atom apparently decreases when the system goes from the ferromagnetic to the antiferromagnetic state. Recently Kouvel[14] and Hargitai[15] have suggested that the magnetic moment of the Rh is zero in the antiferromagnetic state.

Measurements of H_{eff} through the use of the Mössbauer effect provide information about the ^{57}Fe spin magnetization equally well in both the ferromagnetic and antiferromagnetic phases. We have extended previous Mössbauer measurements on FeRh alloys by making a more detailed investigation of the temperature dependence of this effective field in the interesting composition range near 50 at. % Rh, and measurements using alloys containing 50, 52, and 53 at. % rhodium are reported here.

The Mössbauer source used in this experiment was 50 mc of ^{57}Co diffused into a 0.0003-in.-thick copper foil over an area of 0.1 cm^2. This source gave an absorption line width of 0.8 mm/sec when a 0.001-in.-thick type 310 stainless steel foil was used as an absorber. The 50 and 53 at. % alloys were prepared by arc melting by the Metals and Ceramics Division of the Oak Ridge National Laboratory. They were ground and electropolished to a thickness of 0.002 in. and then annealed for 65 hr at 1000°C in a helium atmosphere.

Analysis with x rays showed the 50% sample to have a single, ordered phase with the CsCl structure and a lattice parameter $a = 2.988 \pm 0.001$ A. Through the use of magnetization measurements, the 50% alloy was found to be ferromagnetic above 100°K. Mössbauer measurements were made

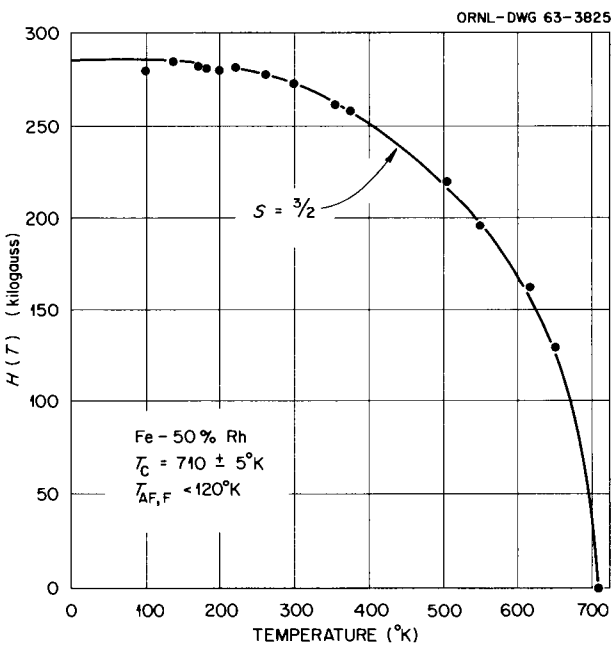

Fig. 1. Effective Field at the Iron Nucleus in FeRh as a Function of Temperature. The solid curve is the Weiss-Brillouin function for $S = 3/2$.

[4] M. Fallot, *Ann. Phys.* **10**, 291 (1938); M. Fallot and R. Hocart, *Rev. Sci.* **77**, 498 (1939).

[5] F. deBergevin and L. Muldawer, *Compt. Rend.* **252**, 1347 (1961).

[6] L. Muldawer and F. deBergevin, *J. Chem. Phys.* **35**, 1904 (1961).

[7] J. Kouvel and C. Hartelius, *J. Appl. Phys.* **33**, 1343S (1962).

[8] P. H. L. Walter, *J. Appl. Phys.* **35**, 938 (1964).

[9] F. E. Obenshain, L. D. Roberts, and H. H. F. Wegener, *Bull. Am. Phys. Soc.* **8**, 43 (1963).

[10] G. Shirane *et al.*, *Phys. Rev.* **131**, 183 (1963).

[11] L. Cser, I. Dezsi, and L. Keszthelyi, *Magy. Tud. Akad. Kozp. Fiz. Kut. Int. Kozlemen.* **12**, 119 (1964).

[12] F. Bertaut *et al.*, *J. Appl. Phys., Suppl.* **33**, 1123 (1962); F. Bertaut, F. deBergevin, and G. Roult, *Compt. Rend.* **256**, 1668 (1963).

[13] G. Shirane, R. Nathans, and C. W. Chen, *Phys. Rev.* **134**, A1547 (1964).

[14] J. S. Kouvel, *11th Annual Conference on Magnetism and Magnetic Materials*, San Francisco, Nov. 16–19, 1965.

[15] C. Hargitai, *Phys. Letters* **17**, 178 (1965).

of the hfs spectra for this sample at temperatures from 100 to 714°K, and the data are shown in Fig. 1. The solid curve in this figure was drawn using the Weiss-Brillouin model for the effective field, H_{eff}, for a system with atomic spins of S equal to $\frac{3}{2}$, and with values of $H_{eff}(0)$ = 285 kilogauss and T_C = 710°K. The data were similarly fitted using S = 1 and 2, but the curve for $S = \frac{3}{2}$ gave a somewhat better fit than S = 1 or 2. The spin $S = \frac{3}{2}$ is consistent with the earlier neutron diffraction measurements[10] of the iron magnetic moment for an alloy of approximately this composition ordered ferromagnetically.

Since the results of the hfs measurements on the 53% alloy were closely similar to those to be presented for the 52% alloy, the measurements on the 53% alloy are not given.

The 52% foil was obtained from J. S. Kouvel and was prepared by the same procedures as the samples which he has used in his bulk magnetization measurements.[7,14] Analysis with x rays showed this sample to have predominantly the CsCl structure. A small percentage of a nonmagnetic phase was also present, which contributed a single unsplit line near the center of the six-line hfs spectrum of the ^{57}Fe in the phase having the CsCl structure. Spectra for the 52% alloy were obtained from 4.2 to 670°K, and the results for H_{eff} are shown in Fig. 2. Near 330°K, H_{eff} decreases sharply by about 20 kilogauss on going from the ferromagnetic state to the antiferromagnetic state. This transition takes place in a temperature range less than 10°K in width, and the Mössbauer hfs peaks were not measurably broadened for temperatures in the vicinity of the transition.

An externally applied magnetic field was used to determine the sign of H_{eff} in the ferromagnetic region for the 50 and 52% samples. The hfs splitting in a field of 8.5 kilogauss was reduced compared to the splitting in 1 kilogauss, indicating a negative H_{eff} for both compositions.

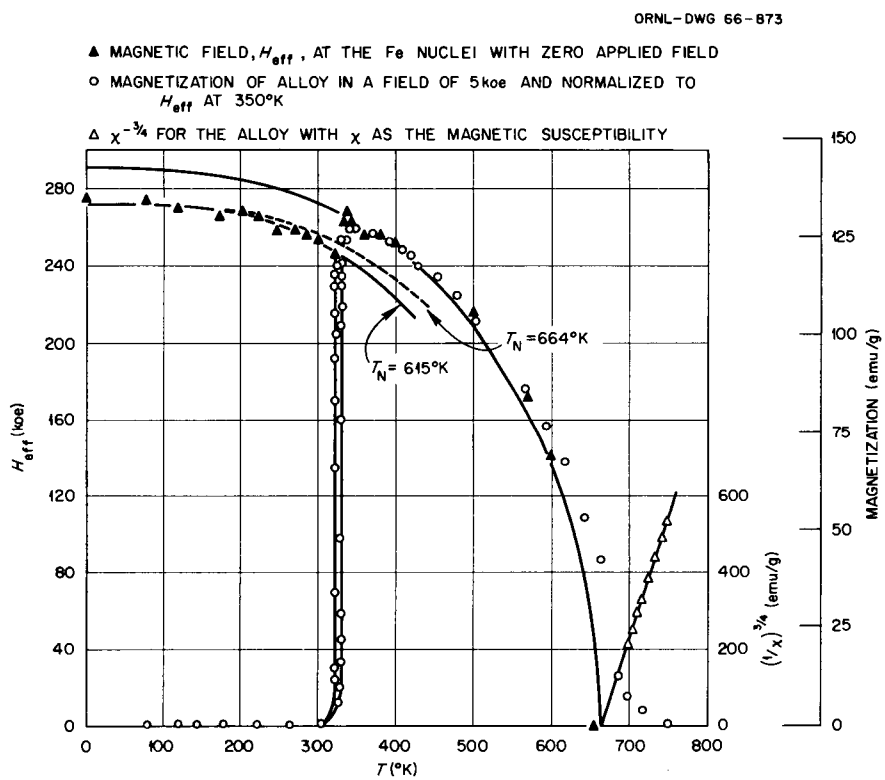

Fig. 2. Effective Field at the Iron Nucleus in $Fe_{0.48}Rh_{0.52}$ as a Function of Temperature Compared with the Magnetization Measurements of Kouvel and Hartelius. The solid curves correspond to $S = \frac{3}{2}$ and to the Néel and Curie temperatures indicated.

In Fig. 2 the Mössbauer data for this sample taken in zero magnetic field have been compared with the magnetization data taken by Kouvel and Hartelius[7,14] on an alloy of the same composition, but their data were taken in an external field of 5 kilogauss. In this figure, their magnetization data and our effective field measurements have been scaled to have the same ordinate near 400°K. We observe that the transition temperature T_1 near 330°K determined by our H_{eff} measurements is in close agreement with T_1 observed in their magnetization measurements. On the other hand, above about 550°K, due to the applied magnetic field, the magnetization data fall less rapidly than H_{eff} with increasing temperature. Above $T \approx 660$°K, H_{eff} goes to zero, whereas the magnetization, taken in a field of 5 kilogauss, remains finite to the highest temperatures of their study. In Fig. 2, the paramagnetic susceptibility data taken by Kouvel and Hartelius have been plotted as $(1/\chi)^{3/4}$ vs T.[16] The extrapolation of this curve to $(1/\chi)^{3/4} = 0$ gives a value for the paramagnetic Curie temperature T_C of 664°K.

Since a Weiss-Brillouin function for $S = 3/2$ gave a good fit to the 50% alloy data for H_{eff}, this function has been used to describe this field for both the ferromagnetic and the antiferromagnetic phases of the 52% sample. In this description, the hfs splittings for the ferromagnetic region were fitted using a value of $H^F_{eff}(0) = 291$ kilogauss and the Curie temperature of 664°K obtained as described above from the magnetic measurements. This choice of Curie temperature gives a very reasonable fit to $H_{eff}(T)$ between T_1 and T_C.

The best fit to the data in the antiferromagnetic region was obtained using the parameters $H^A_{eff}(0) = 272.5$ kilogauss and a Néel temperature $T_N = 615$°K. This fit is shown as a solid curve in Fig. 2. The dashed line in Fig. 2 gives a comparison of the experimental data to a Weiss curve with the parameters $H_{eff}(0) = 272.5$ kilogauss and with $T_N = T_C = 664$°K. The curve with $T_N = T_C$ does not fit the data quite as well as the curve for which T_N is roughly 50° less than T_C. Although the determination of T_N is not very precise, the data suggest that T_N is appreciably less than T_C.

In fitting the Weiss-Brillouin function to the hfs data, Figs. 1 and 2, we have assumed that the hfs splitting could be described by $\mu H_{eff} \cdot I = bI_z m$, with $H_{eff} = bm/\mu$. Here I_z is the z component of the nuclear spin operator I, m is the relative magnetization, $\langle S_z \rangle / S$, where $\langle S_z \rangle$ is the thermal average of the z component of the electron spin operator S, b is an hfs coupling constant, and μ is the nuclear magnetic moment. Then in a given magnetic phase, bm is assumed to follow a Weiss-Brillouin function, where the amplitude of this function $H_{eff}(0)$ is different for the ferromagnetic and the antiferromagnetic phases. Presumably, this change of amplitude is predominantly due to a change of b with volume at T_1.

In interpreting the magnetic properties of FeRh one is led by the presence of the 1% volume change at the transition temperatures to consider Kittel's model for exchange inversion.[17] In this model the exchange coupling varies with lattice parameter and therefore with temperature. Zakharov *et al.*[18] and Pal *et al.*[19] have used Kittel's theoretical results in correlating some of the properties of FeRh, including the variation of lattice constant with temperature, the latent heat at T_1, and the shift of transition temperature T_1 with pressure and applied magnetic field.

We now wish to use the Kittel exchange inversion model to give a phenomenological description of H_{eff}. We shall assume that b is constant for a given magnetic phase and that the temperature dependence of H_{eff} is due to $m(T)$. Although the saturation electron magnetic moment of the iron is near three Bohr magnetons, and the spin $S = 3/2$ gave the best fit of the Weiss-Brillouin function to the data of Fig. 1, we shall use functions for $S = 1/2$ for simplicity. Our purpose in giving the following model calculation is to present a description of $H_{eff}(T) \approx m(T)$ for the whole temperature range, which will show a relationship between T_1, T_C, and T_N.

Since metallic rhodium is nonmagnetic and since it appears that the rhodium moment in the antiferromagnetic phase of FeRh is less than it is in the ferromagnetic phase, we adopt the suggestion of Kouvel[14] and Hargitai[15] that the rhodium moment

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[16] C. Domb and M. F. Sykes, *Phys. Rev.* **128**, 168 (1962); W. Marshall, J. Gammel, and L. Morgan, *Proc. Roy. Soc. (London)* **A275**, 257 (1963).

[17] C. Kittel, *Phys. Rev.* **120**, 335 (1960).

[18] A. I. Zakharov *et al.*, *Zh. Eksperim. i Teor. Fiz.* **46**, 2003 (1964); *Soviet Phys. JETP (English Transl.)* **19**, 1348 (1964).

[19] L. Pal *et al.*, p. 158 in *Proceedings of the International Conference on Magnetism, Nottingham, September 1964*, published in association with the *Proceedings of the Physical Society* by the Institute of Physics and the Physical Society, 1964.

in the antiferromagnetic phase is zero. This suggests that the moment which occurs on the rhodium in the ferromagnetic phase arises from a polarization process.

Let us consider two interpenetrating fcc iron sublattices with magnetizations m_1 and m_2. The relative moment on the rhodium atoms m_{Rh} arising from polarization by the permanent moments on the iron atoms is taken to be proportional to the vector sum $m_{Rh} = K(m_1 + m_2)$ with K independent of the temperature. Thus $m_{Rh} = 0$ in the antiferromagnetic state but adds proportionally to the iron moment in the ferromagnetic state of the alloy. In that a given rhodium interacts simultaneously with all of its eight nearest iron neighbors, the rhodium may be regarded as introducing both first- and second-nearest-neighbor couplings between the iron atoms, but otherwise in this model the rhodium does not contribute explicitly to the magnetic energy or to the entropy of the system. The free energy of the system is given by

$$G = E_{mag} + E_{el} - TS_{mag} , \tag{1}$$

where the elastic energy E_{el} is given by

$$E_{el} = \frac{nR}{2}(a - a_T)^2 , \tag{2a}$$

$$a_T = a_0(1 + \beta T) . \tag{2b}$$

Here n is the number of iron atoms per cubic centimeter, a is the lattice parameter of the actual system, a_T is the lattice parameter in the absence of magnetic interactions, and β is the coefficient of expansion of the alloy. The total magnetic energy is taken to have the form:

$$E_{mag} = -\frac{n}{2}\left[-A(a)\, m_1 \cdot m_2 + \frac{D}{K}(m_1 + m_2)\cdot m_{Rh}\right] \tag{3a}$$

$$= -\frac{n}{2}[-A(a)\, m_1 \cdot m_2 + D(m_1 + m_2)^2] . \tag{3b}$$

By expanding the squared term, we see that this may be written as

$$E_{mag} = -\frac{n}{2}\{[-A(a) + 2D]m_1 \cdot m_2 + Dm_1^2 + Dm_2^2\} , \tag{3c}$$

which contains first- and second-neighbor interactions. In this model, as indicated above, the role of the Rh is to introduce both a first and a second iron neighbor interaction without entering E_{mag} explicitly. Here

$$A(a) = A - \alpha a \tag{4}$$

explicitly contains the lattice parameter dependence of the exchange interaction parameter $A(a)$.

The entropy of a sublattice, $S_{mag}/2$, is assumed to be given by the Bragg-Williams approximation:

$$\frac{S_{mag}}{2} = \frac{n}{2} k \ln 2 - \frac{nk}{4}\left[\ln (1 - m^2) + m \ln \frac{1 + m}{1 - m}\right] . \tag{5}$$

The free energy then becomes

$$G = \frac{3}{8}\frac{n\alpha^2}{R} - \frac{n}{2}(A - \alpha a_T)m^2 + \frac{n}{2} D(m_1 + m_2)^2 - nkT \ln 2 + \frac{nkT}{2} \ln (1 - |m|^2) . \tag{6}$$

The transition temperatures T_N and T_C follow from Eq. (6) and are given by

$$kT_N = A(a_T) , \qquad kT_C = 4D - A(a_T) . \tag{7}$$

Because of the dependence of the exchange interaction on the lattice parameter, Eq. (4), these expressions for T_N and T_C depend upon a_T. At the ferromagnetic to paramagnetic transition T_C, one would use the value of $a_T = a_0(1 + \beta T_C)$ suitable to the actual transition temperature. In discussing T_N, however, all the experimental information which we have about this quantity comes from the temperature region below T_1. As an approximate measure of the interaction below T_1 we use $a_T = a_0(1 + \beta T_1)$ in the expression for T_N, Eq. (7).

At T_1 the free energies of the two magnetic phases will be equal, but the sublattice magnetizations of the two phases will differ somewhat, and by an amount $m_F - m_A = \delta m$. Then at T_1, since $G_F - G_A = 0$, we may write to terms linear in $\delta m/m$,

$$T_N = T_C - \frac{\alpha a_0 \beta}{k}(T_C - T_1) - \left[\frac{2T_1}{1-m^2} - \frac{3\alpha^2 m^2}{kR} - 2T_N\right]\frac{\delta m}{m}. \quad (8)$$

In the square bracket the largest term is $[2T_1/(1-m^2)](\delta m/m)$. At temperatures near $T_C/2$ and below, this term is comparable to the term in $(T_C - T_1)$ of Eq. (8).

At equilibrium, $\partial G/\partial a = 0$, then from Eq. (6) at the transition at T_1

$$\alpha = \frac{R\,\Delta a}{m^2} = \frac{9Ba(\Delta a)}{m^2},$$

where Δa is the change of lattice parameter at T_1 and B is the bulk modulus. Then for $m^2 \approx 0.9$, $a = 2.988$ A as given above, $\Delta a \approx 10^{-10}$ cm,[18] and $B \cong 2 \times 10^{12}$, we have $\alpha \approx 6 \times 10^{-5}$. Then for a coefficient of expansion[18] $\beta \cong 10^{-5}$, the coefficient $\alpha a_0 \beta/k$ of Eq. (8) is approximately 0.13. Neglecting the term in $\delta m/m$ this gives $T_C - T_N \approx 40°$K, which is in accord with our experimental results.

Equation (8) may be written in the approximate form

$$T_1 \cong T_C - \frac{k(T_C - T_N)}{\alpha a_0 \beta}. \quad (9)$$

Since $k/\alpha a_0 \beta \approx 10$, T_1 is seen to depend sensitively on the small difference $(T_C - T_N)$, or equivalently on a small shift in the difference $4D - 2A(a)$, Eq. (7). This corresponds to a high sensitivity of T_1 to a small shift in the relative strength of the Fe-Fe exchange interaction represented by the A term of Eq. (3a) compared to the Fe-Rh interaction represented by the D term.

In going from the FeRh alloy containing 50 at. % Rh, for which T_1 is less than 100°K, to the $Fe_{0.48}Rh_{0.52}$ alloy, where $T_1 = 330°$K, none of the parameters which we have introduced, α, A, or D, for example, would be expected to change very much. However, $k(T_C - T_N)/\alpha a_0 \beta$ of Eq. (9) consists of a small difference multiplied by a large coefficient. Here small changes of A and D could lead to large changes of T_1. It is this term in the model which describes the delicate balance of the magnetic interactions in FeRh. This model may also be in accord with the observations of Walter[8] that the addition of small percentages of transition-metal impurities to FeRh produces large shifts of T_1 while leaving T_C comparatively unchanged.

MAGNETIC MOMENT OF THE 77.3-kev FIRST EXCITED STATE OF ^{197}Au

D. Seyboth[1] L. D. Roberts J. O. Thomson[2]
F. E. Obenshain

Using the Mössbauer effect, the hyperfine structure (hfs) spectrum of the ^{197}Au nucleus has been measured for Au-Fe alloys containing 0.50 and 1.00 at. % gold. The Mössbauer absorption spectrum for 1 at. % ^{197}Au in iron is shown in Fig. 1. The experiments were performed at 4.2°K using a source of ^{197}Pt, which decays through the 77.3-kev state of ^{197}Au. The Au-Fe absorbers contained 100 mg/cm^2 of gold. The position of the six lines of the hfs spectrum could be determined with good precision by a least-squares method. Using a ground-state moment $\mu = 0.1439$ nuclear magneton, we were able to obtain an excited moment $\mu^* = (0.402 \pm 0.025)$ nuclear magneton and a value for the effective magnetic field $|H| = (1.29 \pm 0.03) \times 10^6$ oersteds at the gold nucleus. The excited-state splitting $|2\mu^* H| = (12.68 \pm 0.15)$ mm/sec. These results are in agreement with previous measurements[3] but are of higher precision.

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[3]L. D. Roberts and J. O. Thomson, *Phys. Rev.* **129**, 664 (1963); R. W. Grant *et al.*, *Phys. Rev.* **A133**, 1062 (1964).

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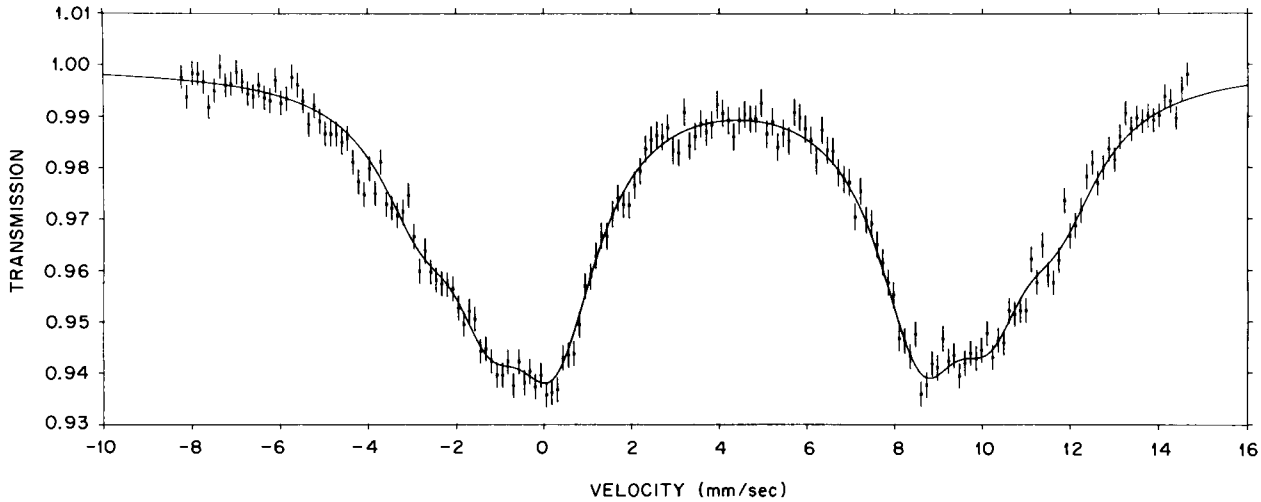

Fig. 1. Mössbauer Absorption Spectrum for 1 at. % ^{197}Au in Fe. The solid line is a fit by a least-squares method.

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^{197}Au HYPERFINE STRUCTURE COUPLING AND ISOMER SHIFT FOR $Au_{0.01}Cu_{x-0.01}Ni_{1-x}$ ALLOYS

J. W. Burton[1] L. D. Roberts J. O. Thomson[2]

Through the use of the Mössbauer effect for ^{197}Au, the effective magnetic field H_{eff} and the electric charge density at the ^{197}Au nuclei have been measured as a function of composition for a series of Cu-Ni alloys containing 1 at. % gold. The measurements were made at 4.2°K. The measured spectra were analyzed by fitting theoretical curves to the data, assuming magnetic splitting and the previously measured ground- and excited-state magnetic moments.[3] For the alloys between 99 and 80 at. % nickel, H_{eff} was found to vary linearly with atomic percent nickel on a line that extrapolated to H_{eff} = 0 at 53 at. % nickel. At 70 and 60 at. % nickel, H_{eff} was somewhat above this line but was found to be zero at 40 and 20 at. % nickel, within experimental error. The isomer shift was found to increase with increasing atomic percent nickel, with a slightly positive curvature. Thus the hfs coupling closely follows the magnetic behavior of the alloy. This result is very similar to that for the hfs for ^{197}Au in Au-Ni alloys.[4] The results are shown in Fig. 1.

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[3]This report and *Bull. Am. Phys. Soc.* **10**, 444 (1965).

[4]*Phys. Div. Ann. Progr. Rept. Dec. 31, 1964*, ORNL-3778, p. 4.

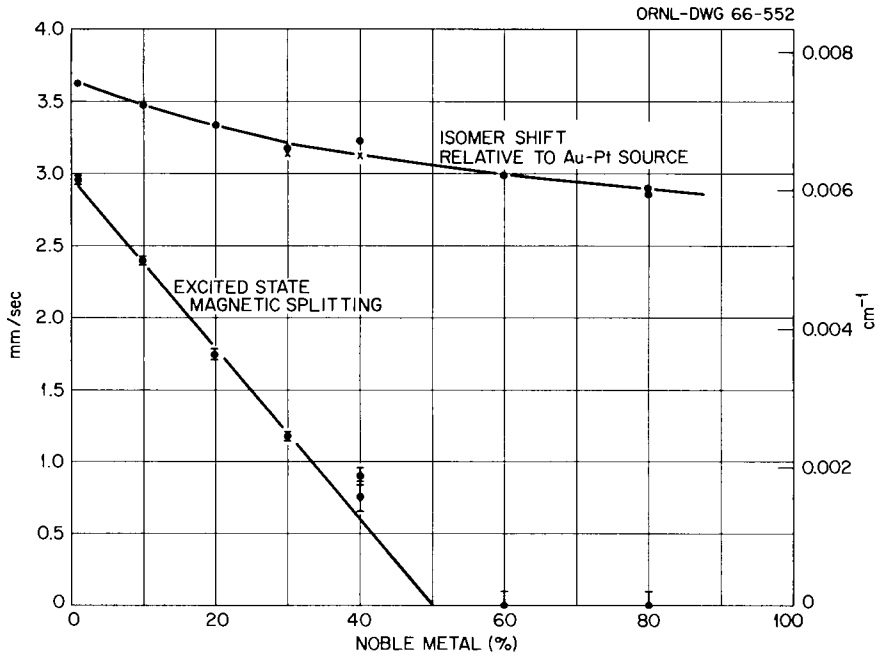

Fig. 1. Isomer Shift and Magnetic Splitting of 1% Au in Cu-Ni Alloys vs Concentration of Noble Metal.

SOLID STATE AND NUCLEAR RESULTS FROM THE MEASUREMENT OF THE HYPERFINE STRUCTURE COUPLING OF ^{197}Au IN ORDERED Au-Mn ALLOYS

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R. G. Scurlock[3]

Gold and manganese form a series of ordered alloys[4] of known crystallographic structure.[5] Neutron diffraction studies of the Au-Mn alloys reveal the magnetic structure associated with the manganese magnetic moments in the various systems,[6] and this structure is of course related to the type of crystalline lattice existing in the given alloy.

The Mössbauer effect of ^{197}Au permits the study of the hyperfine structure coupling at the gold nucleus. This coupling will also depend on the crystalline and magnetic structure of the alloys. Measurement of the hfs coupling gives information about the magnetic state of the gold atoms, about the electric field gradient which exists in these materials, and about the $E2/M1$ ratio for the resonance gamma-ray transition.

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[1]Oak Ridge Graduate Fellow from the University of Tennessee under appointment from Oak Ridge Associated Universities.

[2]Consultant, University of Tennessee, Knoxville.

[3]University of Southampton, Southampton, England.

[4]M. Hansen, *Constitution of Binary Alloys*, p. 216, McGraw-Hill, New York, 1958.

[5]J. H. Smith and P. Gaunt, *Acta Met.* **9**, 819 (1961); J. H. Smith and R. Street, *Proc. Phys. Soc.* **B70**, 1089 (1957); D. Watanabe, *J. Phys. Soc. Japan* **15** 1030 (1960).

[6]G. E. Bacon, *Proc. Phys. Soc.* **79**, 938 (1962); A. Herpin and P. Meriel, *J. Phys. Radium* **22**, 337 (1961); A. J. P. Meyer, *J. Phys. Radium* **20**, 430 (1959).

The first excited state of ^{197}Au, the resonance transition studied here, decays via a 77.3-kev gamma ray with mean life $T_{1/2} = (1.82 \pm 0.10) \times 10^{-9}$ sec. This state is reached by the decay of ^{197}Pt, which is prepared by neutron activation of ^{196}Pt metal. The state has a spin $I^* = \frac{1}{2}$ and nuclear moment $\mu^* = 0.402 \pm 0.025$ nuclear magneton. The ground state has a spin $I = \frac{3}{2}$ and $\mu = 0.1439$ nuclear magneton. The Au-Mn alloy preparation included the following steps: melting the original constituents, homogenizing, annealing, cutting, reannealing, and a final grinding and polishing to obtain thin foil samples. To obtain the ordered phase, the samples were annealed for 100 hr at the following temperatures: AuMn, 575 to 585°C; Au_2Mn, 670 to 700°C; Au_3Mn, 610 to 622°C. X-ray analysis by H. L. Yakel, Metals and Ceramics Division, Oak Ridge National Laboratory, showed that at least 95% of each sample was in the ordered phase. All the Mössbauer measurements were made with both the platinum source and the Au-Mn absorbers at a temperature of 4.2°K.

The structure of ordered AuMn is body-centered tetragonal with the gold atoms in the body-centered positions. Because of the symmetry of the manganese atoms around the gold atoms and because of the antiferromagnetic alignment of the manganese magnetic moments, the magnetic field at the gold nuclei is expected to be zero. In AuMn, the gold Mössbauer spectrum, Fig. 1, gives little, if any, evidence of magnetic or quadrupole splitting. A least-squares fit of a Lorentz line shape gives the width of the line as 2.97 ± 0.05 mm/sec. The sample thickness was 0.24 g/cm^2 of gold metal. The observed width can be explained,

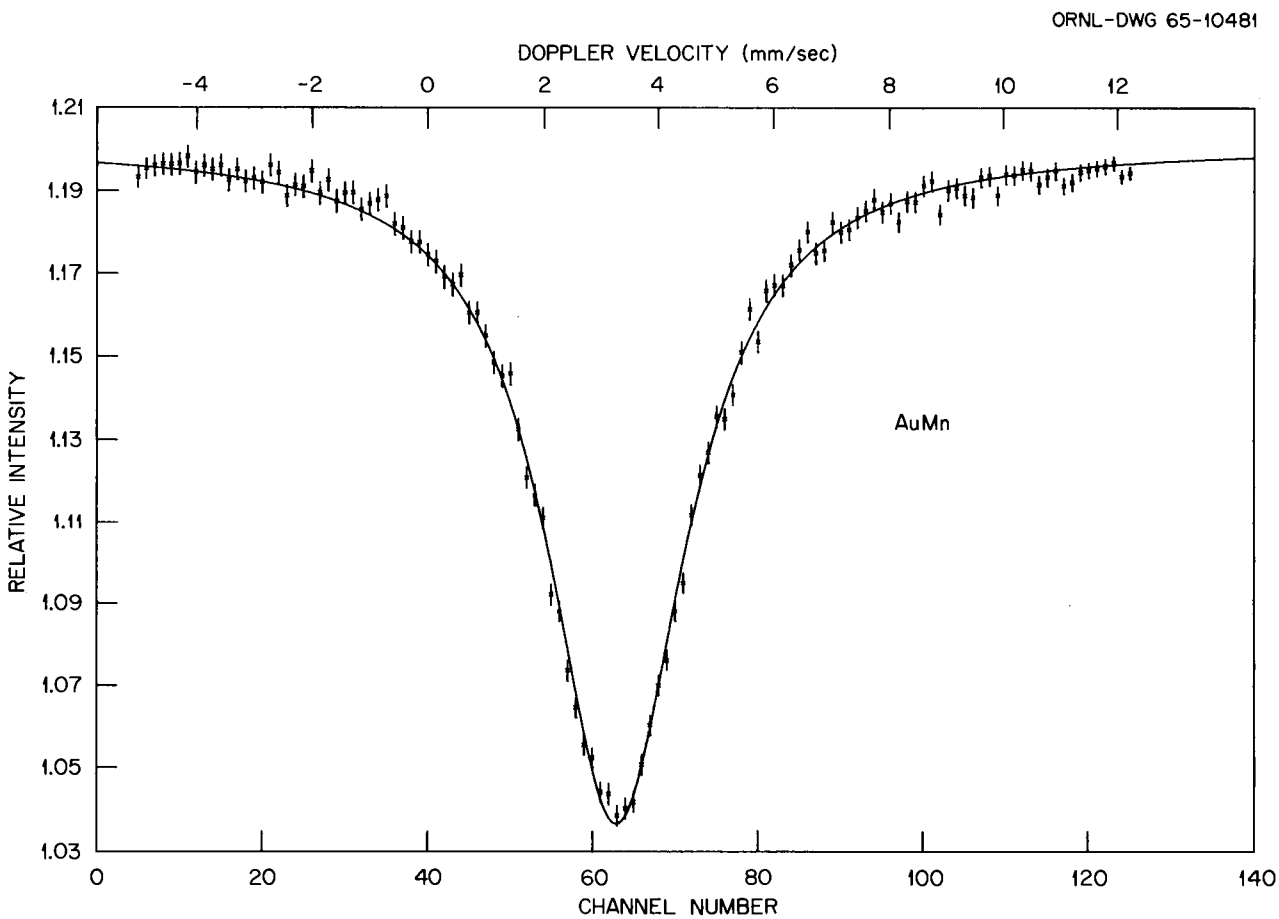

Fig. 1. Mössbauer Absorption Spectrum for ^{197}Au in AuMn. The width of the line can be explained by thick-absorber effects if one assumes an effective Debye temperature for the gold of 173°K.

using the natural line width for the gold absorption, by thick-absorber effects if an effective Debye temperature of 173°K is assumed for the gold in the alloy.

The compound Au_2Mn has an ordered structure of the CaC_2 type. In this structure two layers of gold atoms and a layer of manganese atoms repeat throughout the crystal, as is shown in Fig. 2. Neutron diffraction measurements show that the manganese spins form a helical structure with all the spins within one manganese layer lying parallel to each other and perpendicular to the crystalline c axis. If one then assumes that the magnetic moments of the gold atoms align similarly, the magnetic field interacting with the gold nuclei will also be oriented perpendicular to the crystalline c axis. Because of the crystalline symmetry, the principal axis of any electric quadrupole coupling at the gold nucleus will be along the crystalline c axis. The eight-line Mössbauer spectrum for ^{197}Au shown in Fig. 3 corresponds to the eigenstates

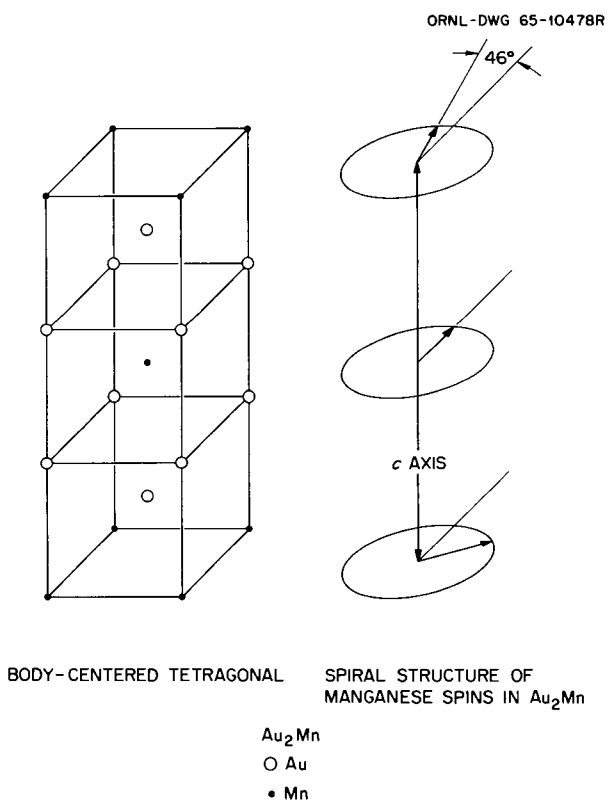

Fig. 2. Crystal Structure of Au_2Mn. The helical structure of the manganese spins is shown on the right.

for the ground-state nuclear spin $I = 3/2$ where the magnetic field and electric field gradient are perpendicular. The solid line, Fig. 3, is the least-squares fit for the line positions given by the following Hamiltonians for the ground state and first excited state:

$$H_g = -\frac{2\mu H_x I_x}{3} + \frac{P}{2}(3I_z^2 - I^2) , \qquad (1)$$

$$H_e = -2\mu^* H_x I_x^* + \Delta E , \qquad (2)$$

where H_x is the effective magnetic field, $\mu^* H_x = 0.663 \pm 0.004 \times 10^6$ gauss-magnetons, and the quadrupole coupling constant $P = 9.23 \pm 0.4 \times 10^{-4}$ cm^{-1}. The quantity ΔE is the isomer shift. The ratio of quadrupole coupling to magnetic-interaction energy is 0.23 ± 0.01. In fitting our data, we have used the solution given by Parker[7] for the eigenvalues of Eq. (1).

The fact that an eight-line spectrum, Fig. 3, occurs enables one to obtain information about the $E2/M1$ ratio for the resonance gamma ray of gold. For the case where the magnetic and electric field axes are parallel, the nuclear states are of the form $|I, m\rangle$, and for a pure magnetic dipole transition only six lines will occur. Where the magnetic and electric field gradient axes are perpendicular, however, each eigenvector of the state $I = 3/2$ will contain all $(2I + 1) = 4$ magnetic substates. Thus even for a pure magnetic dipole transition, eight lines may be expected. Theoretical considerations[8] indicate that the transition is in fact not pure magnetic dipole, but rather that $E2/M1 \approx 0.1$. In this case, transitions with $\Delta m = \pm 2$ would occur and this would also contribute to the intensities of the eight lines. The relative contribution of these two factors to the line intensities observed, Fig. 3, has not yet been completely worked out. The relative intensities of the lines of Fig. 3 are influenced by thick-absorber effects. Further measurements with thinner samples must be made to take this into account.

The compound Au_3Mn has a two-dimensional antiphase domain structure. The gold Mössbauer absorption spectrum is shown in Fig. 4. Assuming

[7] P. M. Parker, *J. Chem. Phys.* **24**, 1096 (1956).

[8] L. A. Sliv (ed.), *Gamma-Luchi*, p. 424, Academy of Sciences of the USSR, Leningrad, 1961.

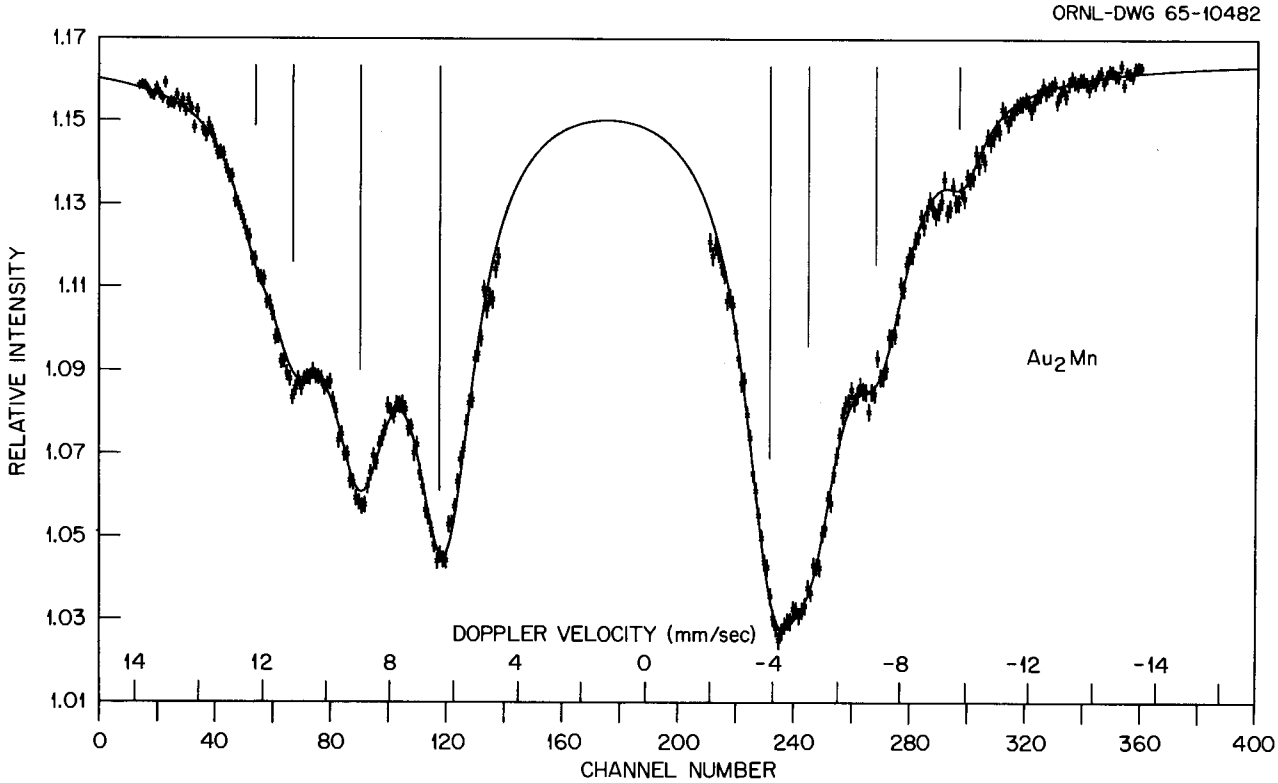

Fig. 3. Mössbauer Absorption Spectrum for ^{197}Au in Au_2Mn. The spacings of the eight lines correspond to eigenstates for spin $\frac{3}{2}$, where the magnetic field and the electric field gradient are perpendicular. These results correspond to $H_x = (1.65 \pm 0.10) \times 10^6$ gauss and $P = (9.23 \pm 0.4) \times 10^{-4}$ cm^{-1}.

pure magnetic dipole radiation, the excited state splitting as determined from a least-squares fit of the six lines shown is $(3.42 \pm 0.03) \times 10^5$ gauss-magnetons. This fit was made under the assumption that quadrupole coupling to the ^{197}Au is zero in this material.

Preliminary results for Au_4Mn, which has a superlattice of the type Ni_4Mo, indicate magnetic splitting with some evidence of a quadrupole interaction.

The Mössbauer isomer shifts with respect to metallic gold are: AuMn, 4.553 ± 0.014; Au_2Mn, 2.808 ± 0.015; and Au_3Mn, 1.777 ± 0.013 mm/sec. Previous measurements[9] for gold solid-solution alloys gave a linear relationship for the isomer shift vs concentration of gold. A graph of the above isomer shift values for the Au-Mn system shows that the isomer shift is not a linear function of the atomic percentage of gold. We feel that this is due to the formation of intermetallic compounds.

[9] L. D. Roberts *et al.*, *Phys. Rev.* **137**, A895 (1965).

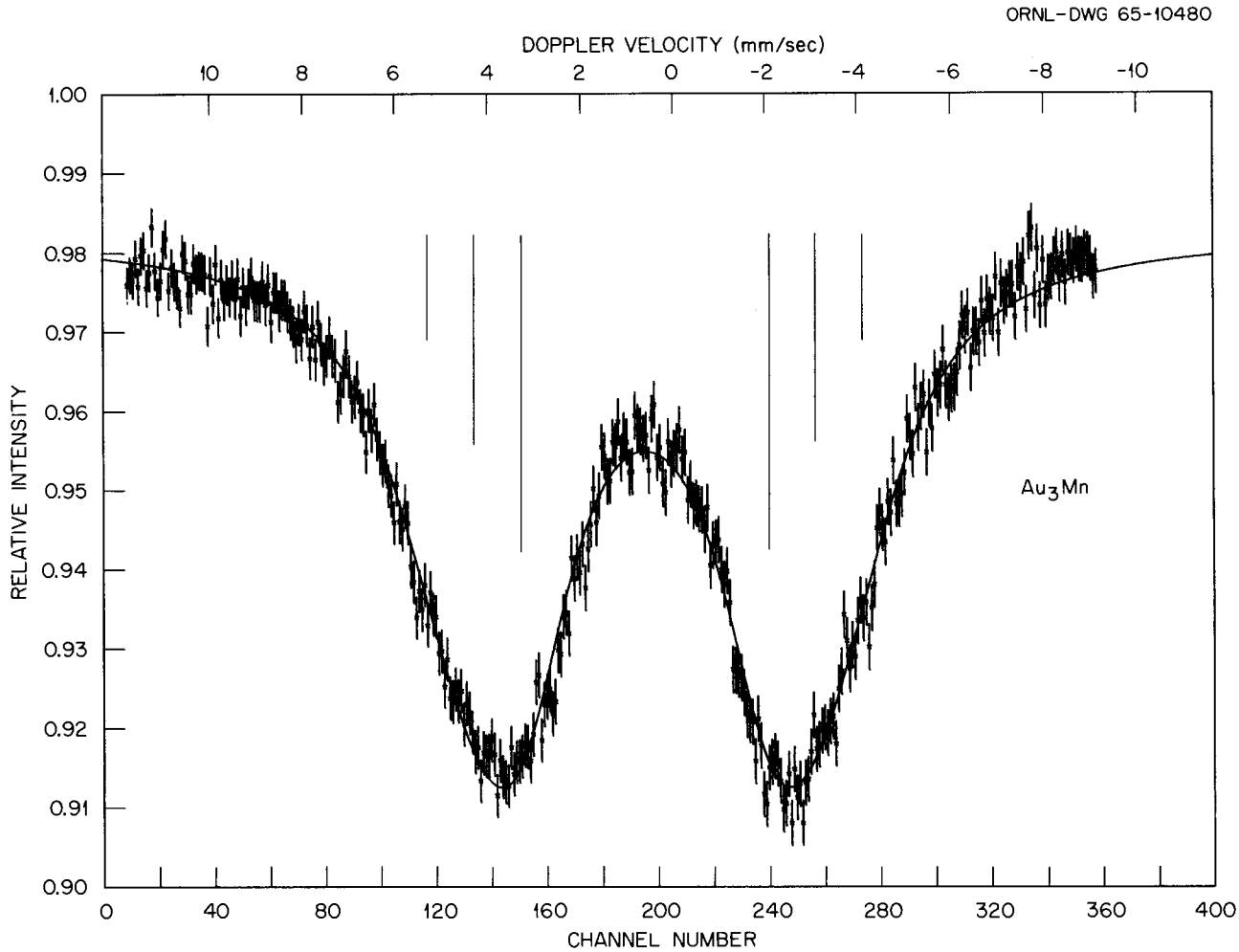

Fig. 4. Mössbauer Spectrum of ^{197}Au in Au_3Mn. The solid line corresponds to a magnetic field of $(8.58 \pm 0.6) \times 10^5$ gauss.

SOLID STATE AND NUCLEAR RESULTS FROM A MEASUREMENT OF THE PRESSURE DEPENDENCE OF THE ENERGY OF THE RESONANCE GAMMA RAY OF ^{197}Au

L. D. Roberts D. O. Patterson[1] J. O. Thomson[2] R. P. Levey[3]

One of the most basic characteristics of an atomic species is the electronic charge which the element assumes when it is placed in different chemical environments. In some cases, for example, sodium in NaCl, it is of course very definitely known that the sodium assumes a positive

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[3](Deceased) formerly of Union Carbide Corporation, Nuclear Division.

charge and the chlorine a negative charge. In some covalently bonded systems and in some metallic alloys, however, the signs and magnitudes of the electronic charges which the constituent elements assume have not in the past been accessible to experimental investigation and are not known. The measurement of the dependence of the energy of the resonance gamma ray of an isotope on its chemical environment can give information about this, and we have previously made a number of measurements of this dependence for metallic gold and a number of its alloys and compounds.[4,5] The isomer shift of the Mössbauer effect has provided a method for making these measurements.

Here we report the measurement of the change due to the compression of the solid of the energy of the recoil-free resonance gamma ray of ^{197}Au bound in metallic gold.[6] The measurement of this change $\Delta E(P) = E_\gamma(P) - E_\gamma(0)$ was made at a temperature of 4.2°K using the Mössbauer method. Here $E_\gamma(0)$ (approximately 77.3 kev) is the energy of this gamma ray emitted from gold at zero pressure, and $E_\gamma(P)$ is the energy of the gamma ray when the gold has been compressed under a pressure P.

In the interpretation of our measurements it will be assumed that

$$\Delta E(P) = kn\,[|\psi_P(0)|^2 - |\psi_0(0)|^2]\,, \qquad (1)$$

where k is a calculable constant, n is a factor[5] depending only on nuclear parameters, and $|\psi_P(0)|^2$ and $|\psi_0(0)|^2$ describe the electron charge density within the nucleus when the gold is under a pressure P or at zero pressure.

In an earlier paper[5] the sign and magnitude of this pressure dependence of the gamma-ray energy $\Delta E(P)$ were predicted. In terms of the velocity units natural to the Mössbauer-type measurement, this dependence was given to terms linear in P as $v(P) = c\,[\Delta E(P)/E_\gamma(0)] \simeq 0.0005P$ cm/sec, where c is the velocity of light and P is the pressure in kilobars. In making this prediction, we have tentatively assumed that $|\psi_P(0)|^2$ is proportional to the density of the bulk solid as a function of pressure. To terms in P^2 and using elastic constants[7] extrapolated to 0°K, this predicted pressure dependence of the gamma-ray energy becomes

$$v(P) = 3.80 \times 10^{-4}P - 0.514 \times 10^{-6}P^2\,, \qquad (2)$$

with v in cm/sec and P in kilobars.

This prediction of $\Delta E(P)$ or of $v(P)$ is based on an experimental and theoretical investigation of the correlation to be expected between the energy E_γ(alloy) of the recoil-free gamma ray emitted by ^{197}Au in a dilute alloy and the residual electrical resistivity per atomic percent $\Delta R/X$ which the gold atoms introduced into the alloy. An acceptable correlation was found between ΔE(alloy) = E_γ(alloy) − $E_\gamma(0)$ and $\Delta R/X$ for dilute alloys of gold in copper, silver, palladium, and platinum under the principal assumptions that (1) the screening of the gold atom in the alloy was predominantly by the conduction electrons (presumably of predominantly s character), (2) that the gold presented an attractive pseudopotential to the conduction electron partial waves of zero orbital angular momentum (s partial waves), and (3) that the s-band populations were 1.0, 1.0, 0.67, and 0.50 for Cu, Ag, Pd, and Pt. The present measurements have been made then as an extension of this earlier study of the dilute alloys of ^{197}Au and also to obtain further information about the nuclear factor n of Eq. (1).

The apparatus used for the high-pressure measurements is shown in Fig. 1. The source of the gold gamma rays was prepared by activating approximately 0.2 g of ^{196}Pt in the Oak Ridge Research Reactor for 24 hr. This source was mounted on a sine-wave transducer immediately above and coaxial with two Bridgman anvils fabricated from sintered boron carbide. These anvils were used to compress a gold foil of 0.002 in. thickness over a circular area of 0.187 in. diameter. These anvils have been loaded to 15 tons or to an average pressure over the 0.187-in.-diam area of approximately 76 kilobars at 4.2°K without failure. The collimated gamma-ray beam was directed normally to the foil and in most of the measurements passed through a circular area 0.125 in. in diameter central to the compressed region. In one measurement at an applied average pressure of 55 kilobars,

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[4] L. D. Roberts and J. O. Thomson, *Phys. Rev.* **129**, 664 (1963).

[5] L. D. Roberts *et al.*, *Phys. Rev.* **A137**, 895 (1965).

[6] L. D. Roberts *et al.*, *Bull. Am. Phys. Soc.* 11, 49 (1966).

[7] K. A. Gschneidner, Jr., p. 302 in *Solid State Physics*, vol. 16, ed. by F. Seitz and D. Turnbull, Academic, New York, 1964.

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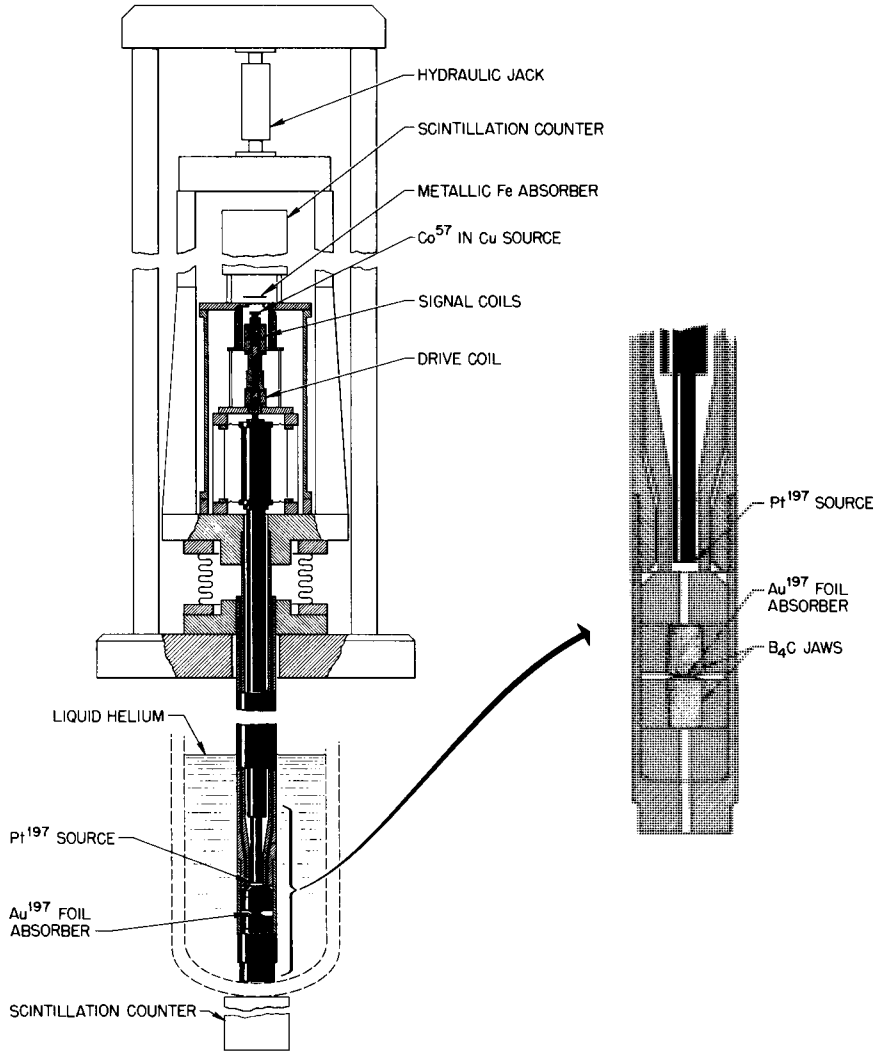


Fig. 1. Apparatus for Mössbauer Absorption Experiments at High Pressure and at Liquid-Helium Temperatures. The use of boron carbide anvils enables one to investigate the pressure dependence of the Mössbauer effect in the absorber with a relatively large solid angle.

the gamma rays were permitted to pass through the entire area of gold of 0.187 in. diameter which was under compression. In spite of the fact that the gamma rays passed through a total thickness of B_4C of 4.4 cm, the source strength was sufficient to give a counting rate of $\sim 1.5 \times 10^5$ counts/min for the 0.125-in.-diam collimated beam using an NaI(Tl) counter. This intensity included resonance gamma rays and an appreciable but undetermined fraction of unresolved x rays.

In making the measurements, a six-line Mössbauer spectrum of metallic iron and the ^{197}Au Mössbauer spectrum were taken with the ^{197}Pt and the ^{57}Co sources mounted on the common sine-wave transducer (Fig. 1). The same basic electronics were simultaneously used in obtaining

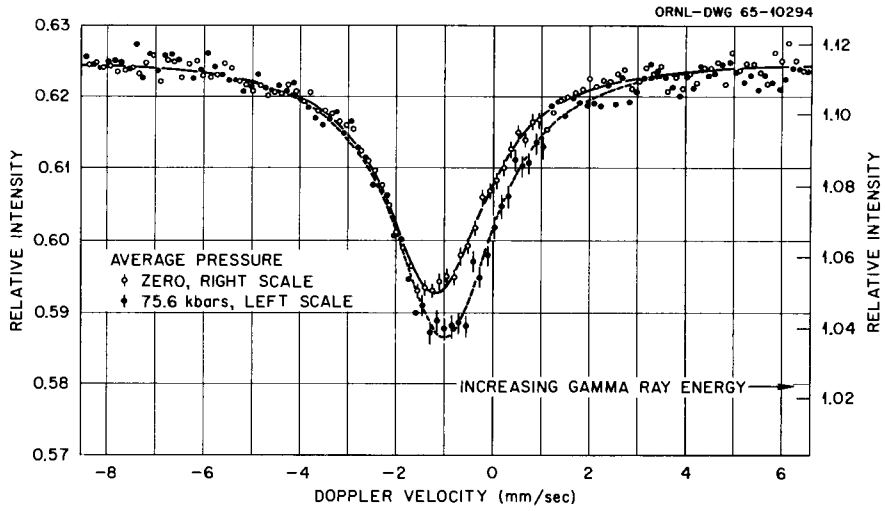


Fig. 2. Mössbauer Absorption Spectra of ^{197}Au in Metallic Gold Showing Shift of Line Center with Pressure. The lines through the data are Lorentzian curves fitted to the data using a least-squares procedure.

the gold and iron spectra. Thus our measurements of $v(P)$ for ^{197}Au gamma rays were made relative to or in direct comparison with the six gamma-ray energies of the iron hfs spectrum[8] which, of course, remained unchanged throughout the series of measurements. Our results for $v(P)$ are then independent of any slight drift in the gain of the electronic equipment.

Figure 2 shows the observed spectrum of ^{197}Au at zero pressure and at an average pressure of 75.6 kilobars. The shift of the line center of the gold resonance gamma ray with compression is well resolved. Using a least-squares procedure, a Lorentz line shape has been fitted to the results of eight measurements made at five average pressures where the collimated gamma-ray beam was 0.125 in. in diameter, and to one measurement at 55 kilobars where the beam was 0.187 in. in diameter. As expected, the line width was found to be independent of pressure to within the experimental error of a few percent. The line centers were located to within an error of about 1% of the line width. Figure 3 shows these results for $v(P)$ and $\Delta E(P)$ as a function of average pressure, along with the predicted value for these quantities, Eq. (2), which is shown by the solid curve.

[8]R. S. Preston, S. S. Hanna, and J. Heberle, *Phys. Rev.* **128**, 2207 (1962).

One of the most important technical problems in high-pressure physics where Bridgman anvils are used is the determination of the pressure distribution between the anvils. Since $\Delta E(P)$ is related to the density of the compressed solid, the measurement of this quantity for different areas of the compressed solid can give information about the density and thus about the pressure distribution.

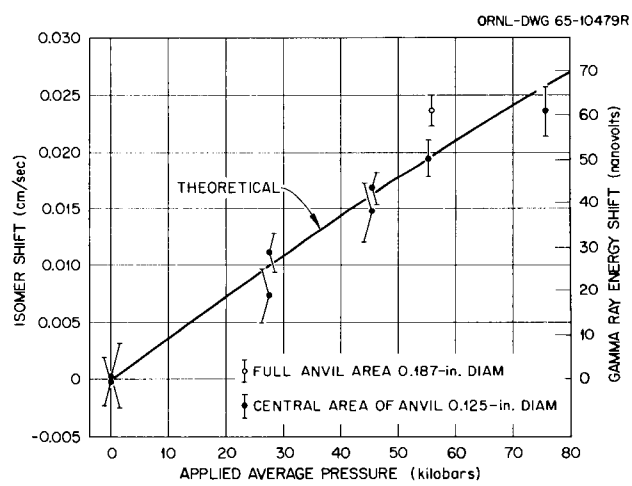


Fig. 3. Change of Energy of the Resonance Gamma Ray as a Function of Pressure for Metallic Gold. The solid curve is that predicted in Eq. (2) of this paper and in ref. 5.

At 55 kilobars we have made a measurement of $\Delta E(P)$ over the entire compressed area 0.187 in. in diameter and over a central region 0.125 in. in diameter. The close agreement of $\Delta E(P)$ for the two measurements (Fig. 3) suggests that any nonuniformity of pressure over the compressed gold foil is only of roughly the same magnitude as the statistical errors in these measurements.

The agreement of the predicted $v(P)$, Eq. (2), with the measurements of this quantity shown in Fig. 3 is much better than was anticipated and must be in some degree fortuitous. This result does nevertheless support our earlier study[5] mentioned above of the correlation found for dilute gold alloys between the ^{197}Au gamma-ray energy (the isomer shift) and $\Delta R/X$, the residual electrical resistance per atomic percent which the gold introduced into the alloy.

In the above correlation study it was found that E_γ(alloy) was greater than $E_\gamma(0)$ for all of the gold alloys which have been studied, and it was concluded that the electronic charge density near the gold nucleus was greater in all of these gold alloys than it is in metallic gold. On the basis of wave functions calculated by Weber, Cromer, and Liberman,[9] it may be concluded that when gold is compressed, the electron charge density at the nucleus increases. From our pressure studies it is found that $E_\gamma(P) > E_\gamma(0)$. Thus the high-pressure work confirms the earlier conclusion that when gold is alloyed, the electron charge density near the nucleus is greater than in metallic gold for all of the alloys investigated. This has a bearing on previous theoretical studies[10] of Au-Pd and Au-Ni which qualitatively suggest the opposite conclusion.

The sign of the nuclear factor n of Eq. (1) tells one the relative size of the gold nucleus in the first excited state as compared to the ground state. Our results together with the wave functions of Weber *et al.*[9] enable one to conclude that the nucleus is larger in its excited state than it is in its ground state. This is in disagreement with the configuration specified by the shell model[11] in which a proton makes a transition from a $d_{3/2}$ ground state to an $s_{1/2}$ excited state.

[9] J. T. Weber, D. I. Cromer, and D. A. Liberman (private communication).

[10] E. P. Wohlfarth, *Proc. Roy. Soc.* **A195**, 434 (1948).

[11] M. G. Mayer and J. H. D. Jensen, *Elementary Theory of Nuclear Shell Structure*, Wiley, New York, 1955.

OPTICS OF THE TOTAL REFLECTION OF NUCLEAR RESONANT RADIATION BY ^{57}Fe[1]

S. Bernstein[2] E. C. Campbell C. W. Nestor, Jr.[3]

In an earlier publication we described our measurements of the intensity of a single-line ^{57}Fe gamma-ray source totally reflected from an ^{57}Fe metal mirror as a function of angle of incidence and frequency of the source and compared the measurements with values calculated from theory. In this report several theoretical and computational aspects of the total reflection of Mössbauer radiation which were not emphasized in the previous work are discussed. Curves of reflectivity vs glancing angle for a set of frequencies are given, showing how the curve shapes vary as the frequency of the gamma rays passes through the resonance frequency. Complete diagrams of the variation of coherent scattering amplitude with frequency for ^{57}Fe are given, from which the reflectivity as a function of frequency in the resonance region may be obtained by graphical interpolation. The polarization and changes in phase produced on reflection as a function of frequency are discussed, and calculated curves are shown. Because of the importance of the nuclear scattering in the resonance region, the polarization and changes of phase produced on reflection are appreciable.

[1] Abstract of published paper: *J. Phys. Chem. Solids* **26**, 883 (1965).

[2] Present address: University of Illinois, Chicago.

[3] Mathematics Division.

ANISOTROPIC ENERGY LOSSES IN A FACE-CENTERED CUBIC CRYSTAL FOR HIGH-ENERGY ^{79}Br AND ^{127}I IONS[1]

S. Datz[2] T. S. Noggle[3] C. D. Moak

KEY WORDS. Channeling. Energy losses of Br and I ions measured in Au single crystal as function of direction in lattice.

Multicomponent beams of bromine and iodine ions from the Oak Ridge tandem accelerator[4] with energies up to 80 Mev have been used to study crystal orientation effects on energy losses in thin gold single crystals.

[1]Abstract of published paper: *Phys. Rev. Letters* 15, 254 (1965).

[2]Chemistry Division.

[3]Solid State Division.

[4]C. D. Moak *et al.*, *Rev. Sci. Instr.* **34**, 853 (1963).

METHOD FOR OBTAINING SECOND DERIVATIVES IN ELECTRON TUNNELING

J. W. T. Dabbs

In studying the conductance of superconductor-insulator-superconductor tunneling junctions, it has been found most helpful to observe the derivative of the conductance as a means of revealing more clearly the rather small variations which appear.[1,2] Thus, the second derivative of the I-V characteristic is useful in observing effects associated with peaks in the phonon spectrum of the superconductor, as well as smaller effects associated with van Hove and other critical points in the spectrum.[3]

A method previously unused for obtaining d^2I/dV^2 in tunnel junctions as a function of applied bias has been developed. Instead of using an electromechanical rate generator[2] or of observing second-harmonic generation[3] caused by the nonlinearity of the junction, an intermodulation ("beat") frequency signal is observed. If a voltage of the form

$$V = V_0 + A \sin \alpha t + B \sin \beta t \qquad (1)$$

is applied to the junction and if $I = f(V)$ is analytic, then an expansion into a Taylor series about the point V_0 gives, among others, the following terms in the current through the junction (and thus through a series resistor):

$$I_{DC} = I_0 + \left(\frac{A^2 + B^2}{4}\right)\left(\frac{d^2I}{dV^2}\right)_{V_0} + \dots , \qquad (2)$$

$$I_\alpha = \left[A \left(\frac{dI}{dV}\right)_{V_0} + \left(\frac{A^3}{8} + \frac{AB^2}{4}\right)\left(\frac{d^3I}{dV^3}\right)_{V_0} + \dots \right] \sin \alpha t \ , \qquad (3)$$

$$I_{\alpha \pm \beta} = \left[\frac{AB}{2}\left(\frac{d^2I}{dV^2}\right)_{V_0} + \left(\frac{A^3B + AB^3}{16}\right)\left(\frac{d^4I}{dV^4}\right)_{V_0} + \dots \right] \cos (\alpha \pm \beta)t \ , \qquad (4)$$

[1]J. M. Rowell, P. W. Anderson, and D. E. Thomas, *Phys. Rev. Letters* **10**, 334 (1963).

[2]D. E. Thomas and J. M. Klein, *Rev. Sci. Instr.* **34**, 920 (1963).

[3]D. J. Scalapino and P. W. Anderson, *Phys. Rev.* **133**, A921 (1964); A. F. G. Wyatt, *Phys. Rev. Letters* **13**, 160 (1964) and references cited there.

$$I_{2\alpha} = \left[\frac{A^2}{4} \left(\frac{d^2 I}{dV^2} \right)_{V_0} + \left(\frac{A^4}{48} + \frac{A^2 B^2}{16} \right) \left(\frac{d^4 I}{dV^4} \right)_{V_0} + \ldots \right] \cos 2\alpha t \ . \quad (5)$$

It is seen that Eq. (4) leads immediately to

$$\left(\frac{d^2 I}{dV^2} \right)_{V_0} = \lim_{A,\, B \to 0} \frac{2}{AB} I_{\alpha \pm \beta} \ . \quad (6)$$

Similarly, Eq. (3) gives

$$\left(\frac{dI}{dV} \right)_{V_0} = \lim_{A \to 0,\, B = 0} \frac{I_\alpha}{A} \ . \quad (7)$$

It should be noted that the second-harmonic term gives

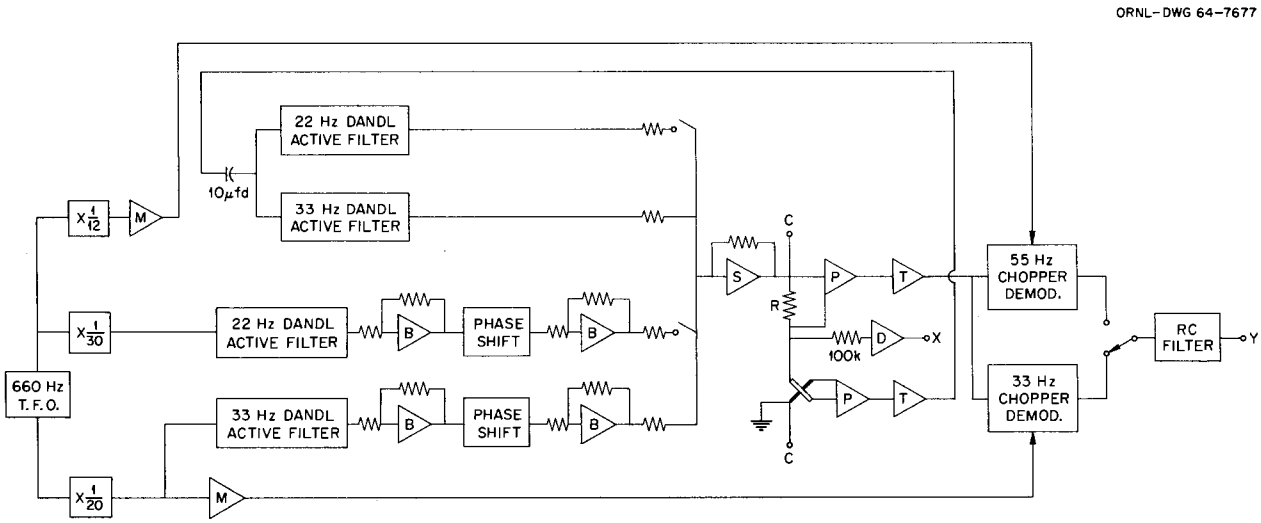
$$\frac{d^2 I}{dV^2} = \lim_{A \to 0,\, B = 0} \frac{4 I_{2\alpha}}{A^2} \ . \quad (8)$$

Thus the intermodulation signal for a given d^2I/dV^2 value is twice as large (for $A = B$) as the second-harmonic signal at frequency $\alpha/2\pi$ or $\beta/2\pi$. The next-higher-order term is six times larger in the intermodulation case (with $A = B$) than in the second-harmonic case; but this is not felt to be a drawback, since the higher-order terms would normally be quite small. The basic approach described here was suggested by the work of Finston *et al.* on measurements of secondary electron flux generated in various media under x-ray irradiation.[4] A number of recent developments in transistor circuits have permitted a much greater degree of reliability and ease as compared with the earlier apparatus.

Figure 1 shows a block diagram of the circuits used. The two most unusual features are (*a*) the use of a locked-phase oscillator system[5] which

[4] R. A. Finston *et al.*, ORNL-2732 (October 1959), unpublished.

[5] Furnished by Philamon Laboratories, Inc., Westbury, L.I., N. Y. (model TFGX-5123).



B = PLUG IN DC COUPLED OPERATIONAL AMPLIFIER (BUFFER)
S = PLUG IN DC COUPLED OPERATIONAL AMPLIFIER (SUMMING)
C-C = CONSTANT BIAS CURRENT SOURCE INPUT POINTS
D = DYNAMICS INST. CO. 4132 DC CHOPPER AMP. (MOD. FOR EXT. OUTPUT)
M = ½ McINTOSH 225 AMPLIFIER
P = 6CW4 NUVISTOR LOW NOISE PREAMP
T = TEKTRONIX 122 LOW NOISE AMPLIFIER (MOD. FOR A = 3000, REVERSED PHASE)
TFO = TUNING FORK OSCILLATOR (PHILAMON TFGX-5123 (INCLUDES SCALERS)

R ≈ 10 Ω
—WWW— = 10k EXCEPT WHERE NOTED

Fig. 1. Block Diagram of Circuit for Obtaining the dI/dV and d^2I/dV^2 in Tunnel Junctions.

eliminates the effects of relative frequency drift among the frequencies $f_1 = \alpha/2\pi$, $f_2 = \beta/2\pi$, and the sum frequency $f_1 + f_2$ and (*b*) the use of a number of identical plug-in operational dc transistor amplifiers (1) as buffer (*B*) and summing (*S*) amplifiers and (2) in a special form of active bandpass filter with high and adjustable *Q* and adjustable center frequency. This filter was developed at ORNL for other applications.[6] Other features of interest are the use of very low flicker noise nuvistor (6CW4) preamplifiers[7] and a rather unusual constant current bias supply circuit suggested to the author by C. E. Nielsen of Ohio State University. Details of these elements are shown in Fig. 2. The feedback loop of Fig. 1 also includes active filter elements and is intended to maintain a nearly constant ac voltage across the junction as required by the analysis given above, while the ac current through the series resistor *R* is monitored with the aid of the synchronous demodulator ("chopper").

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[6]F. T. May and R. A. Dandl, *Rev. Sci. Instr.* **33**, 387 (1961). The detailed circuits shown in the upper half of Fig. 2 include corrections of errors in the original paper. Considerably improved amplifiers of this type with higher frequency capabilities (10^5 hertzes) have also been developed recently (R. A. Dandl, private communication).

[7]P. C. Caringella and W. L. Eisenman, *Rev. Sci. Instr.* **33**, 654 (1962).

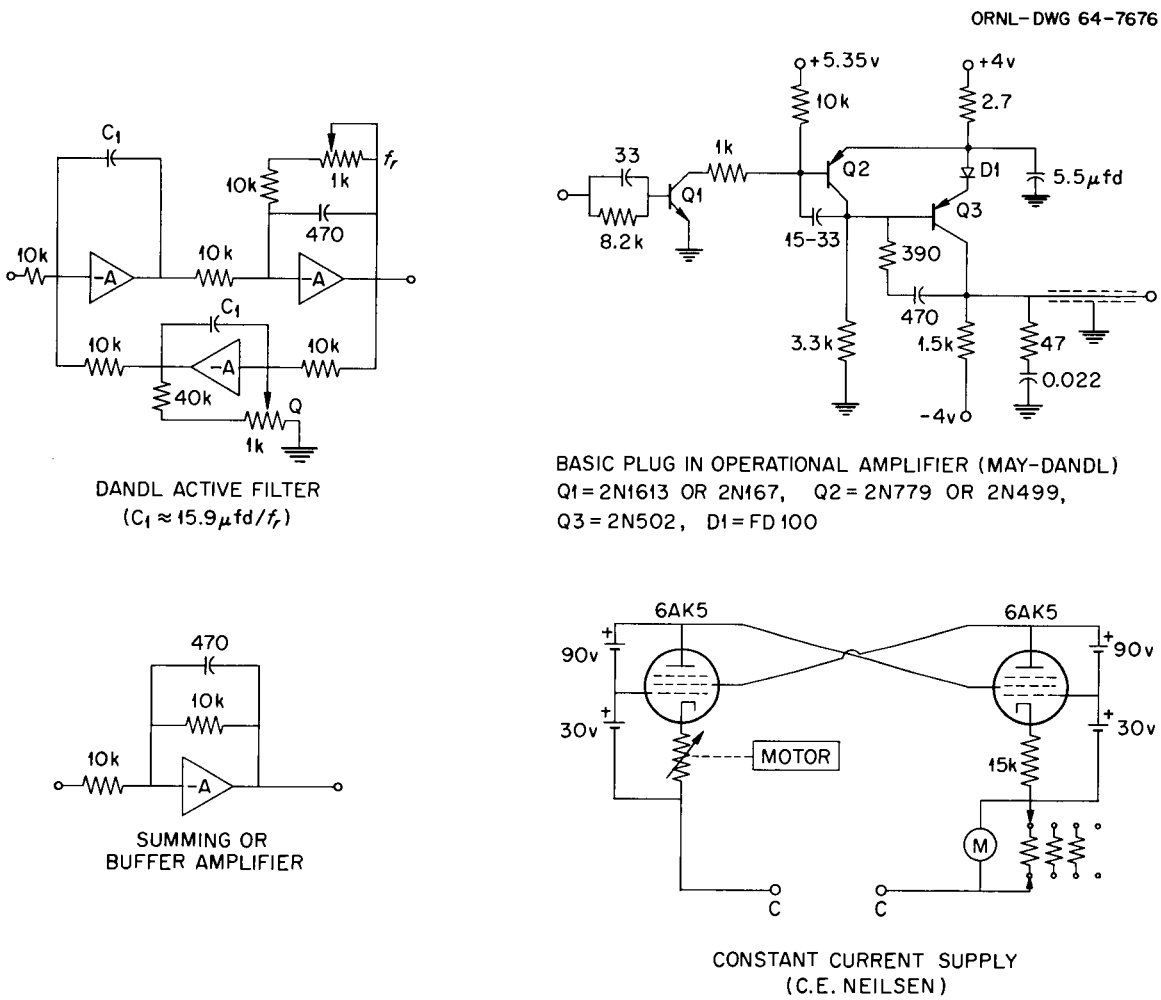

Fig. 2. Circuit Details of Certain Elements Shown in Fig. 1. The detailed circuits shown in the upper half of the figure include corrections of errors in the original paper.[6]

It should be noted that junction capacity effects have been omitted in the analysis. The switches are shown in position for a measurement of dI/dV; changing all switches gives the configuration for d^2I/dV^2 measurements. In the first case the capacitive currents are approximately in quadrature with the desired signal and are largely eliminated by the demodulator; in the second case this is not necessarily true, but these currents add at most a very small constant background at the demodulation frequency, which is made low for this reason. Indeed, such currents should not be observable for typical junctions at biases larger than those where the conductance of the junction becomes appreciable.

The constant current supply when connected across the points c-c of Fig. 1 provide the bias across the junction. This voltage is fed to a floating-input, high-impedance, chopper-stabilized dc amplifier and then to the X coordinate input of an X-Y recorder. The Y input is obtained from a variable, long-time-constant averaging filter[8] which is inserted between the chopper demodulator and the X-Y recorder. The capacitors used in the filter were 200-v polystyrene film units.

Because of the press of other work, the entire arrangement shown in Fig. 1 has not been completed; in particular, the performance of the voltage feedback loop has not been ascertained. The performance of other elements of the system has appeared excellent, however, and the system is presented here in the hope that some of the ideas involved will be useful to others. Obvious modifications in the arrangement shown in Fig. 1 would permit recording as a function of current rather than voltage, or the elimination of one demodulator by using additional active filters, for example.

The author gratefully acknowledges the advice and assistance of R. A. Dandl in connection with the use of the operational amplifiers and filters, and the suggestion of the constant current supply by C. E. Nielsen.

[8]N. T. Larsen, *Rev. Sci. Instr.* **33**, 1200 (1962), Fig. 2.

ALKALI-ATOM–HALOGEN-MOLECULE REACTIONS IN MOLECULAR BEAMS; THE SPECTATOR STRIPPING MODEL[1]

R. E. Minturn[2] Sheldon Datz[2] R. L. Becker

Crossed-molecular-beam techniques have been used to study reactive collisions in some alkali-metal–halogen systems ($Cs + Br_2$, $K + I_2$, $K + Br_2$, $Rb + IBr$). Both the absence of rainbow scattering in elastic scattering distributions and the magnitude of the reactive collision yield suggest large reaction cross sections in the order of 100 A^2 for all the systems studied. The position and width of the angular distributions of alkali halide product molecules indicate forward scattering in the center-of-mass system with recoil energies close to zero.

These observations suggest a stripping mechanism for these reactions, and a model, based upon the simplest possible stripping mechanism, has been proposed to explain the observations. This model, called spectator stripping, predicts the gross features of the distributions and leads to a prediction of the maximum intermolecular distance at which reaction can occur. This corresponds to a reaction cross section of *ca.* 100 A^2.

The effect of electron transfer from the alkali atom to the halogen molecule at large distances is shown to be almost equivalent to spectator stripping for these reactions if the vertical electron affinity of the halogen molecule is used. Even larger cross sections would be predicted if the adiabatic electron affinity were used; however, an evaluation of the probability of adiabatic adjustment of the halogen internuclear distances during the collision time appears to preclude this possibility.

[1]Abstract of paper to appear in the *Journal of Chemical Physics* (February 1966).

[2]Chemistry Division.

MEASUREMENT OF THE RELATIVE ABUNDANCES AND RECOIL ENERGY SPECTRA OF FRAGMENT IONS PRODUCED AS THE INITIAL CONSEQUENCES OF X-RAY INTERACTION WITH CH_3I, HI, AND DI[1]

T. A. Carlson R. M. White[2]

Methyl iodide, hydrogen iodide, and deuterium iodide have been irradiated with x rays whose energies are such that the most probable event is the formation of a vacancy in the *L* shell of iodine. The readjustment to this vacancy, principally by a series of Auger processes, gives rise to extensive ionization and decomposition; and the relative abundances of the fragment ions and their recoil energy spectra have been measured with a specially designed mass spectrometer. As the result of the inner-shell vacancy, CH_3I decomposed primarily into hydrogen, carbon, and iodine ions, having, respectively, the average charges of +1, +2, and +5. Very few molecular ions were observed. The recoil energies were quite large, with values in some cases above 100 ev. A calculation, based on a simple model for a Coulombic "explosion," is shown to be consistent with the data. In the studies made with HI and DI the recoil spectra of H^+ and D^+ are compared with calculations of the kinetic energies expected from multiple ionization. From this comparison there appears to be evidence that the multiply charged molecular ions separate slightly during the time the Auger processes are taking place. Finally, a brief discussion is given concerning the importance of the initial consequence of x-ray interaction in radiation damage.

[1]Abstract of paper submitted for publication.

[2]Baker University, Baldwin, Kan.

CHARGE DISTRIBUTIONS OF KRYPTON IONS FOLLOWING PHOTOIONIZATION IN THE *M* SHELL[1]

M. O. Krause[2] T. A. Carlson

Charge distributions of krypton ions that result from ionization in the *M* shell by x rays have been measured with a magnetic mass spectrometer. X-ray energies ranged from 100 to 1400 ev. The following results are derived from the charge spectra: (1) In filling a hole in the 3*d* shell an Auger process which generates two continuum electrons competes strongly with the common Auger process, which generates one continuum electron. This so-called double Auger process occurs in (31 ± 4)% of the events. (2) The Coster-Kronig transitions 3*p*-3*dN* and 3*p*-3*d*3*d* have nearly equal intensities. (3) Partial absorption coefficients for *M* electrons are poorly predicted by the Stobbe-Hall formula even for energies above 1 kev. Calculated shake-off probabilities of *M* and *N* electrons are given for the sudden removal of a 3*s*, 3*p*, or 3*d* electron.

[1]Abstract of paper to be published.

[2]Thermonuclear Division.

RELATIVE INTENSITIES OF PROMINENT *LMM* AUGER TRANSITIONS IN KRYPTON[1]

M. O. Krause[2]

Relative intensities of prominent *LMM* Auger transitions in krypton have been measured with an electrostatic energy analyzer. With the intensity of the $2p3d3d$ transition as reference, (42 ± 3)% was obtained for the intensity of the $2p3p3d$ transition and (20 ± 2)% for the $2p3p3p$ transition. Theoretical values of 13.4 and 24.5% for the corresponding transitions are in poor agreement with experiment.

[1]Abstract of published paper: *Phys. Letters* 19, 14 (1965).

[2]Thermonuclear Division.

RELATIVE ABUNDANCES OF IONS FORMED AS THE RESULT OF INNER-SHELL VACANCIES IN ATOMS[1]

T. A. Carlson W. E. Hunt[2] M. O. Krause[3]

Relative abundances of differently charged ions were measured following the x irradiation of xenon and, in separate experiments, of mercury. These studies were carried out for a variety of x-ray energies, so as to obtain data as a function of the initial inner-shell vacancies. From the data we have derived the charge spectra that are the consequence of producing an initial vacancy in each of the following shells: the K, L_{I}, $L_{II,III}$, M_{I}, $M_{II,III}$, $M_{IV,V}$, and N shells of xenon; and the L, M, N, and O shells of mercury. These data are correlated with earlier measurements on He, Ne, Ar, and Kr; and empirical rules are set up whereby one may estimate the average charge resulting from an atom readjusting to a vacancy in any shell of any atom.

[1]Abstract of paper to be submitted for publication.

[2]Summer participant from David Lipscomb College, Nashville, Tenn.

[3]Thermonuclear Division.

THE LEAST-SQUARES ADJUSTMENT OF ATOMIC ENERGY LEVELS[1]

K. L. Vander Sluis

A practical solution to the least-squares adjustment of an atomic energy level array is described. This solution, in addition to the obvious advantages of satisfying the condition of least squares and providing a measure of the standard error of the computed results, has the added advantage of being a solution readily adapted to computer use. As a computer program the method uses a minimum of memory space and computer time.

[1]Abstract of paper to be published in the *Journal of the Optical Society of America*.

THE SPECTRA OF ^{208}Po AND THE HYPERFINE STRUCTURE OF ^{209}Po[1]

G. W. Charles

Data are presented on the wavelengths of 97 lines of ^{208}Po, on the wavelengths of 8 lines of Pb I, and on the hyperfine structure of 31 lines of ^{209}Po. From these data, relative values of 26 energy levels of ^{208}Po I have been deduced. The hyperfine structure splittings of 14 of these levels in ^{209}Po have been determined. Some tentative identifications of the levels have been made, based on a determination of the absolute value of the fundamental level $6p^4\ {}^3P_2'$ by application of a Ritz formula to three levels taken as $6p^3(^4S)np\ {}^5P_3'^{\,0}$, $n = 7, 8, 9$. The ionization potential of ^{208}Po has been tentatively estimated as 8.414 v. From the measured splittings of the energy levels of the configuration $6p^4$ of ^{209}Po I, the nuclear magnetic moment of ^{209}Po is estimated to be 0.7_6 nuclear magneton. Mrozowski's identifications of some lines of Po I are examined. It is found that his identifications of λ 4611 and λ 5940 are confirmed by coincidence of frequencies and by hyperfine structure patterns, but that his identifications of the other lines and his determination of $6p^4\ {}^1S_0'$ could not be confirmed by the data of this investigation.

[1]Abstract of paper to be submitted for publication.

CHARGED-PARTICLE CROSS-SECTION DATA CENTER

F. K. McGowan H. J. Kim W. T. Milner

The past year has been devoted primarily to maintaining an up-to-date literature search, compiling cross-section data in tabular form, and preparing a volume of the series *Nuclear Cross Sections for Charged-Particle-Induced Reactions* which includes data for Li, Be, and B. This will be published in the new journal *Nuclear Data,* which is published by Academic Press.

Approximately 4500 sets of data are stored on magnetic tape. Annotated bibliographies are now prepared by using a computer to sort, order, and print from entries and references stored on magnetic tapes. A computer program has been developed to write the captions to the tabular data appearing in the publications from the CPX Data Center.

STATUS REPORT ON THE 3-Mv VAN DE GRAAFF ACCELERATOR

J. P. Judish[1] R. L. Macklin[2]

The 3-Mv Van de Graaff has continued to provide most of our capability for studying fast (kev and Mev range) neutron induced reactions. A large program in inelastic scattering cross-section measurements was initiated during the year. Other programs utilizing the fast (nanosecond) pulsed beam included neutron total cross sections, neutron capture cross sections, a little fission

[1]Instrumentation and Controls Division.

[2]J. A. Biggerstaff was mentor for the 3-Mv program until September.

cross-section work, and neutron reaction studies. The heavy concentration on neutron capture gamma-ray experimental work of previous years was not repeated, although the equipment remained available. The 1.2-m liquid scintillator experimental facility has been under modification for further σ_c/σ_f measurements (on plutonium) during the year and was not used with the accelerator.

An estimate of the apportionment of accelerator time is given in Table 1. This is based on the 80 hr/week that engineering (day) and technical (evenings) help is normally scheduled. Most of the research uses the accelerator as a pulsed fast neutron source, and several experiments remain set up at the various ports between runs. Thus changeover time is minimized and usually coincides with such research preliminaries as electronics hookup, calibrations, and background measurements. In Table 1 changeover time is therefore not distinguished from research time. Because of the factors mentioned above and the relatively long experimental runs (four week average), changeover time is probably less than 2% of the total. Table 2 indicates the experiments and investigators contributing to the 3-Mv accelerator program during the year.

Machine reliability and automation have been improved to the point that a few experiments have been able to run overnight unattended, though this capability is not generally called for.

The 3-Mv accelerator was the first to use terminal pulsing and bunching, and most of the development effort was devoted to perfecting and extending the capabilities of this system. Changes were made in the buncher rf supply frequency, feedthrough insulation, and other electronics so that bunching voltage is now adequate for all the repetition rates now available (from 2 Mc to 1/16 Mc by factors of 2) and for all machine voltages to slightly above 2.7 Mv. This makes the machine much more useful for those experiments, such as inelastic scattering, which can use sub-nanosecond bunching over a wide machine energy range. This is in contrast to the kilovolt neutron time-of-flight work, which has utilized a relatively narrow energy range near 1.9 Mv, just above the ^{7}Li(p,n) threshold.

Table 1. Utilization of 3-Mv Van de Graaff Accelerator Based on an 80-hr Week During Calendar Year 1965

Use	Time Allotted (%)
Research	72
Buncher improvement	9
Other improvement	4
Overhaul	5
Maintenance	18
	108

Table 2. Research Performed by Means of the 3-Mv Van de Graaff Accelerator

Research	Investigators
Pulsed Neutron Time-of-Flight Work	
Inelastic scattering	Biggerstaff, Cassagnou, McConnell, Harlow, Kinney, Perey, Stelson (p. 54)
^{10}B$(n,\alpha)^7$Li, ^{7}Li*	Gibbons, Macklin (p. 47)
Neutron total cross sections	Biggerstaff, Block, Farrell, Kim, Good (pp. 42–44)
Neutron capture cross sections (and fission)	Gibbons, Macklin, Biggerstaff, Good (pp. 44–45, 46, 57)
^{10}B(n,γ) search	Biggerstaff
NASA detector development	Holt, Mendell, Sandie, Singh

A design change was made in the electronics of the nuclear magnetic resonance fluxmeter to allow lock-in control of the analyzer magnet flux. The accelerator can now be run unattended with the assurance that the analyzer magnet flux will remain constant within about 0.01%. Other developments include installation of controls to allow remote buncher tuning and the installation of two vacuum pumps near the target location on two separate beam ports.

The large fraction (18%) of the time that was needed for accelerator maintenance in 1965 can be attributed partly to the following two causes. First a belt change was necessary. It had been in the machine since 1962 and had accumulated 7123 hr of running time. A belt change is usually accompanied by a complete machine overhaul, since components which can be reached only by unstacking the column become accessible. Second, and more importantly, the evidence shows that a high-current, pulsed Van de Graaff requires more maintenance than a Van de Graaff run with the same average current but operating in the dc mode. With a pulsed beam and high peak current, replacement of Einzel lens grids, ion source apertures, and sweeping apertures is needed for every 200 to 300 hr of accelerator use. Cleaning of sputtered metal from inside the lens, pulser, and buncher assembly is also required at similar intervals.

Perhaps as much as half the time needed for such routine reconditioning of the ion source and pulser assembly could be returned to research use of the Van de Graaff if a second complete ion source and pulser assembly were available. The alternate assembly could be repaired, cleaned, tested, and kept ready under vacuum.

With the introduction of terminal bunching on the 5.5-Mv accelerator this year, serious consideration has been given to improvement of peak current performance of the 3 Mv. The neutron experiments currently assigned to the 3 Mv are all limited by the peak current capability. They sacrifice resolution, counting statistics, and signal-to-background ratio in varying proportions.

The peak pulsed accelerator current has run about 0.8 ma before bunching. Similar duoplasmatron ion sources have been built for other applications, yielding over 100 ma proton currents (at considerably higher gas flow rates). Indeed, the 3-Mv Van de Graaff source has delivered several times more current on the test bench than it has on the accelerator. The current thinking on this problem is that pumping speed just below the ion source is inadequate. A getter pump for this region has been designed, but plans are also being laid for a more vigorous attack on the problem by providing substantially greater power and space in the terminal.

STATUS REPORT ON THE 5.5-Mv VAN DE GRAAFF ACCELERATOR

R. L. Robinson W. T. Newton[1]

The most exciting event related to the 5.5-Mv Van de Graaff accelerator during 1965 was the successful pulsing and bunching of the beam prior to acceleration. The pulses were 0.7 nsec wide at half maximum and had peak currents of ~1 ma. At present the pulsing frequency is 4.5 Mc/sec. Work has been initiated to give several other lower frequencies. A new beam port has been added for investigations employing pulsed beams. This beam tube terminates in the low mass scattering room above a pivot point for a carriage capable of holding a neutron detector and shielding weighing 5 tons. This carriage, which is borrowed from the 3-Mv machine, can be rotated through an angle of −110 to 70° relative to the beam direction. The position of the neutron detector can be adjusted on the carriage to give flight paths up to 6 m. The pulsed beam has already been used by two groups to investigate neutrons resulting from proton bombardment of medium-weight nuclei.

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[1]Instrumentation and Controls Division.

Development of the pulsing system required about 16% of the machine time. An estimate of the division of all machine time during 1965 is given in Table 1. One hundred percent is based on a normal work week being 80 hr.

The general categories of research and researchers involved are listed in Table 2. Details of these experiments can be found elsewhere in this report.

An improvement has been obtained in the intensity of the doubly ionized ^{3}He beam, and it is hoped that it can also be applied to the $^4He^{2+}$ beam. Previously, the doubly ionized ^{3}He and ^{4}He intensities were limited by the large singly ionized beams which were also accelerated by the Van de Graaff generator. The singly ionized particles have now been removed by passing the beam, prior to acceleration, through electric and magnetic fields. Appropriate values of these fields permit transmission only of the doubly ionized beam.[2] This technique gave an analyzed $^3He^{2+}$ beam of $\sim$400 na as compared to a previous upper limit of about 150 na.

The pumping system has been improved by replacement of the mercury 500-liter/sec pump located near the accelerating tube with a 1500-liter/sec pump, and the 180-liter/sec mercury pumps located near the analyzing magnet and on the four beam tubes with 300-liter/sec pumps. Besides the obvious advantage of greater pumping speed, these pumps, because they use DC 705 pump oil, require only water-cooled baffles. Thus, the dry-ice traps associated with the mercury pumps, which required filling twice a day and periodic shutdown of the pumps (every three to five weeks) for recycling the mercury, have been eliminated.

In June the highest voltage at which the machine would run dropped steadily until it was less than

[2]This technique was proposed by C. D. Moak.

Table 1. Utilization of 5.5-Mv Van de Graaff Accelerator as Based on an 80-hr Work Week

Use	Time Allotted (%)
Research	54
Pulsing development	16
Improvements	6
Overhaul	21
Changeover[a]	6
Maintenance	9
	112

[a]Changeover is the time required to change from one experiment to another.

Table 2. Research Performed by Means of 5.5-Mv Van de Graaff Accelerator

Type	Investigators
Protons on light nuclei	Bair, Jones, Willard (p. 83)
(p,n) reactions with pulsed beam	Harlow, Kernell, Kim, Perey, Robinson, Stelson (p. 84)
Analog states	Bair, Jones, Kim, Kernell, Robinson, Willard (pp. 84–89)
Total (p,n) and $(^4He,n)$ cross sections	Gibbons, Johnson, Kernell, Macklin (p. 47)
(n,n) reaction on nuclei	Fowler, Johnson (pp. 50–54)
$(n$, fission) reaction	Lamphere
^{3}He reactions on ^{15}N	Biggerstaff, Miller, Seth
Coulomb excitation	Ford, McGowan, Milner, Robinson, Stelson (p. 95)

4 Mv. As a result the machine for the first time in ten years was given a general overhaul. This included:

1. unstacking and carefully cleaning all members of the column,
2. checking and replacing faulty column resistors,
3. replacing the accelerator tube (this had to be done twice since the first tube leaked),
4. replacing the charging belt and charging screens,
5. grinding smooth the inside of the pressure vessel and painting according to a prescription used by High Voltage Engineering Corporation,
6. replacing bearings and polishing the shaft of the drive motor,
7. rewinding the heating elements in the tank-gas dryer.

Since this overhaul, which was done in July and August, the machine has run stably with almost no tank or tube sparks at voltages up to 5.7 Mv. It has not yet been tried at higher voltages.

OAK RIDGE TANDEM ACCELERATOR

C. D. Moak G. F. Wells[1]

During 1965 the tandem accelerator was operated for a total of 2186 hr. Ions used were H, D, ^{3}He, ^{14}N, ^{16}O, ^{19}F, ^{35}Cl, ^{79,81}Br, and ^{127}I. Beam currents, especially of ^{3}He, have been generally higher because of an ion source geometry modification developed first on the accelerator at the University of Pennsylvania. Funds have been received for the development of a new pulsed ion source, and the new source is about half complete. Arrangements have been made with the Physics Department of Yale University for a source of polarized ions, which should be available within the next eight months for use on the tandem accelerator.

The very short life of the new inclined-field accelerator tubes has caused serious losses of operating time, and we have decided to return to the old straight-field tubes until improved designs become available. Lost operating time and greater tube cost per operating hour are not compensated by enough significant operating advantages to justify continued use of inclined-field tubes.

The 2186 hr of research time was apportioned on an approximately equal-share-per-experimenter basis to the experiments listed in Table 1.

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[1]Instrumentation and Controls Division.

Table 1. Experiments Conducted on the Oak Ridge Tandem Van de Graaff

Experiment	Investigators
Proton elastic and inelastic scattering	Robinson, Stelson, and Ford (p. 90) Dickens, Silva, Perey, and Eichler
Coulomb excitation with ^{4}He, ^{16}O, and ^{35}Cl ions	Stelson, Robinson, Milner, and McGowan (pp. 95–97)
Resistivity changes in Au with radiation damage by ^{1}H, ^{2}H, and ^{4}He ions	Volkl, Coltman, and Klabunde
Coulomb-excited Mössbauer effect induced by ^{16}O Ions	Obenshain, Czjzek, Ford, and Love (pp. 104, 105)
^{3}He reactions on ^{15}N	Biggerstaff, Miller, and Seth
Nucleon transfer reactions with ^{14}N and ^{19}F ions	Toth, Gaedke, and Williams Hiebert, Couch, and McIntyre
Proton-induced fission of radium	Schmitt, Pleasonton, Lide, and Konecny (p. 77)
Crystal channeling studies with Br and I ions	Noggle, Datz, Moak, Lutz, Northcliffe, and Schmitt (p. 121)
Response of solid-state detectors with Br and I ions	Walker, Moak, and Dabbs (p. 78)
Radiation-damage studies in single crystals with Br and I ions	Noggle and Oen
Charge states of Br and I ions in crystal channels	Lutz, Datz, Moak, and Noggle

SCATTERING CHAMBER FOR GASEOUS TARGETS

C. M. Jones J. W. Johnson[1] R. M. Beckers[2]

A new scattering chamber, designed primarily for gaseous targets, has been constructed. The chamber has been designed as a flexible instrument, with provision for different types of detectors, targets, and beam entrance systems. In addition, the geometry of the chamber has been defined with a high degree of precision, commensurate with the high absolute accuracy which may be achieved in cross-section measurements with gaseous targets.

The chamber has been equipped with 11 ports for fixed detectors and two rotatable covers in which movable detectors may be mounted. Target gases may be contained in high- or low-pressure gas cells or within the entire volume of the chamber. In the latter mode the target gas may be separated from the accelerator vacuum system by a foil or a differential pumping system.

[1]Instrumentation and Controls Division.

[2]General Engineering and Construction Division.

Initial measurements of known cross sections for the scattering of protons from hydrogen and krypton indicate that the design goal of absolute cross-section measurements accurate to ±1 to 2% has been met. In addition, the chamber has been used for experimental studies of elastic and inelastic scattering of protons from ^{14}N and natural krypton.[3,4]

[3]"Scattering and Reactions Induced by the Proton Bombardment of ^{14}N," this report (contribution by J. K. Bair).

[4]"Scattering of Protons from Kr in the Vicinity of Low-Lying Isospin Analog States," this report (contribution by H. J. Kim).

THIN, LARGE-AREA, GASTIGHT PLASTIC WINDOWS FOR CRYOGENIC AND NUCLEAR APPLICATIONS

J. W. T. Dabbs

The use of thin windows as a means of retaining a gaseous coolant around a beam target while permitting reaction products to pass into a vacuum chamber is a familiar one. In the present instance the requirements were much more severe than usual. The following conditions on the window were required:

1. very small energy loss for fission fragments and alpha particles,
2. essentially gastight to ^3He at 0.5°K, where the gas viscosity is only ~2 micropoises,
3. window and support coolable to 0.5°K,
4. radiant-energy-reflecting coating with absorptivity $\lesssim 0.01$ (equivalent to best values of gold or aluminum),
5. usable area of ~30 cm^2.

The thickness requirement was set at 60 $\mu g/cm^2$ of plastic, 150 $\mu g/cm^2$ of nickel, or 250 $\mu g/cm^2$ of gold, or any combination thereof. Such window thicknesses can be expected to degrade fission fragment energies by about 4 Mev.[1]

The leakage requirement was essentially that there be no pinholes; the process of diffusion could not be eliminated but would fortunately tend to zero as the window material was cooled. This requirement was met by the use of multilayered plastic films.

A modification of the two-stick water-surface technique described by Jaffe[2] was used. A solution of 9.2 g per 100 ml of VYNS-3 powdered resin[3] in cyclohexanone was prepared and distributed uniformly in a bead along one edge of a wooden stick using an eye dropper. Upon placing the stick across an overfull developing tray of water, surface tension causes a film to form and its edge to move rapidly (several centimeters per second) away from the stick. A second stick is placed parallel to the first on the film ~3 to 4 cm from the first and moved away smoothly at a similar speed. In this manner, rather uniform (as judged by apparent color) films of ~7 $\mu g/cm^2$ (average value) are formed. The films are removed by folding over a straight-sided wire loop, thus providing a double thickness. The loop is again placed under the water surface, and second and third films are drawn and picked up. Most of the films used in this work consisted of three double layers, and a number of samples were found to weigh ~40 $\mu g/cm^2$ after drying.

The plastic support cylinder was fluorothene, which was chosen first to match expansion of the VYNS approximately and second because of its flexibility at low temperatures; in the present

[1]C. B. Fulmer, *Phys. Rev.* **139**, B54 (1965).

[2]L. Jaffe, *Ann. Rev. Nucl. Sci.* **12**, 155 (1962).

[3]Union Carbide Corp., Plastics Division, 1371 Peachtree St. NE, Atlanta, Ga. 30309. VYNS is a copolymer of vinyl chloride (~85%) and vinyl acetate (~15%) and is relatively inert.

case, a portion of the sample container also served as a gasket. Unfortunately, the VYNS film was found not to adhere to fluorothene. This problem and the problem of obtaining very smooth edges on the apertures in the plastic sample container (16 apertures 1.3×1.4 cm) were solved by coating the aperture edges with epoxy and allowing the epoxy to harden while rotating the plastic container at 1 rpm overnight before applying the VYNS window material.

The plastic cylinder was mounted on a mandrel. A simple arrangement using a drum and cord with appropriate guides sufficed to hold the rectangular frame stationary at the line of contact with respect to the outer surface of the plastic cylinder onto which the film was rolled. The ends of the film were cut with a hot wire, and the film (applied wet) was broken loose from the sides of the frame as rolling progressed. No adhesive was used. After drying overnight, the assembled plastic can, window, and gasket clamping flange were placed in an oven and baked for 10 to 15 min at 90°C; this caused the windows to become taut and removed final traces of moisture.

Tests of the finished window assemblies (see Fig. 1) using a mass spectrometer leak detector showed leak rates (at 0.05 mm Hg of He pressure) of 2×10^{-6} cm^3 NTP/sec at room temperature within 20 to 30%. Cooling the sample container to ~77°K caused a decrease of at least a factor 10^3. Thus the diffusion rate at this pressure and temperature was less than $\sim 5 \times 10^{-11}$ cm^3 sec^{-1} cm^{-2}. One window was retested after the evaporation of 50 $\mu g/cm^2$ of gold over its outer surface. The room-temperature ^4He diffusion rate was found to be $\sim 3 \times 10^{-10}$ cm^3 sec^{-1} cm^{-2}, again with a large reduction at low temperatures. This window showed an increase in leak rate at an internal pressure of 0.2 mm Hg.

Success in meeting condition 4 above was not achieved; the absorptivity of the 50-$\mu g/cm^2$ gold coating was found to be approximately 0.05; the requirement was obviated by interposing a second window of 133 $\mu g/cm^2$ of nickel with a 50-$\mu g/cm^2$

Fig. 1. Complete Window Assembly. The main body of the assembly is fluorothene plastic with 16 machined apertures approximately ½ in. square. The film covering these apertures consists of six layers of VYNS film 7 $\mu g/cm^2$. A coating of 50 $\mu g/cm^2$ of Au is evaporated over the exterior surface. The container is mounted by means of the flange. A continuation of the fluorothene container serves as a gasket. This gasket may be seen to the right of the flange.

evaporated coating of gold (not pinhole free) between the sample container and the radiant energy source. This arrangement roughly doubles the energy loss of fission fragments, but reduced the radiant heat to small values, as required.

It should be noted that cooling was carried out first in the frame and second in the window material by means of control of radiant heat reaching the assembly. Since the thermal contraction was ~1%, broken windows invariably resulted when this order of cooling was not followed. No cooled plastic windows on metal supports were successful.

The assistance of D. Tumlin, C. T. Hall, and R. H. Ward is gratefully acknowledged.

PUBLICATIONS

Publications which have appeared in print (since the preparation of last year's publication listing in the Annual Report) by Physics Division staff members have included book and journal articles; additionally, reports published have included Ph.D. theses, topical reports, the annual progress report itself, and Information Center reports.

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15th Annual Meeting on Nuclear Spectroscopy and Structure of the Atomic Nucleus, Minsk, USSR, January 22–February 2, 1965

Katharine Way, "New Projects in Scientific Information."

National Aeronautics and Space Administration Conference on Nucleosynthesis, New York, New York, January 25–26, 1965

J. H. Gibbons, "Neutron Capture Cross Section Measurements."

American Physical Society Meeting, New York, New York, January 27–30, 1965

J. A. Biggerstaff, W. M. Good, and H. J. Kim, "Resonance Structure and Strength Functions of the Even Isotopes of Zirconium."

R. C. Block, "Gamma Ray Spectra from Neutrons Captured in ^{56}Fe at the 1148 eV Resonance."

J. L. C. Ford, R. L. Robinson, and P. H. Stelson, "Elastic and Inelastic Scattering of Protons from ^{106}Pd and ^{108}Pd."

J. L. Fowler, "Resonance Parameters for Neutron Scattering from ^{208}Pb."

W. M. Good, D. Paya, and R. Wagner, "Resonance Structure and Strength Functions of Nuclei $40 < A < 70$."

O. Hansen, T. A. Belote, J. H. Bjerregaard, and G. R. Satchler, "Inelastic Scattering of Deuterons and Protons from ^{46}Ca."

C. H. Johnson and R. L. Kernell, "Cross Sections for Isobaric Analogue Resonances in the ^{117}Sn(p,n) and ^{119}Sn(p,n) Reactions."

L. D. Roberts, J. O. Thomson, F. E. Obenshain, W. K. Robinson, and W. B. Newbolt, "The Hyperfine Structure of the 77.3 keV Gamma Ray of ^{197}Au in Ferromagnetic Alloys."

H. W. Schmitt, J. W. T. Dabbs, and P. D. Miller, "Proton-Induced Fission of ^{226}Ra."

K. K. Seth, G. Walter, P. D. Miller, and J. A. Biggerstaff, "^{15}N(^{3}He,p) Reaction and Intermediate States."

AEC Conference on Pulsed Neutron Sources, Washington, D.C., February 18, 1965

J. A. Harvey, "Neutron Cross Section Measurements in Nuclear Physics."

IAEA Symposium on the Physics and Chemistry of Fission, Salzburg, Austria, March 22–26, 1965

J. W. T. Dabbs, F. J. Walter, and G. W. Parker, "Saddle Point Rotational States from Resonance Fission of Oriented Nuclei."

R. W. Lamphere, "Channel Analysis of Neutron Induced Fission of Even-Even Isotopes near Threshold."

H. Maier-Leibnitz, H. W. Schmitt, and P. Armbruster, "Average Number and Energy of Gamma Rays Emitted as a Function of Fragment Mass in ^{235}U Thermal-Neutron Induced Fission."

H. W. Schmitt, J. W. T. Dabbs, and P. D. Miller, "Correlated Fragment Energy Measurements and Mass-vs.-Angle Correlations in ^{226}Ra + p Fission."

H. W. Schmitt, W. M. Gibson, J. H. Neiler, F. J. Walter, and T. D. Thomas, "Absolute Energy Calibration of Solid State Detectors for Fission Fragments and Heavy Ions."

Conference on Nuclear Physics, Toronto, Canada, April 3, 1965

J. A. Harvey, "Capture Gamma Ray Spectra."

Conference on Elementary Particles, Birmingham, England, April 5–7, 1965

H. O. Cohn, W. M. Bugg, G. T. Condo, and R. D. McCulloch, "Exchange Mechanism in ω and ρ Production from the Pion-Nucleon Interaction."

Plasma Physics Theory Meeting, Princeton, New Jersey, April 22–23, 1965

T. K. Fowler and Y. Shima, "Flute Instabilities at Ion Gyrofrequency."

American Association of Physics Teachers (Indiana Chapter Meeting), Hanover, Indiana, April 24, 1965

P. M. Griffin, "An Introduction to the Optical Maser, with Demonstrations."

American Physical Society Meeting, Washington, D.C., April 26–29, 1965

R. C. Block, R. W. Hockenbury, and J. E. Russell, "Neutron Capture Cross Sections of ^{182}W, ^{183}W, ^{184}W, and ^{186}W from 4 eV to 10 keV."

W. M. Bugg, G. T. Condo, H. O. Cohn, N. Gelfand, and G. Lutjens, "ρ^0 Decay Correlations."

T. A. Carlson and M. O. Krause, "Multiple Ionization in Atoms and Its Relationship to Electron Correlation."

G. T. Condo, W. M. Bugg, and H. O. Cohn, "Relative Cross Section for Double N^* (1238) Production in *p-d* Collisions at 3.7 BeV/c."

J. W. T. Dabbs and J. A. Harvey, "Method for Obtaining Bursts of Polarized Neutrons with Energies of 10–700 keV."

J. H. Gibbons and R. L. Macklin, "keV-Range Total Cross Section Resonances in (^{204}Pb + n)."

F. P. Gibson and G. R. Satchler, "Prior-Form DWBA Stripping Program."

M. O. Krause and T. A. Carlson, "Charge Distribution of Krypton Resulting from Photoionization in the *M*-Shell."

C. D. Moak (invited paper), "Channel Effects in Thin Au Single Crystals for High Energy Br and I Ions."

F. E. Obenshain (invited paper), "Mössbauer Effect from Coulomb-Excited Gamma Rays."

L. D. Roberts (invited paper), "Study of the Electronic Structure of Gold Alloys Through the Use of the Mössbauer Effect."

R. L. Robinson, F. K. McGowan, J. L. C. Ford, Jr., and P. H. Stelson, "Low-Lying Levels of ^{75}As."

H. W. Schmitt (invited paper), "Fission Studies, Including New Energy Determinations Based on High-Energy Br and I Ion Measurements."

D. Seyboth, F. E. Obenshain, L. D. Roberts, and J. O. Thomson, "Magnetic Moment of the 77.3 keV First Excited State of ^{197}Au."

G. G. Slaughter and J. A. Harvey, "High Resolution Measurements of Gamma Rays from Thermal Neutron Capture in Niobium."

P. H. Stelson, W. T. Milner, J. L. C. Ford, Jr., F. K. McGowan, and R. L. Robinson, "Reorientation Effect in the Coulomb Excitation of Cd and Ag Nuclei."

W. W. Walker, C. D. Moak, and J. W. T. Dabbs, "Response of Ge and Si Detectors to Energetic Br and I Ions."

International Conference on the Internal Conversion Process, Nashville, Tennessee, May 10–13, 1965

Agda Artna, "Some Conversion Coefficients Which Should Be Measured."

W. B. Ewbank (invited paper), "A Review of Anomalous $E1$ Transitions in the Rotational Regions."

P. H. Stelson (invited talk), "Information on Conversion Coefficients from Coulomb Excitation and Lifetime Measurements."

13th Annual Meeting of Radiation Research Society, Philadelphia, Pennsylvania, May 24–26, 1965

T. A. Carlson (invited paper), "Multiple Ionization in Atoms and Molecules."

Société de Chimie Physique, 15th Annual Meeting on Movements and Changes of Phase in Molecular Solids, Paris, France, May 31–June 4, 1965

R. G. Steinhardt, Jr., W. Neilsen, H. W. Morgan, and P. A. Staats, "Infrared Spectroscopic Study of Condensed Phase Transitions in CF_4."

Conference on Resonant Particles, Athens, Ohio, June 10–12, 1965

W. M. Bugg, G. T. Condo, and H. O. Cohn, "Exchange Mechanisms in *p-n* Collisions."

IAEA Conference on Electromagnetic Isotope Separators and Related Ion Accelerators and Their Application to Physics, Aarhus, Denmark, June 14–18, 1965

S. Datz, T. S. Noggle, and C. D. Moak, "Anisotropic Energy Losses in Face Centered Cubic Crystals for High Energy ^{79}Br and ^{127}I."

American Association of Physics Teachers, University of Tennessee, Knoxville, Tennessee, June 17–19, 1965

J. H. Gibbons (invited paper), "Neutron Capture and Stellar Nucleosynthesis: Quantifying the Qualitative."

T. A. Welton (invited paper), "The Imaging of Atoms with the Electron Microscope."

Gordon Research Conference on Nuclear Chemistry, New London, New Hampshire, June 20–25, 1965

P. H. Stelson (invited paper), "Coulomb Excitation and Inelastic Scattering Measurements on Medium Weight Nuclei."

Study Session of Physics of the Emperor Tandem Van de Graaff Region, Upton, Long Island, New York, June 21–July 16, 1965

P. H. Stelson, "Future Possibilities for Coulomb Excitation Experiments."

2nd International Meeting on Accelerator Targets Designed for the Production of Neutrons, Grenoble, France, June 21–22, 1965

J. H. Gibbons and R. L. Macklin, "^{51}V$(p,n)^{51}$Cr Cross Section from Threshold to 2.25 MeV."

American Physical Society Topical Conference on Research Problems in the Physics of X-Ray Spectra, Ithaca, New York, June 22–24, 1965

M. O. Krause and T. A. Carlson, "Two Electron Emission in Auger and Photoabsorption Processes."

American Physical Society Meeting, New York, New York, June 23–25, 1965

T. K. Fowler (invited paper), "Thermodynamics of Unstable Plasmas."

A. D. MacKellar and R. L. Becker, "Ground State Properties of ^{16}O in the Brueckner Approximation."

C. D. Moak and M. D. Brown, "Stopping Powers of Be, C, Al, Ni, Ag, and Au for Br and I Ions."

R. Muthukrishnan, M. Baranger, and K. T. R. Davies, "Hartree-Fock Calculations of Finite Nuclei."

Army Nuclear Science Seminar, Oak Ridge, Tennessee, July 18–31, 1965

H. B. Willard (invited paper), "Current and Future Problems in Nuclear Structure."

International Conference on the Study of Nuclear Structure with Neutrons, Antwerp, Belgium, July 19–23, 1965

I. Bergqvist, "Fast Neutron Capture Gamma-Ray Spectrum from $^{238}U(n,\gamma)^{239}U$."

I. Bergqvist, J. A. Biggerstaff, J. H. Gibbons, and W. M. Good, "Neutron Resonance Capture in 2s1*d* Shell Nuclei."

J. A. Biggerstaff, W. M. Good, and H. J. Kim, "Neutron Resonance Structure and *s*-Wave Strength Function of the Even Isotopes of Zr."

J. R. Bird, J. A. Biggerstaff, J. H. Gibbons, W. M. Good, and R. L. Macklin, "A Study of the Resonances in Neutron Bombardment of ^{206}Pb and ^{207}Pb."

J. A. Harvey and T. Fuketa, "Strong *p*-Wave Neutron Resonances in ^{120}Sn, ^{118}Sn, and ^{124}Sn."

J. A. Harvey and G. G. Slaughter, "Level Spacing and *s*-Wave Neutron Strength Function of the Odd-Odd Nuclide ^{138}La."

J. A. Harvey and G. G. Slaughter, "High Resolution Measurements of Gamma Rays from Thermal and Resonance Neutron Capture in ^{117}Sn, ^{118}Sn, and ^{120}Sn."

C. H. Johnson and J. L. Fowler, "Intermediate States as Observed by Differential Scattering of Neutrons by Doubly Closed Shell Nuclei."

R. L. Macklin and J. H. Gibbons, "Neutron Capture Cross Sections from 5 to 100 keV."

R. L. Macklin and J. H. Gibbons, "Energy Dependence of the $^{10}B(n,\alpha)^{10}B(n,\alpha\gamma)$ Ratio."

R. L. Macklin and J. H. Gibbons, "On the Absolute Value and Energy Dependence of the $^{3}He(n,p)T$ Reaction."

R. Wagner, W. M. Good, and D. Paya, "S-Wave Neutron Strength Functions of Isotopes in the 3s Resonance Region $40 < A < 70$."

R. Wagner, P. D. Miller, T. Tamura, and H. Marshak, "The Interaction of 350 keV Polarized Neutrons with Oriented ^{165}Ho Nuclei."

Gordon Research Conference on Liquids, Meriden, New Hampshire, August 2–6, 1965

R. G. Steinhardt, Jr., W. Neilsen, H. W. Morgan, and P. A. Staats (invited paper), "Infrared Spectroscopic Study of Condensed Phase Transitions in CF_4."

16th Annual Fisk University Infrared Institute, Nashville, Tennessee, August 16–21, 1965

P. A. Staats, "Experimental Infrared Spectroscopy."

American Physical Society Meeting, Honolulu, Hawaii, September 2–4, 1965

H. O. Cohn, W. M. Bugg, and G. T. Condo, "A Study of the 3 Pion System in the Reaction $\pi^+ + n \rightarrow p + \pi^+ + \pi^- + \pi^0$."

G. R. Satchler (invited paper), "Shell Model Inelastic Scattering from Nuclei."

IAEA 2nd Conference on Plasma Physics and Controlled Nuclear Fusion Research, Abingdon, England, September 6–10, 1965

T. K. Fowler and G. E. Guest, "Anomalous Plasma Diffusion in Magnetic Wells."

International Conference on Polarization Phenomena of Nucleons, Karlsruhe, Germany, September 6–11, 1965

J. W. T. Dabbs and J. A. Harvey, "Method for Obtaining Bursts of Polarized Neutrons with Energies 10–700 keV."

H. B. Willard, S. T. Thornton, and C. M. Jones, "*N-D* Scattering – Vector Polarization of Recoil Deuterons from a Polarized Neutron Beam."

German Physical Society Annual Meeting, Frankfurt, Germany, October 4–9, 1965

D. Seyboth, F. E. Obenshain, and G. Czjzek, "Mössbauereffekt mit γ-Strahlung von Coulomb-Angeregten Kernen" ("Mössbauer Effect with Gamma Radiation from Coulomb Excited Nuclei").

Institute of Electrical and Electronic Engineers Symposium on Nuclear Instruments, San Francisco, California, October 18–20, 1965

E. D. Klema, Frances Pleasonton, H. W. Schmitt, and J. Unik, "Response of Solid-State Detectors to Fission Fragments."

Solid State Sciences Panel Meeting, Oak Ridge, Tennessee, October 25–26, 1965

L. D. Roberts, "The Mössbauer Effect of Au: *a*) In Au Alloys, *b*) As a Function of Pressure."

American Physical Society Meeting, Chicago, Illinois, October 28–30, 1965

R. L. Becker and A. D. MacKellar, "Comparison of Predictions of the Yale and Hamada-Johnston Potentials for the Ground State Properties of ^{16}O."

J. L. C. Ford, Jr., G. Czjzek, F. E. Obenshain, and D. Seyboth, "Observation of the Mössbauer Effect Following Coulomb Excitation of ^{73}Ge."

H. J. Kim and R. L. Robinson, "A Study of the $^{89}Y(p,n)^{89}Zr$ Reaction."

H. W. Schmitt, "Deformabilities of Fission Fragments."

Southeastern Section American Physical Society Meeting, Charlottesville, Virginia, November 1–3, 1965

H. O. Cohn, R. D. McCulloch, W. M. Bugg, and G. T. Condo, "Production and Decay of the f^0 Meson."

J. L. Fowler and C. H. Johnson, "Neutron Scattering from Nitrogen."

W. A. Morgan, E. Silberman, and H. W. Morgan, "Infrared Spectroscopic Studies on the Nitrite Ion."

D. O. Patterson, J. O. Thomson, and R. G. Scurlock, "Magnetic and Electric Quadrupole Coupling to the ^{197}Au Nuclei in Gold Manganese Alloys."

P. H. Stelson (invited paper), "Electric Quadrupole Moments of Nuclei in Excited States."

J. O. Thomson (invited paper), "The Change of Resonance Gamma Ray Energy with Pressure for ^{197}Au."

American Physical Society Topical Conference on Bases for Nuclear Spin-Parity Assignments, Gatlinburg, Tennessee, November 11–13, 1965

E. Guth and R. D. Edge, "Excitation and Disintegration of Nuclei by Low Energy Electrons and X-Rays."

J. A. Harvey, G. G. Slaughter, and M. J. Martin, "Determination of Spins of Neutron Resonances at 45.8 eV in ^{118}Sn and at 62 eV in ^{124}Sn."

F. K. McGowan, P. H. Stelson, R. L. Robinson, W. T. Milner, and J. L. C. Ford, Jr., "Coulomb Excitation of States in the Chromium Nuclei."

R. L. Robinson (invited paper), "Coulomb Excitation."

T. Tamura and R. K. Jolly, "Inelastic Scattering of Deuterons from the Two-Phonon States of ^{60}Ni."

T. Tamura and T. Udagawa, "Static Quadrupole Moment of the First 2^+ State in Vibrational Nuclei."

FOREIGN TRAVEL AND ASSIGNMENTS

A listing is included in the preceding section of this report of 28 papers, authored and/or coauthored by Physics Division staff members, which were presented during the past year at international conferences and meetings in eight countries outside the United States. Visits while abroad were made also, by those Division members who actually attended the sessions, to a number of atomic energy installations and universities for discussions on scientific subjects relating directly to their research endeavors at ORNL. Additionally, the following Division members were assigned abroad during 1965.

J. K. Bair (High Voltage Program) completed a one-year assignment at the Atomic Energy Research Establishment in Harwell, England, where he conducted research in nuclear structure physics. This assignment was a continuation of the profitable liaison in physics between AERE and ORNL, which originated in 1959, and was the sixth such exchange-type assignment of a Physics Division staff member to the Harwell Laboratory.

C. H. Johnson (High Voltage Program) succeeded J. K. Bair during the past summer as the seventh exchange assignee to Harwell. An exchange of information on nuclear spectroscopy is being derived from this assignment.

F. E. Obenshain (Mössbauer Experimental Program) was the first ORNL Division staff member to be assigned to the Kernforschungszentrum in Karlsruhe, Germany, in an exchange program similar to that between AERE and ORNL. He is engaged in low-energy nuclear physics research. In the spring of 1966 the first German exchange assignee to ORNL will be C. Weitkamp.

ANNOUNCEMENT

Oak Ridge Electron Linear Accelerator

The recently approved Electron Linear Accelerator Laboratory[1] will be located west of the Oak Ridge Isochronous Cyclotron Laboratory and south of Swan Lake and is expected to be in operation by 1968. The accelerator will be used as a pulsed neutron source for neutron cross-section measurements up to 1 Mev with emphasis on measurements needed for the United States Fast Reactor Program. It is expected to produce 15-amp pulses of 140-Mev electrons with beam powers up to 50 kw and pulse widths as narrow as 2.3 nsec. The major part of the facility will be underground, beneath 20 ft of earth shielding. Ten flight paths (up to 200 m long) will be placed radially from the neutron target room, 12 ft in diameter and 10 ft high, which can be evacuated. In addition to neutron research, an experimental area has been designed to permit basic physics research in electron scattering and photonuclear reactions.

Physics Division personnel associated with the accelerator facility include J. A. Harvey (Co-director),[2] R. C. Block, R. L. Macklin, G. G. Slaughter, J. W. T. Dabbs, and P. D. Miller.

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[1] Joint project of the ORNL Physics Division and the Neutron Physics Division.

[2] Co-director with the ORNL Neutron Physics Division is F. C. Maienschein.

PERSONNEL ASSIGNMENTS

Listed in other sections of this Report are those Ph.D. candidates engaged in thesis research, co-op students, consultants under subcontract, and summer investigators (including research participants, visitors, student trainees, and loanees) who have been associated with the Physics Division during 1965. Additionally, investigators from three countries other than the United States began or completed temporary assignments with the Division. Presently with the Laboratory from abroad is E. F. P. Konecny of the Universität Giessen in Munich, Germany (Physics of Fission Program). Assignments were completed by the following individuals: H. H. Jung of the Institut für Kernphysik der Universität in Kiel, Germany; H. Ogata[1] from Japan and A. K. Sen Gupta[2] from India (Nuclear Data Group); and D. Seyboth of the University of Erlangen in Erlangen, Germany (Mössbauer Experimental Program).

R. M. Haybron, formerly Professor of Physics at Michigan State University, began a nine-month appointment with the Division's Theoretical Physics Program during this period.

Graduate students assigned as loanees to the Division presently include W. B. Dress from Harvard University (High Voltage Program); P. G. Huray from the University of Tennessee (Mössbauer Experimental Program); and W. G. Love from the University of Tennessee (Theoretical Physics Program).

Graduate students[3] who were formerly classified as loanees to the Division, and who during the past year have been awarded Oak Ridge Graduate Fellowship appointments, include J. K. Baird of Harvard University (High Voltage Program); J. W. Hutcherson of Vanderbilt University (Spectroscopy Research Program); R. L. Kernell of the University of Tennessee (High Voltage Program); D. O. Patterson of the University of Tennessee (Mössbauer Experimental Program); M. Reeves III[4] of the University of Tennessee (High Voltage Program); R. O. Sayer of the University of Tennessee (High Voltage Program); and S. T. Thornton of the University of Tennessee (High Voltage Program).

Intralaboratory transfers were as follows: G. W. Charles (Spectroscopy Research Program) transferred to the Physics Division from the Thermonuclear Division; the Nuclear Data Group transferred from the Physics Division to the Director's Division and included K. Way (Director of the Group), A. Artna, C. T. Chen,[5] W. B. Ewbank, N. B. Gove, and M. J. Martin; M. O. Krause (Charge Spectrometry Program) transferred from the Physics Division to the Thermonuclear Division.

T. K. Fowler (Plasma Physics Program) terminated employment with the Laboratory during 1965 and is now with General Atomic in San Diego, California.

S. Bernstein (Mössbauer Experimental Program) is continuing through 1966 a leave of absence begun in 1964 and is engaged as a Professor of Physics at the University of Illinois.

R. C. Block is assigned to the Rensselaer Polytechnic Institute for the academic year 1965–66 for research on the ORNL-RPI cooperative neutron capture program. Also, as Visiting Professor, he is teaching a course in Applied Nuclear Physics.

P. H. Stelson served as Guest Senior Physicist with the Physics Department of Brookhaven National Laboratory during July 1965. While there he also participated in a study session concerning Physics of the Emperor Tandem Van de Graaff Region and presented a talk entitled "Future Possibilities for Coulomb Excitation Experiments."

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[1]Now with the University of Windsor in Windsor, Ontario, Canada.

[2]Member of ORNL Director's Division at time of departure; now with the Atomic Energy Research Establishment in Harwell, England.

[3]See also "Ph.D. Thesis Research" section, p. 154.

[4]On-campus assignment.

[5]Temporary assignment.

ADVISORY COMMITTEE

Advisory committees are attached to the majority of the research divisions of the Oak Ridge National Laboratory for the purpose of offering advice on the cogency and effectiveness of the many scientific programs under way.

At the June 7–9, 1965, Annual Information Meeting,[1] Physics Division investigators covered 40 topics in 16 areas of research in talks presented before Laboratory staff members, Advisory Committee members, and guests from the AEC and other installations. Advisory Committee members at that time included:

Prof. B. L. Cohen	University of Pittsburgh
Prof. Martin Deutsch	Massachusetts Institute of Technology
Dr. D. R. Inglis	Argonne National Laboratory
Prof. D. L. Judd	Lawrence Radiation Laboratory, Berkeley
Prof. L. J. Rainwater	Columbia University

[1]The Physics Division and the Electronuclear Division hold their Annual Information Meetings jointly and are served by the same Advisory Committee.

SPECIAL LECTURE SERIES

Summer Session on Fission Physics

A Special Lecture Series in Fission Physics was held at the Laboratory during the summer of 1965 in which two prominent leaders in the field of fission physics were the guest speakers. Professor Lawrence Wilets of the University of Washington presented five talks on the subject "Nuclear Models and Their Relationship to Fission Theory"; Dr. James Griffin of the Los Alamos Scientific Laboratory, also in five talks, discussed "Fission Barrier Transition on Fission States – 'Spectroscopy' of Highly Deformed Nuclei."

The lecture series was arranged by four staff members of the Physics Division – H. B. Willard, G. R. Satchler, J. W. T. Dabbs, and H. W. Schmitt – primarily for the benefit of experimental physicists at ORNL with the main purposes being (1) to review the current status of knowledge in the field of fission physics and (2) to discuss the outstanding problems and fruitful areas for future research.

Parts of the lecture series were attended by a limited number (30) of invited experimentalists and theorists from other laboratories active in fission research, who participated in general and group discussions. A number of the invited guests presented informal talks on their own work. These included ten visitors and two ORNL staff members as listed below:

B. V. Bronk	State University of New York
J. M. Ferguson	U.S. Naval Radiological Defense Laboratory
P. Fong	Utica College of Syracuse University
G. E. Gordon	Massachusetts Institute of Technology
E. L. Haines	California Institute of Technology
S. S. Kapoor	Lawrence Radiation Laboratory, Berkeley
W. Loveland	University of Washington
J. C. D. Milton	Chalk River Nuclear Laboratories

F. Plasil	Brookhaven National Laboratory
H. W. Schmitt	Oak Ridge National Laboratory
V. Viola	Argonne National Laboratory
Katharine Way	Oak Ridge National Laboratory

Indications are that the main lectures, the discussion periods which followed, and the informal talks did much toward stimulating the attendees' interest and activity in the field of fission physics.

AMERICAN PHYSICAL SOCIETY

Topical Conference

Staff members of the Physics Division took an active part in a topical conference, "Bases for Nuclear Spin-Parity Assignments," which was sponsored by the American Physical Society and the Oak Ridge National Laboratory and held in Gatlinburg, Tennessee, November 11–13, 1965. The prime objective of this conference was to bring together those nuclear physicists, chemists, and compiling scientists who are interested in, and those who have contributed to, the nuclear spectroscopy for deducing spins and parities of low-lying nuclear states (bound states). Various aspects of nuclear spin-parity assignments were reviewed by invited experts in 20- to 30-min talks. In the six sessions of the conference there were 18 invited papers and 42 contributed papers presented, one of the former and five of the latter by staff members of the Physics Division. The six-member Program Committee responsible for organizing and conducting the conference included two Division members – F. K. McGowan, Chairman, and R. L. Robinson; one Division member, G. R. Satchler, served as Session Chairman.

Authors of the contributed papers were given the option of submitting 600-word summaries along with the usual 200-word abstracts required for APS-sponsored meetings. The conference proceedings will be published by Academic Press Inc. and will include the invited papers and those summary papers which were submitted; abstracts will be published in a 1966 issue of the *Bulletin of the American Physical Society*.

Two hundred thirty-five scientists from universities and installations in the United States, Canada, France, and Germany were among the participants in the three-day meeting.

VISIT BY USSR LOW-ENERGY TEAM TO ORNL

A Soviet delegation of ten low-energy-physics specialists visited the Laboratory Wednesday, December 22, 1965. J. L. Fowler, Director of the Physics Division, was responsible for coordinating the program, in which talks and tours took place primarily in the High Voltage Accelerator Laboratory of the Physics Division and in the Oak Ridge Isochronous Cyclotron Building of the Electronuclear Division. Included also on the agenda for the day were tours and discussions at the fol-

lowing nuclear-structure facilities: Oak Ridge Research Reactor, Nuclear Chemistry, High Flux Isotope Reactor, Mössbauer Experiments, Nuclear Theory, Nuclear Data, Charged Particle Cross Section Compilations, and Separated Orbit Cyclotron. Staff members representing eight ORNL Research Divisions took part in the visit. The Soviet delegation included:

I. M. Frank (Nobel Laureate)	Lebedev Physics Institute, Moscow
A. P. Klyucharev	Ukrainian Physical Technical Institute, Kharkov
N. A. Burgov	Institute of Theoretical and Experimental Physics, Leningrad
A. A. Ogloblin	Kurchatov Atomic Energy Institute, Moscow
L. P. Panikov	USSR State Committee on Utilization of Atomic Energy, Moscow
S. M. Polikanov	Joint Institute of Nuclear Research, Dubna
K. A. Petrzhak	Khlopin Radium Institute, Leningrad
A. I. Solnyshkov	Institute of Electrophysical Apparatus, Leningrad
L. N. Usachev	Physical Technical Institutes, Obninsk
D. P. Filippov	State Committee on Utilization of Atomic Energy, Moscow

MISCELLANEOUS ACTIVITIES OF DIVISIONAL PERSONNEL

Physics Division staff members are frequently requested or appointed to assume certain professional duties which, although related to, are incident to their primary responsibilities at ORNL. Such duties may be in connection with scientific journals, societies, conferences, committees, institutes, etc., and have included during the past year the following:

Agda Artna[1]	Assistant Editor of *Nuclear Data*, journal published by Academic Press Inc.
R. L. Becker	Member of the Program Committee for the International Conference on Nuclear Physics (Gatlinburg, Tennessee, September 1966)
R. C. Block[2]	Reviewer for *Canadian Journal of Physics*
	Member of National Science Foundation Panel for reviewing proposals for college teacher programs

[1]Now with ORNL Director's Division.

[2]Assigned as Lecturer in Nuclear Engineering and Science Department of the Rensselaer Polytechnic Institute, Troy, N.Y. (1965–66).

J. L. Fowler	Member of the National Research Council to represent the American Physical Society in the Division of Physical Sciences
	Chairman of Brookhaven National Laboratory Physics Visiting Committee
	Member of Carnegie Institute of Technology Physics Visiting Committee
	Chairman of Organizing Group to draft petition for forming a Division of Nuclear Physics in the American Physical Society
	Member of American Physical Society Committee on Nuclear Physics (appointed by F. Bloch, President of the Society)
	Member of National Bureau of Standards National Standard Reference Data System Advisory Panel
J. H. Gibbons	Reviewer for *Physical Review*
	Member of the Board of Trustees of the College of Oak Ridge
	Member of Smithsonian Institution Ad Hoc Panel of the Study of Basic Research and Higher Education in the National Capital Area
N. B. Gove[1]	Secretary of the National Academy of Sciences – National Research Council Subcommittee on Nuclear Structure
	Secretary of the National Academy of Sciences – National Research Council Subcommittee on Techniques for the Distribution of Scientific Information
	Reviewer for *Computing Reviews*
	Member of the Program Committee for the American Physical Society Topical Conference on Bases for Nuclear Spin-Parity Assignments (Gatlinburg, Tennessee, November 1965), also Editor of the Conference Proceedings
	Assistant Editor of *Nuclear Data*, journal published by Academic Press Inc.
J. A. Harvey	Reviewer for *Nuclear Science and Engineering*
	Assistant in the preparation of Supplement 2, Second Edition of BNL-325, *Neutron Cross Section Compilation* (Vol. 3 published in 1965)
	Member of Editorial Board of *Nuclear Data*, journal published by Academic Press Inc.
	Member of AEC Computer Index Neutron Data Steering Committee (CINDA)
R. L. Macklin	Member of the Oak Ridge Gaseous Diffusion Plant Nuclear Safety Committee
F. K. McGowan	Member of the Editorial Board of *Nuclear Data*, journal published by Academic Press Inc.
	Chairman of the Program Committee for the American Physical Society Topical Conference on Bases for Nuclear Spin-Parity Assignments (Gatlinburg, Tennessee, November 1965)
P. D. Miller	Reviewer for *Computing Reviews*

C. D. Moak	Member of the AEC Polarized Ion Source Committee
	Member of the Program Committee for the Southeastern Section of the American Physical Society (1964–65)
	Reviewer for *Reviews of Scientific Instruments*
H. W. Morgan	Faculty Member of Fisk University Infrared Spectroscopy Institute
L. D. Roberts	Member of the Executive Committee of the Southeastern Section of the American Physical Society (1964–65)
	Member of the Program Committee of the Southeastern Section of the American Physical Society (1964–65)
R. L. Robinson	Member of the Program Committee for the American Physical Society Topical Conference on Bases for Nuclear Spin-Parity Assignments (Gatlinburg, Tennessee, November 1965), also Associate Editor of the Conference Proceedings
G. R. Satchler	Associate Editor for *Physical Review*
P. A. Staats	Faculty Member of Fisk University Infrared Spectroscopy Institute
P. H. Stelson	Member of the Program Committee for the International Conference on Nuclear Physics (Gatlinburg, Tennessee, September 1966)
	Member of the National Academy of Sciences – National Research Council Subcommittee on Nuclear Structure
	Member of the AEC's Nuclear Cross Section Advisory Group
	Member of the Organizing Committee for the International Conference on the Internal Conversion Process (Nashville, Tennessee, May 1965)
	Member of the Organizing Committee and the Program Committee for the Conference on Neutron Cross Section Technology (Washington, D.C., March 1966)
K. L. Vander Sluis	Member of the National Academy of Sciences – National Research Council Committee on Line Spectra of the Elements
Katharine Way[1]	Editor of *Nuclear Data*, journal published by Academic Press Inc.
	Chairman of the National Academy of Sciences – National Research Council Subcommittee on the Techniques for Distribution of Scientific Information
	Member of the Subcommittee on Nuclear Data of the International Union of Pure and Applied Physics (Commission on Low-Energy Nuclear Physics)
T. A. Welton	Member of Physics Nomination Screening Panel for the 1966 E. O. Lawrence Award
	Reviewer for *Journal of Applied Physics*
H. B. Willard	Member of the Program Committee for the Southeastern Section of the American Physical Society (1964–65)
	Member of the Board of Trustees of the College of Oak Ridge
	Member of the Graduate Council of the University of Tennessee

ACTIVITIES RELATED TO EDUCATIONAL INSTITUTIONS

Research Participants

The Research Participation Program of the Oak Ridge Institute of Nuclear Studies[1] (under contract with the U.S. Atomic Energy Commission) enables selected university faculty members to participate in research, primarily during the summer months, at several major installations of the U.S. Atomic Energy Commission. The Oak Ridge National Laboratory provides most of these appointments; some projects are conducted at the University of Tennessee Agricultural Research Laboratory and at the Oak Ridge Institute of Nuclear Studies, and in 1965 one participant was appointed to the Lawrence Radiation Laboratory. Additionally, appointments are also possible at the Puerto Rico Nuclear Center and at the Savannah River Laboratory. Of mutual benefit to the participant and to the laboratory where he carries out his research, this arrangement between the Oak Ridge Institute of Nuclear Studies and laboratories in Oak Ridge has, since its inception in 1947, been extremely important to the progress of nuclear energy research and development not only in the South, but in the entire nation. To date 817 faculty members from 213 colleges and universities in 43 states, Puerto Rico, and the District of Columbia have engaged in research under this program.

During the summer of 1965, 65 Research Participants, representing 40 colleges and universities in 22 states, received appointments. The following six investigators were engaged in research with the Physics Division of the Oak Ridge National Laboratory: J. W. Burton[2] (Associate Professor and Chairman, Physics Department, Carson-Newman College), Mössbauer Experimental Program; G. T. Condo[2] (Assistant Professor, University of Tennessee), High Energy Physics Program; J. A. Gwin[3] (Assistant Professor, University of Louisville), Spectroscopy Research Program; R. F. O'Connel (Assistant Professor, Louisiana State University), Theoretical Physics Program; J. F. Pizzo (Assistant Professor, Lamar State College of Technology), Theoretical Physics Program; and W. W. Walker (Assistant Professor, University of Alabama), Physics of Fission Program.

Summer Visitors

Other investigators with the Division during the summer of 1965 included five faculty members, one graduate fellow, and three loanees as follows:

Faculty Members. – W. M. Bugg[4] (Associate Professor, University of Tennessee), High Energy Physics Program; R. D. Edge[4] (Professor, University of South Carolina), High Voltage Experimental Program; D. R. Harrington (Assistant Professor, Rutgers University), Theoretical Physics Program; W. T. Pinkston[4] (Associate Professor, Vanderbilt University), Theoretical Physics Program; and R. M. White (Professor, Baker University), Charge Spectrometry Program.

Graduate Fellow. – M. Reeves III[5] (Graduate Student and Teaching Assistant, University of Tennessee), High Voltage Experimental Program.

Loanees. – J. L. Ferguson, Jr., R. Snow, and R. M. Tarbutton (all candidates for the Ph.D. degree at Vanderbilt University), Theoretical Physics Program.

Summer Student Trainee Program

The Summer Student Trainee Program is administered by the Oak Ridge Institute of Nuclear Studies in cooperation with the Oak Ridge National Laboratory under the sponsorship of the U.S. Atomic Energy Commission. The program offers temporary summer appointments, on a competitive basis, to a limited number of students who have completed their junior year of college and who are majoring in the sciences. Primarily for students (citizens of the United States) from small colleges in the southern region, this arrangement

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[1]Name change to Oak Ridge Associated Universities, Inc., becomes effective January 1966.

[2]Consultant to the ORNL Physics Division.

[3]Research Participant with the ORNL Health Physics Division assigned to the Physics Division.

[4]Consultant to the ORNL Physics Division.

[5]Summer assignment arranged through the UT-ORNL Cooperative Educational Program; received appointment in fall of 1965 as Oak Ridge Graduate Fellow, on-campus, University of Tennessee.

affords students the opportunity of working in a full-time research laboratory during the summer months and serves to encourage them to carry on graduate work after they have attained the bachelor degree in science.

In 1965, the seventh year of the Student Trainee Program, 56 summer appointments were made. Students assigned to the Physics Division were selected from a total of 62 applicants whose majors were either in physics or mathematics, and included: P. J. Castleberry (Oklahoma City University), Physics of Fission Program; T. P. Coleman (Augsburg College), High Energy Physics Program; M. W. Masters (David Lipscomb College), High Voltage Experimental Program; H. E. Montgomery, Jr. (Mississippi College), High Voltage Experimental Program; and C. L. Pannel (California Western University), High Voltage Experimental Program.

Cooperative Education Program for Undergraduate Students

Promising students in science and engineering who have completed at least two quarters of undergraduate study are selected to participate in the Cooperative Education Program of the Oak Ridge National Laboratory. Students alternate between equal periods of time spent in school attendance and in work at the Laboratory.

The Co-op Program, now in its 14th year at ORNL, continues to prove a highly successful means both for promoting the professional development of students and for providing valuable technical assistance in the varied research programs at the Laboratory.

Seventeen Co-op students were with the Physics Division during 1965; seven were assigned to the High Energy Physics Program, four to the Theoretical Physics Program, three to the High Voltage Program, and three to the Physics of Fission Program. These students included: R. G. Beidel[6] of the University of Tennessee, F. S. Chwieroth of Drexel Institute of Technology, E. R. Golston of the Georgia Institute of Technology, R. A. Hamilton[7] of the Virginia Polytechnic Institute, C. R. Herschel[8] of the Virginia Polytechnic Institute, J. W. Hill of the Georgia Institute of Technology, H. E. Hite of the Georgia Institute of Technology, M. B. Johnson[6] of the Virginia Polytechnic Institute, S. L. Kramer[6] of Drexel Institute of Technology, D. N. Mashburn[6] of the University of Tennessee, M. Lynne McFadden of the Virginia Polytechnic Institute, R. J. Metzger[6] of the University of Tennessee, H. G. Paris of the Georgia Institute of Technology, R. D. Passmore of Auburn University, J. R. Penland[9] of the University of Tennessee, R. J. Stanton of the Drexel Institute of Technology, and Rebecca Tyson of the University of Tennessee.

Cooperative Program in Graduate Education Between ORNL and the University of Tennessee Supported by the Ford Foundation

The Ford Foundation grant to the University of Tennessee now supports 28 ORNL staff members as part-time faculty members in the Departments of Chemistry, Mathematics, Physics, Biological Sciences, Nuclear Engineering, Engineering Mechanics, Chemical Engineering, and Metallurgical Engineering. These joint appointments, under AEC approval, allow the participants to be released from their Laboratory duties in order to spend 20% of their time at the University teaching courses, supervising theses, consulting with students and other professors, and participating in seminars, staff meetings, and examinations. Physics Division staff members who have continued in this arrangement as Professors of Physics include L. D. Roberts, T. A. Welton, and H. B. Willard.

Oak Ridge Graduate Fellowship Program

There were 37 new applications for predoctoral fellowships during the 1965 calendar year. Fifteen new appointments were begun during the year following recommendations by the ORNL

[6]Completed Co-op assignment during this period.

[7]Transferred Co-op assignment to the Y-12 facility.

[8]Resigned from the Co-op program.

[9]Transferred Co-op assignment to the ORNL Metals and Ceramics Division.

Graduate Fellow Selection Panel. Panel members from the Physics Division included G. R. Satchler and H. B. Willard.

The current distribution of the now 30 Fellows assigned to ORNL under this program includes 15 physicists (8 with the Physics Division), 1 biologist, 1 bacteriologist, 1 electrical engineer, 1 forester, 5 chemists, 1 metallurgical engineer, 1 nuclear engineer, 2 mathematicians, 1 statistician, and 1 zoologist.

AEC Postdoctoral Program

At the present time there are seven AEC Postdoctoral Fellows at the Laboratory. During 1965 F. P. Gibson (Theoretical Physics Program) completed an appointment with the Physics Division and is now with the Stanford Research Institute in Huntsville, Alabama. Budgetary restrictions during the year have continued to limit the growth of the program.

Ph.D. Thesis Research

During the past year, 17 Division staff members served in either an advisory or a supervisory capacity for the thesis research conducted by 20 Ph.D. candidates. Doctorates were granted to two candidates from the University of Tennessee in 1965, and one candidate from Texas A and M University completed the required thesis research late in the year. The following is a listing of the individuals concerned:

Ph.D. Candidate	Staff Member(s)	Field of Research
J. K. Baird[10] Harvard University	P. D. Miller and F. E. Obenshain	Search for Electric Dipole Moment of the Neutron
Raymond Carpenter[11] University of Tennessee	H. W. Morgan and P. A. Staats	The ν_2 Fundamental Vibration-Rotation Band of T_2O
H. R. Child[11,12] University of Tennessee	E. O. Wollan[13] and W. C. Koehler[12]	Magnetic Structure Properties of Some Heavy Rare Earth Alloys (see ORNL-TM-1063)
W. B. Dress[14] Harvard University	P. D. Miller	Neutron Electric Dipole Moment Experiment
R. W. Hockenbury Rensselaer Polytechnic Institute	R. C. Block	Neutron Capture Measurements
P. G. Huray[14] University of Tennessee	L. D. Roberts	Mössbauer Resistance Correlation on the Impurities in Alloys
J. W. Hutcherson[10] Vanderbilt University	P. M. Griffin	Experimental Determination of Electronic Oscillator Strengths for Resonance Lines of Noble Gases by Absorption Spectroscopy
R. L. Kernell[10] University of Tennessee	C. H. Johnson and H. B. Willard	Isobaric Analogue States in Medium Weight Nuclei

[10]Oak Ridge Graduate Fellow.

[11]Doctorate received in 1965.

[12]Now with the ORNL Solid State Division.

[13]Now with the ORNL Director's Division.

[14]Loanee status with the ORNL Physics Division pending Oak Ridge Graduate Fellowship appointment.

T. King Rensselaer Polytechnic Institute	R. C. Block	Neutron Capture Measurements
W. G. Love[14] University of Tennessee	G. R. Satchler	Theory of Nuclear Reactions
A. D. MacKellar[10,15] Texas A and M University	R. L. Becker and T. A. Welton	Nuclear Ground State Properties of ^{16}O by an Extension of the Eden-Emery Method (see ORNL-TM-1374)
J. H. Marable[16] University of Tennessee	T. A. Welton	Nuclear Three-Body Problem
W. T. Milner University of Tennessee	F. K. McGowan	Coulomb Excitation with Heavy Ions
C. W. Nestor, Jr. Vanderbilt University	G. R. Satchler	Theory of Nuclear Structure
D. O. Patterson[10] University of Tennessee	L. D. Roberts and F. E. Obenshain	Pressure Dependence of the Energy of the Resonance Gamma Ray of ^{197}Au and the Hyperfine Structure Coupling of ^{197}Au in Ordered Au-Mn Alloys
S. K. Penny University of Tennessee	G. R. Satchler	Theory of Nuclear Reactions
M. Reeves III[10] University of Tennessee	C. M. Jones and H. B. Willard	Experimental Studies in Polarization Phenomena in the Light Nuclei
R. O. Sayer[10] University of Tennessee	P. H. Stelson	Coulomb Excitation
S. T. Thornton[10] University of Tennessee	H. B. Willard and C. M. Jones	Measurement of Neutron-Deuteron Scattering Lengths
M. L. West II[10] University of Texas	H. B. Willard and C. M. Jones	(n,p) Differential Scattering Cross Section

Oak Ridge Resident Graduate Program of the University of Tennessee

During the past year two members of the Physics Division staff have been affiliated with the Oak Ridge Resident Graduate Program of the University of Tennessee – E. C. Campbell as Acting Director, and R. L. Becker and E. C. Campbell as lecturers in physics.

There are at present 322 students enrolled in the Oak Ridge Resident Graduate Program, of which 22 are candidates for the Ph.D. degree in physics and 24 are candidates for the Master's degree in physics. Since the Resident Graduate Program of the University began operation in 1947, 70 Ph.D. degrees have been granted in physics to students enrolled in the Oak Ridge Program.

Consultants Under Subcontract

Staff members of universities who have served as consultants to the Division during the past year are listed below. Numerous other consultants have worked in collaboration with the various Physics programs and have presented seminar talks during this period.

[15]Thesis research completed in 1965 with doctorate expected in 1966; now with Massachusetts Institute of Technology.

[16]Now with the ORNL Reactor Division.

M. Baranger Carnegie Institute of Technology	Theoretical Physics Program
L. C. Biedenharn, Jr. Duke University	Theoretical Physics Program
W. M. Bugg University of Tennessee	High Energy Physics Program
J. W. Burton Carson-Newman College	Mössbauer Experimental Program
G. T. Condo University of Tennessee	High Energy Physics Program
R. D. Edge University of South Carolina	High Voltage Program
J. B. French University of Rochester	Theoretical Physics Program
J. H. Goldstein Emory University	Spectroscopy Research Program
R. Hefferlin[17] Southern Missionary College	Spectroscopy Research Program
W. G. Holladay Vanderbilt University	Theoretical Physics Program
R. W. Lide University of Tennessee	Physics of Fission Program
J. B. Marion University of Maryland	Low Energy Neutron Time-of-Flight Spectroscopy Program
S. A. Moszkowski University of California at Los Angeles	Theoretical Physics Program
H. W. Newson Duke University	High Voltage Program
A. H. Nielsen University of Tennessee	Spectroscopy Research Program
W. T. Pinkston Vanderbilt University	Theoretical Physics Program
J. O. Thomson University of Tennessee	Low Temperature Program and Mössbauer Experimental Program
K. Wildermuth Florida State University	Physics of Fission Program
L. Wilets University of Washington	Physics of Fission Program
J. H. Wise Washington and Lee University	Spectroscopy Research Program

[17]Formerly consultant with the ORNL Thermonuclear Division.

One graduate student has also been a part-time consultant to the Division:

S. C. Burnett University of Tennessee	Physics of Fission Program

Traveling Lecture Program

The Traveling Lecture Program is conducted in cooperation with the Oak Ridge Institute of Nuclear Studies as a part of the U.S. Atomic Energy Commission's program of encouraging the dissemination of scientific and technical information to universities, particularly those in the South. Laboratory personnel present in their lectures unclassified information to university undergraduate and graduate students and to faculty members. The lectures serve to stimulate interest in research in the university departments and also assist the teaching staff in expanding the scope of instruction offered under the regular curricula. Through such personal contacts, ORNL staff members are also able to observe departmental activities at the universities. During the current academic year (1965–66), eight members of the Physics Division have to date accepted invitations to present 30 lectures under this program; a complete listing of these will appear in the next Annual Report.

Listed below are 14 members of the Division who participated in the Traveling Lecture Program during academic year 1964–65, presenting a total of 30 lectures at 23 different colleges and universities:

R. C. Block	Virginia Polytechnic Institute, December 1, 1964 "Low Energy Neutron Physics"
E. C. Campbell	University of Georgia, January 13, 1965 "The Mössbauer Effect and Nuclear Anomalous Dispersion"
J. L. Fowler	Rice University, February 3, 1965 "Spectra of Closed Shell Plus One Nuclei"
W. M. Good	University of Alabama, November 12, 1964 "Pulsed Van de Graaff Accelerators in Theory and Application"
P. M. Griffin	Berea College, January 11, 1965 University of Louisville, April 23, 1965 "An Introduction to the Optical Maser, with Demonstrations"
C. M. Jones	Louisiana State University (New Orleans), December 1, 1964 Tulane University, November 30, 1964 University of Texas, December 2, 1964 West Virginia University, March 24, 1965 Michigan State University, March 25, 1965 "Nuclear Reactions Leading to Three Particles"
P. D. Miller	Randolph-Macon College, March 15, 1965 "A History of Nuclear Reactions"
	University of Richmond, March 16, 1965 "The Interaction of 350-keV Polarized Neutrons with Polarized Holmium"

H. W. Morgan	Muskingum College, November 18, 1964 "An Introduction to the Optical Maser, with Demonstrations"
F. E. Obenshain	Villa Madonna College, October 14, 1964 Southern Illinois University, October 16, 1964 Sam Houston State College, February 18, 1965 Texas Christian University, February 19, 1965 Tulane University, February 22, 1965 "Application of the Mössbauer Effect to Problems in Nuclear and Solid State Physics"
	Louisiana State University (New Orleans), February 23, 1964 "Mössbauer Investigations of the Magnetic Properties of Solids"
L. D. Roberts	Florida State University, October 1, 1964 "The Correlation Between the Mössbauer Isomer Shift and Residual Electrical Resistance for Gold Alloys"
	Auburn University, May 7, 1965 "The Use of Mössbauer-Effect Gamma Radiation in the Study of Metals"
R. L. Robinson	Mississippi State University, March 4, 1965 "Coulomb Excitation of Even-Odd Medium Weight Nuclei"
	Ohio University, March 26, 1965 "Excitation of Collective States by Inelastic Scattering of 14-MeV Neutrons"
H. W. Schmitt	University of Georgia, November 19, 1964 "Current Research in the Physics of Fission"
Katharine Way[18]	Florida State University, March 11, 1965 "Operation of a Scientific Information Center"
T. A. Welton	Southern Illinois University, November 19, 1964 University of Miami, December 10, 1964 Florida State University, December 8, 1964 "Direct Determination of Molecular Structure by Electron Microscopy"
	University of Alabama, May 6, 1965 "Relativistic Quantum Mechanics with a Fundamental Length"

Visiting Scientists Program in Physics – Colleges

The Visiting Scientists Program in Physics – Colleges, now in its ninth year, is sponsored jointly by the American Association of Physics Teachers and the American Institute of Physics under grants from the National Science Foundation. The Program has the following objectives: (1) to stimulate interest in physics among undergraduates in colleges and universities through visits by leaders in physics research, (2) to provide opportunities for physics staff members of

[18]Now with ORNL Director's Division.

the visited institutions to discuss their research and teaching problems with the visiting physicists, and (3) to acquaint other members of the academic community and the public with recent developments in physics. Emphasis is placed on visits to the smaller colleges and universities. Two Physics Division staff members lectured under this program in 1965:

J. L. Fowler	Dickinson College, Carlisle, Pennsylvania April 7–8, 1965 "Nuclear Science: Foundation of Future Technology" (to the Physics Club) "Spectroscopy of Alkaline Metal Type Nuclei" (for Nuclear Physics Class)
H. B. Willard	Hastings College, Hastings, Nebraska April 22–23, 1965 "Nucleon-Nucleon Interactions"

University Seminars

In addition to lectures presented under the Traveling Lecture Program and the Visiting Scientists Program in Physics, and to talks given at national and international scientific conferences, Divisional staff members receive numerous requests from universities and colleges for seminar talks. Fifteen such invitations were accepted from 11 different educational institutions during this report period:

R. C. Block	Northwestern University, May 26, 1965 "Neutron Capture Experiments Below 10 keV"
	Rensselaer Polytechnic Institute, December 10, 1965 "Neutron Capture Cross Section Measurements"
T. A. Carlson	University of Virginia, September 17, 1965 "Multiple Ionization in Atoms and Molecules"
K. T. R. Davies	Carnegie Institute of Technology, November 12, 1965 Massachusetts Institute of Technology, November 19, 1965 "Hartree-Fock Calculations of Finite Nuclei"
P. M. Griffin	University of Cincinnati, January 9, 1965 DePauw University, April 21, 1965 "An Introduction to the Optical Maser, with Demonstrations"
H. W. Morgan	Hollins College, November 13, 1965 "Laser Lecture Demonstration"
L. D. Roberts	University of Tennessee (Physics Department Information Meeting), November 22, 1965 "The Mössbauer Effect for ^{197}Au in Alloys and as a Function of Pressure"
G. R. Satchler	University of Michigan, October 19 and 21, 1965 "Nuclear Direct Reactions" and "Shell Model and Inelastic Scattering"
H. W. Schmitt	University of Pittsburgh, March 10, 1965 "Fission Studies at Low Excitation Energy"
	University of Washington, November 15, 1965 "Nuclear Fission at Low Excitation Energies"

G. G. Slaughter	Rensselaer Polytechnic Institute, October 21, 1965 "High Resolution Neutron Capture Gamma Ray Spectroscopy"
T. Tamura	University of Washington, October 18, 1965 "Analyses of the Scattering of Nuclear Particles by Collective Nuclei in Terms of the Coupled-Channel Calculation"
T. A. Welton	University of Tennessee (Physics Department Information Meeting), November 22, 1965 "Molecular Structure Determination by High Resolution Electron Microscopy"
H. B. Willard	University of Tennessee (Physics Department Information Meeting), November 22, 1965 "Nuclear Reaction Studies"

American Association of Physics Teachers

The American Association of Physics Teachers met at the University of Tennessee in Knoxville, June 17–19, 1965. Four Physics Division staff members took an active part in the meeting. These included L. D. Roberts[19] and H. B. Willard[19] as members of the five-member Program Committee; and J. H. Gibbons and T. A. Welton[19] who, as invited speakers, presented two of the eight invited papers on the program – 31 contributed papers were given. L. D. Roberts[19] served also as a session chairman.

Infrared Training Institute

H. W. Morgan and P. A. Staats, of the Spectroscopy Research Program of the Physics Division, participated as lecturer and lecturer and laboratory director, respectively, in an Infrared Training Institute held in Sao Paulo, Brazil, February 1–20, 1965; their lectures were concerned with well-known areas of spectroscopy. The course was organized by Fisk University and was jointly sponsored by the Agency for International Development (USA), the Organization of American States, the University of Sao Paulo, and the Academies of Science of Brazil and of the State of Sao Paulo. The concept for this infrared course in South America originated with H. W. Morgan, who, together with P. A. Staats, did much of the organizing and planning for the Institute; both have been actively associated with the Fisk Infrared Institute for the past eight years.

[19] Part-time Professor of Physics at the University of Tennessee.

Institute on Nuclear Science and World Politics

The Oak Ridge Institute of Nuclear Studies, the Carnegie Endowment, and the U.S. Atomic Energy Commission cosponsored an Institute on Nuclear Science and World Politics during the three-week period of April 12–30, 1965. Meetings were held each week day in the ORINS library building.

The primary purpose of the Institute was to increase the understanding of some major concepts of nuclear physics and related technologies in order (1) to examine the role science plays in a technologically advanced society and (2) to explore international political problems having roots in contemporary developments in nuclear science.

The participants included 20 persons in the field of international relations who were selected from colleges, universities, and government agencies; ten of these were staff members of ORNL. One ORNL Physics Division staff member, T. A. Welton, took part in the session which dealt with "The Growth of Nuclear Science and the Technological Society" and gave an after-dinner address entitled "The Frontiers of Nuclear Research."

Annual Summer Institute for Theoretical Physics

The Eighth Annual Summer Institute for Theoretical Physics was held at the University of Colorado in Boulder from June 14 through August 20, 1965. Among the fifteen invited lecturers, prominent in the field of nuclear structure and reactions, was one member of the ORNL Physics Division, G. R. Satchler, who devoted nine lecture hours during July to the topic "The Theory of Nuclear Direct Reactions."

ORINS-ORNL Summer Institute in Modern Physics

A Summer Institute in Modern Physics for physics teachers from small colleges was held in Oak Ridge June 14 through August 6, 1965. This was the fifth such Institute conducted by the Oak Ridge Institute of Nuclear Studies in cooperation with the Oak Ridge National Laboratory and sponsored by the U.S. Atomic Energy Commission. Again this year, the Institute was designed primarily to give participants an opportunity to review modern physics, acquire an understanding of current developments, become familiar with new equipment, and gain greater insight into the development of college courses in the fields of their interests.

Attendance at the Summer Institute was limited to 20 college physics teachers from as many colleges. The major portion of the formally scheduled time was used for classroom lectures, laboratory assignments, and visits to Oak Ridge laboratories. Additional unscheduled time was provided for group discussions, library work, individual study, and attendance at special lectures and discussions.

Physics staff members who lectured during the eight-week period of the Institute included: R. L. Becker (3 lectures on "Nuclear Physics"); J. L. Fowler (15 lectures on "Nuclear Physics"); J. A. Biggerstaff (1 lecture on "Time Measurements in Nuclear Spectroscopy"); and R. L. Robinson (1 lecture on "Energy Levels").

Lecture demonstrations and/or tours conducted in the Division were as follows:

H. B. Willard and P. H. Stelson	"High Voltage Laboratory"
J. A. Harvey, J. W. T. Dabbs, and G. G. Slaughter	"Neutron Physics at ORNL"
P. M. Griffin	"Lasers"
J. O. Thomson, J. W. Burton, L. D. Roberts, and G. Czjzek	"Mössbauer Experiments at ORNL"

Conference – Impact of Science on Society

A four-week conference, "Impact of Science on Society," was conducted July 6 through 30, 1965, by the Oak Ridge Institute of Nuclear Studies in cooperation with the Division of Nuclear Education and Training, the U.S. Atomic Energy Commission, and supported by the National Science Foundation. Twenty-four participants from the faculties of 20 of the sponsoring institutions of the Oak Ridge Institute of Nuclear Studies attended the conference, at which 14 Oak Ridge National Laboratory scientists spoke, including one from the Physics Division, J. H. Gibbons, whose topic was "Little Science in a Big Laboratory."

Primarily, the conference was designed (1) to provide an opportunity for university faculty in the natural and social sciences and humanities to discuss those aspects of science in general, and nuclear technology in particular, that affect man and his society, (2) to discuss nuclear energy and social change in a manner suitable for subsequent use in student courses and adult study groups, and (3) to encourage interdisciplinary cooperation of teaching and research efforts.

First Pacific International Summer School in Physics

The topic covered by the First Pacific International Summer School in Physics which was held in Honolulu, Hawaii, August 9 through September 1, 1965, was "Strong Interactions of Elementary Particles." Other than lecturers, participation in the school was limited to 40 invited physicists. H. O. Cohn (High Energy Physics Group of the Physics Division) was the ORNL representative in attendance. His seminar was entitled "Present Status of the ϵ^0 Meson."

The School was oriented toward experimental and theoretical physicists, and the need for closer mutual understanding between them was stressed.

Approximately one-half of the participants were high-energy physicists, whose work demands a lucid and fairly detailed understanding of present-day theories of elementary particles; the other half were theoretical physicists, primarily of the younger generation.

ORNL PHYSICS SEMINARS

Divisional seminars are normally held at the Laboratory each Friday at 3:15 PM; for topics of especial timeliness or interest additional talks are frequently scheduled. C. M. Jones assumed the duties of seminar chairman in June 1965, replacing R. L. Becker, who served as seminar chairman the preceding year. Lectures presented during calendar year 1965 are listed below:

January 8	W. M. Bugg, University of Tennessee "Symmetries and Resonances in Elementary Particle Physics"
January 11– February 10	R. Z. Roskies,[1] Princeton University "Theory of Lie Groups" (first in series of 11 talks)
January 15	A. Zucker, ORNL "The Scattering of 40 MeV Polarized Protons"
January 21	E. H. Taylor, ORNL "The Last Time I Saw Sverdlovsk"
February 5	P. D. Miller, ORNL "Nuclear Interaction of Polarized Neutrons with Polarized Holmium"
February 12	J. S. Faulkner, ORNL "Electronic Structure of Disordered Systems"
February 19	J. H. Gibbons, ORNL "Neutron Capture and Isotopic Abundance: The Primary Empirical Evidence for Stellar Nucleosynthesis"
February 26	A. M. Green, Institute for Advanced Studies "The Oxygen Isotopes"
March 5	Charles Hill, Lockheed Aircraft Company "A Model for Estimating Proton-Induced Gamma Ray Spectra"
March 12	J. F. Schooley, National Bureau of Standards "Superconductivity in Semiconducting Strontium Titanate"
March 19	M. M. Block, Northwestern University "Recent Neutrino Experiments at CERN"
March 26	G. Dearnaley, Los Alamos Scientific Laboratory "Fluctuations in (α,p) Reactions, and Channeling of Ions in Single Crystal Semiconductors"

[1]Presented as part of a Special Theoretical Seminar Series coordinated by J. B. McGrory.

April 2	J. de Boer, Rutgers University "The Reorientation Effect in the Coulomb Excitation of ^{114}Cd"
April 9	John Burton, Carson-Newman College "The Mössbauer Effect of ^{57}Fe on the Surface of Tungsten"
April 23	C. D. Moak, ORNL "Artificial Fission Fragments"
May 4	M. J. Moravcsik, Lawrence Radiation Laboratory, Livermore "Parity Experiments in Particle Reactions"
May 7	D. M. Seyboth, University of Erlangen "Mössbauer Effect of ^{61}Ni Using Coulomb Excitation"
May 14	M. Sakai, University of Tokyo "Investigation of Two Phonon Vibrational States with $(p,2n\gamma)$ Reactions"
May 21	G. S. Hurst, ORNL "Swarm and Beam Studies of Electron Capture"
May 25	K. Nishimura, Japan Atomic Energy Research Institute and Northwestern University "Studies of Excitation Cross Sections of $(n,n'\gamma)$ Reactions"
May 28	H. H. Wickmann, Bell Telephone Laboratories "Mössbauer Studies of Paramagnetic Hyperfine Interaction and Relaxation Effects"
June 4	J. W. T. Dabbs, ORNL "IAEA Fission Conference, Salzburg; Garching Reactor Station, Munich, Germany"
June 25	R. D. Present, University of Tennessee "Electromagnetic Properties of the ^{7}Li Nucleus"
July 2	H. W. Morgan, ORNL "Infrared Spectroscopy in Brazil"
July 6	M. A. Melvin, Florida State University "The Inhomogeneous Lorentz Group — I"
July 8	J. H. Marable,[1] ORNL "The Faddeev Equations"
July 9	M. A. Melvin, Florida State University "Galactic Super High Energy Sources and Gravitational Collapse"
July 13	M. A. Melvin, Florida State University "The Inhomogeneous Lorentz Group — II"
July 14	M. A. Melvin, Florida State University "The Inhomogeneous Lorentz Group — III"
July 16	A. E. S. Green, University of Florida "Meson Theory of Nuclear Forces"
July 21	D. Harrington,[1] Rutgers University "The Faddeev Equations"
July 23	R. F. O'Connell, Louisiana State University "Present State of the Theory of Internal Conversion and Related Processes"
July 30	K. L. Vander Sluis, ORNL "Atomic Spectra of Erbium"
August 6	R. T. Folk, Lehigh University "The Wave Functions for Few-Nucleon Systems"

August 9	A. H. Wapstra, Instituut voor Kernphysich Onderzoek, Amsterdam "Detection of Cosmic Ray Electrons in an Artificial Satellite"
August 12	T. Tamura,[1] ORNL "A Program to Calculate Bound State Wave Functions in a Deformed Well"
August 16	R. M. Tarbutton,[1] Vanderbilt University "Mixed Configuration Shell Model Calculations in the Region $A = 87-90$"
August 20	R. D. Edge, University of South Carolina "Photodisintegration and ^{14}N"
August 23	A. Michaudon, CEN, Saclay "Study of the Statistical Properties of the Interaction of Resonance Neutrons with Fissile Nuclei"
August 27	C. Wong, Princeton University "Superheavy Nuclei and Supernovae"
September 7	M. Baranger,[1] Carnegie Institute of Technology "The Gordon Conference"
September 9	Fred Vaslow, ORNL "Some Aspects of the Interaction of Ions in Water"
September 15–17	B. B. Goodman, Centre National de la Recherche Scientifique, France "Type II Superconductivity"
September 16	Y. E. Kim,[1] ORNL "Realistic Forces in the Nuclear Shell Model"
September 24	K. T. R. Davies, ORNL "Hartree-Fock Calculations of Finite Nuclei"
October 1	J. H. Gibbons, ORNL "Some Aspects of the Human Population Problem"
October 7	Paul Shanley,[1] Northeastern University "A Three-Body Model of Deuteron Stripping"
October 8	H. B. Willard, ORNL "Report on the International Conference on Polarization Phenomena of Nucleons"
October 15	T. A. Tombrello, California Institute of Technology "Three- and Four-Body Final States from $^3He + {}^3He$"
October 22	T. A. Belote, Massachusetts Institute of Technology "Nuclear Spectroscopy in the $f_{7/2}$ Shell"
October 29	B. C. Diven, Los Alamos Scientific Laboratory "Neutron Experiments with Nuclear Explosions"
November 5	N. H. Lazar, ORNL "Progress in DCX-2 Experiments and the ORNL Controlled Fusion Program"
November 8	S. A. Moszkowski, University of California at Los Angeles "Nuclear Spectra with Surface Delta Interaction"
November 19	F. G. Perey, ORNL "Low Energy Nuclear Physics at Saclay"
December 3	W. G. Pollard, ORINS "Quarks"
December 10	P. R. Bell, ORNL "The Mariner IV Measurement of Mars"

December 13	C. O. Beasley,[1] ORNL "Cold Plasma Stabilization in Hot Electron Plasmas"
December 17	D. Robson, Florida State University "Isobaric Spin Resonances"
December 20	K. H. Koppe, University of Kiel, Germany "Macroscopic Theory of Superconductors of the Second and Third Kinds"
December 22	B. Muhlschlegel, University of Cologne, Germany "Theory of Superconducting Alloys in Strong Magnetic Fields"

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