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ORNL-4743

PHYSICS Division - Annual PROGRESS REPORT

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Period Ending December 31, 1971

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Printed in the United States of America. Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road, Springfield, Virginia 22151
Price: Printed Copy $3.00; Microfiche $0.95

ORNL-4743
UC-34—Physics

Contract No. W-7405-eng-26

PHYSICS DIVISION
ANNUAL PROGRESS REPORT
For Period Ending December 31, 1971

J. L. Fowler, Director
G. R. Satchler, Associate Director
P. H. Stelson, Associate Director

Felix E. Obenshain, Editor

MAY 1972

OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37830
operated by
UNION CARBIDE CORPORATION
for the
U.S. ATOMIC ENERGY COMMISSION

Reports previously issued in this section are as follows:

ORNL-2718	Period Ending March 10, 1959
ORNL-2910	Period Ending February 10, 1960
ORNL-3085	Period Ending February 10, 1961
ORNL-3268	Period Ending February 10, 1962
ORNL-3425	Period Ending January 31, 1963
ORNL-3582	Period Ending January 31, 1964
ORNL-3778	Period Ending December 31, 1964
ORNL-3924	Period Ending December 31, 1965
ORNL-4082	Period Ending December 31, 1966
ORNL-4230	Period Ending December 31, 1967
ORNL-4395	Period Ending December 31, 1968
ORNL-4513	Period Ending December 31, 1969
ORNL-4659	Period Ending December 31, 1970

Contents and Summary

2. HIGH ENERGY PHYSICS

From 8-GeV/c π^+d interactions we have found that either one of the two resonances reported in the T region has a dominant decay into other than the reported decay modes or that there is a third resonance in this region.

3. NUCLEAR STRUCTURE, REACTIONS, AND RADIOACTIVITY

3*a*. Systematics

A report of the Ad Hoc Panel on Nuclear Data Compilations Committee on Nuclear Science National Research Council, published by National Academy of Sciences, Committee on Nuclear Science, 2101 Constitution Avenue, Washington, D.C. 20418.

Abstract of published paper: *Nucl. Data Tables* A9, 469 (1971).

The work of the Nuclear Data Project for the calendar year 1971 is reviewed. In addition to a list of revised A-chain compilations, the continuing development of computer aids and the interaction between the Project and researchers in the field and applied users are discussed.

Abstract of ORNL-4655.

3*b*. $A \leqslant 22$

Abstract of published paper: *Phys. Rev. Lett.* 26, 909 (1971).

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

A prominent peak is observed at forward angles ($\leqslant 11^\circ$) in the spectrum of alpha particles if ^{3}He is bombarded by 63.7-, 71.7-, and 81.4-MeV alphas. Evidence is presented that this peak is due to a sequential decay process involving the 2.18-MeV excited state in ^{6}Li. However, the shape of the alpha-spectrum can only be explained by postulating that in the c.m. system the alpha-particle is emitted preferentially in forward directions ($\sim 30^\circ$) with respect to the original ^{6}Li* direction. No explanation for this effect has as yet been found.

Abstract of paper submitted for publication in *Nuclear Instruments and Methods.*

3c. $22 < A \leqslant 100$

4. FISSION

5. MÖSSBAUER SPECTROSCOPY

6. ATOMIC AND MOLECULAR PHYSICS

7. INSTRUMENTATION AND EXPERIMENTAL TECHNIQUES

8. OMNIANA

Foreword

This is the 14th Physics Division Progress report made on an annual basis. However, it is the first report since the merger of the Electronuclear Division and the Nuclear Data Project with the Physics Division. 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.

The Contents and Summary for this report includes subject headings, and at the end of the report an Author Index. The divisional monthly reports, which consist of about 200 words summarizing at least one activity of the division each month, are included and give an overview of various research efforts. The reports for 1971 may be found at the beginning of this report. Papers involving development of instrumentation, applied physics, and status reports on our research facilities are included in the section "Instrumentation and Experimental Techniques." The last section "Omniana" is a collection of information about the division and the activities of the staff and their guests.

MONTHLY REPORTS OF THE PHYSICS DIVISION

The Divisional monthly reports, which consist of about 200 words, summarize at least one activity of the Division for each month of the year. These reports for the Division for calendar year 1971, with references to the literature updated as of the time of submission of this annual report, are as follows:

High-Resolution Inelastic Cross-Section Measurements – January

Among the most important properties of nuclei for nuclear technology are their cross sections for inelastic neutron scattering, but these cross sections are among the most difficult to measure. Recently, Perey, Kinney, and Macklin[1] have adapted the apparatus installed at the 40-m flight path of ORELA for the neutron capture cross-section program[2] to measure neutron inelastic scattering with high energy resolution. They detect deexcitation gamma rays in a 4π geometry with a hydrogen-free fluorocarbon liquid scintillator, using 0.125 nsec/m neutron time-of-flight resolution. For the initial experiments on ^{7}Li, ^{23}Na, ^{27}Al, ^{28}Si, ^{56}Fe, and ^{51}V, they analyze the data up to the threshold of the second excited state of the nuclei. In order to evaluate the background, they used a carbon sample. The ^{7}Li data served to determine the neutron flux. The inelastic cross sections for ^{23}Na, ^{28}Si, and ^{56}Fe showed great resonance structure with peak-to-valley ratios larger than those found in the total cross sections. The energy resolution was sufficient to identify all the resonances observed in the inelastic cross section with resonances in the total cross sections. By improving the instrumentation and the analysis, Perey et al.[1] expect to extend the technique to obtain data beyond the second inelastic level of nuclei.

1. F. G. Perey, W. E. Kinney, and R. L. Macklin, pp. 191–95 in *Proceedings Third Conference on Neutron Cross Sections and Technology* (Knoxville, Tennessee, March 1971), ed. by R. L. Macklin, USAEC Conf-710301, vol. 1, 1971.
2. R. L. Macklin and B. J. Allen, *Nucl. Instrum. Methods* 91, 565–71 (1971).

Core Polarization and the Nucleon-Nucleus Spin-Spin Interaction – February

The forces between two nuclei can be deduced from observations on collisions between them. Recently, there have been remarkable advances in the detailed description of the interaction between nuclei which starts from the basic forces between nucleons (neutrons and protons), the constituent particles of nuclei.[1] This fundamental approach, which is being pursued aggressively at ORNL, allows one to relate observations on nuclear scattering to a wide range of other nuclear phenomena. For example, G. R. Satchler has shown[2] that there is a connection between the spin-spin interaction term in the optical potential describing the scattering of a projectile with spin by an odd mass target nucleus and the observed deviation of nuclear magnetic moments from the Schmidt line values predicted by the single-particle shell model. He points out that nucleus core polarization (renormalization of the effective interaction due to virtual excitations of the core) will reduce the spin-spin interaction in the case of scattering in the same way this type of polarization quenches the spin contributions to the magnetic moment of an odd nucleon. Using the magnetic moments of the ^{41}Ca-^{41}Sc pair, he is able to calculate approximately the spin-spin term observed in the scattering of nucleons from ^{59}Co.

1. W. G. Love and G. R. Satchler, *Nucl. Phys.* 159, 1 (1970).
2. G. R. Satchler, *Phys. Lett.* 34B, 37 (1971).

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Products of the $^{58,60,62}Ni(^{16}O,x)$ Reactions – March

For the last several years it has been emphasized that heavy ion reactions allow one to fill in the gaps of knowledge about nuclei between those just stable against neutron emission and those unstable against proton emission. The low gamma-ray background, versatility, and reliability of the ^{16}O ion beams from the tandem Van de Graaff machine permit definitive experiments in this direction. Robinson et al.[1] have studied nuclei around $A = 74$ by bombarding separated targets of ^{58}Ni, ^{60}Ni, and ^{62}Ni with 30- to 45-MeV ^{16}O ions to produce $^{58,60,62}Ni(^{16}O,x)$ reactions. They identified the products with a combination of half-life and gamma-ray energy measurements and investigated detailed decay schemes with gamma-gamma coincidence apparatus in which one gamma ray was detected with a 30-cc Ge(Li) crystal in coincidence with another counted with an NaI scintillator. They found that the cross section of the $^{60}Ni(^{16}O,pn)^{74}Br$ reaction increases by a factor of about 100 between 33 and 39 MeV ^{16}O energy and is about 20 mb at 38 MeV. At 42.5 MeV the cross section for this reaction is more than eight times the cross section of the reaction $^{60}Ni(^{16}O,2n)^{74}Kr$. Gamma rays from the decay of 44-min ^{74}Br indicated that there are levels in ^{74}Se at 634.0, 1269.2, 1362.0, 1619.1, 1884.7, 2107.1, 2563.3, 2662.3, and 3077.2 keV. Previously, only two levels in ^{74}Se were known.

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1. R. L. Robinson, H. J. Kim, J. L. C. Ford, Jr., E. Collins, and J. H. Hamilton, *Bull. Amer. Phys. Soc.* 16, 626 (1971).

Computational Correction of Aberrations in Electron Micrographs – April

Phase-contrast electron micrographs consist of a two-dimensional display of the internal atomic electrostatic potential of the sample, as spread by aberrations, diffraction, etc. This display is obscured by random fluctuations arising from electron statistics and random substrate arrangement. Alteration of molecular structure by radiation damage limits the electron flux allowable[1] and therefore limits the statistics. T. A. Welton[2] has evolved a systematic simple procedure for extracting from such imperfect data both the most probable configuration and the probability of error incurred by using this most probable result. The micrograph is scanned and the sample density values placed on tape. A selected square of data is Fourier transformed and its statistical properties analyzed to obtain several crucial functions of the instrumental parameters. The transform is then multiplied by a function, which is constructed according to a simple recipe from the statistical functions first determined. The result is then inverse transformed to obtain the most probable sample, freed of most noise and instrumental imperfections. A number of tests have been performed with very good results, and it is felt that this method may be of fairly general applicability to one-, two-, and three-dimensional data sets with spatial (or temporal) spread and with added random error.

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1. T. A. Welton, pp. 338–39 in *Proceedings 26th Annual Meeting Electron Microscopy Society of America* (New Orleans, Louisiana), Claitor's Publishing Division, Baton Rouge, 1968.
2. T. A. Welton, pp. 94–95 in *Proceedings 29th Annual Meeting Electron Microscopy Society of America* (Boston, Massachusetts), Claitor's Publishing Division, Baton Rouge, 1971.

New Effects Observed in X-Ray Spectra from Fast Iodine Ions – May

Since the x-ray spectrum from heavy elements is coming to be used as a tool for identifying elements, it is important to find out how x-ray spectra depend on the condition of the atoms, such as, for example, their charge state. With the ORNL tandem Van de Graaff, S. Datz, C. D. Moak, and B. R. Appleton[1] have studied the L x-ray spectra of fast iodine ions stopping in various target materials, using an Si(Li) x-ray detector. They found that the intensity ratio of the iodine $L\alpha_{12}$ and $L\beta_1$ lines varies as much as a factor of 6 from target to target. This discovery indicates a strong differentiation in vacancy production in the $2p_{3/2}$ and $2p_{1/2}$ subshell of iodine. The applicability of the Fano-Lichten level-crossing model is uncertain since no diagrams have been constructed which include spin-orbit coupling; however, it seems clear that some sort of

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1. S. Datz, C. D. Moak, and B. R. Appleton, *Bull. Amer. Phys. Soc.* 16, 563 (1971).

pseudomolecular orbital model must be invoked to explain the strong sensitivity of the ion spectrum to the target element. Datz et al. determined the x-ray production cross section for each line in the spectra for 16 different targets (Z = 6 to 82) and observed oscillations in the region of shell binding energy overlap. They found that the energy shifts in the lines, indicating the degree of ionization of the emitting atom, varied with subshell as well as with principal quantum number and collision energy.

^{3}He Elastic Scattering in the 50- to 71-MeV Energy Range – June

One of the most dependable tools for obtaining information in nuclear spectroscopy has been the nuclear stripping reactions, and (d,p) stripping has been used extensively to extract parameters of nuclear levels of target nucleus plus one neutron nuclei. Because of the difficulties associated with neutron detection, (d,n) stripping has not been used nearly as much for determining the level properties of the corresponding mirror nuclei. The $(^3\text{He},d)$ stripping reaction allows this type of information to be readily obtained by use of charged-particle detection, but optical-potential parameters are required for mass 3 scattering in order to analyze the stripping results. At the Oak Ridge Isochronous Cyclotron (ORIC), Hafele, Fulmer, and Kingston have made a study of elastic scattering of ^{3}He at 50 MeV for ^{59}Co and ^{60}Ni;[1] at 60 MeV for ^{27}Al, ^{48}Ti, ^{51}V, ^{52}Cr, ^{53}Cr, ^{59}Co, ^{60}Ni, and ^{144}Sm; and at 71 MeV for ^{60}Ni, ^{208}Pb, and ^{209}Bi. Since they have extended their measurements to large scattering angles where the cross sections are very small, they are able to resolve the ambiguities in the optical-model analysis of scattering of composite particles which occurred in previous studies. For example, the large-angle scattering of 60-MeV ^{3}He from ^{27}Al shows that the absorption term in the optical potential is peaked at the surface. Also, the large-angle scattering data allow a selection of the real potential well depth from among the several which fit forward-angle scattering.

1. J. C. Hafele, C. B. Fulmer, and F. G. Kingston, *Phys. Lett.* 31B, 17 (1970).

The Angular Distribution of Photoelectron Spectra from Atoms and Molecules – July

Photoelectron spectroscopy, by giving binding energies for each molecular orbital, has afforded an experimental basis on which to test molecular orbital theory. The measurement of the angular distribution of the photoelectrons ejected from molecules should offer an additional powerful tool for understanding the nature of these orbitals. T. A. Carlson et al.[1] have measured the photoelectron spectra as a function of angle between the incident photon and the ejected photoelectron for the following gases: Ar, Kr, Xe, H_2, N_2, O_2, CO, NO, HCl, N_2O, CO_2, COS, CS_2, H_2O, H_2S, CH_4, CH_3F, CH_3Cl, CH_3Br, CH_3I, CH_2F_2, $C(CH_3)_4$, $Si(CH_3)_4$, $Ge(CH_3)_4$, $Sn(CH_3)_4$, $Pb(CH_3)_4$, C_2H_4, and C_6H_6. They studied each gas with the He I resonance line (21.22 eV), and in a few cases with the Ne I (16.85 eV and 16.67 eV) lines produced in a gas discharge lamp. The lamp is mounted on a movable platform so that the angle between the incident photon and the ejected photoelectron can be scanned continuously from 20 to 140°. Their electron spectrometer employs two spherical sector plates capable of double focusing. They found the agreement between experiment and theory for the elementary systems of rare gases and H_2 to be very good. In addition, they were able to explain the behavior of more complex molecules in terms of expected alterations in the molecular orbitals throughout a series of homologous compounds.

1. T. A. Carlson, G. E. McGuire, A. E. Jonas, K. L. Cheng, C. P. Anderson, C. C. Lu, and B. P. Pullen, presented at International Conference on Electron Spectroscopy (Asilomar, California, September 1971).

Equilibrium Quadrupole and Hexadecapole Deformations in ^{230}Th and ^{238}U – August

We have known for some years that very heavy nuclei such as ^{238}U are not spherical but are instead shaped like a football. Such a shape can be described by an equation $R(\theta) = R_0[1 + \beta_2 Y_{20}(\theta)]$, where Y_{20} is the spherical harmonic function. Recent theoretical work suggests that the presence of an additional refinement in the shape of very heavy nuclei – a $\beta_4 Y_{40}$ term, popularly called a hexadecapole distortion – can exert a sizable influence on nuclear properties and must be properly accounted for in calculations which are extrapolated into the region of "superheavy" elements. The group in the Laboratory concerned with Coulomb excitation has used the tandem Van de Graaff in conjunction with the Enge split-pole magnetic spectrograph to measure, with 15-keV resolution, the elastic and inelastic scattering of 17- and 18-MeV alpha particles from targets of ^{230}Th and ^{238}U.[1] From the differential cross sections, measured at 150° for ^{230}Th and at 150 and 90° for ^{238}U, the experimenters found the *excitation probabilities* for transitions from the ground state to the 2^+ and the 4^+ states. They extracted the quadrupole and hexadecapole transition probabilities, from which they could obtain the β_2 and β_4 parameters giving the shapes of ^{230}Th and ^{238}U. They found the hexadecapole, β_4, deformation parameters to be 0.110 ± 0.027 for ^{230}Th and 0.100 ± 0.028 for ^{238}U. These are some 25 to 50% larger than theoretical estimates.

1. F. K. McGowan, C. E. Bemis, Jr., J. L. C. Ford, Jr., W. T. Milner, R. L. Robinson, and P. H. Stelson, *Phys. Rev. Lett.* 27, 1741 (1971).

Charge Asymmetry Effects in the Reaction ^{2}H(^{4}He,^{3}H)^{3}He – September

The nuclear force, although highly complex, appears to be insensitive to or invariant to the electrical charge of the interacting nucleons. A consequence of this is that in a nuclear reaction like the $^4\text{He} + ^2\text{H} \rightarrow ^3\text{He} + ^3\text{H}$ reaction, the yields of ^{3}He and ^{3}H should be symmetric about 90° in the center-of-mass system. A group,[1] using the alpha-particle beam from the Oak Ridge Isochronous Cyclotron, has tested this symmetry principle by measuring the reaction product ^{3}He at an angle θ and at a supplementary angle $180° - \theta$. Since these angles were symmetrically located with respect to 90°, the ratio of the observed yields should be identical to unity for all choices of the angle θ. The group found deviations as large as 15 to 20% from the predicted symmetry, and these deviations persisted for different bombarding energies. A possible source for this apparent violation of the charge independence of the nuclear forces is in the Coulomb interaction. A distorted-wave calculation, based on the assumption that the reaction proceeds via a combination of single-proton and single-neutron transfers, reproduces the trend of the observed asymmetries. In the calculation the asymmetry comes from the difference in the bound-state form factors for the proton and the neutron transfers. This difference arises from the disimilar Coulomb energies of ^{3}H and ^{3}He.

1. E. E. Gross, E. Newman, W. J. Roberts, R. W. Rutkowski, and A. Zucker, *Phys. Rev. Lett.* 24, 473 (1970).

p-Wave Neutron Capture Gamma-Ray Spectra from ^{98}Mo – October

The valency neutron model for neutron radiative capture assumes that radiative widths for neutron resonances may be calculated by considering the motion of a single neutron in a potential well. The model gives radiative widths proportional to the product of the reduced neutron widths of the initial and final states. Measurements of radiative neutron capture made at the BNL fast chopper with a ^{98}Mo target demonstrated the validity of this model for *p*-wave resonances below 1 keV. Recently, a collaborative effort of physicists at BNL and ORNL has extended these measurements to 5 keV by use of the Oak Ridge Electron Linear Accelerator.[1] These physicists have determined radiative transition rates from gamma-ray spectra following neutron capture at 21 resolved resonances. Between 1 and 4 keV the resonances have significantly smaller neutron widths than those below 1 keV, so that statistical processes might be expected to dominate the capture reaction. Indeed this is the case; the scientists did not observe the regularities expected from the valency model. Above 4 keV, however, the *p*-wave strength function increases, so that for a resonance at 4.842 keV, with a neutron width of 0.71 eV, they found the ground-state radiation width of 11.8 ± 3 mV, in good agreement with the valency model prediction. Other gamma transitions of this resonance were not in such good agreement with the theory.

1. G. W. Cole, S. F. Mughabghab, M. Bhatt, O. A. Wasson, R. E. Chrien, and G. G. Slaughter, submitted for publication in *Proceedings International Conference on Statistical Properties of Nuclei (Albany, New York, August 1971)*.

New Alpha-Emitting Isotopes with $N = 86$ and 87 – November

The study of alpha decay is not only a convenient way to identify new isotopes but also results in a direct measurement of the alpha decay energy, information which is useful for nuclear mass determinations. K. S. Toth, R. L. Hahn, and M. A. Ijaz,[1] with the heavy ions available at ORIC, have made a systematic search for missing isotopes in the region of $N = 86$ and 87. They used an experimental technique based on stopping recoil products ejected from thin targets in a jet of helium gas. After the recoils are deposited from the jet onto catchers, they measure the alpha spectra with Si(Au) surface-barrier detectors. By means of excitation function data and parent-daughter relationships, Toth et al. have discovered seven new rare-earth alpha emitters: ^{156}Yb, ^{157}Yb, ^{155}Tm, high-spin and low-spin isomers of ^{156}Tm, and high-spin isomers of both ^{153}Ho and ^{154}Ho. In their latest experiments, they produced ^{155}Tm and the two isomers of ^{156}Tm by bombarding ^{144}Sm and ^{147}Sm with ^{14}N ions or by bombarding ^{162}Er with ^{3}He. The final values for the alpha-decay energies and half-lives of these three radioactive species are as follows: (1) ^{155}Tm, $E_\alpha = 4.45 \pm 0.01$ MeV, $T_{1/2} = 39 \pm 3$ sec; (2) ^{156}Tm (low-spin isomer), $E_\alpha = 4.23 \pm 0.01$ MeV, $T_{1/2} = 80 \pm 3$ sec; and (3) ^{156}Tm (high-spin isomer), $E_\alpha = 4.46 \pm 0.01$ MeV, $T_{1/2} = 19 \pm 3$ sec.

1. K. S. Toth, R. L. Hahn, and M. A. Ijaz, *Bull. Amer. Phys. Soc.* **16**, 539 (1971); also *Bull. Amer. Phys. Soc.* **16**, 1162 (1971).

Shell-Model Theory of Nuclei – December

One of the fundamental problems of nuclear physics is to understand how a nucleus consisting of many discrete particles can exhibit the collective features manifested in some experimental data. The nuclear shell model is the fundamental microscopic model on which almost all microscopic nuclear theories are based. Each nucleon interacts directly with every other nucleon in the nucleus through a two-body force. The shell-model assumption is that most of the effects of all these mutual interactions can be represented by a picture in which all the particles move independently in one central force field. The Oak Ridge–Rochester shell-model program was developed to carry out microscopic calculations of the properties of a large number of nuclei in terms of the shell model. E. C. Halbert and J. B. McGrory, together with colleagues outside the Laboratory,[1–3] using this program, have studied nuclei throughout the periodic table, but they have concentrated on the $A = 18$ to 38 nuclei. They have satisfactorily accounted for the energy-level spectra and the single-particle strength to many levels in these nuclei with their calculations. They have also reproduced many features of the observed collective behavior of these nuclei, including rotational and vibrational motion. In particular, they have accurately accounted for the signs and relative magnitudes of all measured quadrupole moments in the *s-d* shell.

1. E. C. Halbert, J. B. McGrory, B. H. Wildenthal, and S. P. Pandya, *Advances in Nuclear Physics*, vol. 4, pp. 315–442, ed. by M. Baranger and E. Vogt, Plenum, New York, 1971.
2. B. H. Wildenthal, J. B. McGrory, E. C. Halbert, and H. D. Graber, *Phys. Rev.* **C4**, 1708 (1971).
3. B. H. Wildenthal, E. C. Halbert, J. B. McGrory, and T. T. S. Kuo, *Phys. Rev.* **C4**, 1266 (1971).

1. Theory

RENORMALIZED BRUECKNER-HARTREE-FOCK CALCULATIONS USING A G MATRIX WHICH SUMS THE POTENTIAL INSERTIONS IN PARTICLE LINES

K. T. R. Davies R. J. McCarthy[1] P. U. Sauer[2]

One of the major problems of Brueckner and Brueckner-Hartree-Fock (BHF) calculations is choosing the intermediate-state wave functions and energies to use in calculating the reaction matrix G. The reaction matrix is defined by

$$G(\omega) = v + v \frac{Q}{\omega - H_{ab}} G(\omega) , \quad (1)$$

where v is the nucleon-nucleon potential, Q forbids scattering into occupied single-particle (SP) states, and ω is an energy parameter determined through Brueckner self-consistency. The only undefined quantity is the two-particle Hamiltonian H_{ab}, which determines the intermediate-state wave functions and energies.

In principle, the choice of H_{ab} is arbitrary, since the Brueckner-Goldstone expansion is valid for any choice of basis. However, the convergence of the Brueckner-Goldstone expansion depends strongly on H_{ab}, and it is generally agreed that H_{ab} should be chosen to cancel (at least in some average way) the higher-order diagrams left out of a BHF calculation.

Since our BHF calculations are carried out by expanding the SP wave functions in a harmonic oscillator basis, it is computationally convenient to choose H_{ab} as a two-particle oscillator Hamiltonian

$$H_{ab} = H_{\mathrm{HO}} . \quad (2)$$

It is also possible – and quite easy – to modify the energies of the intermediate states by adding a constant shift, C, to the SP oscillator energies. One can then vary the parameter C in an attempt to cancel the effect of higher-order diagrams. This choice of intermediate state Hamiltonian,

$$H_{ab} = H_{\mathrm{HO}} - 2C , \quad (3)$$

has been used in a number of binding energy calculations,[3] and the results have been shown to be very sensitive to the choice of C.

A third choice for H_{ab} is based on results of nuclear matter calculations[4] which indicate that three- and four-body cluster contributions to the binding energy are small if the intermediate states are defined by plane waves. The finite-nucleus equivalent of plane-wave intermediate states is obtained by defining[5]

$$H_{ab} = QT_{ab}Q , \quad (4)$$

where T_{ab} is the two-body kinetic energy operator. This form of intermediate-state Hamiltonian is more difficult to handle than the oscillator form but has the advantage of being more directly related to nuclear matter calculations. Using Eq. (4) rather than Eq. (2) to define the intermediate-state Hamiltonian also has the advantage of including the diagrams of Fig. 1 in a first-order BHF calculation.

1. Carnegie-Mellon University, Pittsburgh, Pa.
2. Physikalisches Institut der Universität, Freiburg, Germany.

3. A. D. MacKellar and R. L. Becker, *Phys. Lett.* **18**, 308 (1965); R. L. Becker and A. D. MacKellar, *Phys. Lett.* **21**, 201 (1966); R. L. Becker, A. D. MacKellar, and B. M. Morris, *Phys. Rev.* **174**, 1264 (1968).
4. T. K. Dahlblom, *Acta Acad. Aboensis* **B29**, 1 (1969); B. D. Day, *Phys. Rev.* **187**, 1269 (1969).
5. B. H. Brandow, *Phys. Rev.* **152**, 863 (1966); H. S. Köhler, *Nucl. Phys.* **A98**, 569 (1967); M. Baranger, in *Nuclear Structure and Nuclear Reactions, Proceedings of the International School of Physics "Enrico Fermi," Course XL, Varenna, 1967*, ed. by M. Jean and R. A. Ricci, Academic, New York, 1969; P. U. Sauer, *Nucl. Phys.* **A150**, 467 (1970).

We have begun a new series of spherical renormalized BHF calculations, using Eqs. (2)–(4) to define the intermediate-state Hamiltonian. In particular, we are interested in studying the saturation properties obtained with various definitions of H_{ab}. The results obtained using Eq. (4) to define H_{ab} are also being compared with the work of Negele,[6] who used an effective interaction derived from a nuclear matter G matrix. Preliminary results indicate that the form chosen for H_{ab} has little effect on the saturation properties obtained. Both the oscillator and QTQ form yield results close to those Negele[6] obtained when he used an unadjusted interaction. We are also comparing the effect of neglecting the higher partial waves not defined in the Reid soft-core potential.[7] We find that the higher partial waves are negligible for light nuclei but cannot be ignored in heavy nuclei.

Finally, a suitable comparison of the results from Eqs. (2) and (4) will enable us to calculate the energy due to the diagrams shown in Fig. 1. This energy can then be used to estimate the particle-line, two-body correlation correction to the rms radius. The hole-line correlation correction can be calculated from the occupation probability diagrams. Thus we will be able to approximately calculate the rms radius, including the diagrams shown in Fig. 2. Diagrams 2*a* and 2*b* are of comparable magnitude and of opposite sign. However, preliminary work indicates that 2*b* is somewhat larger than 2*a*, so that the rms radius increases when correlation corrections are included. Also, this effect seems to be enhanced when the gap between occupied and unoccupied states is decreased by shifting the intermediate-state spectrum.

6. J. W. Negele, *Phys. Rev.* C1, 1260 (1970).
7. R. V. Reid, *Ann. Phys. (New York)* 50, 411 (1968).

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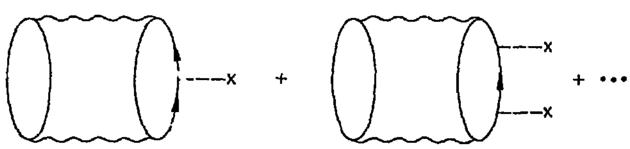

Fig. 1. Diagrams containing potential insertions in particle lines. Wavy lines signify *G*-matrix interactions, while dashed lines terminated by an X signify potential insertions.

ORNL-DWG 70-15555

Fig. 2. Two-body correlation corrections to the rms radius. The dot represents the operator r^2.

CENTER-OF-MASS CORRECTIONS IN NUCLEAR SELF-CONSISTENT FIELD THEORIES[1]

K. T. R. Davies R. L. Becker

Of various methods for making center-of-mass corrections to nuclear wave functions, one is found to be particularly suitable for calculations of the Hartree-Fock type, including those of Brueckner theory. For a spherical nucleus, expressions are derived for the corrections to the single-particle potential, the single-particle energies, the separation energies, the total binding energy, and the rms mass and proton and neutron radii. The matrix formulation of Hartree-Fock theory in a harmonic oscillator basis is employed. The limiting case of the single-oscillator configuration is discussed. Questions arise concerning the center-of-mass corrections when the Brueckner theory is renormalized with occupation probabilities. It is argued that within the Brueckner-Hartree-Fock approximation it is more accurate not to renormalize the center-of-mass corrections.

1. Abstract of published paper: *Nucl. Phys.* A176, 1 (1971).

RENORMALIZED BRUECKNER-HARTREE-FOCK CALCULATIONS OF ^{4}He AND ^{16}O WITH CENTER-OF-MASS CORRECTIONS[1]

Richard L. Becker K. T. R. Davies M. R. Patterson[2]

The goal of predicting from realistic nuclear forces the saturation properties (binding energy and matter distribution) and the separation energies of nuclei has been found to require refinements beyond the BHF approximation. For the light nuclei, calculations with pure oscillator wave functions have shown considerable improvement when a certain third-order contribution (Brandow's saturation potential, closely related to the Brueckner-Goldman *rearrangement potential*) is included in the self-consistent field. This may be done most conveniently by the use of Brandow's renormalization of the Brueckner theory with occupation probabilities. For a stringent test of the theory the single-particle wave functions are improved over pure oscillator ones by the radial Hartree-Fock procedure, and accurate corrections of radii and energies for the motion of the center of mass are made. Two center-of-mass correction methods studied previously are compared. The results of calculations for ^{4}He and ^{16}O with the Reid soft core and Hamada-Johnston interactions, employing a self-consistent choice of at least the lower part of the excited single-particle spectrum, are generally good. Although the renormalization improves the relation between binding and radius, it appears that additional refinements will be required, especially as the nucleon number increases.

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1. Abstract of paper to be submitted for publication in the *Physical Review*.
2. Mathematics Division.

ANALOGUE OF KOOPMANS' THEOREM ON SEPARATION ENERGIES IN THE RENORMALIZED BRUECKNER-HARTREE-FOCK THEORY[1]

R. L. Becker M. R. Patterson[2]

The near equality of separation energies and single-particle energies which holds in Hartree-Fock (Koopmans' theorem) but fails badly in Brueckner-Hartree-Fock is shown analytically to be recovered in RBHF by virtue of the connection between the energy dependence of the effective interaction and the occupation probabilities of the normally occupied states.

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1. Abstract of published paper: *Nucl. Phys.* A178, 88 (1971).
2. Mathematics Division.

THE DEFORMED RENORMALIZED BRUECKNER-HARTREE-FOCK APPROXIMATION AND ITS APPLICATION TO ^{12}C[1]

Richard L. Becker M. R. Patterson[2] R. C. Braley[3] W. F. Ford[3]

The RBHF theory of spherical nuclei is generalized to apply to the deformed intrinsic states of nonspherical nuclei, and calculations with the Hamada-Johnston interaction are carried out for ^{12}C by expansion in the *jj*-coupling, oscillator basis through the *g-d-s* shell. The oblate ground state and two prolate states are found. The energetics, radii, electric moments, and $B(E2)$ values for the ground-state band are compared with experiment and with density-dependent Hartree-Fock calculations.

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1. Abstract of paper to be submitted for publication in *Physical Review Letters*.
2. Mathematics Division.
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A SEARCH FOR NEW COUPLING SCHEMES. THE NUCLEAR *f-p* SHELL[1]

K. T. Hecht[2]

The failure of the SU(3) scheme to give a good description for nuclei in the *f-p* shell has led to a search for alternate coupling schemes. In SU(3) the single-particle state with $\ell = 1 + 3$ is built from three totally symmetrically coupled angular momentum 1 objects (oscillator quanta). It is also possible to obtain this single-particle state from two antisymmetrically coupled spin 2 "objects" [leading to SU(5) and R(5)] or from two symmetrically coupled spin 3/2 "objects" [leading to SU(4) and Sp(4)], where these two schemes are related since R(5) and Sp(4) have Lie algebras of the same structure. In all, three new group chains of the type $U(10) \supset G \supset R(5) \supset R(3)$ can be considered as bases for possible classification schemes, within G = SU(5), SU(4), or R(10). The potential usefulness of these schemes is tested in terms of simple schematic models and an analysis of the wave functions of the low-lying levels for two particles. Explicit expressions are given for infinitesimal generators and Casimir operators, and branching rules are discussed.

1. Abstract of published paper: *Particles Nucl.* **2**, 117 (1971).
2. Work performed while an NSF Senior Postdoctoral Fellow on leave of absence from Department of Physics, University of Michigan, Ann Arbor, September 1970–September 1971.

THE USE OF SU(3) IN THE ELIMINATION OF SPURIOUS CENTER-OF-MASS STATES[1]

K. T. Hecht[2]

SU(3) recoupling techniques are used to give explicit constructions of the spurious states in the SU(3) scheme of the harmonic oscillator shell model. A compact formula is derived for *all* spurious states of excitation $1\hbar\omega$ in $1p$ shell nuclei. Spurious states of excitation $1\hbar\omega$ in heavier nuclei can be written down from a general formula whenever the needed fractional parentage coefficients are known. Calculations of spurious states of excitation $2\hbar\omega$ are illustrated with the simple example ^{16}O. It is shown how the purely nonspurious parts can be projected out of specific core excited states such as those of the weak coupling model for hole and particle states of high SU(3) symmetry. Most of the SU(3) recoupling coefficients needed for the construction of spurious states can be simply related to ordinary SU(2) Racah coefficients.

1. Abstract of published paper: *Nucl. Phys.* **A170**, 34 (1971).
2. Work performed while an NSF Senior Postdoctoral Fellow on leave of absence from Department of Physics, University of Michigan, Ann Arbor, September 1970–September 1971.

GAMMA-RADIATION DOSIMETRY FOR ARBITRARY SOURCE AND TARGET GEOMETRIES[1]

Lincoln B. Hubbard[2]

The FORTRAN program DOSE1 calculates the first collision dose for gamma rays in arbitrary finite geometry of source, absorber, and target. The total volume, including both source and target, is subdivided into small rectangular parallelepipeds. The absorption is calculated for each elementary volume traversed from the source to the target volume. The contributions from all sources are summed to give point specific absorbed fractions for each elementary volume. The total absorbed fraction is the average of the point functions. The approach used here differs markedly from the current dosimetry procedures using the Monte Carlo method.

1. Abstract of paper to be published in *Computer Physics Communications.*
2. Department of Physics, Furman University, Greenville, S.C.; consultant to Physics Division.

HIDDEN CONFIGURATIONS AND EFFECTIVE INTERACTIONS

E. C. Halbert J. B. McGrory B. R. Barrett[1]

There are many ways to view effective interactions. Here our viewpoint is that of physicists interested in shell models with *several* nucleons outside a closed shell, instead of just one or two. From this viewpoint, the problem of "renormalization" can be described briefly as follows. Suppose we want to construct shell models for nuclei in the mass range $A_0 ... A_n$; and suppose we already know a $(0 + 1 + 2)$-body Hamiltonian H which would give useful models if it were diagonalized in a certain large shell-model vector space S. In order to simplify the calculations, we seek an effective Hamiltonian $\mathcal{H}$ to be used for some of the same nuclei $A_0 ... A_n$ but within a smaller space $\mathcal{S}$. We want to construct an operator $\mathcal{H}$ which will strike a good compromise between two criteria. First, we want the low-lying eigenvalue spectra of $\mathcal{H}$-in-$\mathcal{S}$ to strongly resemble the low-lying eigenvalue spectra H-in-S. Second, we want $\mathcal{H}$ to be simple – most preferably, a $(0 + 1 + 2)$-body operator.

As an example: we might have S spanned by all states of configurations $(0d_{5/2}, 1s_{1/2}, 0d_{3/2})^{4-16}$, with $\mathcal{S}$ spanned by all states of configurations $(0d_{5/2}, 1s_{1/2})^{4-16}$.

In this report we consider three alternative ways of constructing $\mathcal{H}$: simple perturbation methods, least-square search, and "Brandow's suggestion." First we shall sketch these three methods, then criticize them briefly, and then describe some numerical applications.

In perturbation methods, $\mathcal{H}$ is obtained by summing part of an infinite series. Commonly, the individual terms are represented by Feynman-Goldstone diagrams. One popular way of obtaining a $(0 + 1 + 2)$-body operator $\mathcal{H}$ is to cut off the perturbation series at second order, and also ignore all contributions except $(0 + 1 + 2)$-body terms. (The *full* second-order calculation would yield terms up to particle rank 3.)

A second way to get $\mathcal{H}$ is by least-square search. Suppose that we can solve *part* of the big H-in-S problem – for example, suppose we can handle all the big-model nuclei which correspond to four or fewer active nucleons in the small model. Then we can assume some simple $(0 + 1 + 2)$-body form for $\mathcal{H}$, and adjust its parameters by requiring a least-square fit to some chosen subset of the H-in-S energies. Of course, by extrapolation, we hope that this solution for $\mathcal{H}$ will be useful for heavier nuclei, too.

There is a third way to construct $\mathcal{H}$ which we call "Brandow's suggestion." The basic idea is this. We select a subset of H-in-S eigenvalues E_I, and simply assign to each member a reasonable model wave function ψ_I, where ψ_I belongs to $\mathcal{S}$. Then we let

$$\mathcal{H}' = \sum_I |\psi_I\rangle E_I \langle\tilde{\psi}_I| \, . \qquad (1a)$$

For (1*a*), we choose the set $\tilde{\psi}_I$ so that each $\tilde{\psi}_I$ also belongs to $\mathcal{S}$, and so that

$$\langle\psi_I|\tilde{\psi}_J\rangle = \delta_{IJ} \, . \qquad (1b)$$

Formula (1) gives us an operator whose eigenvalues exactly match some H-in-S eigenvalues. Brandow has suggested that the assigned eigenvectors ψ_I be, essentially, *projections* of the corresponding H-in-S eigenvectors on the small space $\mathcal{S}$. Suppose now that we can solve all the H-in-S problems corresponding to zero, one, and two active particles in the small model, $\mathcal{H}$-in-$\mathcal{S}$. Let us then choose, for the levels E_I in (1), a subset of H-in-S levels having dimensions which coincide with those of the (J, T) subspaces in $\mathcal{S}$ for zero, one, and two active nucleons. When these values E_I are inserted in (1), we get an operator $\mathcal{H}'$ whose eigenvalues exactly match eigenvalues of H in the $(0 + 1 + 2)$-body subspaces of S. Although $\mathcal{H}'$ operates only in the $(0 + 1 + 2)$-body subspace of $\mathcal{S}$, its matrix elements immediately define a more general $(0 + 1 + 2)$-body operator $\mathcal{H}$. As in the least-square method we extrapolate, and hope that this $(0 + 1 + 2)$-body operator $\mathcal{H}$ will be useful for heavier nuclei, too.

In this short report, we shall not thoroughly criticize these three methods. In brief: all three methods have difficulties associated with the choice of levels E_I to be fitted. The large model, H-in-S, has many more states than the small model, $\mathcal{H}$-in-$\mathcal{S}$; and the *full* set of H-in-S levels includes some "intruders" (that is, it includes some levels which cannot be fitted by using any simple Hamiltonian within the small space $\mathcal{S}$). In fact, the H-in-S spectrum is usually *not* clearly divisible into pure "intruder" states and pure "nonintruder" states, and that mixing causes more trouble. If we ask $\mathcal{H}$ to fit intruder levels, then it will necessarily be a complicated operator, having (for example) important three-body terms. Thus in perturbation theory there are questions about which subset of $\mathcal{H}$-in-$\mathcal{S}$ levels the series should be

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designed to converge toward. In least-square searches, it may be difficult to pick a good, "intruder-free" subset of states on which to search. Similarly, in the Brandow method there may be problems in choosing a proper subset of H-in-S levels to insert in (1).

However, in the rest of this report, we shall say no more about these problems, but just describe some numerical applications. Two simple cases have been treated. In each case, the small space $\mathcal{S}$ is one which people have already used in trying to describe real nuclei.

The first application is for nuclei A = 17...20. In this case, we let S be the three-shell space spanned by all states of configurations $(d_{5/2}, s_{1/2}, d_{3/2})^{A-16}$, and we let $\mathcal{S}$ be the two-shell space spanned by all states of configurations $(d_{5/2}, s_{1/2})^{A-16}$. In the full three-shell space, S, we used the realistic Hamiltonian H suggested in 1967 by T. T. S. Kuo.[2] We then used the least-square method to obtain an operator $\mathcal{H}$. We ran our two-shell search on 36 low-lying H-in-S levels. (The least-square solution for $\mathcal{H}$ is sensitive not only to the choice of levels searched on, but also to other details of the search criteria. Therefore the least-square results reported here should not be viewed as *the* definitive solution for a two-shell model to fit $d_{5/2}$-$s_{1/2}$-$d_{3/2}$ energies from the Kuo Hamiltonian.)

Besides the least-square Hamiltonian, we investigated results from three other Hamiltonians all used in the $d_{5/2}$-$s_{1/2}$ space. First, we used the unrevised Kuo Hamiltonian H; second, an operator $\mathcal{H}$ renormalized according to simple second-order perturbation theory; and third, the (1 + 2)-body part of an effective $\mathcal{H}$ renormalized according to the Brandow method. (As first generated, this Brandow Hamiltonian was somewhat non-Hermitian, but we symmetrized it before using it in the shell-model calculations.)

Our expectation was that only the least-square solution would give pleasing energy fits for masses 19 and 20. We thought that perturbation theory would do poorly, because the denominators in this case are small – between 4 and 10 MeV. (And after all, people have been worrying about the goodness of convergence for denominators as large as 28 MeV.)[3] How about the Brandow method? For mass 18, which has two active nucleons, some of the three-shell eigenstates involve 50% admixture of $d_{3/2}$ configurations. So we expected that, in struggling to perfectly fit these mass 18 states, the Brandow method might create a Hamiltonian quite unsuitable for masses 19 and 20.

These expectations were borne out, but only in a mild way. The second-order and Brandow fits did turn out to be worse than the least-square fit, but not terribly so. Here are the rms deviations from 29 excitation energies: 0.65 MeV for Brandow, 0.55 for second order, 0.26 for least-squares. Table 1 shows a small sampling of the energy fits. In Table 1, in the column of three-shell (H-in-S) energies, the ground-state entries are energies with respect to ^{16}O, but all the other entries are ordinary excitation energies. Succeeding columns show *deviations* of the two-shell energies from the three-shell energies. This table shows that, when used in $\mathcal{S}$, the unrevised Hamiltonian H gives substantial deviations; it obviously needs renormalization. The second-order, the Brandow, and the least-square solutions all show deviations smaller than those from the unrevised Hamiltonian H. Of course the Brandow solution fits mass 18 exactly, because that is the way it was constructed. But in general, beyond mass 18 the Brandow solution is no better than the second-order solution.

Table 2 shows some wave-function results. The column headed PROJSQ lists the intensity of each three-shell wave function in the two-shell space. Some of these entries are as small as 0.3 and 0.4. Nevertheless, the projected wave functions, *when normalized to unit strength*, are often very closely matched by the small-model eigenfunctions. To measure this matching, we take the overlap of the normalized projected wave

Table 1. Examples of $\mathcal{H}$-in-S fits to H-in-S energies E_I

For ground states, E_I means the energy with respect to ^{16}O, but for other states, E_I means excitation energy within the nucleus. All energies and deviations are in million electron volts.

Nucleus	J	E_I	Deviations from E_I as yielded by four choices of $\mathcal{H}$			
			H	Second order	Brandow	Least-square
^{18}F	1	13.4	+3.2	+0.4	0.0	−0.4
	3	0.9	−2.7	−0.8	0.0	−0.2
	5	1.4	−3.2	−0.4	0.0	−0.3
^{20}O	0	24.7	+2.1	−1.3	−0.9	+0.0
	2	1.5	−0.4	+0.2	+0.0	−0.1
	0*	3.3	−1.0	+0.1	+0.1	−0.1
^{20}Ne	0⁺	41.6	+7.4	+1.0	+2.0	0.2
	2⁺	1.5	−0.4	+0.0	−0.1	−0.2
	4⁺	3.9	−0.9	+0.7	+0.0	−0.0
	6⁺	8.2	−3.1	+0.4	−0.6	−0.0
	8⁺	12.4	−4.7	+0.3	−0.9	0.3

2. T. T. S. Kuo, *Nucl. Phys.* **A103**, 71 (1967).
3. B. R. Barrett, in *Proceedings of Gull Lake Symposium on the Two-Body Force in Nuclei, East Lansing, Michigan, Sept. 7–10, 1971.*

function with the small-model eigenfunction, and then square that overlap. As Table 2 shows, these squared overlaps are often very close to unity. In short, Table 2 shows that, for many low-lying states, you get almost the same small-space wave functions whether you use (*a*) normalized projections of the three-shell wave functions, (*b*) eigenfunctions of H in the two-shell space, or (*c*) eigenfunctions of renormalized Hamiltonians obtained by our second-order, Brandow, or least-square methods.

We have made a similar analysis of effective-interaction renormalizations for the nuclei $A = 41...44$. In that case, we let S be the four-shell space spanned by all states of configurations $(f_{7/2}, p_{3/2}, f_{5/2}, p_{1/2})^{A-40}$, and we let $\mathcal{S}$ be the two-shell space spanned by all states of configurations $(f_{7/2}, p_{3/2})^{A-40}$. The qualitative results are very similar to those discussed above for the *s-d* shell.

In the two cases we have studied, the (1 + 2)-body part of the Brandow Hamiltonian gives fits not much better than the (1 + 2)-body part of a second-order perturbation solution. This result suggests that if a better (1 + 2)-body Hamiltonian, $\mathcal{H}$, is found (say by least-square search), then that superiority probably comes about mainly because $\mathcal{H}$ mocks up the effects of three-body terms, not because $\mathcal{H}$ includes higher-order corrections to the two-body part of a second-order-perturbed Hamiltonian.

These studies are being extended so as to investigate the nature and importance of three-body terms in the effective Hamiltonian.

Table 2. Comparison between H-in-S wave functions and $\mathcal{H}$-in-$\mathcal{S}$ wave functions

The heading PROJSK stands for "projection squared": it is the intensity of the H-in-S eigenstate in the vector space $\mathcal{S}$. The heading OVLPSQ stands for "overlap squared"; it is the squared overlap of the $\mathcal{H}$-in-$\mathcal{S}$ eigenstate with the normalized projection-on-$\mathcal{S}$ of the corresponding H-in-S eigenstate. An entry P means perfect overlap; this happens when the H-in-S basis has only one state of the pertinent A, J, T combination.

Nucleus	J	PROJSQ	OVLPSQ (in %) as yielded by four choices of $\mathcal{H}$			
			H	Second order	Brandow	Least-square
^{18}F	1	0.5	89	100	100	94
	3	0.9	100	100	100	100
	5	P	P	P	P	P
^{20}O	0	0.8	99	100	100	100
	2	0.8	99	97	99	84
	0*	0.4	99	100	100	100
^{20}Ne	0	0.5	99	99	99	94
	2	0.5	99	99	99	96
	4	0.4	89	96	98	96
	6	0.4	87	94	96	96
	8	0.3	P	P	P	P

THEORY OF LEVEL STRUCTURE IN ^{49}Sc AND ^{48}Sc[1]

S. D. Bloom[2] J. B. McGrory S. A. Moszkowski[3]

The Oak Ridge–Rochester code has been used to study the $J^\pi = 3/2^-$ states generated by the configuration $(1f_{7/2})^8(2p_{3/2})$ in ^{49}Sc. Excitation energies, $M1$ transitions, and $E2$ transitions amongst the five levels, including the analog or A state at $E_x = 11.56$ MeV, were calculated and compared with experiment where possible. The beta decay of ^{49}Ca to the $3/2^-$ level at 3.08 MeV (the lowest-lying $3/2^-$ level) was also calculated. Two interactions were used, the well-known Kuo-Brown or KB force and a new interaction which we call the PMM force, the latter being derived mainly from direct-reaction cross sections of nucleons on various nuclei. Both KB and PMM interactions lead to cancellations which cut down both the beta decay of ^{49}Ca and the $M1$ decay of the A state to the lowest-lying $3/2^-$ state at 3.08 MeV. In addition, a super-strong $M1$ decay to a $3/2^-$ level or complex of levels with excitations $\gtrsim 7$ MeV is predicted. The $E2$ decays of all the predicted $3/2^-$ states to the $7/2^-$ ground state were also calculated. Comparison with experiment here is hampered by the role of fine structure of the A state, but experiment is weaker than theory by a factor of 10 (KB) to 60 (PMM).

The $(1f_{7/2})^8$ group of levels in ^{48}Sc were also calculated ($J^\pi = 0^+ \to 7^+$). The PMM force gave excellent agreement with recent experimental results, while the KB force gave relatively poor agreement, as might be expected from the severe truncation of the calculation. The suggestion is that the phenomenological basis of the PMM force corresponds physically to the $(1f_{7/2})^8$ space of ^{48}Sc.

1. Abstract of paper to be published in *Nuclear Physics*.
2. Lawrence Radiation Laboratory, Livermore, Calif.
3. Department of Physics, U.C.L.A., Los Angeles, Calif.

SPHERICAL STATES IN ^{44}Sc[1]

J. B. McGrory   E. C. Halbert

Conventional shell-model calculations of energy levels in ^{44}Sc, and of strengths for proton stripping and neutron pickup to states in ^{44}Sc, are reported. The results are in excellent agreement with a set of states observed below 1.5 MeV in ^{44}Sc. There are at least 18 states below this energy which are not accounted for by the shell-model results.

1. Abstract of published paper: *Phys. Lett.* 37B, 9 (1971).

STRUCTURE OF NUCLEI WITH MASSES A = 30–35 AS CALCULATED IN THE SHELL MODEL[1]

B. H. Wildenthal[2]   J. B. McGrory   E. C. Halbert   H. D. Graber[3]

Properties of positive-parity states of nuclei with A = 30–35 have been calculated in a shell-model space which encompasses all Pauli-allowed basis vectors of all configurations

$$(0s)^4(0p)^{12}(0d_{5/2})^{n_1}(1s_{1/2})^{n_2}(0d_{3/2})^{n_3}$$

for which $n_1 \geqslant 10$. Two different empirical Hamiltonians, one of a δ-function form, were used. Calculated energies and spectroscopic factors are in good agreement with an extensive body of experimental data. The model wave functions also yield satisfactory agreement with many available experimental data on electric quadrupole observables if effective charges of $0.5e$ are added to the proton and neutron. The model predictions for magnetic dipole observables are generally in qualitative agreement with experimental observations, but inconsistencies between theory and experiment are more noticeable in this area.

1. Abstract of published paper: *Phys. Rev.* C4, 1708 (1971).
2. Department of Physics and Cyclotron Laboratory, Michigan State University, East Lansing.
3. Cornell College, Mt. Vernon, Iowa.

CALCULATIONS WITH A 1s, 0d SHELL MODEL FOR A = 34–38 NUCLEI[1]

B. H. Wildenthal[2]   E. C. Halbert   J. B. McGrory   T. T. S. Kuo[3]

Results are presented of calculations made in the full space of sd shell-model wave functions for positive-parity states in the nuclei with A = 34–38. We employed in this work several different effective Hamiltonians, some of which had two-body parts obtained by reaction-matrix techniques from the Hamada-Johnston scattering potential. The observables calculated were energy-level spectra, single-nucleon spectroscopic factors, and $E2$ and $M1$ moments and transition strengths. These calculations yield fair to good agreement with many of the observed nuclear-structure data in this mass region.

1. Abstract of published paper: *Phys. Rev.* C4, 1266 (1971).
2. Michigan State University, East Lansing.
3. State University of New York at Stony Brook, Stony Brook, L.I.

THE GROUND STATE OF ^{40}Ca

L. B. Hubbard[1]   J. B. McGrory   H. P. Jolly[2]

The ground-state wave function for ^{40}Ca has been calculated in a basis of 176 configurations containing all $2\hbar\omega$ excitations in addition to the doubly closed shell configuration. The phenomenological Gaussian force and the realistic Tabakin force were employed. The eight spurious states were explicitly projected out in the phenomenological calculation. In the realistic calculation the $2\hbar\omega$ particle-hole configurations were neglected and the spurious states not projected out. This latter approximation was found to have a minor effect on the results.

1. Consultant from Furman University, Greenville, S.C.
2. Division of Health Sciences Communication, S.U.N.Y., Stony Brook, N.Y.

The ground state was found to be in the doubly closed shell configuration about 70% of the time. In our basis, each configuration consisted of two specific holes coupled to good values of total J and T; none of these configurations had an intensity of more than a few percent in the ground state. Since 30% of the ground state in this calculation was $2p$-$2h$, we can expect $4p$-$4h$ configurations to have a modest intensity in the ground state; this intensity was not calculated.

The energy of the ground state was found to lie about 10 MeV below the pure closed-shell configuration. Thus mixing of $2p$-$2h$ configurations in ^{40}Ca accounts for about 3% of the total binding.

The first excited state of the calculation was found to lie more than 15 MeV above the ground state. This corroborates the usual assumption that the low-lying 0^+ excited states of ^{40}Ca cannot be characterized properly without including $4\hbar\omega$ excitations.

A POSSIBLE TRUNCATION OF THE SHELL-MODEL BASIS IN TERMS OF "FAVORED-PAIR" CORRELATIONS

K. T. Hecht[1] J. D. Draayer[1] J. B. McGrory

To study the feasibility of carrying out shell-model calculations in nuclei with both several active protons and neutrons in different major shells, the following simple idealized model has been studied. (1) The proton and neutron configurations are chosen to be

$$(p_{3/2}p_{1/2}f_{5/2})^{n_p}$$

and

$$(g_{7/2}d_{5/2}d_{3/2}s_{1/2})^{n_n} ,$$

respectively, so that results for the separate proton and neutron basis states to be used in any approximation scheme can be compared with the results for exact shell-model calculations. (2) The proton and neutron single-particle energies for these active shells are separately taken to be degenerate. (3) The two-body interaction among nucleons (p-p, n-n, and p-n) is approximated by the surface delta interaction (SDI).

To effect the severe truncation of the full shell-model space needed to make possible a shell-model study with both active protons and neutrons in such shells, the separate proton and neutron parts of the shell-model basis are built from a superposition of the favored pair states (with $J \neq 0$, as well as $J = 0$) of the SDI.[2] In the neutron configuration $(g_{7/2}d_{5/2}d_{3/2}s_{1/2})^{n_n}$, with n_n = 4, for example, there are 94 shell-model states with J_n = 2. Of these, only three are retained in the truncation scheme. One is the state with total seniority $v_n = 2$, built from the favored $J = 2$ pair state of the SDI. The remaining states are built from those superpositions of the 15 $v_n = 4$ states with total pseudospin[2] of zero which can be built from superpositions of favored $J \neq 0$ pairs only. There are only two such states with $v_n = 4$. Their energies in this highly truncated basis lie within 0.3% (for the lower) and 10% (for the higher) of the exact shell-model results using the full basis. In addition, the strong $B(E2)$ values for the transitions from these states to similar favored states with other J values are within 5% or better of the results of exact calculations.

A truncation of the shell-model space based on such superpositions of favored-pair states leads to a manageable shell-model basis (dimensions $\lesssim 200$). (1) The numbers of states in the separate proton and neutron parts of the basis are small enough (8 to 15 for the proton space, 15 to 30 for the neutron space). They are also the key states in the following sense. (2) They include all the low-lying energy eigenstates of the separate p-p and n-n parts of the interaction. (3) They contain most of the collective coherence of the separate proton and neutron configurations. (4) The matrix elements of the n-p part of the interaction between two favored states are in general very large compared with the matrix elements between a favored and an excluded state. The latter effect is studied from several points of view, in particular in terms of sum rules for the matrix elements of the surface multipole operators from which the n-p part of the SDI is built. For most of the low-lying favored states the sum over *all* favored states gives more than 90% of the total sum rule for the squares of matrix elements of the surface multipole operators.

The results of shell-model calculations in this truncation scheme, with n_p and $n_n \leqslant 6$, show some of the features of a quadrupole vibrational spectrum, although the $B(E2)$ ratios for the transitions $2_2^+ \to 2_1^+$ and $4_1^+ \to 2_1^+$ relative to $2_1^+ \to 0_1^+$ are too weak by factors of

1. University of Michigan, Ann Arbor.

2. K. T. Hecht and A. Adler, *Nucl. Phys.* A137, 129 (1969).

about 2.3 and 1.4 respectively. The $E2$ rate of the transition $2_1^+ \rightarrow 0_1^+$ is enhanced by a factor of about 1.5 relative to a weak coupling model based on a superposition of separate 2^+ proton and neutron states which exhaust the full $E2$ sum rule of the active part of the separate proton and neutron spaces. The presence and exact nature of a 0^+ member of the 0^+, 2^+, 4^+, "vibrational triplet" is dependent on the inclusion of the key favored states with total seniorities $v_p = 6$ and $v_n = 6$.

THE TWO-BODY INTERACTION IN NUCLEAR SHELL-MODEL CALCULATIONS[1]

J. B. McGrory

The mechanics of shell-model calculations are discussed with particular emphasis on the role of the two-body effective interaction. Typical results for *s-d*-shell calculations are discussed, as is the sensitivity of the calculated results to changes in the effective interaction. The effects of space truncation on the effective interaction are illustrated.

1. Abstract of paper to be published in *Proceedings Gull Lake Symposium on the Two-Body Force in Nuclei, East Lansing, Michigan, Sept. 7–10, 1971.*

VALIDITY OF STRUTINSKY'S THEORY OF RENORMALIZATION[1]

S. J. Krieger[2] C. Y. Wong

The validity of Strutinsky's theory of renormalization is examined by comparing its predictions with those of a Hartree-Fock (HF) calculation for the nucleus ^{32}S. Very good agreement is obtained if the single-particle states from the HF calculation are used in the Strutinsky calculation. For a conventional Strutinsky calculation using a phenomenological Nilsson potential, agreement with HF results is not as good. The latter agreement is improved if one treats the quadrupole moment of the density rather than that of the average potential as the independent variable.

1. Abstract of paper submitted for publication in *Physical Review Letters.*
2. University of Illinois at Chicago Circle, Chicago.

EFFECTS OF NUCLEAR COLLECTIVITY ON THE TOTAL NEUTRON CROSS SECTION[1]

C. Y. Wong T. Tamura[2] H. Marshak[3] A. Langsford[4]

A study is made of the effect of the nuclear collectivity on the variation of the total neutron cross section with respect to the incident energy ranging from 4 to 20 MeV. It is found that the higher the collectivity, the smoother is the excitation function, for both deformed and vibrational nuclei. This feature is understood qualitatively in terms of the nuclear Ramsauer effect and is explained quantitatively by coupled-channel calculations. These calculations further reveal that deformed nuclei have larger total cross sections and smoother variations than do the vibrational nuclei. For vibrational nuclei, it is also found that the quadrupole deformation has a slightly larger effect on the smoothness than does the octopole deformation, if they have the same deformation parameter.

1. Abstract of paper submitted for publication in the *Physical Review.*
2. University of Texas, Austin.
3. National Bureau of Standards, Washington, D.C.
4. A.E.R.E., Harwell, Berkshire, England.

DYNAMICAL DISTORTION OF NUCLEI IN HEAVY ION REACTIONS[1]

A. S. Jensen[2] C. Y. Wong

The dynamics of the deformation is considered for two spherical nuclei in head-on collisions. Both the Coulomb interaction and the nuclear interaction are taken into account. The interaction barrier, above which the two nuclei collapse together, changes as a result of dynamical distortions. This change is positive or negative, depending on the combination of target and projectile. The magnitude of the change is, however, only a few percent even in the most favorable case considered. From the studies of the dependence of the excitation energy on collision energies, one observes an interesting interference between the Coulomb and the nuclear interaction for different multipoles as the interaction barrier is approached. The studies of the dynamics of distortion also make it possible to trace the history of two nuclei moving toward fusion until a neck begins to appear.

1. Abstract of published paper: *Nucl. Phys.* A171, 1 (1971).
2. Atomic Energy of Canada Limited, Chalk River Nuclear Laboratories, Chalk River, Ontario, Canada.

TARGET EXCITATIONS AND THE IMAGINARY PART OF THE OPTICAL POTENTIAL

C. L. Rao[1] G. R. Satchler

Contributions to the imaginary part of the optical model potential for protons from inelastic excitations of the target nucleus are being investigated.

The generalized optical potential for elastic scattering of a nucleon by a nucleus can be written as

$$U_{\rm opt} = (\Phi_0|V|\Phi_0) + \left(\Phi_0|VQ\frac{1}{E - H_{QQ} + i\epsilon}QV|\Phi_0\right)$$
$$= V_{00} + \Delta U ,$$

where Φ_0 is the target ground state, Q projects off the ground state, and V is the interaction between the projectile and the target.

The first term has been studied earlier by Owen,[2] using a sum of realistic nucleon-nucleon interactions for V. Remarkable agreement with the real parts of phenomenological optical potentials was found. We are investigating the second term, which gives the imaginary (absorptive) part of the potential, as well as contributing to the real part. This term takes account of all nonelastic processes, such as inelastic scattering, pickup, and compound formation. At present we are restricting attention to the contributions from the excitation of discrete states of the target which are observed strongly in inelastic scattering experiments.

Clearly, ΔU is nonlocal because of the propagator. Further, this propagator is not diagonal in the target states because of the interaction V_{QQ} contained in H_{QQ}. For convenience in calculation, we have taken V_{00} to be a real and local Woods-Saxon potential $U_0(r)$, although in principle one should use the nonlocal potentials calculated by Owen.[2] Further, we replace V_{QQ} by $U_0(r)$, this making the propagator diagonal in the target states. The intermediate states are then distorted waves for the incident nucleon scattering off excited states of the target. These excited states are taken to be vibrational states, and the interaction V is the usual deformed optical potential.[3] The coupling strengths (or deformation parameters β_L) are taken from analyses of actual excitation of these states, in particular by (α,α').[3]

The calculations are done using codes due to Reeves.[4] The first constructs the real and imaginary parts of the nonlocal potential ΔU for a given set of target states, etc. The second then calculates the scattering from $U_0(r) + \Delta U$. At present, most attention has been paid to 30-MeV protons on ^{40}Ca with various choices of excited states. Three 2^+ states observed[3] near 8 MeV are represented by a single state with $\beta_2 = 0.309$. An energy-weighted sum rule is used to estimate the strengths of the higher excited states which are not resolved or identified experimentally. Calculations were made to study the effect of various distributions of this "missing" strength by postulating levels at various

1. Consultant and graduate student from the University of Tennessee.
2. L. W. Owen and G. R. Satchler, *Phys. Rev. Lett.* 25, 1720 (1970); Ph.D thesis, University of Tennessee, 1970.
3. A. M. Bernstein, *Advan. Nucl. Phys.* 3, 325 (1969).
4. M. Reeves, Ph.D thesis, University of Tennessee, 1970; CTC report CTC-32 (1970); M. Reeves and L. W. Owen, *J. Comput. Phys.* 4, 572 (1969).

energies. The effects of arbitrarily increasing the strengths of known low-lying levels were also examined. One measure of the importance of the coupling is the absorption cross section, σ_A. Some examples of the calculations are given in Table 1, which lists the spin-parity, excitation energy, and deformation parameter for the states included and the resulting σ_A. In addition, for example, a run was made with ten 3^- states distributed between 3.73 and 9.5 MeV and exhausting the octopole sum rule; this resulted in σ_A = 480 mb. Indeed, it is difficult while using reasonable parameters to get σ_A above about 500 mb, which is only about 50% of the experimental value. Arbitrarily increasing the coupling parameters β_L does increase σ_A until it saturates at the geometrical value of nearly 1 b. As Table 1 indicates, simply adding a few more states does not increase σ_A by much. Of course there are a very large number of states available, but it seems likely that these do not represent the direct excitation of collective surface modes but are to be regarded as contributing to rearrangement (pickup) collisions and compound formation. The former processes may be better described by a different choice of intermediate states, as was done in a calculation of the imaginary part of the deuteron optical potential.[4]

The differential cross sections generated by the potentials $U_0 + \Delta U$ were treated as "experimental" data and subjected to conventional optical-model analysis so as to obtain local equivalent potentials for comparison with those obtained from analyses of actual scattering measurements. The effect of ΔU on the real part of the potential is small. The imaginary parts of these local equivalent potentials are concentrated at the nuclear surface, peaking at radii between $1.1A^{1/3}$ and $1.2A^{1/3}$. This behavior is not surprising, because the model interaction V is a surface-coupling potential, but it is to be contrasted with the empirical potentials whose imaginary parts extend to much larger radii, peaking at about $1.35A^{1/3}$. This perhaps is another indication that pickup reactions are an important source of the absorptive strength in the outer surface region.

Only energy-conserving transitions contribute to the imaginary part of ΔU. These include excitations with $E_x > 30$ MeV with the incident particle captured into a bound state. Such bound states in the continuum constitute compound formation but were not included in the present calculations. It is hoped to extend the codes to allow these processes to be computed also.

Other aspects of the potential ΔU which are being studied include its energy dependence and the effect of its nonlocality on the scattering wave functions.

Table 1

L, π	E_x (MeV)	β_L	σ_A (mb)
2^+	3.9	0.143	42
2^+	8.0	0.309	176
3^-	3.73	0.354	164
$3^-, 3^-$	3.73, 15.72	0.354, 0.404	320
5^-	4.48	0.192	37
$2^+, 2^+, 3^-, 3^-, 5^-$	3.9, 8.0, 3.73, 15.72, 4.48	0.143, 0.309, 0.354, 0.404, 0.192	490

TOWARDS A MICROSCOPIC DESCRIPTION OF THE SCATTERING OF NUCLEONS FROM NUCLEI[1]

G. R. Satchler

The microscopic theory of elastic and inelastic scattering of nucleons from nuclei is reviewed.

1. Abstract of paper to be submitted for publication in *Comments on Nuclear and Particle Physics*.

SOME STUDIES OF THE EFFECTIVE INTERACTION FOR INELASTIC ALPHA SCATTERING[1]

G. R. Satchler

Some "microscopic" calculations of inelastic alpha scattering are presented, both with a folded interaction plus some estimate of exchange effects and with a Gaussian approximation to a phenomenological interaction obtained from nucleon-alpha scattering. The former gives agreement with measurements on the 3^- excitations of ^{40}Ca and ^{208}Pb but fails for the 5^- in ^{40}Ca. The latter interaction is too weak.

1. Abstract of published paper: *Particles Nucl.* 2, 265 (1971).

EFFECTIVE INTERACTIONS FOR INELASTIC DEUTERON SCATTERING[1]

G. R. Satchler

The effective nucleon-deuteron interaction to be used in a microscopic description of inelastic scattering is discussed. Reasonable agreement with experiment is obtained when exchange terms and a phenomenological imaginary interaction are included.

1. Abstract of published paper: *Phys. Lett.* 36B, 169 (1971).

ON THE EFFECTIVE INTERACTION FOR INELASTIC DEUTERON SCATTERING[1]

G. R. Satchler

The effective deuteron-nucleon interaction to be used in a microscopic description of inelastic deuteron scattering is discussed. Reasonable agreement with experiment is obtained when exchange terms and a phenomenological (collective model) imaginary interaction are included.

1. Abstract of published paper: *Particles Nucl.* 2, 147 (1971).

ADIABATIC DEUTERON MODEL AND THE ^{208}Pb(*p,d*) REACTION AT 22 MeV[1]

G. R. Satchler

It is shown that the adiabatic treatment of deuteron breakup during stripping reactions proposed by Johnson and Soper is able to explain the results obtained previously for the ^{208}Pb(*p,d*) reaction at 22 MeV without the use of an arbitrary radial cutoff. Some discussion is also given of the sensitivity of the predictions to the parameters of the model.

1. Abstract of published paper: *Phys. Rev.* C4, 1485 (1971).

INELASTIC SCATTERING OF 61-MeV PROTONS FROM ^{90}Zr AND ^{89}Y[1]

M. L. Whiten[2] Alan Scott[3] G. R. Satchler

NUCLEAR REACTION: ^{90}Zr(*p,p'*), E_p = 61.2 MeV: measured $\sigma(E_{p'}, \theta)$. ^{90}Zr deduced levels, some β_L. Enriched target, 98.6%.

Differential cross sections for the excitation by 61.2-MeV protons of the first seven resolved states in ^{90}Zr have been measured over the angular range 18 to 105°. The results are analyzed using a microscopic model including knock-on exchange and core polarization, with central interactions of Yukawa and Hamada-Johnston type. The analogous excitations of the 5$^-$ state in ^{90}Zr and the 9/2$^+$ state in ^{89}Y are compared; it is shown that core polarization of the *E*5 type is more important for the former, but there may be additional core polarization of *M*4 type in the latter transition. It is also shown that unnatural parity exchange may be important for the excitation of the $(g_{9/2})^2$ sequence of states in ^{90}Zr. Both microscopic and collective models were used for the 3$^-$ state in ^{90}Zr.

1. Abstract of paper submitted for publication in *Nuclear Physics.*
2. This work performed in partial satisfaction of requirements for the Ph.D as an N.D.E.A. Fellow, 1969–70, and a Graduate Assistant at the University of Georgia, 1967–69. Present address: Department of Chemistry and Physics, Armstrong College, Savannah, Ga.
3. University of Georgia, Athens. Part of this work was carried out while an ORAU Summer Participant.

EVIDENCE FOR A COMPLEX EFFECTIVE INTERACTION IN INELASTIC SCATTERING?[1]

G. R. Satchler

A somewhat "frivolous" model is used to introduce an imaginary component into the effective nucleon-nucleon interaction for a microscopic description of inelastic scattering. Considerable improvement is obtained in fitting the $^{40}Ca(p,p')$ cross sections.

1. Abstract of published paper: *Phys. Lett.* 35B, 279 (1971).

A GENERALIZED CORE-POLARIZATION MODEL FOR INELASTIC SCATTERING[1]

G. R. Satchler W. G. Love[2]

A deformed-potential model for including core-polarization effects in microscopic descriptions of inelastic scattering has been generalized to include spin and isospin oscillations. It is shown how these effects may be related to data for inhibited or enhanced electromagnetic and beta transitions.

1. Abstract of published paper: *Nucl. Phys.* A172, 449 (1971).
2. University of Georgia, Athens.

FORM FACTORS AND ANALYSIS OF (*p,d*) PICKUP FOR SOME LIGHT NUCLEI[1]

G. M. McAllen[2] W. T. Pinkston[2] G. R. Satchler

The microscopic approach to calculating form factors for single-nucleon transfer reactions is applied to several pickup reactions on ^{12}C, ^{14}N, and ^{16}O. It is shown that for such nuclei, one obtains the greatest discrepancies between such form factors and form factors obtained from the conventional well-depth procedure. Unfortunately, it is also for such light nuclei that the usual distorted-wave method is most difficult to apply. Because of the ambiguity resulting from the necessity of using sharp radial cutoffs in the distorted-wave integrals and the sensitivity of results to the cutoff used, the adiabatic model of Johnson and Soper for the deuteron distorted waves was also used. Considerable improvement is found for the strong transitions. A cutoff is no longer required. However, the results for the weak transitions, for which microscopic form factors were used, were little changed, so that the interpretation of these remains inconclusive. The *changes* in cross section produced by using the microscopic form factor are comparable for the two distorted-wave prescriptions.

1. Abstract of published paper: *Particles Nucl.* 1, 412 (1971).
2. Vanderbilt University, Nashville, Tenn.

PARTICLE-GAMMA ANGULAR CORRELATIONS FOLLOWING NUCLEAR REACTIONS INDUCED BY A POLARIZED BEAM[1]

A. A. Debenham[2] G. R. Satchler

A general formalism, based upon the phase-consistent treatment of Rose and Brink, is presented for particle-gamma angular correlations following reactions induced by polarized incident particles. The symmetry properties of the correlation are discussed. Some special cases are mentioned briefly.

1. Abstract of paper to be submitted for publication in *Particles and Nuclei.*
2. Department of Physics, University of Birmingham, England; present address: Eidgenössische Technische Hochschule, Zürich, Switzerland.

STABILITY OF NUCLEI WITH NEW TYPES OF TOPOLOGY: TOROIDAL AND SPHERICAL BUBBLE NUCLEI[1]

C. Y. Wong

Attention is fixed on nuclei with new types of topology proposed by Wheeler many years ago. Only the simplest of these, the toroidal and the spherical bubble, are considered in both the liquid-drop model and the independent-particle model. In the liquid-drop model, a toroidal nucleus with a fissility parameter $x \geqslant 1.0$ is stable against symmetry-preserving breathing deformations due to the balance between Coulomb repulsion and surface tension. However, at the breathing deformation minimum, the nucleus is unstable against sausage deformations which make the torus thicker in one azimuthal angle and thinner in another. In the hydrodynamical liquid-drop model, a toroidal vortex nucleus with a simple free vortex does not help stabilize the nucleus against sausage deformations either. For a spherical bubble nucleus, results in the liquid-drop model indicate that it is stable against the breathing deformation for $x \geqslant 2.1$. However, at the breathing deformation minimum, it is unstable against one type of spheroidal deformation or another. In the single-particle model, there are shells in both the toroidal and the bubble nuclei. The presence of these shells may allow some doubly magic toroidal and bubble nuclei to gain additional stability against collective vibrations. We focus our attention on these nuclei and study their deformation surfaces with Strutinsky's theory of renormalization. It is found that the doubly magic toroidal nuclei $^{180}Po^t$, $^{188}Ra^t$, $^{200}Ra^t$, $^{212}Ra^t$, $^{204}Cm^t$, $^{216}Cm^t$, $^{228}Cm^t$, $^{212}Fm^t$, $^{224}Fm^t$, and $^{232}Fm^t$ (where the superscript t stands for toroidal shape) have relatively equilibrium minima at their various toroidal aspect ratios which may be metastable against large-scale collective vibrations. It is also found that the doubly magic spherical bubble nuclei $^{174}Yb^b$ and $^{250}104^b$ (where b stands for bubble configuration) may have metastable equilibrium configurations when the inner radius is equal to about three-tenths of the outer radius. The present calculation also reveals that ^{200}Hg in its ground state may already be a bubble nucleus with a small hole in the interior.

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

ATOMS WITH TOROIDAL NUCLEI

J. L. Fowler

There have been theoretical speculations that nuclear matter in the form of toroidal nuclei might possibly be stable through nucleon vortex motion, shell effects, or other non-liquid-drop effects.[1,2] It is conceivable that such nuclear matter might be extruded from a neutron star during a supernova explosion.[3] If this, or any other mechanism, is a source of toroidal nuclei, and they are indeed stable, one would like to have some idea of the physical properties of atoms with such nuclei.

The Thomas-Fermi electron distribution allows an estimate of some of these properties. One solves Poisson's equation

$$\frac{\nabla^2 V}{e} = -4\pi e\, \eta(r)$$

for the electrostatic potential, V/e (V is the potential energy of the electrons). $\eta(r)$, the electron density, can be obtained from statistical mechanics by counting possible quantum mechanical states for an electron up to a kinetic energy E, where E may be a relativistic energy:

$$\eta = \frac{1}{3\pi^2 \hbar^3}\left(E\frac{E+2\mu c^2}{c^2}\right).$$

Thus with $E = -V(r)$,

$$\nabla^2 V = \frac{4\pi e^2}{3\pi^2 \hbar^3}\,[-2\mu\, V(r)]^{3/2}\left[1 - \frac{V(r)}{2\mu c^2}\right]^{3/2}.$$

The relativistic correction[4] included in the last bracket neglects a relativistic spin-orbit term.[5] We should solve this equation in a toroidal or ring coordinate system,

1. J. A. Wheeler, private communication.
2. C. Y. Wong, *Bull. Amer. Phys. Soc.* 16, 1151 (1971).
3. J. L. Fowler, *Bull. Amer. Phys. Soc.* 16, 1151 (1971).
4. M. S. Vallarta and N. Rosen, *Phys. Rev.* 41, 708 (1932).
5. N. H. March, *Advan. Phys.* 6, 1 (1957).

but such a differential equation in this system is very difficult to handle, partially because the equation is not separable in two of the coordinates. Near the surface of the ring the solution should be approximately given by that around a long cylinder of positive charge.

The solutions shown in Fig. 1, then, are for an infinite linear array of protons of linear density ρ protons/unit length. Here, distance is measured in the natural unit of length in this system,

$$\frac{\sqrt{3\pi a_0}^{3/4}}{4\rho^{1/4}},$$

and potential in units $2\rho e^2$. a_0 is the first Bohr radius, $\hbar^2/\mu e^2$. The differential equation is realtively easy to handle numerically if the independent variable is the log of the distance from the center of the cylinder. Now, Siemens and Bethe[6] have concluded that nuclear matter in the form of a very prolate spheroid might be stable

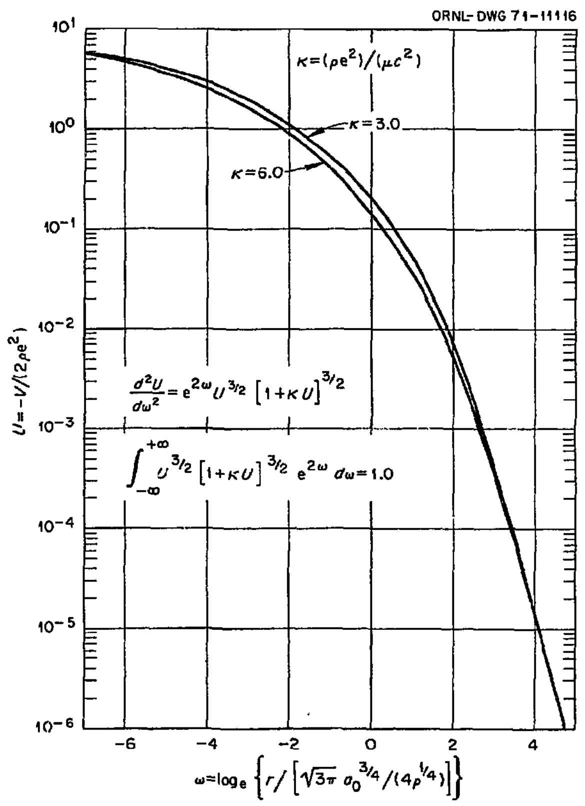

Fig. 1. Thomas-Fermi potential as a function of the logarithm of the distance from the origin for a linear atom, for two relativistic parameters κ = 3.0 and κ = 6.0.

for a radius of 3 fm and Z/A = 0.38. This makes $\kappa = \rho e^2/\mu c^2$ = 4.0. The two solutions shown in Fig. 1 bracket this case. The integral

$$\int_{-\infty}^{+\infty} U^{3/2}(1+\kappa U)^{3/2}\, e^{2\omega} = 1.0$$

is the condition for charge conservation and holds for the solutions shown here to five or six decimal places.

Figure 2 gives the solution for κ = 4.0. Here the unit of length is 2.45×10^{-10} cm, and 80% of the electrons are inside a radius equal to this length. Thus for the linear approximation to work, the azimuthal radius of the torus must be $\cong 10^3$, or greater than the radius of the nuclear matter. Intuitively, one might not expect a ring of nuclear matter, even if it were stable, to have an azimuthal radius so large compared with the radius of the nuclear matter. But if nuclear matter of this type were indeed formed in a supernova explosion, it is conceivable that long cylinders of nuclear material might be extruded from the neutron core.

In any case, since this approximation is available, let us examine it to see some of its consequences. We can, for example, find the radius at which the electron density is equal to the density of electrons midway between atoms of a heavy-element crystal. This occurs at about ω = 4.66, or $r = 2.6 \times 10^{-8}$ cm. At twice this density the radius is $\sim 2.3 \times 10^{-8}$ cm. For the situation in which the azimuthal radius is $\sim 2.5 \times 10^{-10}$ cm, this gives a matter density of 10^3 g/cc. This density would decrease proportional to a decrease in the azimuthal radius, at least initially.

Ring atoms in at least one-half of the cases should have a magnetic moment arising from an odd unpaired electron's movement around the ring,

$$\mathfrak{M} = \frac{e}{2\mu c}\mathbf{a}_T \times \mathbf{p}_z .$$

Near the surface of the atom, the electron density may be low enough so that the approximation of independent motion in the average field may be valid. Thus the solution of the wave equation at the top of Fig. 2, for an electron moving in the average field V, allows an estimate of p_z, the momentum of the electron along the azimuthal direction of the ring. M is the quantum number for rotation about the axis of the cylinder

6. P. J. Siemens and H. A. Bethe, *Phys. Rev. Lett.* **18**, 704 (1967).

considered here. The eigenvalue for this radial wave equation is

$$\epsilon - \frac{4k^2}{3\pi\sqrt{a_0\rho}},$$

where ϵ is the electron binding energy and k is 2π times the reciprocal wavelength along the Z direction measured in our units of length.

Plotted in the upper right-hand corner are two wave functions for outermost electrons with the eigenvalues given beside each curve. For electrons just bound, these eigenvalues allow an estimate of p_z. Since the nuclear mass goes as a_T, the azimuthal radius, the magnetic moment per unit mass can be calculated and for this case is 0.04 G cm/g. It is not obvious how this quantity varies as the azimuthal radius decreases, but it seems likely that the magnetic moment per gram might increase. Incidentally, the high values of M for the electron states, described by the wave function plotted in Fig. 2, represent a high angular velocity of electrons around the nuclear matter, the kind of motion which for nucleons would tend to stabilize the nucleus.[2]

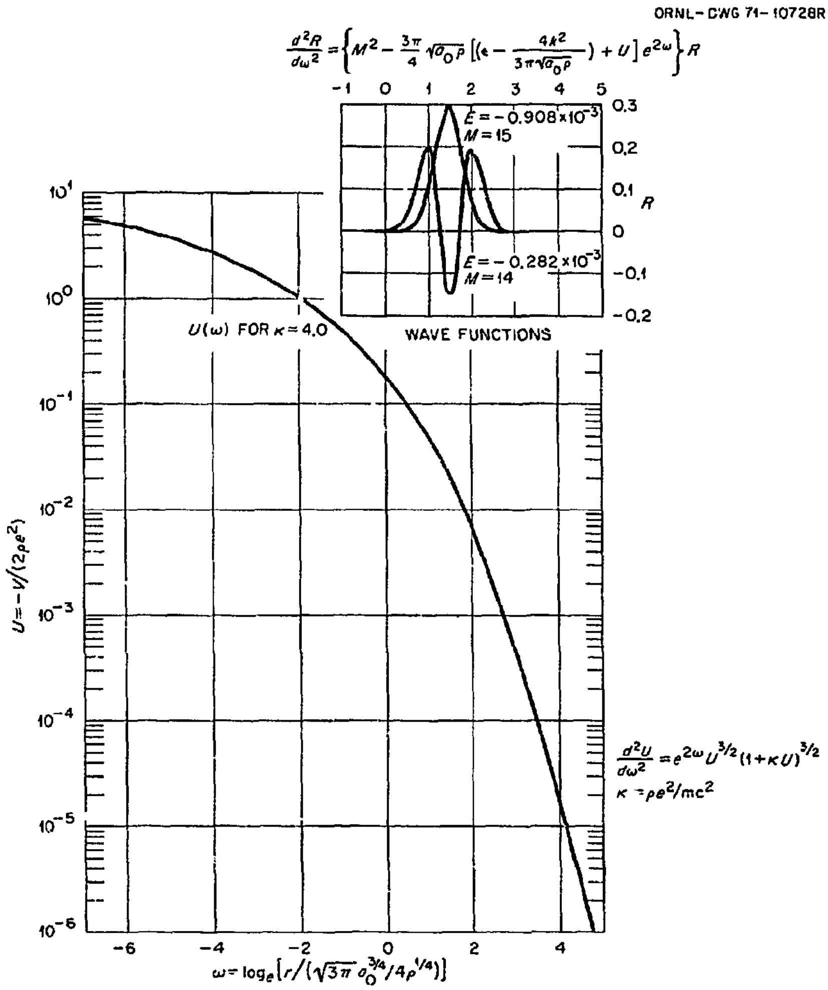

Fig. 2. Thomas-Fermi potential for infinite linear atom with linear charge density and ratio of protons to nucleons suggested by Siemens and Bethe. Solutions of cylindrical wave equation near surface of this atom are in the upper right-hand corner.

HARTREE-FOCK CALCULATIONS FOR α-TYPE (s,d) SHELL NUCLEI WITH A SIMPLE EFFECTIVE INTERACTION[1]

S. J. Kreiger[2] Steven A. Moszkowski[3]

Nuclear properties, such as ground-state energies, rms charge radii, and intrinsic quadrupole moments are calculated, using the Hartree-Fock method, for self-conjugate even-even (s,d)-shell nuclei. The internucleon interaction is a spin-independent S-state version of the Skyrme interaction. The density dependence of the G matrix is simulated by a three-body repulsive delta interaction. The connection between the latter and a density-dependent two-body delta interaction is discussed in the appendix.

Our results for binding energies and rms radii agree much better with experimental values than earlier calculations done by one of us (S. J. K.) using a different, density-independent, interaction. It also gives generally better results for binding energies than the results of Zofka and Ripka and of Lassey and Volkov, and comparable results for rms radii.

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1. Abstract of paper submitted for publication in the *Physical Review.*
2. Consultant from University of Illinois, Chicago.
3. University of California, Los Angeles.

2. High Energy Physics

RELATIVE CAPTURE RATES FOR SLOW π^-, K^-, Σ^- IN A NEON-HYDROGEN MIXTURE[1]

W. M. Bugg[2] G. T. Condo[2] E. L. Hart[2] M. R. Jhaveri[3] H. O. Cohn R. D. McCulloch[4]

We find the relative hydrogen capture rates for π^-, K^-, and Σ^- in a 24-mole % mixture of neon in hydrogen to be 17 ± 5%, 26 ± 5%, and 48 ± 6% respectively. A possible mechanism for these differences is presented.

1. Abstract of paper submitted for publication in the *Physical Review.*
2. Consultant from the University of Tennessee, Knoxville.
3. University of Tennessee, Knoxville.
4. Mathematics Division.

PROBLEMS OF INTERPRETATION OF K MESIC ATOMS[1]

W. M. Bugg[2] G. T. Condo[2] E. L. Hart[2] H. O. Cohn R. D. McCulloch[3]

It is shown that the value of the principal quantum number from which K^- mesons are captured has not reliably been determined. It is also pointed out that the original emulsion data, suggesting a neutron hole in heavy nuclei, carry implications regarding pion reabsorption that are not understood.

1. Abstract of published paper: *Particles Nucl.* 2(4), 201 (1971).
2. University of Tennessee, Knoxville.
3. Mathematics Division.

MULTIPION DATA ON THE T REGION

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M. M. Nussbaum[3] J. M. Scarr[4]

It has long been known that the bosonic mass spectrum in the mass region above 1.5 GeV/c^2 is rich in resonant states. For example, at the present time, the likelihood is that at least four different states have been identified in the so-called R region (1.6 to 1.85 GeV/c^2).[5-9] Evidence is now accumulating that a similar grouping of states may also be occurring in the T region (2.05 to 2.25 GeV/c^2). The initial indication of structure in this mass region was supplied by the CERN Missing-Mass Spectrometer Group,[5] which observed a narrow isovector state at a mass of 2.195 ± 0.013 GeV with a width less than 13 MeV. Subsequently, structure has been observed in the $I = 1$ $N\bar{N}$ total cross section,[10] and Kalbfleisch et al.[11] have presented evidence for a

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2. Mathematics Division.
3. University of Cincinnati, Cincinnati, Ohio.
4. Brookhaven National Laboratory, Upton, L.I., New York.
5. M. N. Focacci et al., *Phys. Lett.* 17, 890 (1966); B. Levrat et al., *Phys. Lett.* 22, 714 (1966).
6. ABC Collaboration, *Nucl. Phys.* B22, 109 (1970).
7. T. Ferbel, *Meson Spectroscopy*, p. 354, W. A. Benjamin, New Yrok, 1968.
8. I. K. Kenyon et al., *Phys. Rev. Lett.* 23, 146 (1969).
9. J. Ballam et al., *Phys. Rev.* 3D, 2606 (1971); H. Brain et al., *Nucl. Phys.* B30, 213 (1971).
10. R. J. Abrams et al., *Phys. Rev. Lett.* 18, 1209 (1967).
11. G. Kalbfleisch et al., *Phys. Lett.* 29B, 259 (1969); *Nucl. Phys.* (to be published).

$pp\pi$ state from a series of $\bar{p}p$ formation experiments. In addition, strong evidence for an even G parity isovector state at a mass of 2.157 ± 0.01 GeV/c with a width of 78 ± 20 MeV has been obtained by Kramer et al.[12] in a 13-GeV/c π^+p experiment. Thus current indications are that there exist at least two isovector states of opposite G parity in the T region. In this experiment we find that at least one of these states has a dominant decay mode other than those alluded to above, or that there is a third resonance in this mass region.

Our data derive from an experiment utilizing 7.87-GeV/c π^+ mesons incident on the 80-in. BNL deuterium bubble chamber. Since the main thrust of this work concerns the decays of neutral states, we have required all events to have a visible spectator proton, and, to minimize scanning biases, we have required all events to have momentum transfer less than 50 $m\pi^2$ between the incident π^+ and outgoing bosonic systems. With these restrictions, each event corresponds to ~0.6 μb of cross section.

The dipion mass spectrum from the reaction $\pi^+d \to pp\pi^+\pi^-$ is shown in Fig. 1. Aside from the ρ^0, f^0, and g^0 signals, there is no compelling evidence for the production of any other state. In particular, there is no more than marginal evidence for T production at 2140 MeV. In fact, except for the presence of the f^0, this histogram is virtually identical to the $\pi^+\pi^0$ spectrum presented by the ABC collaboration[13] from an 8-GeV/c π^+p experiment. Figure 2 exhibits the neutral five-pion spectrum from the reaction $\pi^+d \to pp\pi^+\pi^+\pi^-\pi^-\pi^0$, with the shaded area representing the results of a $\rho^0\rho^0\pi^0$ selection. We note that, with the background estimate as indicated, the five-pion spectrum contains a greater than three-standard-deviation enhancement in the T region. However, no signal survives when the $pp\pi$ restriction is made. Furthermore, no evidence of resonant formation is present in the $\rho^\pm\pi^\mp\rho^0$ final state in

12. S. L. Kramer et al., *Phys. Rev. Lett.* **25**, 396 (1970).
13. ABC Collaboration, *Nucl. Phys.* **B4**, 501 (1968).

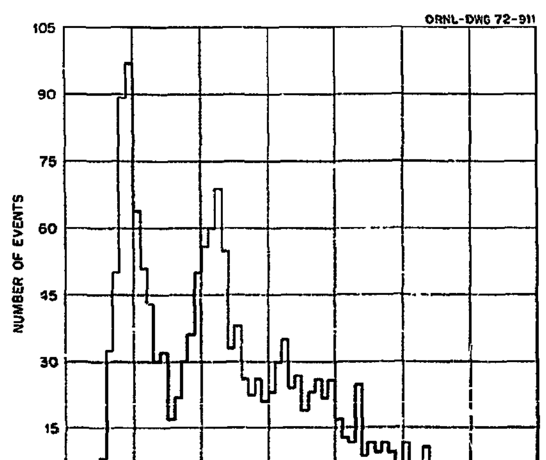

Fig. 1. Dipion mass spectrum from the reaction: $\pi^+d \to pp\pi^+\pi^-$.

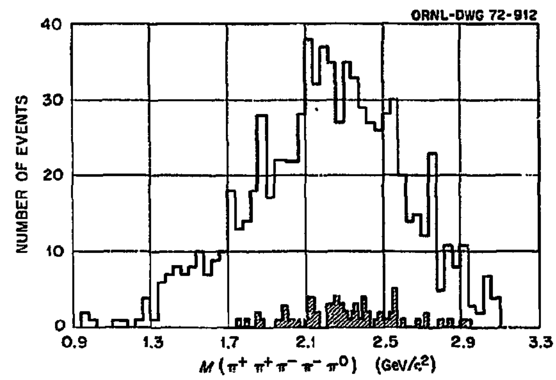

Fig. 2. Five-pion mass spectrum from the reaction: $\pi^+d \to pp\pi^+\pi^+\pi^-\pi^-\pi^0$. The shaded area indicates the $\rho^0\rho^0\pi^0$ spectrum.

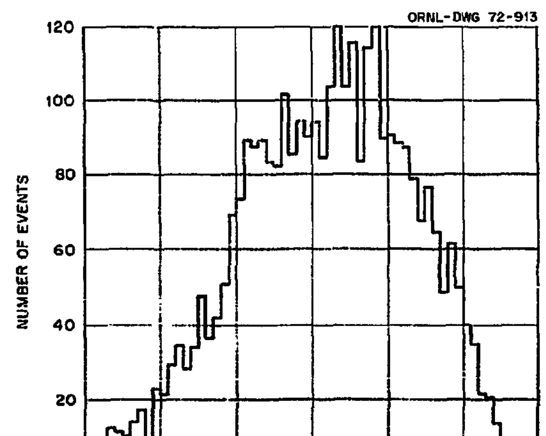

Fig. 3. Bosonic mass spectrum from the reaction: $\pi^+d \to pp\pi^+\pi^-$MM (MM ≥ $2\pi^0$).

this experiment. We therefore conclude that neither the even G parity state observed by Kramer et al.[12] nor the $pp\pi$ reported by Kalbfleisch et al.[11] is produced with any appreciable cross section (<20 μb) in 8-GeV/c charge exchange π^+n interactions.

The crux of the present paper appears in Fig. 3, which presents a histogram of the bosonic system from the reaction $\pi^+d \to pp\pi^+\pi^-$(MM), where (MM) denotes missing mass ($\geq 2\pi^0$). It is clear that strong enhancements are present in both the T and U mass regions. (Phase space for a multipion system recoiling off a nucleon reaches its maximum value at a mass >2.4 GeV/c^2.) While the enhancement at 2.33 ± 0.02 GeV/c^2 can be correlated with the U meson, it is clear, from Figs. 1 and 2, that no such identification is possible for the observed T in this experiment. We therefore conclude that either the previously observed T systems have dominant decay modes other than those reported or else there exists a third state with a substantial decay mode into at least four pions. Since the 5π channel (without ρ correlations) exhibits a greater than three-standard-deviation enhancement in the T region, the suggestion can be made that we are observing a 5π resonance with a mass of 2.15 ± 0.03 GeV/c^2 which decays both into $\pi^+\pi^+\pi^-\pi^-\pi^0$ and into $\pi^+\pi^-\pi^0\pi^0\pi^0$.

3. Nuclear Structure, Reactions, and Radioactivity

3a. Systematics

NUCLEAR DATA COMPILATIONS: THE LIFEBLOOD OF THE NUCLEAR SCIENCES AND THEIR APPLICATIONS[1]

P. H. Stelson

The Ad Hoc Panel on Nuclear Data Compilations was convened in the spring of 1969 to assess and evaluate the current situation and to make recommendations for reducing the dangerous backlog that has developed with ever-increasing momentum during the past decade. The panel members were chosen with the aim of achieving a proper balance between experimentalists and theorists and between university professors and staff members of national laboratories.

The Panel convened for the first time on May 1, 1969, in Washington, D.C., held a second meeting on August 24, 1969, in Montreal, and a third one on April 26, 1970, again in Washington. The Panel has studied the structure and functioning of the nuclear data compilations, their value to the nuclear sciences, and their manifold applications. Its recommendations are designed to reverse the present trend and to bring nuclear data compilations up to date in the most expedient manner.

The panel members were Gertrude Scharff-Goldhaber, Brookhaven National Laboratory, *Chairman;* Fay Ajzenberg-Selove, Physics Department, University of Pennsylvania; Guy T. Emery, Physics Department, Indiana University; George Ewan, Chalk River Laboratory, Canada (now in the Physics Department, Queens University, Kingston, Ontario); Ernest Henley, Physics Department, University of Washington; Arthur K. Kerman, Physics Department, Massachusetts Institute of Technology; Lawrence M. Langer, Physics Department, Indiana University; John O. Rasmussen, Chemistry Department, Yale University; James S. Robertson, Medical Department, Brookhaven National Laboratory; John Schiffer, Argonne National Laboratory and University of Chicago; Paul Stelson, Oak Ridge National Laboratory.

1. A Report of the Ad Hoc Panel on Nuclear Data Compilations, Committee on Nuclear Science, National Research Council, published and available through National Academy of Sciences, Committee on Nuclear Science, 2101 Constitution Avenue, Washington, D.C. 20418.

REACTION LIST FOR CHARGED-PARTICLE-INDUCED NUCLEAR REACTIONS: PART I – $Z = 1$ TO $Z = 98$ (H TO Cf), JULY 1970–JUNE 1971; PART II – COULOMB EXCITATION, 1956–JUNE 1971[1]

F. K. McGowan W. T. Milner

Part I of this reaction list for charged-particle-induced nuclear reactions has been prepared from the journal literature for the period from July 1970 through June 1971. Each published experimental paper is listed under the target nucleus in the nuclear reaction with a brief statement of the type of data in the paper. The nuclear reaction is denoted by A(*a*,*b*)B, where $M_a \geq$ (one nucleon mass). There is no restriction on energy.

1. Abstract of published paper: *Nucl. Data Tables* **A9**, 469–619 (1971).

Nuclear reactions involving mesons in the outgoing channel are not included. Beginning with this supplement, theoretical papers which treat directly with the analysis of nuclear reaction data and results are included in the reaction list. In Part II is presented a reaction list for the Coulomb excitation reaction which has been prepared from the journal literature for the period from 1956 through June 1971.

NUCLEAR DATA PROJECT

D. J. Horen R. L. Auble F. E. Bertrand Y. A. Ellis W. B. Ewbank
M. B. Lewis M. J. Martin S. Raman M. R. Schmorak D. C. West

During the calendar year 1971, the Nuclear Data Project continued its efforts to update the A-chain compilations, improve communications between the Nuclear Data Project and researchers in the field as well as other compilers of nuclear data, pursue the utilization of computer aids in the compilation process, and pursue interactions with applied users of nuclear data. Of course, a major event was the initiation of the NSF–NIRA Program (see below), which is coordinating with the Nuclear Data Project in an effort to accomplish updating of mass chains for $A > 44$ by 1974. These topics are more thoroughly discussed in the following.

Nuclear Data Sheets

Revised A chains.

A = 84, R. L. Auble
A = 85, D. J. Horen
A = 86, R. L. Auble
A = 87, H. Verheul (consultant)
A = 109, F. E. Bertrand
A = 110, F. E. Bertrand and S. Raman
A = 111, S. Raman and H. J. Kim
A = 113, S. Raman and H. J. Kim
A = 121, D. J. Horen
A = 198, R. L. Auble
A = 199, M. B. Lewis
A = 200, M. J. Martin
A = 201, R. L. Auble
A = 202, R. L. Auble
A = 203, R. L. Auble
A = 204, M. J. Martin
A = 205, M. R. Schmorak
A = 207, M. R. Schmorak and R. L. Auble
A = 208, M. B. Lewis
A = 209, M. J. Martin
A = 210, M. B. Lewis
A = 211, S. C. Pancholi (consultant) and M. J. Martin
A = 229, Y. A. Ellis
A = 231, A. Artna-Cohen (consultant)
A = 233, Y. A. Ellis
A = 235, A. Artna-Cohen (consultant)
A = 237, Y. A. Ellis
A = 239, A. Artna-Cohen (consultant)
A = 241, Y. A. Ellis

"Recent References." All reports received thus far indicate that "Recent References" has been well received. This conclusion is based upon verbal comments, answers to a questionnaire, and observation of citations to "Recent References" in a number of reports. "Recent References" is published triannually as part of the *Nuclear Data Sheets*. Keywording of calculational (theoretical) papers was initiated in 1970. Samples will be distributed to test researchers' opinions.

"Recent References (September 1970–December 1970)," W. B. Ewbank, D. C. West, S. H. Dockery, F. W. Hurley, and S. C. Rader

"Recent References (January 1971–April 1971)," D. C. West, F. W. Hurley, and S. C. Rader

"Recent References (May 1971–August 1971)," D. C. West, F. W. Hurley, S. H. Dockery, and S. J. Ball

Current Nuclear Level Schemes: A = 118–139

The Nuclear Data Project was fortunate to have received voluntary assistance from seven non-Project members (one from ORNL and six from ANL) in the preparation of *Current Nuclear Level Schemes.* The content was extended to include level half-lives, as well as spectroscopic factors.

Current Nuclear Level Schemes: A = 118–139, A. J. Elwyn, J. R. Erskine, R. E. Holland, D. J. Horen, J. E. Monahan, J. P. Schiffer, R. K. Smither, and P. H. Stelson

Research Papers, Verbal Presentations, etc.

Most members of the Nuclear Data Project are actively engaged in experimental or theoretical research, and write-ups of the works are included in this annual report. These amount to nine published papers, 12 abstracts presented at APS meetings, and five ORNL reports.

Computerization (Nuclear Data File)

Programming was completed to allow production of reference lists for specific nuclei. (This program was essential to make feasible communication with the

NIRAs.) All references for the years 1960 up to the present are now on file. Pre-1960 references are being added. The programming was done in part by Frank Hammerling (Mathematics Division – ORNL) and staff members at K-25.

Efforts are under way to revise the programming used for plotting level schemes and tabulating data. Changes in the data formats and operating programs are being made to simplify the input and utilization. When completed, these changes will result in improved efficiency in the data handling and production processes. In addition, they will establish the input formats for a nuclear structure data file. It is anticipated that the modified formats will prove acceptable to data producers and that it will prove to be convenient for the transmittal of their data in a computer-readable form to the Nuclear Data Project. Those persons working on this project include M. Feliciano and C. Webster of the Mathematics Division and D. Horen, F. Bertrand, and M. Schmorak of the Nuclear Data Project.

Use of Evaluated Data by Applied Users

We are continuing efforts to establish contact with applied users of nuclear structure data. These attempts have taken the form of responses to requests for specific data, as well as initiation of inquiries to applied users. Two examples of responses to requests are the following.

Decay schemes and characteristics were compiled for the radioactive atoms ^{83m}Kr, $^{85m,85}Kr$, ^{87}Kr, ^{88}Kr–^{88}Rb, ^{131m}Xe, $^{133m,133}Xe$, $^{135m,135}Xe$, ^{137}Xe–^{137}Cs, and ^{138}Xe–^{138}Cs. Listed in tabular form are half-lives, energies, and intensities for each of the atomic and nuclear radiations emitted by these radioactive atoms. This information was requested by Dr. Jacob Kastener, Chief, Technical Assessment Branch of the Division of Radiological and Environmental Protection, USAEC. (Prepared by M. J. Martin.)

Recommended characteristics for the decay of ^{109}Cd were prepared. These values were requested by the Isotopes Development Center at ORNL. The information was also furnished to the NRC Subcommittee on Use of Radioactivity Standards. (Prepared by D. J. Horen.)

Coordination with Other Compilation Groups

A meeting of representatives of centers active in compiling low-energy nuclear physics data was held at BNL in September. The meeting was called by S. Pearlstein (National Neutron Cross Section Center, BNL) and D. Horen and was attended by F. Ajzenberg-Selove (Energy Levels of Light Nuclei), E. G. Fuller (Photonuclear Data Center), R. L. Heath (Gamma Ray Spectrum Catalogue), N. E. Holden (Chart of the Nuclides), J. M. Hollander (Table of Isotopes), F. K. McGowan (Charged-Particle Cross Section Data Center), and R. Taschek (International Nuclear Data Committee).

The functions of each center were reviewed, and discussions concentrated on achieving ways of minimizing duplication of effort and maximizing cooperation between the different centers. A summary of the meeting is available in the form of a BNL Memorandum. It is planned to hold additional meetings, some of which would include representatives of applied users of evaluated nuclear data.

Some specific cooperative ventures presently under way include:

Table of isotopes: The Nuclear Data Project provides all the scanning for the LRL group, which provides cross-checking of the Project's files. This arrangement seems to be working well.

Mass adjustment: The Nuclear Data Project continues to provide A. H. Wapstra with references pertaining to mass data. The latter keeps ORNL (N. B. Gove) supplied with evaluated, current mass information.

Nuclear spins and moments: The Nuclear Data Project supplies G. H. Fuller with references pertaining to nuclear spins and moments. The latter maintains a current evaluated file of these quantities.

Non-Project Mass Chain Compilers

S. C. Pancholi (India) is presently completing a compilation of $A = 212$.

K. K. Seth (U.S.A.) is completing a compilation of $A = 206$.

H. Verheul (Holland) is presently completing a compilation of $A = 91$.

A. Artna-Cohen (U.S.A.) continues to compile for the Nuclear Data Project. (Compilations completed in 1971 are listed under Book and Journal Articles, this report.)

National Science Foundation–Nuclear Information Research Associate Program

The Nuclear Data Project is providing all reference lists for the 12 NIRAs. In addition, production and publication of their compilations will be handled by the Nuclear Data Project. One preliminary compilation was received in 1971.

A GRAPHICAL COMPARISON OF CALCULATED INTERNAL CONVERSION COEFFICIENTS: HAGER-SELTZER vs SLIV-BAND[1]

W. B. Ewbank

For many years the Nuclear Data Group has used the calculations of theoretical internal conversion coefficients by Sliv and Band as a standard for comparison with measured conversion coefficients. Since about 1965, a computer has been used to perform a reproducible interpolation between the tabulated values. The calculations by Hager and Seltzer include some improvements over those of Sliv-Band. Hager-Seltzer have also made exact calculations for many more values of Z and energy, so that interpolation is simpler and more accurate. Recently, the Nuclear Data Project obtained a magnetic-tape copy of the published table, and the new calculation can now be used for comparison in the *Nuclear Data Sheets*.

With computer-readable files of both calculations on hand, it seemed desirable to prepare a systematic comparison as a guide to both experimental and theoretical nuclear physicists. The Computer-Graphics programming package, prepared by the Mathematics Division at ORNL, makes easy the systematic graphical presentation of the many numerical comparisons.

1. Abstract of ORNL-4655 (July 1971).

3b. $A \leqslant 22$

EVIDENCE FOR A $T = 1/2$ RESONANCE IN THE ^{3}He SYSTEM[1]

A. van der Woude M. L. Halbert[2] C. R. Bingham[3] B. D. Belt[4]

Evidence for a broad resonance in the ^{3}He system has been found in the excitation function for the radiative capture of deuterons by protons. Supporting evidence is provided by the behavior of the angular distributions. The resonance is centered at (19.5 ± 0.5)-MeV excitation, has a width of about 2 MeV, and is most likely characterized by $(L^\pi, S, T) = (1^-, 1/2, 1/2)$.

1. Abstract of published paper: *Phys. Rev. Lett.* 26, 909 (1971).
2. On temporary assignment at Brookhaven National Laboratory, Upton, N.Y.
3. Consultant from the University of Tennessee, Knoxville.
4. West Georgia College, Carrollton.

CHARGE-ASYMMETRY EFFECTS IN THE REACTION ^{2}H(^{4}He,^{3}He)^{3}H[1]

E. E. Gross[2] E. Newman M. B. Greenfield[3] R. W. Rutkowski[4]
W. J. Roberts[5] A. Zucker[6]

NUCLEAR REACTIONS: ^{2}H(^{4}He,^{3}He)^{3}H, E_α = 49.9, 64.3, 82.1 MeV; measured $\sigma(\theta)$ and ratio of τ/t. Deduced isospin conservation.

Differential cross sections for the process ^{2}H(^{4}He,^{3}He)^{3}H are presented for ^{4}He beam energies of 82.1, 64.3, and 49.9 MeV. The measurements were made to test the Barshay-Temmer theorem, which requires ^{3}H and ^{3}He yields to be independently symmetric about 90° c.m. We find a pronounced deviation from 90° c.m. symmetry, which is angle and energy dependent. A DWBA analysis, assuming the reaction mechanism to be a simple $\ell = 0$ nucleon pickup process, can qualitatively account for the observed deviations.

1. Abstract of paper to be published in the *Physical Review* (March 1972).
2. On leave from ORNL; present address: Niels Bohr Institute, Copenhagen, Denmark.
3. Graduate Fellow from the University of Tennessee, supported by an Army Research Office grant; present address: Florida State University, Tallahassee.
4. Oak Ridge Graduate Fellow from the University of Tennessee under appointment from Oak Ridge Associated Universities; present address: U.S. Atomic Energy Commission, Oak Ridge, Tennessee.
5. Oak Ridge Graduate Fellow from the University of Tennessee under appointment from Oak Ridge Associated Universities.
6. On leave from ORNL; present address: National Academy of Sciences, Washington, D.C.

ALPHA PARTICLES FROM THE BOMBARDMENT OF ^{3}He BY ALPHAS

M. L. Halbert[1] A. van der Woude N. M. O'Fallon[2] R. F. Nelson[3]

Evidence for a broad resonance in ^{3}He at an excitation energy of about 20 MeV was seen in the radiative capture of deuterons by protons.[4] Spectra of alpha particles emitted at forward angles ($\leq 11°$) from the bombardment of ^{3}He gas by a beam of 63.7-MeV alphas show a strong peak at an energy corresponding to the inelastic excitation of this apparent resonance.[5] Figure 1 shows the peak in the 5° raw data, with and without ^{3}He gas in the target chamber. A similar peak is prominent in bombardments at 71.7 and 81.4 MeV, as seen in the gas-in, gas-out difference spectra shown in Figs. 2 and 3. However, at the two higher bombarding energies, the peak position does not correspond to an excitation of 20 MeV. It was concluded that the peak was not produced by inelastic scattering.[6] Additional measurements reported here indicate that a sequential decay process involving the first excited state of ^{6}Li is the most likely candidate for explaining the origin of the prominent peak,[7] but some perplexing questions remain unanswered.

1. On temporary assignment at Brookhaven National Laboratory, Upton, N.Y.
2. University of Missouri at St. Louis. Supported by a travel grant from ORAU.
3. ORAU Summer Trainee from Iowa State University, Ames.
4. A van der Woude, M. L. Halbert, C. R. Bingham, and B. D. Belt, *Phys. Rev. Lett.* **26**, 909 (1971).
5. M. L. Halbert and A. van der Woude, *Phys. Rev. Lett.* **26**, 1124 (1971).
6. M. L. Halbert and A. van der Woude, *Phys. Rev. Lett.* **26**, 1679 (1971).
7. This possibility was suggested to us independently by M. J. Saltmarsh and R. E. Brown.

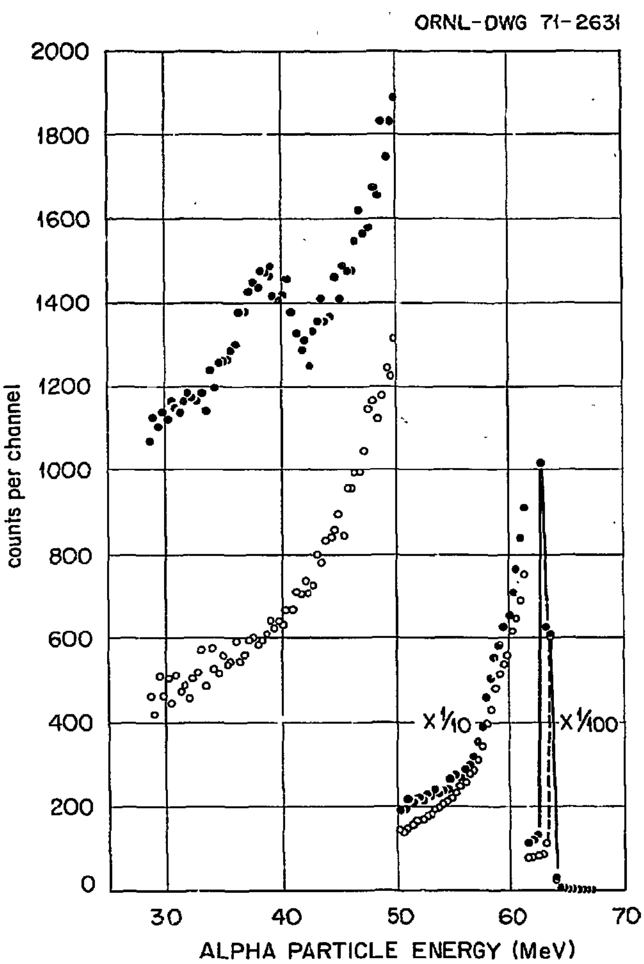

Fig. 1. Spectra of alpha particles observed at 5° with (•) and without (○) ^{3}He gas in the target. The bombarding energy at the center of the target was 63.7 MeV.

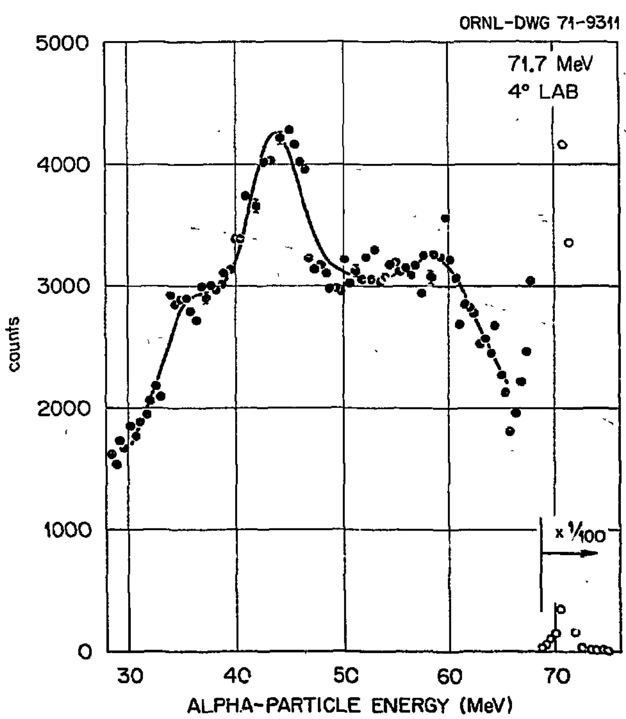

Fig. 2. Gas-in, gas-out difference spectrum of alpha particles at 4° with a bombarding energy of 71.7 MeV. The curve is a least-squares fit (see text).

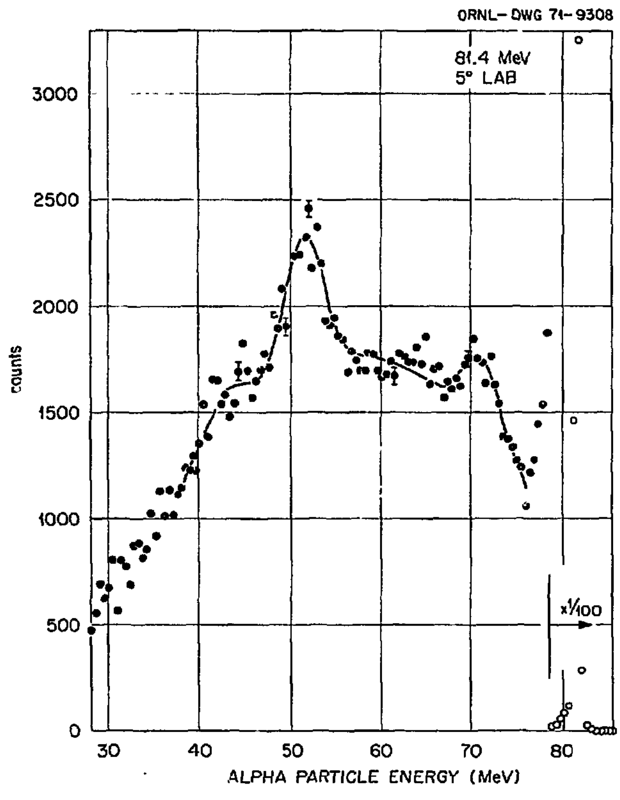

Fig. 3. Gas-in, gas-out difference spectrum of alpha particles at 5° with a bombarding energy of 81.4 MeV. The curve is a least-squares fit (see text).

Cross Sections

Consider the sequential process

$$\alpha + {}^3\text{He} \rightarrow p + {}^6\text{Li}^* \\ \quad\quad\quad\quad\quad \hookrightarrow \alpha + d\,. \tag{1}$$

The first excited state of ^{6}Li (2.18 MeV) is unstable to $\alpha + d$ breakup. Since the breakup energy is small compared to the kinetic energy of the ^{6}Li* here, all alphas from the $\alpha + d$ fragmentation are confined to a narrow cone about the initial direction of the ^{6}Li*. If the forward alpha peak arises from process (1), it must therefore be due to forward-emitted ^{6}Li*. The corresponding protons would be emitted backward, and measurement of their spectrum could provide valuable information on the yields of the ^{6}Li* before breakup.

Accordingly, proton spectra were measured at 71.7-MeV bombarding energy for 11 angles from 121.4 to 170.2°. A 500-μ silicon surface-barrier counter was used. Figure 4 shows two of these spectra. The strongest peak in each one is at the correct energy for protons corresponding to ^{6}Li* (2.18), while the peak about 20 channels higher corresponds to the ground-state protons. The 170.2° spectrum also shows a weak group (at channel 80) corresponding to protons leaving ^{6}Li in its 3.56-MeV state.

The center-of-mass cross sections inferred from the proton spectra are shown by the open and closed circles in Fig. 5 for the ground, 2.18-MeV, and 3.56-MeV states. Two states of ^{6}Li (ground and 3.56 MeV) are particle-stable and were observed at forward angles with the same ΔE-E telescope that provided the alpha-particle spectra. The cross sections derived from the ^{6}Li observations are shown by the triangles. These results are in satisfactory agreement with those derived from the proton yields.

The four open squares in Fig. 5 show the ^{6}Li* (2.18 MeV) cross section calculated from the area of the prominent alpha peak at laboratory angles of 3.5, 4, 5, and 7° on the hypothesis that these alphas come from breakup of that state.[8] The yields agree well with the

8. It was assumed here that the breakup alphas observed at a given laboratory angle came from ^{6}Li* emitted at the same angle. Actually this is not so – the half angle of the breakup cone is about 5°. But, since the cross section (*a*) does not vary substantially over this range of angles and (*b*) is monotonic, it is probably safe to characterize the alpha yield at a given angle as the average yield of ^{6}Li* emitted at the same angle.

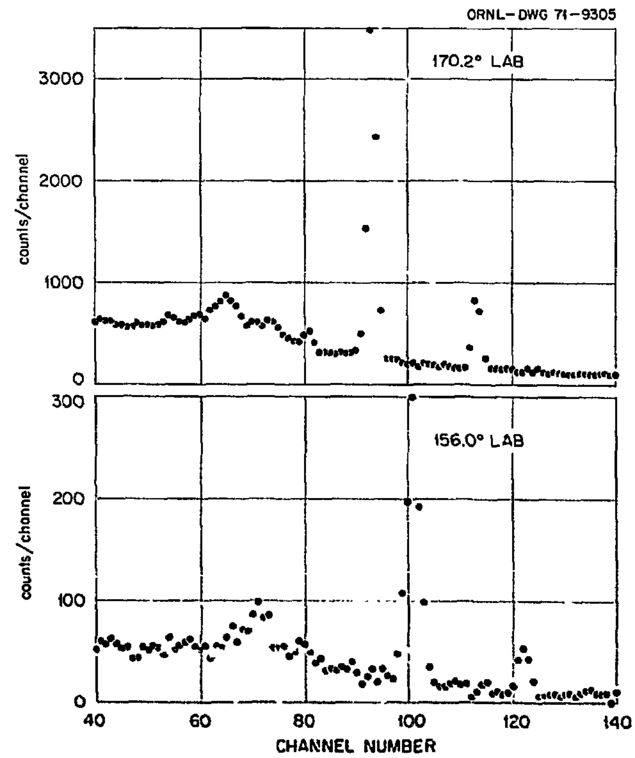

Fig. 4. Back-angle proton spectra at 71.7 MeV.

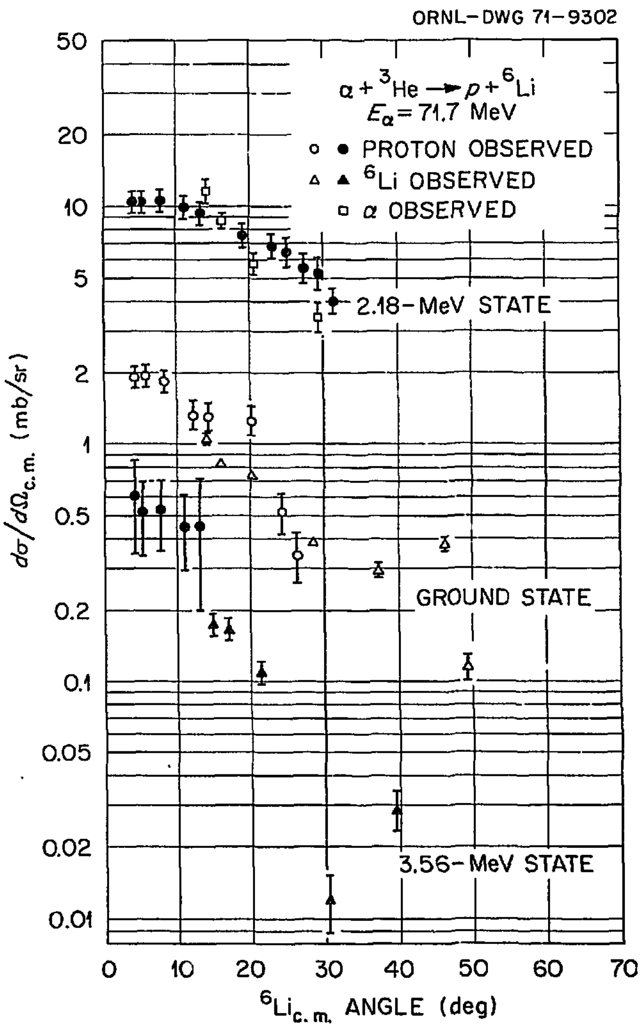

Fig. 5. Cross sections for exciting various states of ^{6}Li, as obtained from observation of protons (○, ●), ^{6}Li (△, ▲), and alpha particles (□).

proton yields. We conclude that the $\alpha + d$ fragmentation of $^6Li^*$ (2.18 MeV) provides sufficient numbers of alpha particles to account completely for the intensity of the prominent peak.

Peak Position

Most of the alpha spectra show evidence for one peak above and one below the prominent one. For example, the smooth curves in Figs. 2 and 3 are least-squares fits to sums of three peaks on a (quadratic) continuum. In some cases no peaks at all could be discerned. Figure 6 shows the centroids and widths (FWHM) of the peaks for all angles at which statistically reliable least-squares fits were found. The absence of the lowest peak in the 63.7-MeV data is due to an instrumental cutoff.

The prominent peak is presumably due to reaction (1). The laboratory energy of the breakup alphas of the reaction depends on the angle, θ', between the directions of the initial $^6Li^*$ and the alpha in the final $\alpha + d$ c.m. system. This relationship is shown by the full lines in Fig. 6 for $\theta' = 0$ and 180°. Some of the alphas appear to have an energy greater than the limiting value, especially for the 81.4-MeV data. Sequential decay via higher excited states of ^{6}Li or via other processes (see below) can give rise to higher-energy alphas.

The centroid energies correspond to θ' of about 30°. There are practically no particles in the peak with energies corresponding to $\theta' > 90°$. This is puzzling if one expects the breakup to be uniform in the $\alpha + d$ c.m. system. A calculation for alphas observed at 4° was made in which a c.m. distribution uniform in solid angle was transformed to the laboratory system with weighting of the $^6Li^*$ (2.18) intensity according to the proton data of Fig. 5. The resulting alpha spectrum is more rectangular than the observed peak, and the width is twice as large.

Two other sequential decays are possible:

$$\alpha + {}^3He \rightarrow d + {}^5Li \quad \hookrightarrow \alpha + p \tag{2}$$

and

$$\alpha + {}^3He \rightarrow n + {}^6Be \quad \hookrightarrow \alpha + 2p\,. \tag{3}$$

Process (3) is probably unimportant, since the ground state of ^{6}Be is an isobaric analog of the 3.56-MeV state of ^{6}Li, which is about 20 times weaker than the 2.18-MeV state (see Fig. 5).

In process (2), even the ground state of ^{5}Li may contribute, since it is particle-unstable. In fact, its width is about 1.5 MeV; the shaded regions of Fig. 6 show the range of alpha-particle energies due to this width for breakup angles of 0 and 180°.

The energy of the highest peak is generally consistent with forward emission of alphas from the ground-state breakup of ^{5}Li, while the lowest peak is consistent with backward emission from breakup of $^6Li^*$ (2.18 MeV). It may be noted that the main peak has the correct energy for backward emission from ^{5}Li, although, as pointed out above, the alpha yields can be completely accounted for by breakup of $^6Li^*$ (2.18).

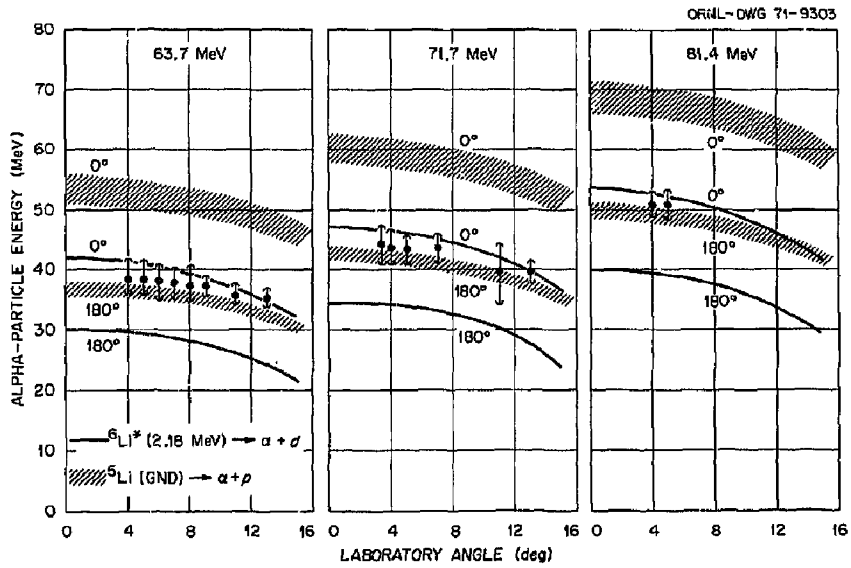

Fig. 6. Alpha-particle energies as a function of angle for three bombarding energies. The full points and their flags represent experimental centroid energies and widths (FWHM) of the prominent alpha peak at angles where it was clearly discerned. The open points refer to the two minor peaks. The full curves and shaded areas are described in the text.

THIN ^{6}Li(n,α)T TRANSMISSION FLUX MONITOR[1]

R. L. Macklin N. W. Hill[2] B. J. Allen[3]

NUCLEAR REACTIONS: ^{6}Li(n,α)^{3}H, E = 3–500 keV; measured neutron flux. ^{7}Li deduced level, Γ. Enriched target.

A thin glass scintillator system has been developed for fast time-of-flight neutron monitoring at the ORELA electron linear accelerator. Beam backgrounds under 1% from 6 to 100 keV, negligible environmental background, beam flash recovery in 1.25 μsec, and time resolution of less than 2 nsec have been achieved on a 40-m flight path. The monitor can be used in transmission, on line, introducing additional dips of less than 4% in the transmitted neutron spectrum at 55, 200, 240, and 440 keV and higher from the constituents of the glass scintillator.

1. Abstract of paper submitted for publication in *Nuclear Instruments and Methods.*
2. Instrumentation and Controls Division.
3. On leave from Australian Atomic Energy Commission.

EXCITATION OF ISOSPIN TRIPLETS IN NUCLEAR REACTIONS

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NUCLEAR REACTIONS: $^{10}B(^{10}B,^{10}B^*)^{10}B^*$, $^{10}B(^{10}B,^{10}Be)^{10}C$, $^{10}B(d,^{6}Li^*)^{6}Li^*$, $^{10}B(d,^{6}He)^{6}Be$, measured $\sigma(\theta)$, compared cross sections to members of isospin triplets.

Isospin is a useful concept in nuclear structure. The demonstrated existence of analog states, that is, adjacent members of isospin multiplets, amply illustrates the point.

The concept of isospin conservation may also be useful for understanding some aspects of nuclear reactions. It is known that certain reactions are strongly influenced by isospin selection rules, but many features of the role of isospin in nuclear reactions remain to be investigated.

Adair,[1] in 1952, pointed out that charge independence, or isospin conservation, establishes certain relationships among particular nuclear reactions. It follows, for example, from Adair's argument that, in the reactions $^{16}O(p,t)^{14}O$ to the ground state and $^{16}O(p,^{3}He)^{14}N$ to the 2.31-MeV state, the differential cross section for the tritons should be twice that for the ^{3}He after correction for any phase space difference. Cerny and Pehl[2] have found that the prediction is experimentally verified for 44-MeV protons.

Gross et al.[3] investigated the reaction $^{4}He(d,t)^{3}He$, in which the reaction products are isospin mirrors of each other and the two analogous reaction channels, $^{4}He(d,t)^{3}He$ and $^{4}He(d,^{3}He)t$, are spatial inversions of each other. In that experiment, deviations from the predictions of charge symmetry were observed.

If we extend Adair's argument to reactions that can excite three or more members of isospin multiplets, some interesting predictions come out.

Consider the reaction $A + B \rightarrow C + C'$, where C and C′ are two members of an isospin multiplet. Assume that A + B constitutes a system with definite isospin. A means of satisfying this condition is to require that A have a definite isospin and B have isospin 0. If isospin is conserved, the total wave function describing the C + C′ system must also be an eigenfunction of $T^2 = [T(o) + T(r)]^2 = \frac{1}{2}[T^+(o)\,T^-(r) + T^-(o)\,T^+(r)] + T_z(o)\,T_z(r)$, where o and r refer to the observed and the recoil particles respectively. The total wave function must have the form

$$\psi = \sum_{ij} C(tm_i m_j|TM)\,\chi_{m_i}{}^{t}(o)\,\chi_{m_j}{}^{t}(r)\,\phi(o)\,\phi(r)\,U\,. \qquad (1)$$

χ is an isospin function. The spin and other internal variables of the particles are described by ϕ. U is a function describing the relative motion of two kinematically identical particles. The functions ϕ and U may contain summations over substates. The isospin of the multiplet is t, and m is its projection. T is the total isospin of the system, and M is its projection. The coefficients can be recognized as Clebsch-Gordan coefficients. It should be noted that, since T^2 commutes with an operator that interchanges o and r, the interchanged wave function is also an eigenfunction of T^2 and T_z with the same eigenvalues and, in fact, is not a new state.

The measurement of the charge of the observed particle amounts to a measurement of its isospin projection. It is apparent from Eq. (1) that several values of the isospin projection are contained in the wave function, that the relative magnitudes of these projections are determined by Clebsch-Gordan coefficients, and that the relative magnitudes are independent of the angle of observation. Thus, if the final state can be described by a single value of isospin, the differential cross sections for observing the several components of the isospin multiplet differ only by multiplicative Clebsch-Gordan coefficients.

We have attempted to study the reaction

$$^{10}_{5}B_5 + {}^{10}_{5}B_5 \rightarrow {}^{10}_{6}C_4 + {}^{10}_{4}Be_6 \text{ or } {}^{10}_{5}B_5{}^* + {}^{10}_{5}B_5{}^*\,,$$

where $^{10}B^*$ signifies the first $T = 1$ state of ^{10}B. If isospin is conserved, equal numbers of ^{10}C, $^{10}B^*$, and ^{10}Be should be observed at any angle. (This result might look surprising if one ignores the concept of isospin and thinks of the production mechanism of $^{10}B^*$ as inelastic scattering and of ^{10}C and ^{10}B as exchange transfer reactions.)

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2. Joseph Cerny and Richard H. Pehl, *Phys. Rev. Lett.* 12, 619 (1964).
3. E. E. Gross, E. Newman, W. J. Roberts, R. W. Rutkowski, and A. Zucker, *Phys. Rev. Lett.* 24, 468 (1970).

A ^{10}B target was bombarded with 50-MeV ^{10}B ions from ORIC. The broad-range spectrograph with solid-state position-sensitive detectors in the focal plane was used for particle detection and identification. A strong peak appears in the ^{10}B spectrum, which we have identified with the 3.59-MeV state. The −3.48-MeV Q value that characterizes the double excitation of the first T = 1 state in ^{10}B was not resolved from the 3.59-MeV state, and we were forced to abandon the study pending a significant improvement in technique.

We have now turned our attention to $^{10}B(d,^{6}Li^{*})^{6}Li$ and $^{10}B(d,^{6}He)^{6}Be$, for which the same isospin arguments hold. We plan to study this reaction both by bombarding boron with deuterons and deuterium with boron ions.

STATES IN ^{8}Be STUDIED THROUGH THE REACTION $^{11}B(p,\alpha)^{8}Be$ WITH 40-MeV PROTONS[1]

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NUCLEAR REACTIONS: $^{11}B(p,\alpha)$, $^{11}B(p,^{3}He)$, E = 40 MeV; measured $\sigma(E_\alpha, \theta_\alpha)$, $\sigma[E(^{3}He), \theta(^{3}He)]$. ^{8}Be deduced level, Γ. ^{11}B target.

Spectroscopy of the alpha and tau particles from 40-MeV proton bombardment of ^{11}B reveals transitions to ^{8}Be states up to 19 MeV. The ratio of excitation of the 16.6-MeV state to the 16.9-MeV state is 2.3 ± 0.4. The $^{8}Be(4^{+})$ state is found at 12.5 MeV with a width of 4.0 ± 0.5 MeV. States in ^{9}Be excited most strongly are the ground state and 2.43-MeV level; a state at 3.1 MeV is excited with about 1% of the strength of the ground-state transition. Angular distributions show forward peaking for all states.

1. Abstract of published paper: *Nucl. Phys.* **A172**, 555–68 (1971).
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NEUTRON TRANSFER TO THE GROUND STATE OF ^{14}C IN THE $^{13}C(^{14}N,^{13}N)^{14}C$ REACTION[1]

R. M. Gaedke[2] W. Tobocman[3] K. S. Toth

NUCLEAR REACTIONS: $^{13}C(^{14}N,^{13}N)^{14}C$, E = 12.5–20.5 MeV; measured $\sigma(E)$; deduced spectroscopic factor. Enriched target.

Thick targets of ^{13}C (91.7%) were bombarded with ^{14}N ions accelerated in the Oak Ridge Tandem Van de Graaff, and the cross section for the neutron-transfer reaction $^{13}C(^{14}N,^{13}N)^{14}C$ was measured from 12.5 to 20.5 MeV. The cross section measured in this energy range is due predominantly to transfers that proceed to the ^{14}C ground state, since the threshold for the reaction to populate the 6.09-MeV first excited state is 17.6 MeV. The measured excitation function was then compared with cross sections calculated from the recent DWBA treatment of Schmittroth, Tobocman, and Golestaneh.[4] It was possible to find an optical potential for which the DWBA matched the observed excitation function above 14-MeV (lab) incident energy. From this fit, the spectroscopic factor for the ^{14}C ground state was determined. The excitation function for the compound nucleus reaction $^{13}C(^{14}N,2p)^{25}Na$ was also measured for ^{14}N incident energies from 13.5 to 20.5 MeV.

1. Abstract of published paper: *Phys. Rev.* **C3**, 1444 (1971).
2. Present address: Trinity University, San Antonio, Tex.
3. Case Western Reserve University, Cleveland, Ohio.
4. F. Schmittroth, W. Tobocman, and A. A. Golestaneh, *Phys. Rev.* **C1**, 377 (1970).

R-MATRIX ANALYSIS OF THE TOTAL AND (n,α) CROSS SECTION FOR NEUTRONS ON ^{16}O

C. H. Johnson J. L. Fowler R. M. Feezel

NUCLEAR REACTIONS: $^{16}O(n,n)$; $^{16}O(n,\alpha)^{13}C$, measured $\sigma_{nT}(E)$, 600 to 930 keV, 1390 to 1640 keV, deduced J^π, reduced widths.

We have used the multilevel two-channel R-matrix theory[1] to describe the total cross section of ^{16}O for neutrons up to 5.8 MeV and the (n,α) reaction cross sections from 3- to 5.8-MeV neutrons. Following the suggestion of Vogt[2] and his co-workers,[3,4] we fit off resonance using phase shifts calculated[5] for scattering from a real diffuse-edge potential. Also, following their suggestion, we choose the R-matrix boundary inside the tail of the potential and calculate[5] Coulomb wave functions which are modified from the usual functions by the presence of this tail. Our potential is a conventional energy-independent Woods-Saxon well with a Thomas-type spin-orbit term.

For s and d waves we choose the four well parameters to be V_0 = 54.16 MeV, V_{so} = 7.47 MeV, r_0 = 1.22 F, and a = 0.72 F in order to satisfy four experimental requirements. These are that the $1d_{5/2}$ and $2s_{1/2}$ states be bound at energies coinciding with those observed in ^{17}O, that the final fitted s-wave cross section at thei ıal energies agree with the observed[6] free-atom cross section of 3.74 ± 0.06 b, and that the unbound $1d_{3/2}$ state be close to the centroid of the observed $3/2^+$ states. For $d_{3/2}$ waves we do not use the model phase shifts directly but subtract the $1d_{3/2}$ term from a multilevel R-function expansion so that we can, in effect, replace this single-particle state by its observed fragments. The reduced width of the $1d_{3/2}$ state is of special interest. Following the suggestions of Vogt and co-workers,[2-4] we choose a radius, $r_b = 1.256\, r_0$, such that this width is $\hbar^2/\mu r_b{}^2$.

For p waves we find that this potential gives much too large phase shifts to fit the data. Thus, for p waves and also for f waves, we change the well depths to V_0 = 46 MeV and V_{so} = 3 MeV.

Using these potential phase shifts and the known[7] J^π for most of the states, we adjusted the level energies and widths to obtain the best visual fit to both the total and (n,α) cross sections below 5.8 MeV. Figure 1 shows this fit. Data shown as points for the total cross section are our measurements from this and preceding years.[8] The crosses represent data from the University of Wisconsin.[9] The letter X indicates a narrow resonance of unknown J^π. The letter R indicates resonances of known J^π that were not included in the R matrix. The lower figures show the partial cross sections and the J^π assignments. The (n,α) cross sections at the upper right are those of Bair and Haas[10] but reduced by 20%. The curve through these points is also from the analysis.

The adjustment of the parameters to obtain this visual fit was relatively easy except in the region of overlapping levels from about 3.9 to 4.5 MeV. Here, in order to fit both the total and (n,α) cross sections, we find it necessary to assign $1/2^+$, rather than $1/2^-$, to the 4.05-MeV resonance and to introduce two underlying $1/2^-$ states at about 4.1 and 4.3 MeV.

1. A. M. Lane and R. S. Thomas, *Rev. Mod. Phys.* **30**, 257 (1958).
2. E. Vogt, *Rev. Mod. Phys.* **34**, 723 (1962).
3. E. Vogt, G. Michaud, and H. Reeves, *Phys. Lett.* **19**, 570 (1965).
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5. Mark Reeves III, private communication.
6. J. R. Stehn, M. D. Goldberg, B. A. Magurno, and R. Wiener-Chasman, BNL-325, 2d ed., suppl. No. 2.
7. F. Ajzenberg-Selove, *Nucl. Phys.* **A166**, 1 (1971).
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9. A. Okazaki, *Phys. Rev.* **99**, 55 (1955); H. R. Striebel, S. E. Darden, and W. Haeberli, *Nucl. Phys.* **6**, 188 (1958); D. B. Fossan, R. L. Walter, W. E. Wilson, and H. H. Barschall, *Phys. Rev.* **123**, 209 (1961).
10. J. K. Bair and F. X. Haas, *Phys. Div. Annu. Progr. Rep. Dec. 31, 1970*, ORNL-4659, p. 38.

Table 1. Energies and widths in kilo-electron volts for the $3/2^+$ states

E_γ (lab)	E_r (lab)	E_{ex}	γ^2	Γ (cm)	$\gamma^2/(\hbar^2/\mu r_b{}^2)$ (%)
709	1000	5083	2035	196	68.9
1838	1833	5867	28	6.6	1.0
3536	3250	7200	500	280	16.9
4311	4167	8062	252	71	8.5
5159			123		4.2
				Sum	99.5

The analysis shows that the broad resonance near 5.6 MeV has $J^\pi = 3/2^-$. If the level were $3/2^+$ it would exhibit a deep interference minimum preceding the peak.

There are several other interesting results of the analysis. The most interesting is that, as shown by Table 1, the reduced widths of the five $3/2^+$ resonances add up to almost exactly the single-particle $1d_{3/2}$ width from the potential model. This is good evidence that these five levels constitute nearly all of the fragments of the $1d_{3/2}$ state. In particular, the well-known 5.083-MeV state in ^{17}O has only 69% of the total strength.

In Table 1 we define a resonance energy E_r to be a point of inflection or maximum slope in the phase shift and the width Γ to correspond to this phase shift $\pm \pi/2$. The ^{17}O excitation energies E_{ex} are computed from E_r.

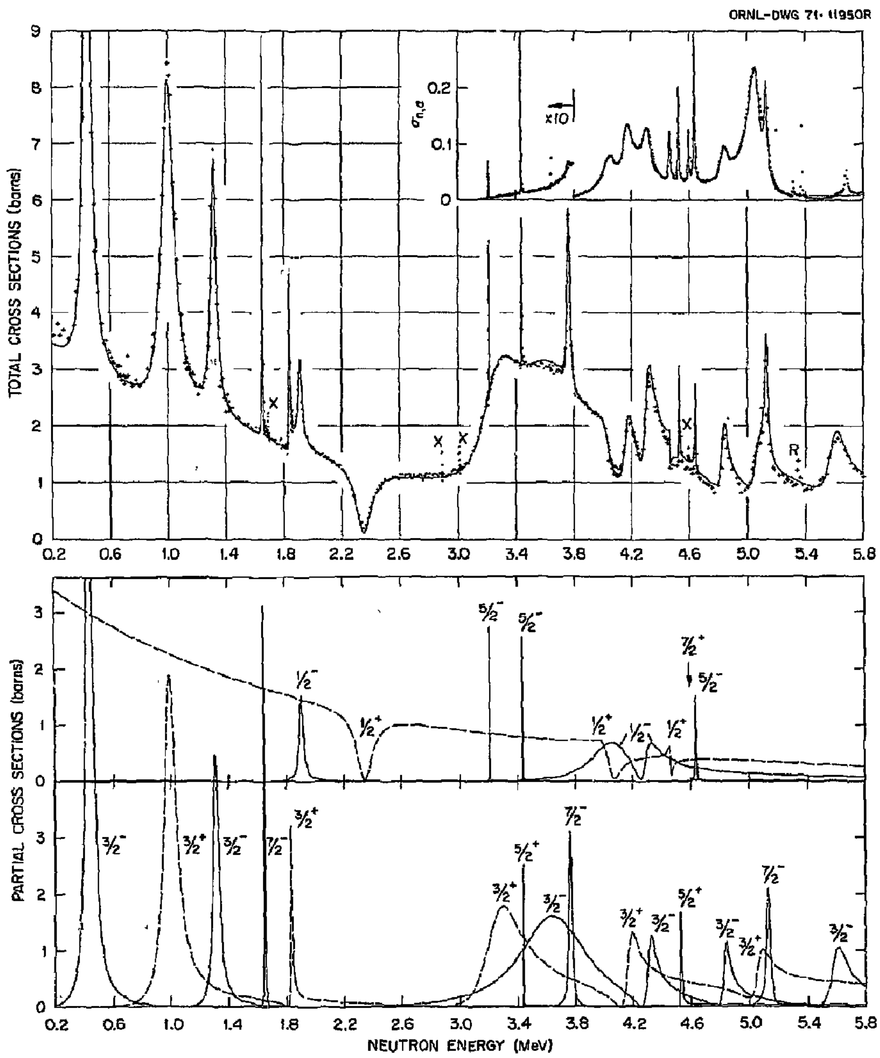

Fig. 1. *R*-matrix fit to the total and (n,α) cross sections for neutrons on ^{16}O. The lower two figures show partial cross sections for the indicated J^π values.

TOTAL CROSS SECTIONS FOR MILLION-ELECTRON-VOLT NEUTRONS AT THE ORELA 200-m STATION

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NUCLEAR REACTIONS: $^{16}O(n,n)$, E_n = 0.6 to 4.0 MeV, measured σ_T, deduced level width, J^π, 1.651-MeV resonance.

We initiated use of the 200-m flight station at ORELA by measuring the neutron total cross section of ^{16}O for neutron energies above 600 keV. We chose ^{16}O because its cross section has been studied[2] in detail and with good resolution by use of the 5.5-MV Van de Graaff accelerator. For the present transmission measurements, our matching BeO and Be scatterers were each 6 in. in diameter and contained 0.1831 molecule/b, and we detected the transmitted neutrons in two $3\frac{1}{4}$-in.-diam NE110 plastic scintillators optically coupled to RCA 4522 phototubes. The average thickness of each plastic was 2 cm, and the effective centers were 198.733 m from the center of the neutron source. The times are measured relative to the arrival of the gamma burst, and the neutron flight time is found by the addition of the transit time for gamma rays.

We correct the transmissions for background and for dead time in an EGG clock. The 4-μsec dead time of this time digitizer is, in fact, the effect which limits our usable beam intensity. For the present work we restricted the neutron beam so that the maximum dead-time correction with the Be sample was 15% for about 800-keV neutrons. At that energy the correction to the cross section is 0.36 b, but it is less at both higher and lower energies.

The background arises mostly from gamma rays which are produced by the transmitted fast neutrons. Since gamma rays produce relatively large light pulses, this background is present not only in the early time channels where fast neutrons are detected but also in later channels where the neutron pulses fall below the counter bias. From observations with various counter bias settings, we find that the background intensity decreases slowly with a half-life of about 30 μsec. Thus we measure the background in the later channels where there are no neutron pulses and then extrapolate backward to the earlier neutron time channels. Since this background has its origin from fast neutrons which are transmitted with an effective or observed ^{16}O cross section of 2.5 b, the correction lowers those cross sections that are below 2.5 b and raises those that are above. At the peaks of the 1.00- and 1.651-MeV resonances the backgrounds were 5% with the BeO sample in place and the corrections to the peak cross sections were 2.4%. At other energies the background is less, except below about 500 keV, particularly at the 442-keV resonance, where it is too large to give a reliable correction. Reliable measurements at that resonance will require thinner scattering samples and lower bias settings.

Figure 1 shows the observed cross section near the 1651-keV resonance. Both the energy and width (corrected for resolution) of the resonance are in excellent agreement with those observed[2,3] using neutrons from the $^7Li(p,n)^7Be$ reaction. The fact that the observed peak cross section exceeds the maximum allowed for J = 5/2 and the fact[4] that the scattered neutrons are f

1. Centenary College, Shreveport, La.
2. C. H. Johnson, J. L. Fowler, and R. M. Feezel, this progress report.
3. J. L. Fowler, C. H. Johnson, and F. X. Haas, *Proceedings of the International Symposium on Nuclear Structure Contributions (Dubna, U.S.S.R., July 1969)*, p. 1 (1968).
4. R. O. Lane, A. S. Langsdorf, J. E. Monahan, and A. J. Elwyn, *Ann. Phys.* (New York) **12**, 135 (1961).

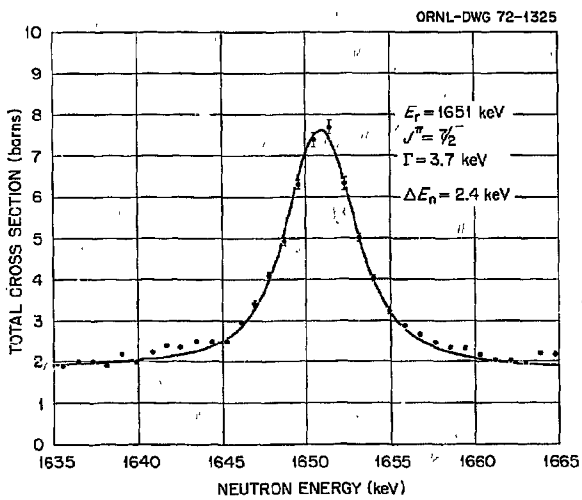

Fig. 1. Neutron total cross section near the 1651-keV resonance for ^{16}O. The curve is the fit for the indicated parameters.

waves show clearly that $J^\pi = 7/2^-$. The solid curve is calculated for a laboratory width of $\Gamma = 3.7$ keV and a 2.4-keV normal resolution function.

The observed width of the gamma burst in the detector was 4.5 nsec. If this were the only source of time spread, the neutron energy resolution at this 1651-keV resonance would be 1.32 keV. Thus, assuming that the other effects add in quadrature, we must introduce other contributions of the order of 2 keV to make up the total 2.4-keV width. Part of this certainly arises from neutron transit times in the source and detector. The required variation in flight path is about 10 cm. We need to investigate this further; but, in any case, the resolution below 2 MeV is already better than the best achieved[2,3] at this laboratory with the ^{7}Li(p,n)^{7}Be source.

THE NEUTRON TOTAL CROSS SECTION OF ^{16}O AND ^{40}Ca[1]

J. L. Fowler C. H. Johnson F. X. Haas[2] R. M. Feezel[3]

NUCLEAR REACTIONS: ^{16}O; E_n = 1.75 to 4.35 MeV; ^{40}Ca, E_n = 0.82 to 2.1 MeV, measured $\sigma_{n,T}(E)$.

The ^{7}Li(p,n) reaction produced by monoenergetic protons on thin lithium targets served as a neutron source to measure the cross section of ^{40}Ca from 1.0 to 2.1 MeV with 4-keV resolution, and from 0.82 to 1.8 MeV with 2-keV resolution. In the common region from 1.0 to 1.8 MeV, there were 45 peaks seen with 4-keV resolution and about twice as many with 2 keV. The ^{16}O cross section, measured previously with ^{7}Li(p,n) neutrons, was extended to 4.34 MeV with about 5-keV resolution. Since the correction for the second group of neutrons from the ^{7}Li(p,n) source becomes large at these higher energies, the ^{16}O cross section was remeasured with T(p,n) neutrons from 1.75 to 4.35 MeV with 30-keV resolution. Results from the two sources agree except near narrow resonances. In particular, the s-wave minimum at 2.35 MeV is 0.13 b for the ^{7}Li(p,n) source and, corrected for resolution, 0.134 b for the T(p,n) source. Recent ^{7}Li(p,n) data show the ^{16}O resonance at 3.765 MeV has $J = 7/2$.

1. Abstract of paper published in *Proceedings of the Third Conference on Neutron Cross Sections and Technology, March 1971, Knoxville, Tennessee,* Conf. No. 710301, vol. 1, p. 179.
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THE INVESTIGATION OF EXCITED STATES OF ^{22}Ne USING THE ^{18}O(α,γ) CAPTURE REACTION[1]

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NUCLEAR REACTIONS: ^{18}O(α,γ)^{22}Ne, E < 3 MeV; measured $\sigma(E; E_\gamma^0, E_\gamma^1, \theta_{\gamma l})$. ^{22}Ne deduced levels, J, π, ℓ, γ mixing. Enriched target.

The excitation function for the ^{18}O(α,γ)^{22}Ne reaction has been measured below E_α = 3 MeV using isotopically enriched Ge^{18}O targets and time-of-flight techniques. Resonance structures were observed at bombarding alpha-particle energies of 1.51, 2.18, 2.45, 2.53, 2.70, 2.87, and 2.91 MeV, which correspond to excited states of ^{22}Ne with the following excitation energies, angular momenta, and parities: 10.91 MeV, $J^\pi = 1^-$; 11.45 MeV, $J^\pi = 1^-$; 11.67 MeV, $J^\pi = 2^+$; 11.74 MeV, $J^\pi = 1^-$; 11.88 MeV, $J^\pi = 1^-$; 12.01 MeV, $J^\pi = 2^+$; 12.05 MeV, $J^\pi = 0^+$. Partial widths for the ground-state and first excited-state transitions are presented, together with mixing parameters for the first excited-state transitions.

1. Abstract of paper submitted for publication in the *Physical Review.*
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CROSS-SECTION MEASUREMENTS FOR THE TRANSFER REACTIONS ($^{14}N,^{13}N$) AND ($^{19}F,^{18}F$) INDUCED ON ^{19}F, ^{23}Na, AND ^{51}V[1]

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NUCLEAR REACTIONS: ^{19}F, ^{23}Na, $^{51}V(^{19}F,^{18}F)$, E = 25–45 MeV; $^{19}F(^{14}N,^{15}N)$, E = 10–27 MeV; $^{51}V(^{14}N,^{13}N)$, E = 26–42 MeV; measured $\sigma(E)$; deduced neutron reduced-width ratio. Natural targets.

Thick targets of ^{19}F, ^{23}Na, and ^{51}V were bombarded with ^{14}N and ^{19}F ions accelerated in the Oak Ridge Tandem Van de Graaff. Cross sections were measured for the neutron-transfer reactions $^{19}F(^{14}N,^{15}N)^{18}F$, $^{19}F(^{19}F,^{18}F)^{20}F$, $^{23}Na(^{19}F,^{18}F)^{24}Na$, $^{51}V(^{14}N,^{13}N)^{52}V$, and $^{51}V(^{19}F,^{18}F)^{52}V$ at energies close to the Coulomb barriers for the various target and projectile combinations. The data were analyzed by the use of the tunneling theory of Breit et al. The theory was found to account for the shapes of the excitation functions of the first three reactions listed above. The excitation functions for the two reactions with ^{51}V as the target nucleus were found to have slopes that were steeper than that predicted by the tunneling theory. This is thought to be an indication that even at energies below the Coulomb barrier, excited states in ^{52}V are populated in the transfer process. By assuming that the neutron reduced width in ^{52}V is the same in both the ^{19}F and ^{14}N induced reactions, a reduced-width ratio was extracted for the transferred neutron in ^{19}F to that in ^{14}N. The ratio was found to be ~2.0 as compared with values of ~3.7 extracted earlier from low-energy cross-section data for ($^{19}F,^{18}F$) and ($^{14}N,^{13}N$) reactions on targets of ^{10}B and ^{14}N. If the ±30% error limits on the experimental cross sections are taken into account, the value of 2 is not in disagreement with the earlier-determined ratios of 3.7. We feel, however, that the difference arises because transfers to the ground states in ^{11}B and ^{15}N are predominant at low bombarding energies. Since this is apparently not so for the reactions with ^{51}V (see above), the ^{19}F reaction may populate different states in ^{52}V than the ^{14}N reaction would populate; the reduced-width ratio would then not be the same as that extracted from the data with ^{10}B and ^{14}N targets.

1. Abstract of published paper: *Phys. Rev.* C4, 98 (1971).
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3. Present address: Knoxville College, Knoxville, Tenn.

HEAVY-ION NEUTRON YIELDS

J. K. Bair W. B. Dress C. H. Johnson P. H. Stelson

NUCLEAR REACTIONS: $^{12}C(^{16,18}O,xn)$, $^{16,18}O(^{16,18}O,xn)$; E = 15 to 55 MeV; $^{63,65}Cu(^{16,18}O,xn)$, $^{58,60,61,62,64}Ni(^{16}O,xn)$, $^{58,60,62,64}Ni(^{18}O,xn)$, $^{66}Zn(^{16}O,xn)$, $^{64,66}Zn(^{18}O,xn)$, E = 35 to 55 MeV. Measured total neutron yields.

Preliminary absolute total neutron yields from the ^{16}O bombardment of thin carbon targets were reported in the 1970 Physics Division Annual Progress Report. These measurements have been extended to targets of $^{16,18}O$, $^{63,65}Cu$, $^{58,60,61,62,64}Ni$, and ^{66}Zn. The recent availability of an ^{18}O beam from the tandem accelerator has permitted similar measurements of the total ($^{18}O,xn$) yield on the above targets plus ^{64}Zn.

THE ENERGY LEVELS OF ^{21}Na[1]

F. X. Haas[2] C. H. Johnson J. K. Bair

NUCLEAR REACTIONS: ^{20}Ne$(p,\gamma)^{21}$Na, E = 0.98 to 2.2 MeV; measured E_γ, I_γ, Γ, enriched targets; deduced ^{21}Na levels, Q value. ^{20}Ne$(d,n)^{21}$Na, E = 3.6 to 6 MeV. Measured absolute differential cross sections, enriched targets; deduced levels and spectroscopic factors.

The energy levels of ^{21}Na were investigated using ^{20}Ne$(p,\gamma)^{21}$Na and ^{20}Ne$(d,n)^{21}$Na reactions. The gamma-ray spectra were observed with a Ge(Li) detector and the neutron spectra by a neutron time-of-flight system. From the gamma-ray energy measurements the excitation energies in ^{21}Na were found to be 331 ± 3, 1717 ± 3, 2426 ± 2, 2800 ± 4, 3545 ± 3, 3679 ± 4, 3867 ± 4, 4117 ± 11, and 4297 ± 4 keV. The 3679-keV level was first seen in this work. A ^{20}Ne$(p,\gamma)^{21}$Na Q value of 2434 ± 2 keV was deduced by combining our results with published proton resonance energies. Branching ratios were determined for the upper five levels, which are those observed as (p,γ) resonances. Also observed was direct or nonresonant capture into the 331- and 2426-keV states. Angular distributions for the ^{20}Ne$(d,n)^{21}$Na reaction were measured for all of these levels and for levels at 4453 ± 12 keV and 5009 ± 12 keV for incident deuteron energies of 3.60, 4.88, 5.57, and 5.94 MeV. The bound states at 331 and 2426 keV have clearcut stripping patterns with $\ell = 2$ and $\ell = 0$ respectively. The unbound 4117-keV state has a stripping pattern consistent with $\ell = 1$. Its laboratory width from the gamma-ray work is 125 keV. The combined evidence of the branching ratios, reduced widths, and stripping patterns shows that the 4117-keV level is the mirror of the 4.73-MeV level in ^{21}Ne. A brief review of the literature is given for the low-lying levels in ^{21}Na.

1. Abstract of paper to be submitted for publication in *Nuclear Physics*.
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3c. $22 < A \leqslant 100$

HIGH-RESOLUTION INELASTIC CROSS-SECTION MEASUREMENTS[1]

F. G. Perey[2] W. E. Kinney[2] R. L. Macklin

NUCLEAR REACTIONS: ^{56}Fe$(n,n\gamma)$, ^{23}Na$(n,n\gamma)$, ^{28}Si$(n,n\gamma)$, ^{7}Li$(n,n\gamma)$ (standard), E = 400–3600 keV; measured $\sigma(E)$. Enriched ^{7}Li target, others natural.

A program of inelastic scattering measurements has been initiated at ORELA. Data are obtained by detecting the deexcitation gamma rays in a 4π geometry with a flight path of 40 m. The present detector is a hydrogen-free carbon fluoride liquid scintillator used in capture cross-section measurements. The initial set of measurements was performed with only 0.125-nsec/m resolution to investigate the technique. Data were reduced up to the threshold of the second excited state for ^{7}Li, C, Na, Si, and Fe. The carbon data were used for a background determination and the ^{7}Li data for flux determination. The data for Na, Si, and Fe will be presented. The cross sections show great resonance structure with peak-to-valley ratios larger than those found in the total cross section. The energy resolution is sufficient to identify all the resonances observed in the inelastic cross sections with resonances in the total cross sections. Various aspects of the experimental technique will be discussed.

1. Abstract of paper published in *Proceedings of Third Conference on Neutron Cross Sections and Technology*, CONF-710301.
2. Neutron Physics Division.

DECAY OF ^{72}Br

E. Collins[1] R. L. Robinson H. J. Kim J. H. Hamilton[1] J. L. C. Ford, Jr.

RADIOACTIVITY: ^{72}Br; measured $T_{1/2}, E_\gamma, I_\gamma$. ^{72}Se deduced levels, γ branching

In a program to determine the cross sections for various nuclear reactions induced by heavy ions,[2] over 30 gamma rays were observed with the same 77-sec half-life from a radioactive product(s) produced by bombardment of ^{58}Ni with 46-MeV ^{16}O ions. Four of these gamma rays could be assigned to levels excited by the decay of ^{72}Br.[3] The others have not been reported previously, but their half-lives suggest they could also be from this radioactivity. In part to ascertain the levels and gamma rays of ^{72}Se and in part to see if some of the gamma rays are due to products other than ^{72}Br, we have determined gamma-ray energies and intensities and deduced which gamma rays were in coincidences.

Gamma rays were detected with a 30-cm^3 Ge(Li) detector for 6 min after each of twenty-eight 6.7-min irradiations of a 1-mg/cm^2 ^{58}Ni target with ^{16}O ions. During the detection period, the data were stored as six sequential spectra. From these the half-life associated with each gamma ray was ascertained.

Gamma-gamma coincidences were recorded in a two-parameter 512 × 32 channel array. The second detector was a 7.62 × 7.62 cm NaI crystal. Coincidences were recorded for 200 sec after each of 250 200-sec irradiations.

A decay scheme based on these studies is given in Fig. 1. Gamma rays with the same half-life that we have not been able to place in the diagram have energies in kilo-electron volts (and intensities) of: 398.2 (2.4), 1061.6 (7.5), 1261.1 (1.2), 1434 (1.5), 2088.8 (2.8), 2107.1 (1.3), 2150.7 (1.0), and 2282.7 (1.7). At present, we have no reason to believe these gamma rays are not from the decay of ^{72}Br.

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1. Physics Department, Vanderbilt University, Nashville, Tenn.

2. R. L. Robinson, H. J. Kim, and J. L. C. Ford, Jr., *Proceedings of the Symposium on Heavy Ion Reactions and Many-Particle Excitations, Sept. 8–14, 1971;* to be published in *Colloque du Journal de Physique.*

3. E. Nolte, W. Kutschera, Y. Shida, and H. Morinaga, *Phys. Lett.* **33B**, 294 (1970).

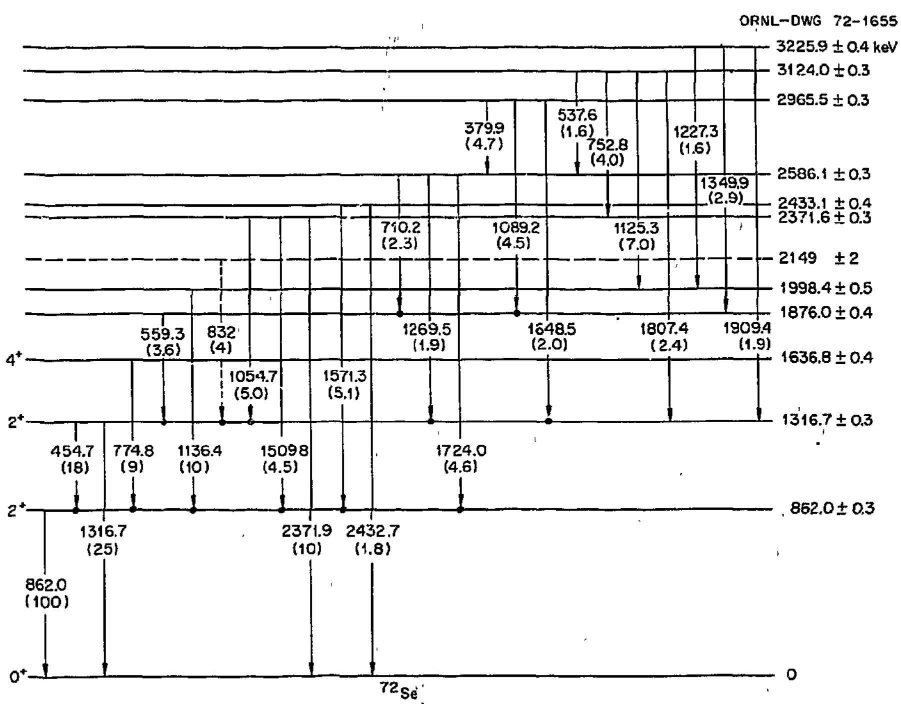

Fig. 1. Energy-level diagram for ^{72}Se.

COULOMB EXCITATION OF ^{81}Br[1]

R. L. Robinson F. H. McGowan W. T. Milner P. H. Stelson

NUCLEAR REACTIONS: ^{81}Br($\alpha,\alpha'\gamma$), E = 2.5–8.2 MeV, ^{81}Br(^{16}O, ^{16}O$'\gamma$), E = 33 MeV, measured E_γ, I_γ, $\gamma(\theta)$, $\gamma\gamma(\theta)$, Doppler broadening; ^{81}Br deduced levels, J, π, $B(E2)$, $B(M1)$, $T_{1/2}$.

Coulomb excitation of the low-lying levels in ^{81}Br was effected with 2.5- to 8.2-MeV alpha particles and 33-MeV ^{16}O ions. From the resulting gamma-ray spectra, gamma-ray energies and yields, gamma-ray angular distributions, in one instance a gamma-gamma angular correlation, and Doppler broadening of the gamma-ray peaks were obtained. Level energies, spins, $B(E2)$ and $B(M1)$ transition probabilities, and half-lives were deduced from these data for states at 275.9, 538.2, 566.0, 650.0, 767.1, 828.5, 836.5, and 1322.7 keV. The level properties are compared to those calculated by Stewart and Castel using an intermediate coupling unified model.

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1. Abstract of paper to be submitted for publication in *Nuclear Physics.*

ANGULAR CORRELATION OF GAMMA RAYS FROM COULOMB-EXCITED ^{63,65}Cu[1]

R. L. Robinson Z. W. Grabowski[2]

NUCLEAR REACTIONS: ^{63,65}Cu($\alpha,\alpha'\gamma\gamma$), E_α = 5.5, 7.0 MeV; measured E_γ, I_γ, $\gamma(\theta)$, $\gamma\gamma(\theta)$. ^{63,65}Cu deduced mixing δ, $B(E2)$, $B(M1)$. Enriched targets.

The multipole admixture of the transitions between the low-lying $7/2^-$ and $5/2^-$ states of ^{63,65}Cu has been obtained from angular distributions and gamma-gamma angular correlations. The states were excited via Coulomb excitation effected with alpha particles. The admixture δ for the 365.3-keV gamma ray in ^{63}Cu is -0.105 ± 0.025. For the 366.7-keV gamma ray in ^{65}Cu it is -0.16 ± 0.06. Values extracted with these admixtures for the $B(E2)$ and $B(M1)$ transition rates are: $(2.8^{+1.6}_{-1.2}) \times 10^{-50}$ e^2 cm^4 and (0.24 ± 0.04) $(e\hbar/2Mc)^2$ for the 365-keV gamma ray and $9.2^{+8.0}_{-6.0}$ and 0.34 ± 0.08 for the 367-keV gamma ray.

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NUCLEAR SPECTROSCOPY OF ^{50}Cr[1]

S. Raman R. L. Auble W. T. Milner J. B. Ball F. K. McGowan
P. H. Stelson R. L. Robinson J. Rapaport[2]

RADIOACTIVITY: ^{50}Mn; measured $T_{1/2}$, E_γ, I_γ.
NUCLEAR REACTIONS: ^{50}Cr($p,p'\gamma$), E = 8.4 MeV; measured E_γ, I_γ. ^{52}Cr(p,t), E = 31.4 MeV; measured $\sigma(E_t, \theta)$. ^{50}Cr(^{35}Cl, ^{35}Cl$'\gamma$), E = 54 MeV; measured $B(E2)$, Doppler shift attenuation. ^{50}Cr deduced levels, J, π, γ branching, $T_{1/2}$.

The nuclear excited states of ^{50}Cr were studied by means of the decay of 1.7-min ^{50}Mn, the ^{50}Cr($p,p'\gamma$) and ^{52}Cr(p,t) reactions, and Coulomb excitation with ^{35}Cl ions. Gamma-ray branching ratios and precise level energies were obtained for 23 excited states in ^{50}Cr. The L values from the (p,t) reaction are employed to suggest or confirm the spin and parity assignments for eight excited states. The mean lifetime of the 783.3-keV, 2^+ state was determined as 12.1 ± 1.2 psec from the measured $B(E2)\uparrow$ value and as 10 ± 2 psec from Doppler shift measurements. The experimental level scheme for ^{50}Cr is compared with that for the cross-conjugate nucleus ^{46}Ti and with a calculated level scheme.

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1. Abstract of paper to be published in *Nuclear Physics.*
2. Present address: Department of Physics, Ohio University, Athens, Ohio.

810.6–863.6 keV $\gamma\gamma$-DIRECTIONAL CORRELATION IN ^{58}Fe[1]

N. C. Singhal[2] A. V. Ramayya[2] J. H. Hamilton[2] S. Raman

RADIOACTIVITY: ^{58}Co; measured $\gamma\gamma(\theta)$. ^{58}Fe deduced mixing ratio. NaI(Tl)-Ge(Li).

The 810.6-863.6 keV $\gamma\gamma$-directional correlation has been measured with an NaI(Tl)-Ge(Li) detector system. The NaI window was set on the 810.6 + 863.6-keV composite peak. From the (810.6 NaI gate)–(863.6 Ge spectrum) data at 90, 135, and 180°, we deduced A_2 = +0.51 ± 0.03 and A_4 = +0.09 ± 0.04. These results disagree with the values previously obtained from ^{58}Co decay (with NaI-NaI detector systems) but agree with the values from $\gamma\gamma(\theta)$ studies following thermal neutron capture by ^{57}Fe.

1. Abstract of published paper: *Z. Phys.* **245**, 50 (1971).
2. Vanderbilt University, Nashville, Tenn.

NEW OBSERVATIONS IN THE A = 49 DECAY CHAIN; LEVELS IN ^{49}Sc AND ^{49}Ti[1]

E. Eichler[2] S. Raman

RADIOACTIVITY: ^{49}Ca; measured $E_\gamma, I_\gamma, \gamma\gamma(\theta)$; deduced log ft 49Sc; measured E_γ, I_γ; deduced log ft. ^{49}Sc, ^{49}Ti deduced levels, J, π.

The gamma rays from 8.7-min ^{49}Ca and from 57.4-min ^{49}Sc have been measured with a 40-cm^3 Ge(Li) detector. It is proposed that ^{49}Ca populates levels in ^{49}Sc at 2228.6, 2371.8, 3084.4, 3516.6, 4071.9, 4493.3, and 4738.2 keV. The ^{49}Sc decay populates levels in ^{49}Ti at 1622.6 and 1761.9 keV. Limits on probable spin and parity values for these levels have been established. Mixing ratios for the 1408.9-keV gamma ray were obtained from angular-correlation measurements. Weak transitions observed in this study provide further insights into the structure of ^{49}Sc levels, in particular, the $1/2^+$ and $3/2^+$ hole states.

1. Abstract of published paper: *Phys. Rev.* C3, 2268 (1971).
2. Chemistry Division.

LOG ft VALUES FOR SECOND-FORBIDDEN AND OTHER TYPES OF BETA TRANSITIONS

S. Raman N. B. Gove[1] J. K. Dickens[2] T. A. Walkiewicz[3]

RADIOACTIVITY: ^{24}Na; measured E_γ, I_γ. ^{24}Mg deduced levels, log ft. ^{144}Pm; measured $E_\gamma, I_\gamma, \gamma\gamma$ coin. ^{144}Nd deduced levels, log ft. ^{65}Ni; measured E_γ, I_γ. ^{65}Cu deduced levels, log ft. Ge(Li) detector.

We have critically examined approximately 30 experimental log ft values for second-forbidden non-unique (ΔJ = 2, no parity change) β^- transitions. We find that these values generally lie in the 11.9 to 13.6 range. The only well-established exception[4] appears to be log ft = 11.0 for the ^{59}Fe ($3/2^-$ ground state) to ^{59}Co ($7/2^-$ ground state) β^- transition. The strong rule currently used[5] for spin-parity assignments is that if 5.8 $\leqslant$ log ft $\leqslant$ 10.6, the transition is allowed or first forbidden. We found several apparent violations of this rule in cases where the existence of the beta transition and its intensity were inferred from gamma-ray measurements. In most cases we feel that these apparent violations are not convincing because the possibility of missing gamma rays has not been fully explored.

The limit of 10.6 in the above rule is partly based on a reported[6] log ft = 10.7 for a second-forbidden ($4^+ \rightarrow 2_2{}^+$) transition in the decay of ^{24}Na. We reexamined

1. Mathematics Division.
2. Neutron Physics Division.
3. Edinboro State College, Edinboro, Pa. ORAU Summer Research Participant.
4. D. E. Wortman and L. M. Langer, *Phys. Rev.* **131**, 324 (1963).
5. See Introduction to any recent issue of *Nuclear Data Sheets.*
6. K. P. Artamonova, L. V. Gustova, Yu. N. Podkopaev, and O. B. Chubinskii, *Zh. Eksp. Teor. Fiz.* 39, 1593 (1960) [translation, *Sov. Phys. JETP* 12, 1109 (1961)].

the gamma spectrum and, indeed, observed a weak (8 × 10^{-6} per ^{24}Na decay) gamma ray at 4283.9 keV which is responsible for the log *ft* value. However, there could still be a gamma transition (as yet unobserved) from the 3^+ state to the $2_2{}^+$ state. Thus the present limit[7] is log $ft \geqslant 10.9$.

In the case of ^{144}Pm, a log *ft* of 10.6 was reported for a second-forbidden beta transition. In our Ge(Li)-Ge(Li) coincidence measurements, we detected a weak 694.0-keV gamma ray $[I(694.0\ \gamma)/I(696.6\ \gamma) = 0.0045]$, which leads to log $ft > 11.1$ for the relevant transition.[8]

In the decay of ^{65}Ni there is a possible second-forbidden β^- transition. Our initial measurements suggested that it might have a low log *ft* value. The intensity of gamma rays feeding the 770.6-keV level in ^{65}Cu was 0.086 ± 0.002%, whereas the intensity of the 770.6 γ was 0.095 ± 0.001%, leaving an imbalance of 0.009%, or log $ft = 9.7 \pm 0.2$. We sought additional gamma rays which could be transitions between known levels in ^{65}Cu and observed a weak (0.01 ± 0.001%) 954.5-keV gamma ray which is capable of absorbing the intensity imbalance (log $ft > 10.3$).[9]

We have also examined other types of beta transitions such as first-forbidden, first-forbidden unique, second-forbidden unique, third- and fourth-forbidden, and $0^+ \rightarrow 0^+$ isospin-forbidden transitions. The results of this survey are expected to lead to a revision of the rules for spin-parity assignments from log *ft* values.

7. S. Raman, J. K. Dickens, N. B. Gove, and T. A. Walkiewicz, *Bull. Amer. Phys. Soc.* **16**, 1433 (1971).
8. S. Raman, *Bull. Amer. Phys. Soc.* **15**, 1628 (1970).
9. N. B. Gove and S. Raman, *Bull. Amer. Phys. Soc.*, Washington Meeting, April 1972.

YIELDS OF RADIONUCLIDES IN THIN IRON TARGETS BOMBARDED WITH 40-MeV TO 16-GeV ELECTRONS[1]

C. B. Fulmer K. S. Toth I. R. Williams[2] G. F. Dell[3] T. M. Jenkins[4]

NUCLEAR REACTIONS: Fe(e, x)^{52}Fe, ^{54}Mn, ^{52}Mn, ^{51}Cr, ^{48}V, ^{48}Cr, ^{47}Sc, ^{44}Sc^m, ^{24}Na; E = 40 MeV to 16 GeV; measured $\sigma(E)$. Natural target.

Yields of several radionuclides in thin iron targets were measured for electron bombarding energies of 40 MeV to 16 GeV. In general the yields appear to approach zero at bombarding energies near threshold energies for nuclide production by nucleon emission from the target nucleus. The effect of bombarding energy on the yield surface for cascade-evaporation reactions was investigated by comparing ratios of yields; the results suggest that except for the slope of the ridge the shape of the yield surface does not vary with energy for bombarding energies above a few hundred million electron volts.

1. Abstract of published paper: *Phys. Rev.* C3, 1955 (1971).
2. Consultant from Knoxville College, Knoxville, Tenn.
3. Cambridge Electron Accelerator, Cambridge, Mass.; present address: Brookhaven National Laboratory, Upton, N.Y..
4. Stanford Linear Accelerator Center, Stanford, Calif. 94305.

RATIO OF PHOTODISINTEGRATION TO ELECTRODISINTEGRATION OF Al, Fe, and Ta BOMBARDED WITH 5.0-GeV ELECTRONS[1]

C. B. Fulmer K. S. Toth I. R. Williams[2] G. F. Dell[3]

NUCLEAR REACTIONS: ^{27}Al(e,x)^{24}Na, ^{7}Be; Fe(e,x)^{52}Mn, ^{48}Cr, ^{44}Sc^m, ^{24}Na; Ta(e,x)^{175}Hf, ^{177}La; E = 5.0 GeV; measured F values. Natural targets.

The cross-section ratio for photodisintegration to electrodisintegration was measured for targets of aluminum, iron, and tantalum bombarded with 5.0-GeV electrons. These ratios (or F values) were determined for a total of six cascade-evaporation reactions in which

1. Abstract of published paper: *Phys. Rev.* C4, 2123 (1971).
2. Consultant from Knoxville College, Knoxville, Tenn.
3. Cambridge Electron Accelerator, Cambridge, Mass.; present address: Brookhaven National Laboratory, Upton, N.Y.

as many as 12 nucleons are emitted from the target nucleus. The F values for the six reactions average 2.1 and vary little with target mass and with the number of emitted nucleons. In addition, F values were also measured for two other reactions whose mechanisms involve fragmentation and/or fission-like processes. The average of these two F values is 3.25, or about 50% larger than for the cascade-evaporation reactions.

DIFFERENTIAL CROSS SECTIONS AT FORWARD ANGLES FOR HYDROGEN AND HELIUM PARTICLES FROM 62-MeV PROTONS INCIDENT ON ^{60}Ni[1,2]

R. W. Peelle[3] F. E. Bertrand

NUCLEAR REACTIONS: ^{60}Ni(p,xp), (p,xd), (p,xt), $(p,x\ ^3\text{He})$, $(p,x\alpha)$, E = 61.7 MeV; measured absolute $\sigma(\theta)$ for each exit particle type; secondary energy range ≈2–60 MeV. Solid-state counter telescope.

Tabulated differential cross sections are presented for the production, at angles of 15, 20, 25, and 40°, of proton, deuteron, triton, ^{3}He, and alpha particles from ^{60}Ni bombarded by 62-MeV protons. Continuum cross sections are listed in ~1-MeV bins for energies above lower cutoffs which range from 4 to 15 MeV for the different types of exit particles. For a considerable energy range within each spectrum, only the integral cross section is known. The proton-, deuteron-, and alpha-particle cross sections are the same in the continuum region above the evaporation peak as those cross sections previously observed for ^{54}Fe and ^{56}Fe, but the corresponding yield of tritons is higher from ^{60}Ni and ^{56}Fe than from ^{54}Fe.

1. Work funded by National Aeronautics and Space Administration under order L-12, 186.
2. Abstract of ORNL-4698 (June 1971).
3. Neutron Physics Division.

LEVEL STRUCTURE OF ^{44}Ti[1]

J. Rapaport[2] J. B. Ball R. L. Auble T. A. Belote[3] W. E. Dorenbusch[4]

NUCLEAR REACTIONS: ^{46}Ti(p,t), E = 51 MeV; measured $\sigma(E_t, \theta)$, Q. ^{44}Ti deduced levels, L, J, π, enhancement factors. Enriched target.

The level structure of ^{44}Ti has been studied by the ^{46}Ti(p,t) reaction at a proton energy of 51 MeV. Experimental angular distributions were compared with distorted-wave Born-approximation calculations to determine the angular momentum transfers. Spin, parity, and enhancement factors were extracted for the levels observed up to 9.330-MeV excitation energy. The measured Q value for the ground-state transition was determined to be −14.235 ± 0.010 MeV. A strong L = 2 transition at E_x = 6.600 MeV is assigned as the T = 1 analog of the ^{44}Sc ground state, and an L = 0 transition at 9.330 MeV is assigned as the T = 2 analog of the ^{44}Ca ground state.

1. Abstract of paper to be published in the *Physical Review*.
2. Ohio University, Athens.
3. Massachusetts Institute of Technology, Cambridge.
4. Wayne State University, Detroit, Mich.

ENERGY LEVELS IN ^{48}Cr OBSERVED IN THE ^{50}Cr$(p,t)^{48}$Cr REACTION[1]

W. E. Dorenbusch[2] J. B. Ball R. L. Auble J. Rapaport[3] T. A. Belote[4]

NUCLEAR REACTIONS: ^{50}Cr(p,t), E = 51 MeV; measured $\sigma(E_t, \theta)$, Q. ^{48}Cr deduced levels, L, J, π. Enriched target.

Energy levels of ^{48}Cr have been studied with the ^{50}Cr$(p,t)^{48}$Cr reaction at 51 MeV. Spin and parity assignments have been made for levels below 9 MeV of excitation. The measured ground-state Q value was -15.100 ± 0.008 MeV. Levels at 5.790 and 6.100 MeV were identified as the $T = 1$ analogs of the ground and first excited states in ^{48}V respectively. A doublet is observed at 8.75 MeV near the energy expected for the $T = 2$ analog of the ^{48}Ti ground state.

1. Abstract of published paper: *Phys. Lett.* **37B**, 173 (1971).
2. Wayne State University, Detroit, Mich.
3. Ohio University, Athens.
4. Massachusetts Institute of Technology, Cambridge.

IMPORTANCE OF LARGE-ANGLE DATA IN OPTICAL-MODEL ANALYSIS OF HELION ELASTIC SCATTERING[1]

C. B. Fulmer J. C. Hafele[2]

NUCLEAR REACTIONS: ^{27}Al(h,h), ^{52}Cr(h,h), E = 59.8 MeV; measured $\sigma_{el}(\theta)$; optical-model analysis, deduced potentials. Natural target and enriched target.

Optical-model analyses which include data far into the backward hemisphere for elastic scattering of complex projectiles at intermediate energies are found to produce optical potentials with many of the common ambiguities removed. This paper reports differential cross-section data with an extensive optical-model analysis for 59.8-MeV helions elastically scattered from ^{27}Al and ^{52}Cr. The data include scattering angles back to 166° for ^{27}Al and to 149° for ^{52}Cr. Optical-model fits to these data are satisfactory only with a surface-peaked absorption term and with a spin-orbit term included in the potential. The discrete or family ambiguity in the potential is removed, and continuous ambiguities are notably suppressed.

1. Abstract of a paper to be published in the *Physical Review, Section C.*
2. 1969 and 1970 ORAU Summer Research Participant from Washington University, St. Louis, Mo.

OPTICAL-MODEL ANALYSIS OF HELION ELASTIC SCATTERING BY ^{60}Ni IN THE ENERGY RANGE OF 29.6–71.1 MeV

C. B. Fulmer J. C. Hafele[1]

NUCLEAR REACTIONS: ^{60}Ni(h,h), E = 29.6, 35.1, 49.7, 59.5, 71.1 MeV; optical-model analysis, deduced potentials and energy dependence. Enriched target.

In this work we have analyzed elastic scattering data from ^{60}Ni at five energies ranging from 29.6 to 71.1 MeV. Two of the angular distributions were measured at the Washington University Cyclotron;[2] the three higher energy sets of data were obtained at the Oak Ridge Isochronous Cyclotron. In all cases the data extend beyond 100°, with data at three of the energies extending beyond 140°.

The analyses were done with the global search program GENOA.[3] Earlier analyses had indicated the need for a spin-orbit term in the potential and a preference for a surface-peaked absorption term. Our analysis of 60-MeV data from several targets had also

1. Physics Department, Washington University, St. Louis, Mo.; 1969 and 1970 ORAU Summer Research Participant at ORNL.
2. J. W. Leutzelschwab and J. C. Hafele, *Phys. Rev.* **150**, 1023 (1970).
3. F. G. Perey, unpublished.

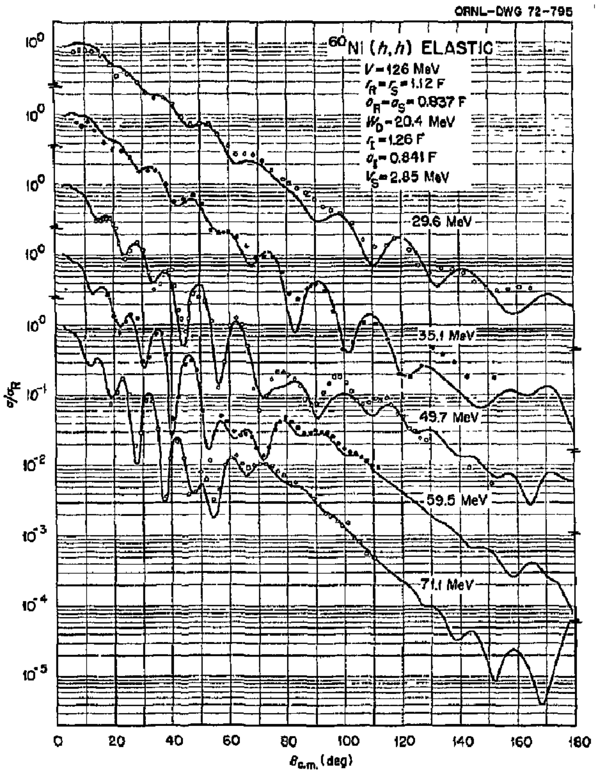

Fig. 1. Optical-model fits with a common potential to helion elastic scattering by ^{60}Ni at five incident energies.

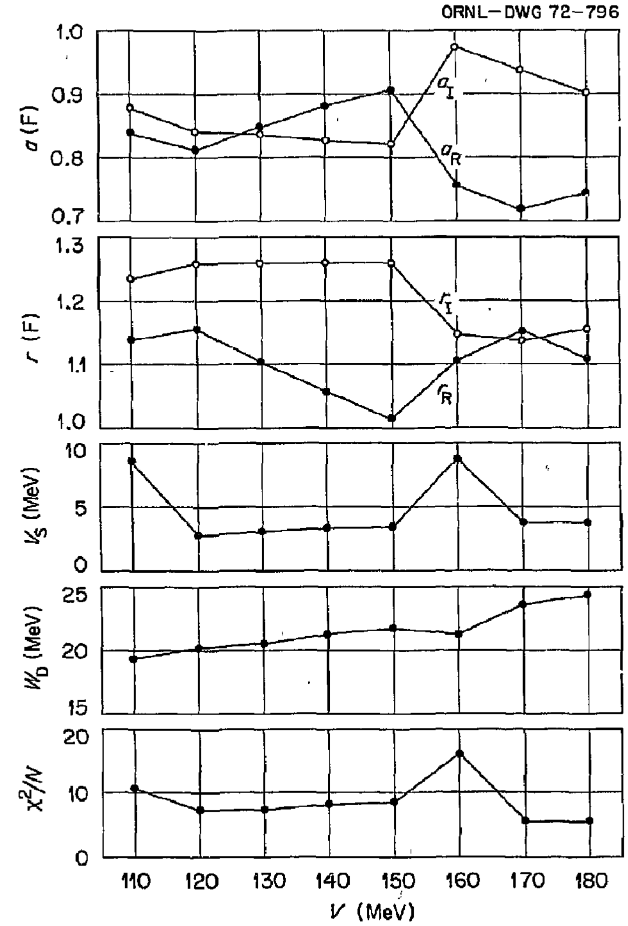

Fig. 2. Parameter values obtained from optical-model searches on helion elastic scattering data for ^{60}Ni at five energies. The parameters were common to all data sets. V was gridded in 10-MeV intervals.

shown a preference for a real well depth near 120 MeV. The flexibility of the code GENOA permits some of the parameters to be common to all data sets, while other parameters are data-set dependent. For an initial search on the five data sets, we required all of the parameters to be common to all of the data sets. The resulting fits are shown in Fig. 1. Over the energy range of the data, there is considerable change in the shapes of the angular distributions. In particular, there is a large-angle featureless region in the higher-energy angular distributions. The optical-model predictions do a reasonable job of reproducing most of the features of each of the data sets. The absorption radius is ~10% larger than the real radius, while the diffuseness terms are approximately equal.

We did a grid-type analysis of the five data sets as follows. A value was assigned to the real well depth, and χ^2 was minimized by varying the other parameters. Then the real well depth was incremented and the procedure repeated. The results of this analysis are summarized in Fig. 2. The χ^2 is the average for all five data sets. In the region between 120 and 150 MeV, there is evidence for the well-known VR^n ambiguity. The surface absorption term does not change much, nor does the radius for the absorption well. Above ~170 MeV, there appears to be another potential that fits the data. In fact, χ^2 is slightly smaller than that for the lower well. This does not show the complete picture, however. In Fig. 3 the large-angle prediction for the 170-MeV potential is compared with that of the 126-MeV potential for the 71-MeV case. We observe rather large differences in the large-angle region beyond the range of the experimental data. Beyond ~110° the falloff of the 170-MeV curve is less than that of the 126-MeV curve. These large-angle differences are progressively smaller for the lower energies. This suggests, we believe, that large-angle elastic scattering data at sufficiently high energy can be very useful in removing the ambiguities of the optical-model potential for helion elastic scattering and presumably for other strongly absorbed particles.

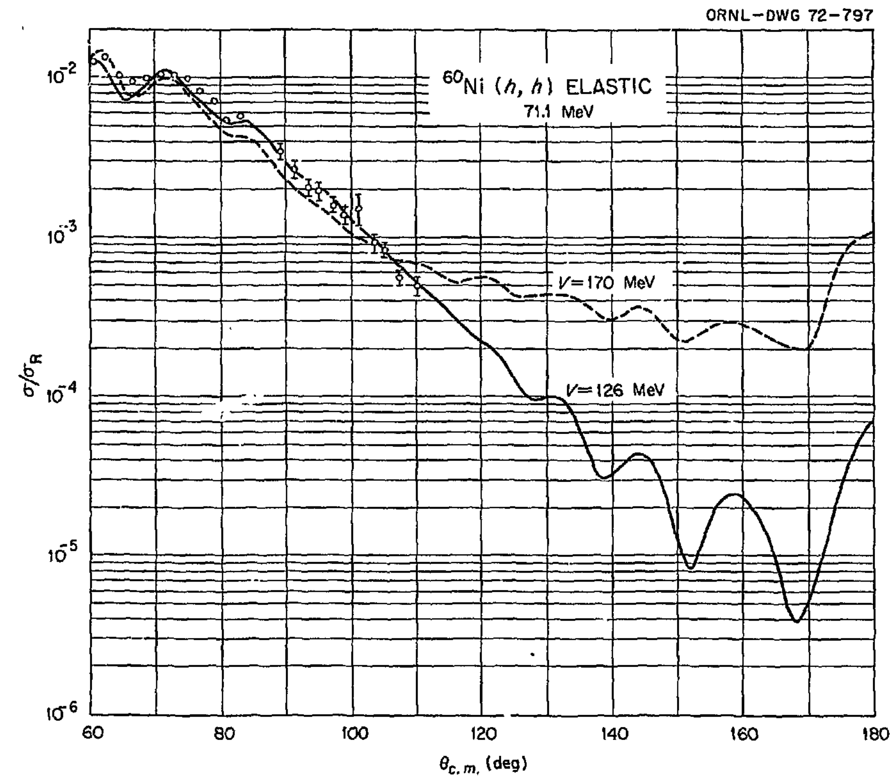

Fig. 3. Optical-model predictions for V = 126 MeV and V = 170 MeV potentials for 71.1-MeV helion elastic scattering by ^{60}Ni.

While the data do not extend to sufficiently large angles to indicate a clear choice of the two potentials, we believe large-angle data would show a preference for the 126-MeV potential. This is based on 60-MeV experimental data from other targets. Some of these data are compared in Fig. 4. These are smooth curves drawn through data points. Both the aluminum and chromium data show the large-angle featureless falloff region to extend to at least 140°. In Fig. 3 the 170-MeV angular distribution for ^{60}Ni does not exhibit this behavior, while the 126-MeV curve does.

We believe the importance of large-angle helion elastic scattering has been demonstrated. Hafele, Chatlis, and Foster[4] reported some initial results obtained from a magnetic deflection system that permits measurement of cross sections in the angular range of 150 to 190°. We used that system to measure an excitation function for 180° elastic scattering of helions from ^{60}Ni. The energy region covered is from 21 to 32 MeV. The data are compared in Fig. 5 with a calculated excitation function obtained by using the parameters from the search that is presented in Fig. 1. The agreement of the data with the calculated excitation function is rather good in both magnitude and structure of the excitation function. These data were obtained with beams from the Washington University Cyclotron and extend to almost the highest energy available there. It is obviously desirable to extend these measurements to higher energy, where there is more pronounced structure in the excitation function.

In 1967, Gibson et al.[5] reported the results of an optical-model analysis of 37- and 43-MeV helion elastic scattering data; in that work they observed evidence for a weak energy dependence of the real well depth. The data from ^{60}Ni studied in the present work cover a somewhat larger energy range. We thus decided to examine it for evidence of an energy dependence of the real and imaginary well depths. The geometrical and spin-orbit parameters shown in Fig. 1 were used as fixed parameters, and searches were made for each data set by varying only the real and surface-absorption well depths. The values of the real well depth thus obtained

4. J. C. Hafele, C. Chatlos, and C. C. Foster, *Bull. Amer. Phys. Soc.* **16**, 830 (1971).

5. E. F. Gibson, B. W. Ridley, J. J. Kraushaar, and M. E. Rickey, *Phys. Rev.* **155**, 1194 (1967).

are plotted in Fig. 6 along with a straight-line least-squares fit to the points. The value of $dV/dE = -0.14$ is in agreement with the results reported by Gibson et al.[5] from an analysis of helion scattering of ^{58}Ni for a somewhat smaller range of energy. In a similar plot of W_D as a function of incident energy, a straight-line least-squares fit to the points yields $W_D \cong$ (2˘ ⁾ – 0.04E) MeV.

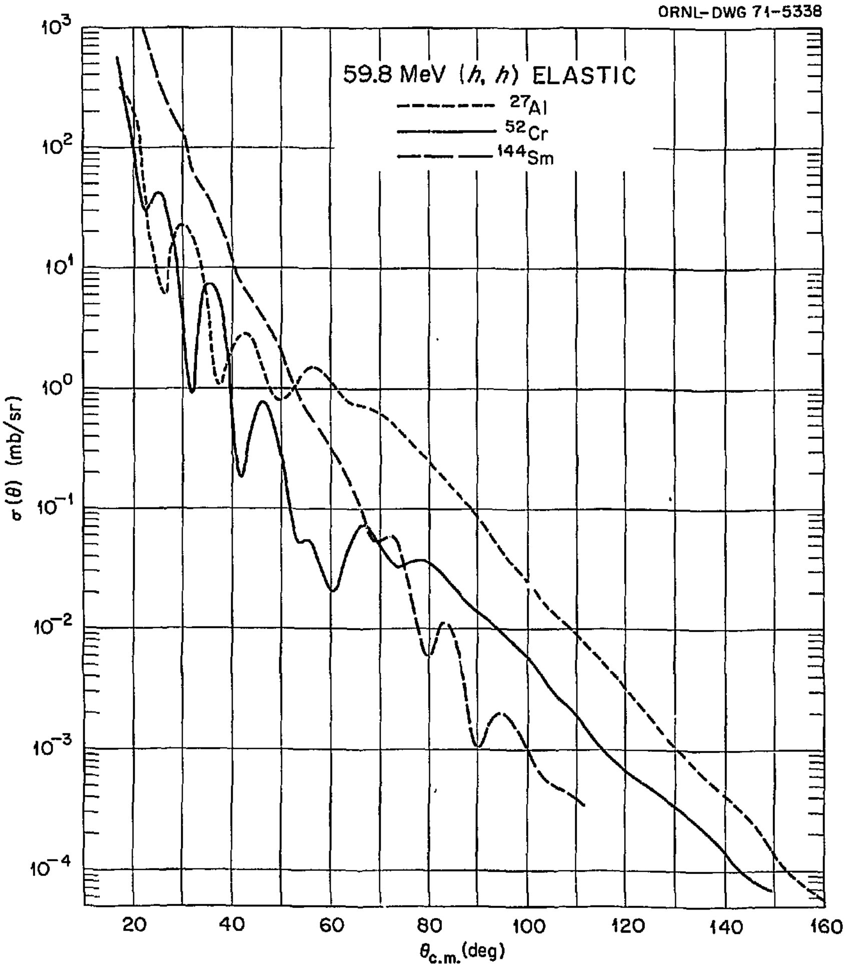

Fig. 4. Measured 59.8-MeV helion elastic scattering angular distributions from three targets of a wide range of mass.

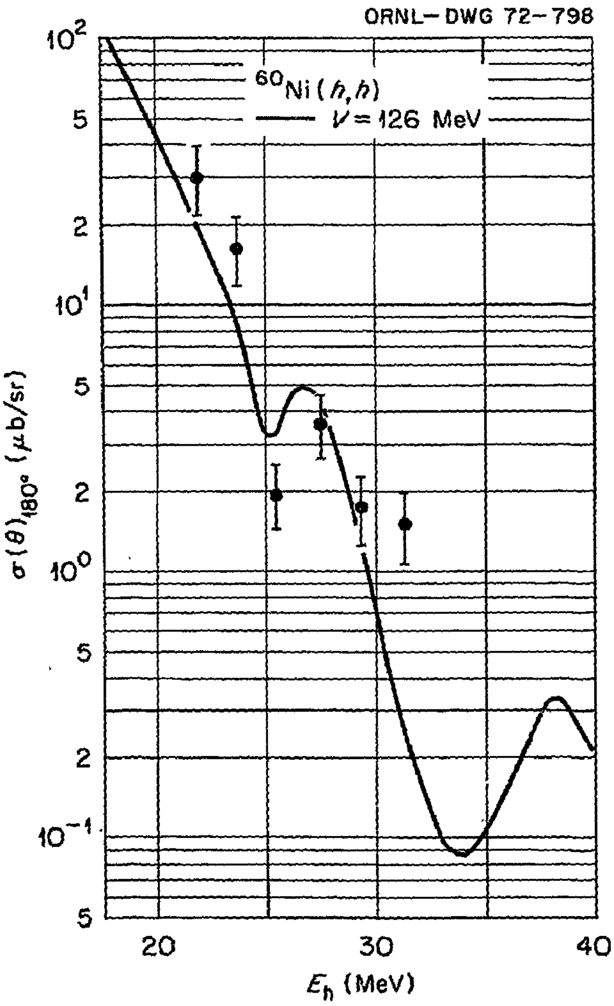

Fig. 5. Measured cross sections for 180° elastic scattering of helions by ^{60}Ni compared with excitation function predicted by optical model using the parameters shown in Fig. 1.

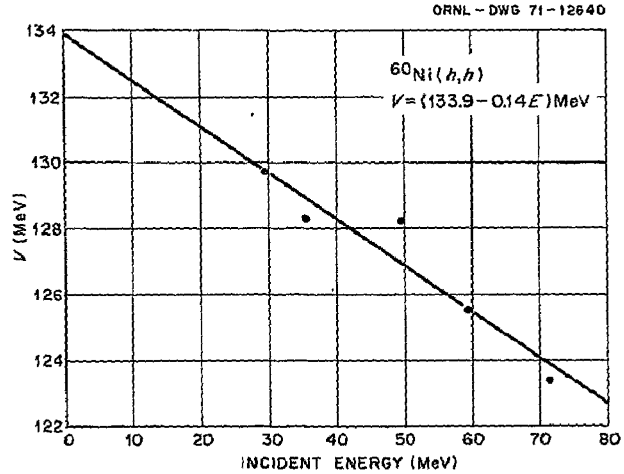

Fig. 6. Values of V vs incident energy obtained from optical-model fits to measured elastic scattering angular distributions.

ACCURATE MEASUREMENTS OF THE MINIMA IN THE NEUTRON TOTAL CROSS SECTIONS OF NATURAL IRON

J. A. Harvey N. W. Hill[1] W. E. Kinney[2] A. St. James[3]

NUCLEAR REACTIONS: Fe; measured σ_{nT}; E_n = 20 to 500 keV.

Knowledge of the neutron total cross section for iron in the regions of the minima is of paramount importance in being able to calculate the transport of neutrons through thick shields of iron or stainless steel in the Fast Flux Test Facility. Comparisons of transport calculations using cross sections presently in ENDF/B (i.e., MAT 1124) with experiments conducted last year at the ORNL Tower Shielding Facility indicated that the existing total cross sections in the minima below

1. Instrumentation and Controls Division.
2. Neutron Physics Division.
3. Student participant in Great Lakes Colleges Association Program, fall 1971, from Denison University.

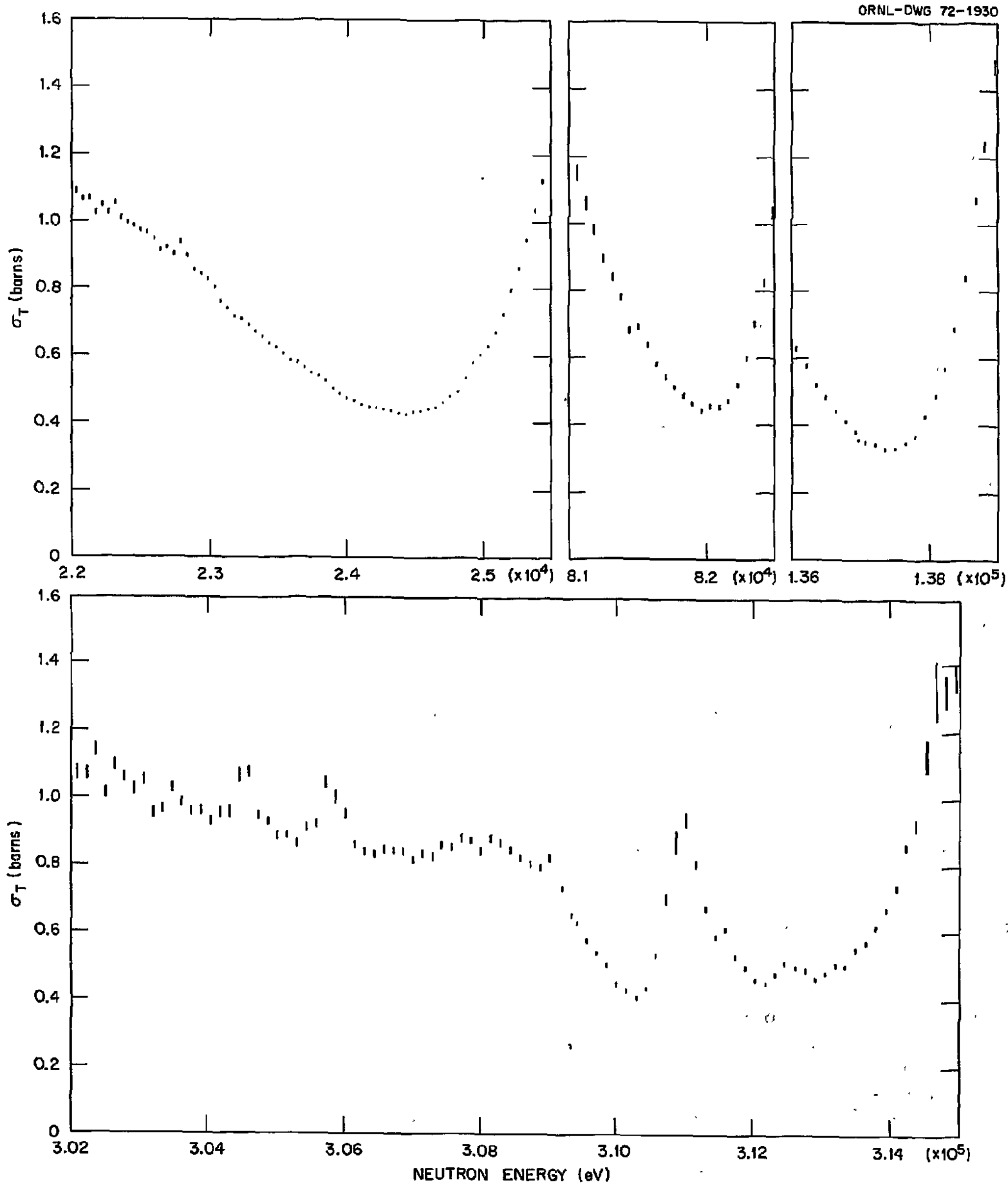

Fig. 1. Neutron total cross section of several minima in natural iron.

400 keV were inaccurate (in general they were too high) and that additional total cross-section measurements in this energy region were necessary.

We have made transmission measurements using 30-nsec bursts and 800 pulses per second from ORELA with three ^{6}Li glass scintillation detectors at 80 m and using 9-nsec bursts with an NE 110 plastic scintillator at 200 m. For all measurements, a $9\frac{9}{16}$-in.-thick piece of Armco iron was inserted in the $1\frac{3}{4}$-in.-diam. collimator, which is 8 m from the neutron source. Although this iron sample had only 0.1% Mn, the large 23.70-keV resonance in manganese showed up clearly in the 24.5-keV "window." Many intense nearly monoenergetic groups of neutrons were observed, and the background between these groups was ≪1% of the peaks. Samples of high-purity iron containing only 0.033% Mn, 0.03% Cu, 0.05% Ni, and 0.02% Si were cycled into the neutron beam to measure the total neutron cross section of this high-purity iron for these Fe "window" neutrons. Three different thicknesses of high-purity iron (6, 12, and 20 in.) were measured at 80 m with an energy resolution of 40 eV at 25-keV neutron energy, increasing to 1.4 keV for 250-keV neutrons. Since the windows are a few kilo-electron volts wide, this resolution is sufficient for accurate measurements below ~250 keV. For the higher-energy windows the 12-in.-thick sample was measured using an NE 110 detector at 200 m. The energy resolution for these measurements varied from 0.15 keV at 200 keV to 0.5 keV at 500 keV to 1 keV at 800 keV. Some of the results are shown in Fig. 1.

Similar measurements using thick samples of natural iron have been reported recently by Rahn et al.[4] using the Nevis Synchrocyclotron. Although the energies of the "windows" are in good agreement with our measurements, the minima in our data are ~10 to 20% lower than those reported by Rahn. Also, considerable structure is evident in a few of the higher-energy windows (e.g., at 313 keV), which was not reported by Rahn. R. C. Block et al.[5] have recently made measurements with a thick iron sample and report a value of 0.50 ± 0.03 b for elemental iron at 24.6 keV, in good agreement with data of Rahn but considerably higher than our value of 0.43 ± 0.01 b. However, the iron sample used by Block contained 0.7% Mn, and hence the 23.7-keV resonance in Mn might account for the discrepancy. We have also measured the total cross section of enriched samples of ^{54}Fe and ^{57}Fe for these window neutrons. In the 24.5-keV window the ^{54}Fe content in natural iron accounts for 0.30 b and the ^{57}Fe 0.12 b. Hence, the ^{56}Fe cross section at this energy is <0.02 b.

4. Rahn, Camarda, Hacken, Havens, Liou, Rainwater, Slagowitz, and Wynchank, "Measurements of the Cross Section Minima in Natural Iron," to be published in *Nuclear Instruments and Methods.*

5. Block, Hockenbury, Turinsky, and Alfieri, "The Application of Resonance Filtered Beams to Time-of-Flight Experiments," PRI Linear Accelerator Project, Progress Report for April 1, 1971–June 30, 1971, AEC Contract No. AT(30-1)-328.

NEUTRON TOTAL CROSS SECTION MEASUREMENTS AT ORELA IN THE ELECTRON VOLT AND KILO-ELECTRON-VOLT ENERGY REGION

J. A. Harvey W. M. Good N. W. Hill[1] J. L. Mitchell[2] R. M. Feezel[3]

NUCLEAR REACTIONS: 29 nuclides; measured σ_{nT}, E_n = 10–300,000 eV. Enriched targets.

During the past year, neutron transmission measurements have been made from a few electron volts to several hundred kilo-electron volts using 18-, 80-, and 200-m flight paths. Measurements were made upon two small samples of ^{244}Cm (60 and 10 mg of Cm_2O_3 with cross-sectional areas of 7 mm^2) with a single ^{6}Li glass scintillator ($4\frac{1}{2}$ in. in diameter and $\frac{1}{2}$ in. thick) located 18 m from the neutron target.[4] The energy resolution obtained ($\Delta E/E$ = 1/300) due to the moderation time in the neutron source and detector is less than the Doppler width of the resonances up to ~200 eV. Forty resonances have been observed up to 600 eV. The analysis of the data is in progress. The only other nuclide measured in the electron-volt energy range was ^{242}Pu.[4] Three metallic ^{242}Pu samples with cross-sectional areas of ~0.5 cm^2 were cooled to liquid nitrogen temperature to reduce the Doppler broadening of the resonances. Three ^{6}Li glass scintillators were used at the 80-m flight station. With 28-nsec bursts, the

1. Instrumentation and Controls Division.

2. ORAU undergraduate research trainee, summer 1971, from Valdosta State College.

3. Cooperative student from Auburn University.

4. Experiment in collaboration with experimenters from Aerojet Nuclear Company, Idaho Falls, Idaho.

energy resolution was <0.1%. Hence, the resolution was less than the Doppler width up to ~2 keV neutron energy and less than average spacing up to 20 keV. Over 200 resonances have been observed, and the analysis of the data to obtain resonance parameters is in progress.

The other transmission measurements during the past year were performed in the energy region from a few kilo-electron volts to several hundred kilo-electron volts. Most of the data were taken with two or three ^{6}Li glass detectors at the 80-m flight station using samples of enriched isotopes of a few square centimeters area. Measurements were made with ~5-nsec bursts from the linac, resulting in an energy resolution less than 0.1% over the entire energy region. The nuclides studied were ^{29}Si, ^{30}Si, ^{39}K, ^{41}K, ^{40}Ca, ^{42}Ca, ^{43}Ca, ^{44}Ca, ^{47}Ti, ^{49}Ti, ^{54}Fe, ^{56}Fe, ^{57}Fe, ^{92}Mo, ^{98}Mo, ^{116}Sn, ^{117}Sn, ^{118}Sn, ^{120}Sn, ^{122}Sn, ^{124}Sn, ^{203}Tl, ^{205}Tl, ^{204}Pb, ^{206}Pb, and ^{207}Pb. Since the spacings of the resonances in these nuclides are a few hundred electron volts or more, the energy resolution is, in general, sufficient to resolve resonances up to several hundred kilo-electron volts energy. A sample of the data obtained is shown in Fig. 1 for four of the isotopes of calcium. The data have been

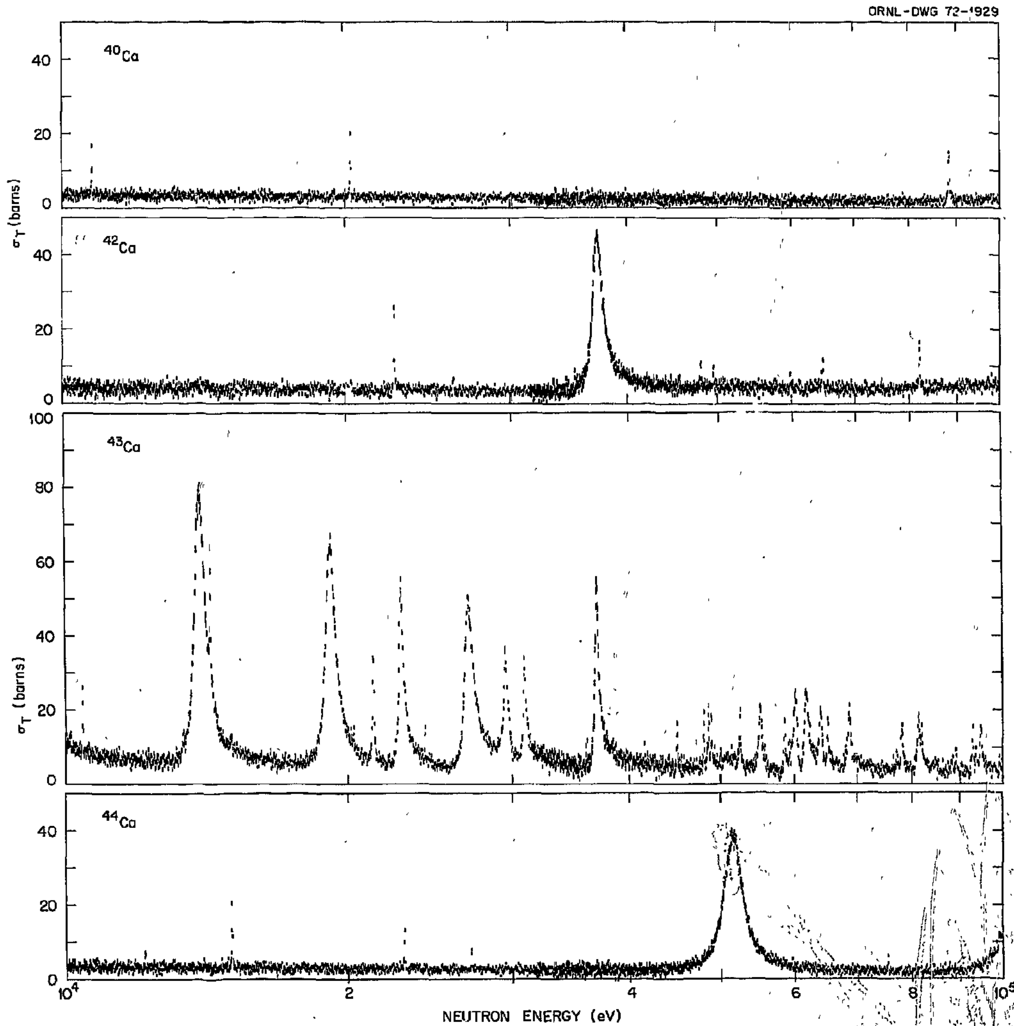

Fig. 1. Total cross sections of ^{40}Ca, ^{42}Ca, ^{43}Ca, and ^{44}Ca measured at ORELA.

corrected for the 4.168-μsec dead time in the EG&G clock (which is followed by an eight-word buffer), a constant room background, a time-dependent background which depends on the neutron spectrum, and the contribution of oxygen and carbon, since calcium carbonate samples were used. Much effort was devoted to investigating the shape and cause of the time-dependent background by the use of monoenergetic neutron groups and thick iron filters. A computer program was written to correct for this time-dependent background. Analysis of some of the data is in progress, but improved rapid-analysis programs using the new data analysis equipment are needed in order to complete the analysis in a reasonable time. However, *s*-wave resonances, except for very small resonances, are readily identified because of the interference between resonance and potential scattering. Many resonances are obviously not *s* wave.

Transmission measurements were also made upon samples of ^{120}Sn and ^{209}Bi with ^{6}Li glass detectors 200 m from the target. With the development of the new NE 110 plastic detector described elsewhere in this progress report, transmission measurements will be possible above 10 keV at 200 m with samples of only a few square centimeters area. The time-dependent background will also be less with this new NE 110 detector than with ^{6}Li glass scintillators.

HYDROGEN AND HELIUM PARTICLES PRODUCED BY 59-MeV ALPHA-PARTICLE BOMBARDMENT OF ^{12}C, ^{16}O, AND ^{54}Fe[1,2]

F. E. Bertrand R. W. Peelle[3]

NUCLEAR REACTIONS: ^{12}C, ^{16}O, ^{54}Fe$(\alpha,x\alpha)$; (α,xp), (α,xd), (α,xt), $(\alpha,x\,^3\mathrm{He})$; measured absolute $\sigma(\theta)$ for each exit particle type; E = 58.8 MeV; secondary energy range ≈2–59 MeV. Solid-state counter telescope.

Differential cross sections are presented for the production of protons, deuterons, tritons, and alpha particles from ^{12}C and ^{54}Fe bombarded by 58.8-MeV alpha particles. Spectra are presented for the same particles from ^{16}O, but with rather large uncertainty. Continuum cross sections in 1- or 2-MeV-wide bins are listed for five to six angles and with low-energy cutoffs which range from ~2 to 7 MeV, dependent on the type of exit particle. Angle-integrated and energy-integrated cross sections are also given. Total integral cross sections are given for emission of the five hydrogen and helium ions. Comparisons are shown between the $(\alpha,x\alpha)$ and (p,xp) reaction in ^{54}Fe and ^{12}C for E_α and E_p about 60 MeV.

1. Work funded by the National Aeronautics and Space Administration under order L-12, 186.
2. Abstract of ORNL-4694 (July 1971).
3. Neutron Physics Division.

LEVELS OF ^{50}Mn FROM THE ^{50}Cr$(h,t)^{50}$Mn REACTION[1]

C. M. McKenna[2,3] K. W. Kemper[2] J. D. Fox[2] J. W. Nelson[2] J. B. Ball

NUCLEAR REACTIONS: ^{50}Cr$(^3\mathrm{He},t)$, E = 39.5 MeV; measured $\sigma(E_t,\theta)$. ^{50}Mn deduced levels, J, π. Enriched target.

Levels of ^{50}Mn were observed via the ^{50}Cr$(h,t)^{50}$Mn reaction at 39.5 MeV bombarding energy, using the broad-range magnetic spectrograph at ORIC. Differential cross sections were measured in the angular range from 4 to 56° in 4° intervals. A total of 29 states below 4-MeV excitation in ^{50}Mn were identified. A microscopic DWBA analysis, including a tensor force and assuming pure $f_{7/2}$ configurations, was used to obtain J^π assignments for nine levels below 2-MeV excitation. Anomalies reported in previous (h,t) studies were observed: (1) the interaction strengths required to normalize the fits for natural parity states increased with J, and (2) for the high-spin $T_<$ states, angular shifts between the theoretical and experimental angular distributions were observed. The energy level scheme is compared with results of ^{50}Cr$(p,n)^{50}$Mn and ^{50}Cr$(p,n\gamma)^{50}$Mn experiments, as well as with a theoretical level scheme from shell-model calculations.

1. Abstract of published paper: *Phys. Rev.* C5, 145 (1972).
2. Florida State University, Tallahassee.
3. Present address: Ohio University, Athens.

STRAIGHT-BACK ELASTIC ALPHA SCATTERING FROM ^{48}Ti, ^{52}Cr, ^{53}Cr, AND ^{58}Ni[1]

P. T. Sewell[2] J. C. Hafele[2] C. C. Foster[3] N. M. O'Fallon[3] C. B. Fulmer

NUCLEAR REACTIONS: ^{48}Ti(α,α), ^{52}Cr(α,α), ^{53}Cr(α,α), ^{58}Ni(α,α), E = 13–29 MeV; measured $\sigma_{el}(\theta)$ at and near 180° as function of energy. Enriched targets.

Differential cross sections were measured at and near 180° for elastic alpha scattering from ^{58}Ni at 12 energies between 13 and 29 MeV and from ^{48}Ti, ^{52}Cr, and ^{53}Cr at 6 energies between 20 and 29 MeV. The data cover the angular range from 152 through 180° to −172°. The differential cross sections at 180° are sensitively dependent on both the bombarding energy and the target mass, and the angular distributions exhibit a "glory peak" at 180°. For the case of ^{58}Ni, measured cross sections are an order of magnitude larger than those predicted by optical-model calculations with a potential obtained from earlier studies of alpha scattering data forward of 140°.

1. Abstract of a paper to be published in the *Physical Review, Section C.*
2. Washington University, St. Louis, Mo.
3. University of Missouri, St. Louis, Mo.

HEAVY-ION REACTION CHANNELS DETERMINED FROM INDUCED RADIOACTIVITY MEASUREMENTS[1]

R. L. Robinson H. J. Kim J. L. C. Ford, Jr.

Gamma-ray measurements following heavy-ion bombardment were used to determine the absolute cross sections for different reaction channels. The radioactive products were identified by half-life, gamma-ray energies, and intensities. Reaction products formed by the bombardment of ^{58,60}Ni targets with 38- to 46-MeV oxygen ions have been studied.

1. Abstract of paper to be published in the *Proceedings of the Symposium on Heavy Ion Reactions and Many-Particle Excitations, Sept. 8–14, 1971;* to appear in the *Colloque du Journal de Physique.*

EFFECT OF CHANGING INITIAL ANGULAR MOMENTUM DISTRIBUTION ON THE $E2$ TRANSITIONS BETWEEN THE GROUND-STATE ROTATIONAL BAND MEMBERS

H. J. Kim R. L. Robinson W. T. Milner Z. W. Grabowski[1]

NUCLEAR REACTIONS: ^{58}Ni(^{16}O,2$p\gamma$)^{72}Se, ^{58}Fe(^{16}O,2$n\gamma$)^{72}Se, E = 38–46 MeV. Measured $\sigma(E;\gamma)$, $\sigma(\theta)$. Enriched targets.

Because energetic heavy-ion projectiles carry in a large amount of angular momentum in nuclear reactions and resulting compound nuclei have a high degree of spin alignment, it is expected that the evaporation of a few nucleons would not rock this initial alignment significantly. One consequence of this expectation is that the angular distributions of the stretched $E2$ gamma-ray transitions between members of a ground-state rotational band of the residual nucleus populated by heavy-ion reactions have a large A_2 and small A_4 (e.g., if 85% aligned, A_2 = +0.35 and A_4 = −0.09 for the $E2$ gamma ray from a 10^{+} state). This has been observed by numerous investigators.[2] If one assumes that an evaporating process produces a Gaussian distribution for the population of magnetic substates, then the values of A_2 and A_4 for a given $E2$ transition are uniquely related to each other and the width of the Gaussian. Lieder and Draper[3] have shown that the experimental results, including those from the (α, xn) reactions populating the ground-state band of even Se

1. Participant from Purdue University.
2. See, for example, D. G. McCanley and J. E. Draper, *Phys. Rev.* C4, 475 (1971).
3. J. E. Draper and R. M. Lieder, *Nucl. Phys.* A141, 211 (1970).

isotopes, can be successfully analyzed by the Gaussian model.

An alternative way to consider this problem is in the framework of the cascade radiation from an aligned system of nuclei. In this approach the alignment caused by a given spin sequence involved in a decay chain is evaluated. An appropriately weighted sum of these realignments for all possible spin sequences then gives the net realignments. Figure 1 shows what has been said in a schematic way. It is to be noted that for a given spin sequence the realignment consists of two factors. The alignment factor is purely geometrical and involves spins only, and the dynamical aspect of the reaction is entirely contained in the weighting factor. The notation used in Fig. 1 is that given in ref. 4. Unlike the Gaussian model, there is no a priori condition that A_2 values for stretched $E2$ transitions have to be positive.

We investigated the energy dependence of the yields and angular distributions for the stretched $E2$ gamma-ray transitions between the members of the ground-state rotational band of ^{72}Se via the ^{58}Ni(^{16}O,2p)^{72}Se and ^{58}Fe(^{16}O,2n)^{72}Se reactions. Thin targets (~60 μg/cm^2) were investigated with 38- to 46-MeV ^{16}O ions. The fractional yields to the different members of the rotational band were determined from the observed gamm-ray yields by assuming the level scheme given elsewhere in this report. The anisotropy parameters, $R = W(0°)/W(90°)$, were determined from the gamma-ray yields measured with two detectors ($\theta = 0°$ and $90°$). The results for the ^{16}O + ^{58}Ni case are shown in Figs. 2 and 3.

From Fig. 2 we note that the fractional population increases with projectile energy for the high-spin members of the band and decreases for the low-spin members. We believe this is associated with the fact that the angular momentum distribution in the initial compound nucleus changes markedly with projectile energy near the Coulomb barrier (~42 MeV). This can be seen in Fig. 4, where the calculated spin distributions are shown for two energies. The angular distributions measured at 40, 42, 44, and 46 MeV using a thicker target indicated that the values of A_4 are negligible in this energy range. The A_2 values corresponding to measured anisotropy $R = W(0°)/W(90°)$ assuming $A_4 = 0$ are also indicated in Fig. 3. The broken line labeled "complete alignment" shows the maximum value possible for the $8^+ \rightarrow 6^+$ transition. It is noteworthy that the anisotropies for the 8^+ and 6^+ states go through "threshold"-like behavior, whereas the anisotropies for the 4^+ and 2^+ states remain the same. We also note the interesting fact that the A_2 values for the 8^+ and 6^+ states are negative at low bombarding energies. This fact, as previously stated, is incompatible with the Gaussian model. The results for the ^{58}Fe(^{16}O,2n)^{72}Se case are qualitatively similar to those shown in Fig. 3, indicating that the "threshold"-like behavior is more likely to be a general feature of heavy-ion-induced reactions rather than a particular feature for the ^{58}Ni(^{16}O,2p)^{72}Se reaction. This view is also supported

4. T. Yamazaki, *Nucl. Data* A3, 1 (1967).

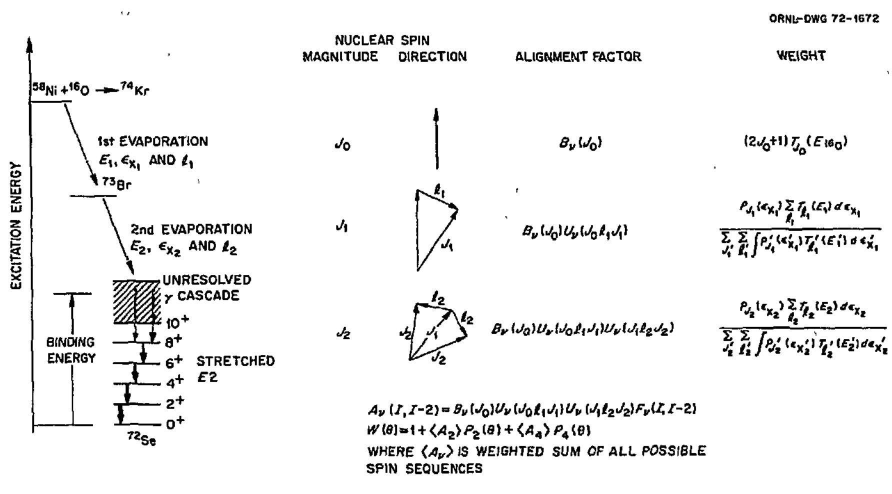

Fig. 1. Schematic illustration of the evaporation process. Notation used is given by T. Yamazaki, *Nucl. Data A* 3, 1 (1967). As elaborated by J. O. Rasmussen and T. T. Sugihara, *Phys. Rev.* 151, 992 (1966), unresolved statistical gamma-ray decay may be ignored in so far as the decay to high-spin residual states is concerned.

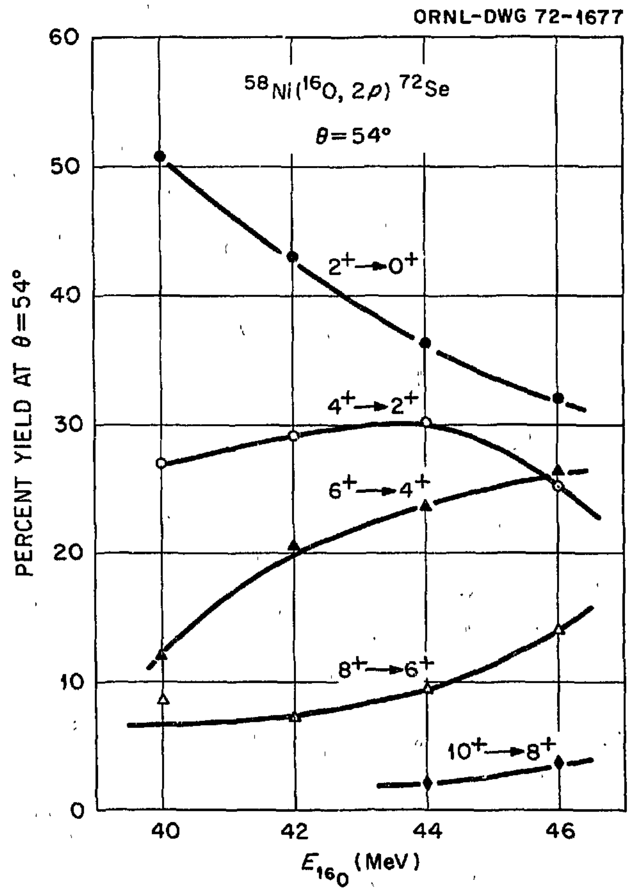

Fig. 2. Fractional yield of different rotational band members.

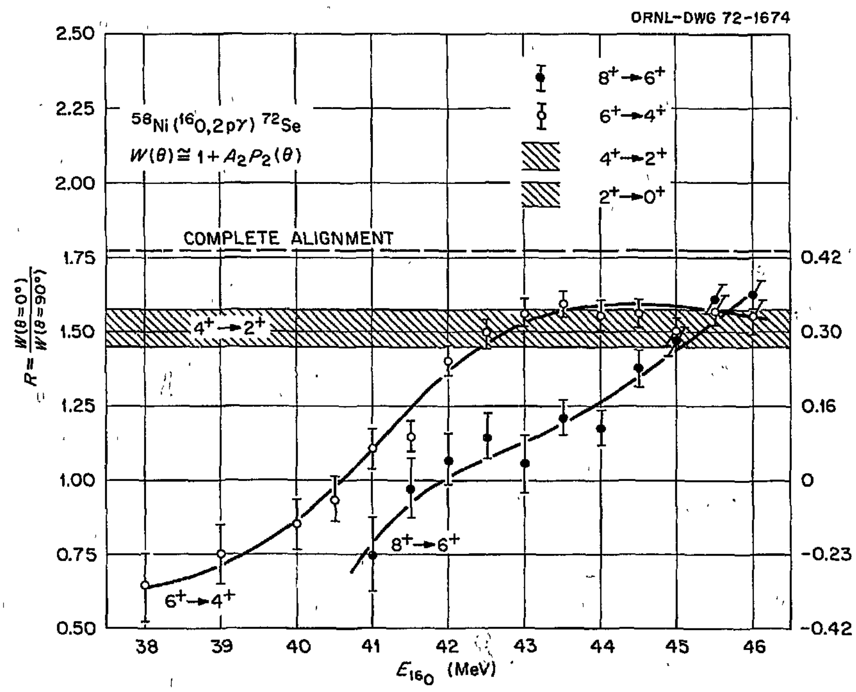

Fig. 3. Anisotropies for the various gamma rays for the projectile energy range 38 to 46 MeV. Anisotropies for the $4^+ \to 2^+$ and $2^+ \to 0^+$ gamma rays fall in the shaded band.

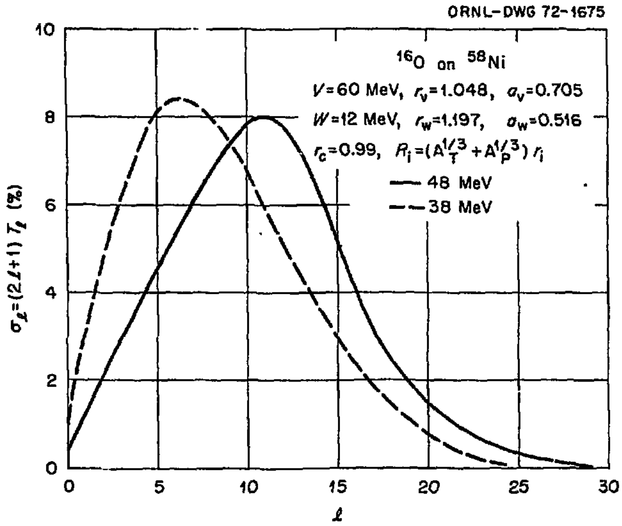

Fig. 4. Distributions of partial reaction cross sections, σ_ℓ, for two projectile energies. Transmission factors, T_ℓ, were calculated with the opical potential parameters shown.

by the limited results we obtained for the ^{60}Ni(^{16}O,2*p*)^{74}Se reaction.

A detailed calculation of the evaporation process outlined in Fig. 1 is in progress. It is anticipated that the calculation is flexible enough to explain the fractional population for the different band members observed. However, the negative A_2 values for the 6^+ and 8^+ states seem very anomalous. Even without performing a detailed calculation, it can be shown that there is no spin sequence which results in a negative A_2 for the 8^+ state if we limit proton evaporation with $l \leqslant 3$.

COLLECTIVE ROTATIONAL BAND IN ^{72}Se AND ^{74}Se EXCITED BY (^{16}O,2*p*), (^{16}O,2*n*), AND (^{18}O,2*n*) REACTIONS

H. J. Kim R. L. Robinson W. T. Milner W. T. Bass[1]

NUCLEAR REACTIONS: ^{58}Fe(^{16}O,2*n*)^{72}Se, ^{58}Ni(^{16}O,2*p*)^{72}Se, ^{58}Fe(^{18}O,2*n*)^{74}Se, ^{60}Ni(^{16}O,2*p*)^{74}Se, E = 38–46 MeV; measured $\sigma(E;\gamma)$, $\gamma\gamma$, deduced levels, J, π. Enriched targets.

During the course of investigating some characteristic features associated with the ^{16}O-induced reactions on Ni and Fe targets, it was felt necessary that we determine the properties of those states which are strongly populated by these reactions. The level scheme for ^{72}Se was investigated via the ^{58}Ni(^{16}O,2*p*) and ^{58}Fe(^{16}O,2*n*) reactions, and the level scheme for ^{74}Se was investigated via the ^{60}Ni(^{16}O,2*p*) and ^{58}Fe(^{18}O,2*n*) reactions. The information contained in Fig. 1 was deduced from the gamma-gamma coincidence results [using Ge(Li)-Ge(Li) as well as Ge(Li)-NaI], the angular distribution results, the yield curves, and the time distributions of the gamma rays. The time distributions were obtained by the pulsed-beam–delayed-coincidence method. Besides the gamma rays belonging to the dominant transitions shown in Fig. 1, we observed many additional weak gamma rays that can be ascribed to the transitions in ^{72}Se and ^{74}Se.

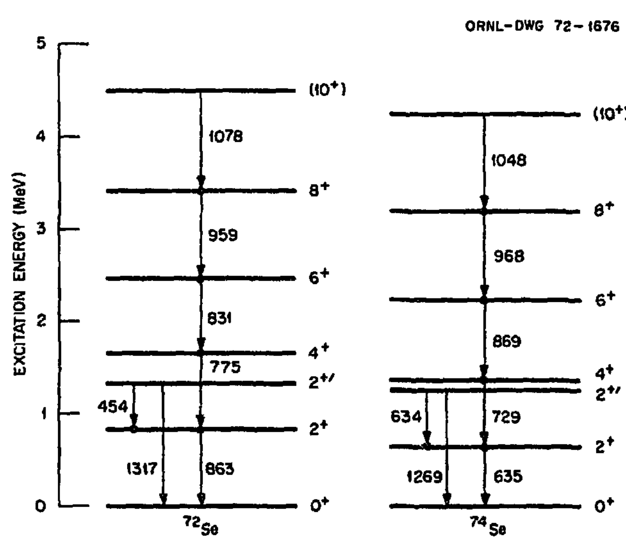

Fig. 1. Energy levels and their properties for ^{72}Se and ^{74}Se.

1. Present address: Department of Physics, Macon Junior College, Macon, Ga.

STUDY OF THE ZIRCONIUM ISOTOPES WITH THE (p,t) REACTION[1]

J. B. Ball R. L. Auble P. G. Roos[2]

NUCLEAR REACTIONS: $^{90,91,92,94,96}Zr(p,t)$, E = 38 MeV; measured $\sigma(E_t, \theta)$, Q. $^{88,89,90,92,94}Zr$ deduced levels, L, J, π, enhancement factors. Enriched targets.

The (p,t) reaction has been studied on all stable isotopes of zirconium at a proton energy of 38 MeV. Triton spectra were analyzed with a magnetic spectrograph yielding overall resolution on the order of 25 keV. Comparison of experimental angular distributions with two-nucleon-transfer distorted-wave Born-approximation calculations is made to extract spin-parity assignments and transition enhancement factors for many of the observed levels. The observed L = 0 transitions are discussed in terms of the shell model and the pairing-vibration model. The levels observed in $^{88,89,90,92,94}Zr$ are compared with results of other experiments to derive a number of new level assignments. Measurements are also obtained of the one- and two-neutron binding energies from Q values deduced for the (p,t) and (p,d) ground-state transfer reactions.

1. Abstract of published paper: *Phys. Rev.* C4, 196 (1971).
2. University of Maryland, College Park.

A SEARCH FOR 0^+ STATES IN ^{92}Mo AND ^{94}Mo POPULATED THROUGH THE (p,t) REACTION

J. S. Larsen[1] J. B. Ball C. B. Fulmer

NUCLEAR REACTIONS: $^{92,94,96}Mo(p,t)$, E = 31 MeV; measured $\sigma(E_t, \theta)$. $^{90,92,94}Mo$ deduced levels, J, π. Enriched target.

It has been shown that ^{88}Sr can be regarded as an inert core for the low-lying levels of nuclei in the mass 90 region. The ground states of the Mo isotopes will, in such a model, contain four protons distributed in the $2p_{1/2}$ and $g_{9/2}$ orbitals and be of the form

$$\alpha(\pi p_{1/2})_0{}^2 \, (\pi g_{9/2})_0{}^2 + \beta(\pi g_{9/2})_0{}^4 \, .$$

The orthogonal configuration will result in a low-lying 0^+ excited state. If the linear combination is unchanged as neutrons are added to the $N = 50$ core, such 0^+ states cannot be populated by the (p,t) reaction. However, if configuration changes occur due to the added neutrons, population of the 0^+ states through the (p,t) reaction supplies a sensitive probe to determine the extent of these changes.

Another class of 0^+ states in nuclei at and above closed shells is the so-called pairing vibrations. They are states consisting of pairs of particles excited from the

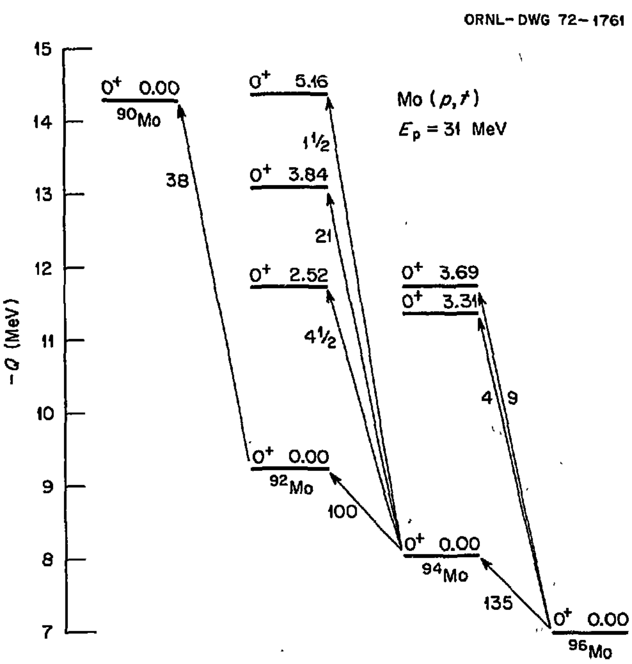

Fig. 1. Relative transition strengths observed to 0^+ states for the (p,t) reactions on $^{92,94,96}Mo$ targets.

1. Visiting scientist from Niels Bohr Institute, Copenhagen, Denmark.

core into the valence shell. They will occur at higher energies and are generally of considerable strength. They are excited in the (p,t) reaction by removal of a neutron pair from the closed core.

In this study we have examined the $^{94}Mo(p,t)^{92}Mo$ and $^{96}Mo(p,t)^{94}Mo$ spectra. They were obtained at a bombarding energy of 31 MeV, and the tritons were detected with photographic plates in the broad-range spectrograph. The overall resolution was about 20 keV. Spectra were obtained at every 5° from 5° to 65° for the ^{94}Mo target and 5° to 45° for ^{96}Mo. The sensitivity of our experiment was such that states with intensities down to 1% of the ground-state strength were analyzed. The observed levels are listed in Table 1.

In Fig. 1 are shown the observed $L = 0$ transitions with their relative strengths. [The $^{92}Mo(p,t)$ reaction was measured at three angles, and the ground-state transition was analyzed for comparison with the other ground-state transitions and the strengths of the pairing vibrations.] The state at 2.515 MeV in ^{92}Mo is considered to be the orthogonal proton state. The analogous state in ^{94}Mo was not seen, indicating that the proton configuration is remarkably unaffected by the presence of two additional neutrons. The higher excited 0^+ states are considered to be the pairing vibration. The combined strength of these two states is about 60% of the ground-state transition $^{92}Mo \rightarrow {}^{90}Mo$. In the zirconium isotopes (two protons less) this ratio was found to be 71%. In addition, we observe that the energy centroid of the levels is shifted to lower energy than expected from the pairing-vibration theory and from what was observed in the zirconium isotopes. Both intensity and energy shift for the pairing vibration levels in ^{92}Mo more closely resemble the behavior of such states observed previously in ^{142}Nd. This suggests that the shell closure at $N = 50$ is not as complete in the molybdenum isotopes as in the zirconium isotopes. The results from this work will be used to examine the validity of shell-model wave functions calculated for these nuclei.

Table 1. Levels observed in the $^{94,96}Mo(p,t)$ reactions

^{92}Mo		^{94}Mo	
E (MeV)	J^π	E (MeV)	J^π
0.000	0^+	0.000	0^+
1.506	2^+	0.879	2^+
2.277	(4^+)	1.578	4^+
2.515	0^+	1.872	(2^+)
2.844	(3^-)	2.071	2^+
3.090		2.300	$3^-, 4^+$
3.535	(2^+)	2.397	2^+
3.833	0^+	2.428	
3.915	2^+	2.537	5^-
4.141	4^+	2.567	4^+
4.298	2^+	2.612	
4.483	2^+	2.772	
5.155	0^+	2.870	
		3.314	0^+
		3.367	5^-
		3.399	2^+
		3.450	(2^+)
		3.689	0^+
		3.788	3^-
		3.984	2^+
		4.083	2^+
		4.130	2^+

THE $^{90}Zr(d,n)^{91}Nb$ AND $^{96}Zr(d,n)^{97}Nb$ REACTIONS[1]

J. L. Horton[2] C. L. Hollas[2] P. J. Riley[2] S. A. A. Zaidi[2]
C. M. Jones J. L. C. Ford, Jr.

NUCLEAR REACTIONS: $^{90}Zr(d,n)^{91}Nb$, $^{96}Zr(d,n)^{97}Nb$, E = 12 MeV. Measured $\sigma(E, E_n, \theta)$. ^{91}Nb, ^{97}Nb, deduced angular momentum transfer values and spectroscopic factors.

The (d,n) reaction on ^{90}Zr and ^{96}Zr has been studied at 12 MeV deuteron bombarding energy using the neutron time-of-flight technique with an overall neutron time resolution of 1.9 nsec. Angular distributions of neutron groups leading to states in ^{91}Nb and ^{97}Nb were measured in the angular range between 15 and 60°. The measured cross sections were analyzed in the framework of the distorted-wave theory of stripping reactions to deduce l values and proton spectroscopic factors of states in the residual nuclei. The results are compared with the corresponding data available from (^3He, d) studies. Arguments based on the shell-model theory have been used to make tentative spin assignments. The fractionation of the single-particle proton states and their centroid energies are determined.

1. Abstract of paper submitted for publication in *Nuclear Physics*.
2. University of Texas, Austin, Tex. 78712.

SPECTROSCOPY OF $^{93,95,97}Tc$ THROUGH THE (*d,n*) REACTION[1]

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C. M. Jones *J. L. C. Ford, Jr.*

The (*d,n*) reaction on ^{92}Mo, ^{94}Mo, and ^{96}Mo has been studied at 12 MeV deuteron bombarding energy using the neutron time-of-flight technique with an overall neutron time resolution of 1.9 nsec. Angular distributions of neutron groups leading to states in ^{93}Tc, ^{95}Tc, and ^{97}Tc were measured in the angular range between 15 and 70°. The measured cross sections are analyzed in the framework of the distorted-wave theory of stripping reactions to deduce the *l* values and proton spectroscopic factors of the states in the residual nuclei. The results are compared with the corresponding data available from (^{3}He, *d*) studies. Arguments based on the shell-model theory have been used to make tentative spin assignments. The fractionation of the single-particle states and their centroid energies are determined. Tentative ^{92}Mo, ^{94}Mo, and ^{96}Mo ground-state configurations are deduced from the analysis.

1. Abstract of published paper: *Phys. Rev.* **C4**, 1864 (1971).
2. University of Texas at Austin, Department of Physics, Austin, Tex. 78712.

A TEST OF THE VALENCY MODEL OF NEUTRON CAPTURE IN $^{92}Mo(n,\gamma)^{93}Mo$

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S. F. Mughabghab[2] G. W. Cole[2]

NUCLEAR REACTIONS: $^{92}Mo(n,\gamma)^{93}Mo$, E = 0.3–100 keV; measured E_γ, I_γ. ^{93}Mo deduced *levels, J, π. Enriched target.*

The valency model of neutron capture[3,4] has proved successful in predicting partial radiative widths in ^{92}Mo and ^{98}Mo for low-energy *p*-wave resonances with large reduced neutron widths.[5] This experiment extends the previous measurements on ^{92}Mo to higher neutron energies. A Ge(Li) diode viewed a 250-g enriched sample (97% ^{92}Mo) at a 10.4-m flight station at ORELA. Pulse-height spectra of 4096 channels each were collected for resonance and background time groups for incident neutron energies from 300 eV to 100 keV.

Figure 1 shows the energy-level diagram of ^{93}Mo. This nuclide is formed by the (*n,γ*) reaction on the zero-spin target ^{92}Mo. The spins and parities of the capturing states are $1/2^+$ for incident *s*-wave neutrons and $1/2^-$ and $3/2^-$ for incident *p*-wave neutrons. A triangle on the right of the horizontal lines indicates that a primary transition from the capturing state is observed in the present experiment, and a triangle on the left indicates an observed deexcitation transition to the ground state. A new level was established by this experiment at an excitation of 2141 keV. Fortunately for the purpose of this experiment, most of the spins, parities, and spectroscopic factors for the final states were known from previous (*d,p*) measurements.[6] Note that a transition from the capturing state to the ground state is probable only for a capturing-state spin of 3/2; transitions from the spin 1/2 capturing states are inhibited by the required spin change of 2. The presence of this transition was the basis of the assignment of a spin of 3/2 to those resonances; its absence does not prove the contrary. Primary transitions to the first excited state of spin 1/2 are probable for all *s*- and *p*-wave resonances. Figure 2 shows some representative high-energy gamma-ray spectra for four resonances. The numbers on the peaks identify the double-escape peaks (E_γ − 1022 keV) of primary gamma rays with the terminating state (0 = ground state, 1 = first excited state, etc.), and *F* and *S* indicate full-energy and single-escape peaks. The domination of

1. Guest Assignee from Brookhaven National Laboratory.
2. Brookhaven National Laboratory.
3. A. M. Lane and J. E. Lynn, *Nucl. Phys.* **17**, 586 (1960).
4. J. E. Lynn, *The Theory of Neutron Resonance Reactions*, p. 330, Clarendon Press, Oxford, 1968.
5. Mughabghab, Chrien, Wasson, Cole, and Bhat, *Phys. Rev. Lett.* **26**, 1118 (1971).
6. J. B. Moorhead and R. A. Moyer, *Phys. Rev.* **184**, 1205 (1969).

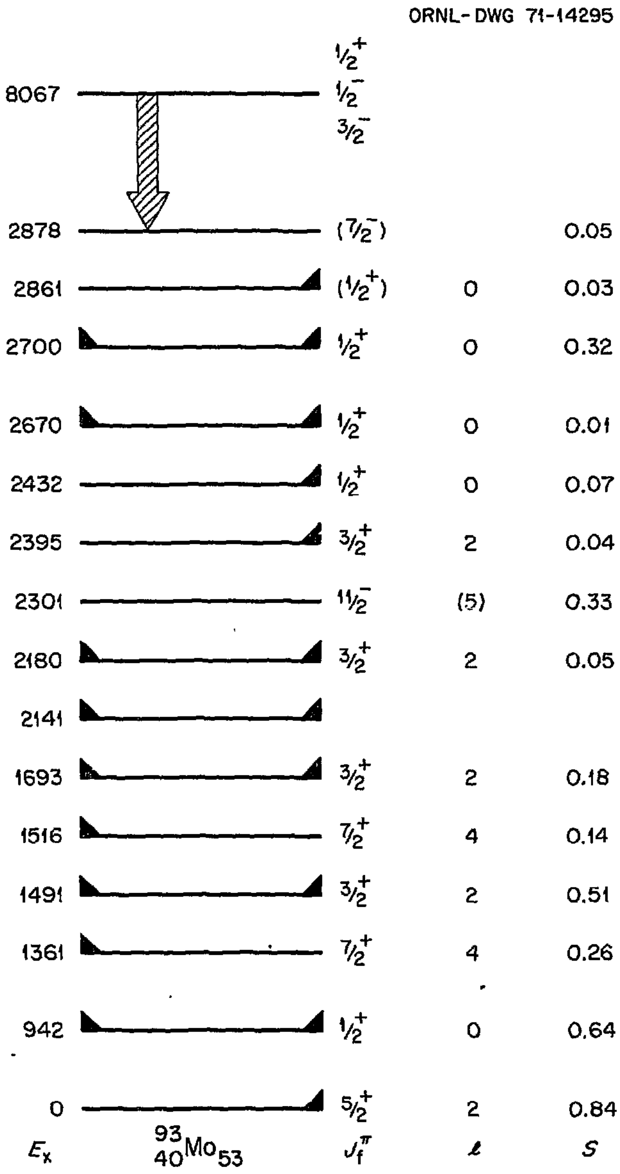

Fig. 1. Energy-level diagram for ^{93}Mo. Energies in left vertical column are in kilo-electron volts. Triangles on the right of a horizontal line indicate an observed primary transition to that level; triangles on the left indicate an observed deexcitation transition to the ground state. Spectroscopic factors from (d,p) experiments are given in the right vertical column.

the 7129-keV transition to the first excited state, present in 16 of 19 p-wave resonances, is an indication of the nonstatistical nature of the neutron capturing process for this nuclide. The 348-eV resonance has considerable strength below 5.5 MeV. This strength is missing in the other spectra in Fig. 2, which are more typical of the remaining 19 resonances. It now remains to compare the data with the predictions of the valency neutron model.

Lane and Lynn[3] and Lynn[4] have suggested that the partial radiative widths for neutron capture in resonances may be calculated by considering the motion of a single neutron in a potential well, ignoring the contribution of core transitions. The final state must have essentially single-particle character. Ignoring spin and gamma-ray energy factors, the partial radiation widths should then be proportional to the single-particle matrix element (evaluated in ref. 4) and the product of the reduced neutron widths of the initial and final states. The primary transitions to states having large final-state spectroscopic factors (right column, Fig. 1) should dominate, in this case the transitions to the ground state and the first excited state. A complete test of the model requires knowledge of the final-state spins and spectroscopic factors (known), the initial-state (resonance) spins (partially determined in this experiment), the resonance neutron widths (being measured), and the total resonance radiation width (unknown). Since all of the required parameters are not known, only the dependence on the properties of the low-lying final states can be tested.

The best examples of the agreement with the model are shown for $2p_{3/2}$ resonances in Fig. 3. On the left are the experimental partial radiative widths, normalized to the sum of 12 high-energy gamma-ray lines, while the valency model predictions are on the right. Figure 4 shows the comparison in the same format for $3p_{1/2}$ resonances. The 23.9-keV resonance has the largest p-wave reduced neutron width of 1.3 eV. Again, the agreement is excellent. Other resonances show agreement ranging from indifferent to poor, so the net result is 5 out of 19 resonances with good agreement. However, these five resonances are not the ones with the largest reduced neutron widths. Figure 5 shows the averaged spectra for the three types of resonances. The dominance of the 7129-keV transition to the first excited state is evident, as is the ground-state transition in the average for the $p_{3/2}^-$ capturing states. Single-particle effects are evidently significant for these two gamma rays, with the transition to the first excited state showing more single-particle nature than the ground-state transition. This is consistent with the observation of Lane that the p-to-s transitions are more single particle than the p-to-d transitions.

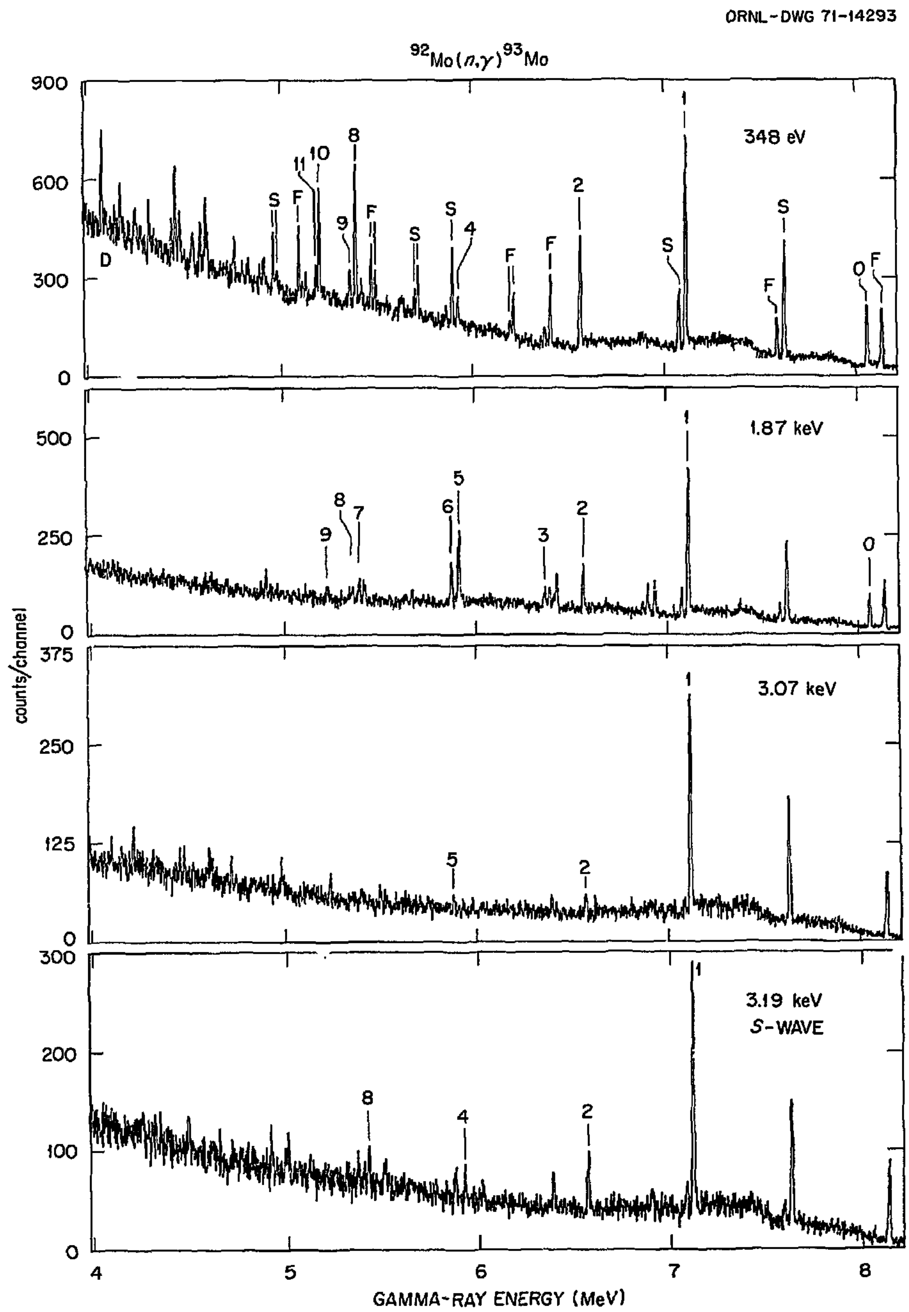

Fig. 2. Ge(Li) pulse-height spectra for neutron capture gamma rays from four neutron resonances. The numbers identify the double-escape peaks ($E = E_\gamma - 1022$ keV) of the primary gamma rays with the terminating state (0 = ground state, 1 = first excited state, etc.). The letters *F* and *S* identify the full-energy and single-escape peaks.

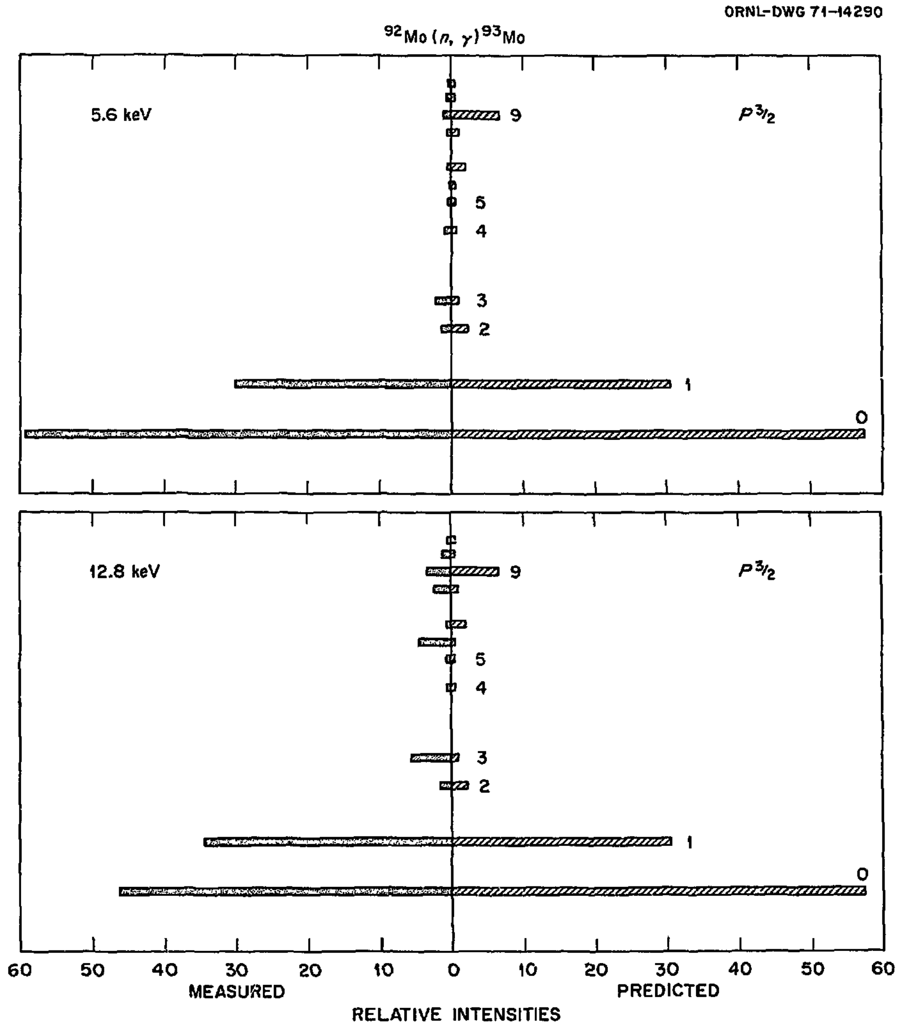

Fig. 3. A comparison of the measured gamma-ray intensities (left), normalized to the sum of 12 high-energy primary transitions, to the predictions of the valency neutron model (right), for $2p_{3/2}$ resonances.

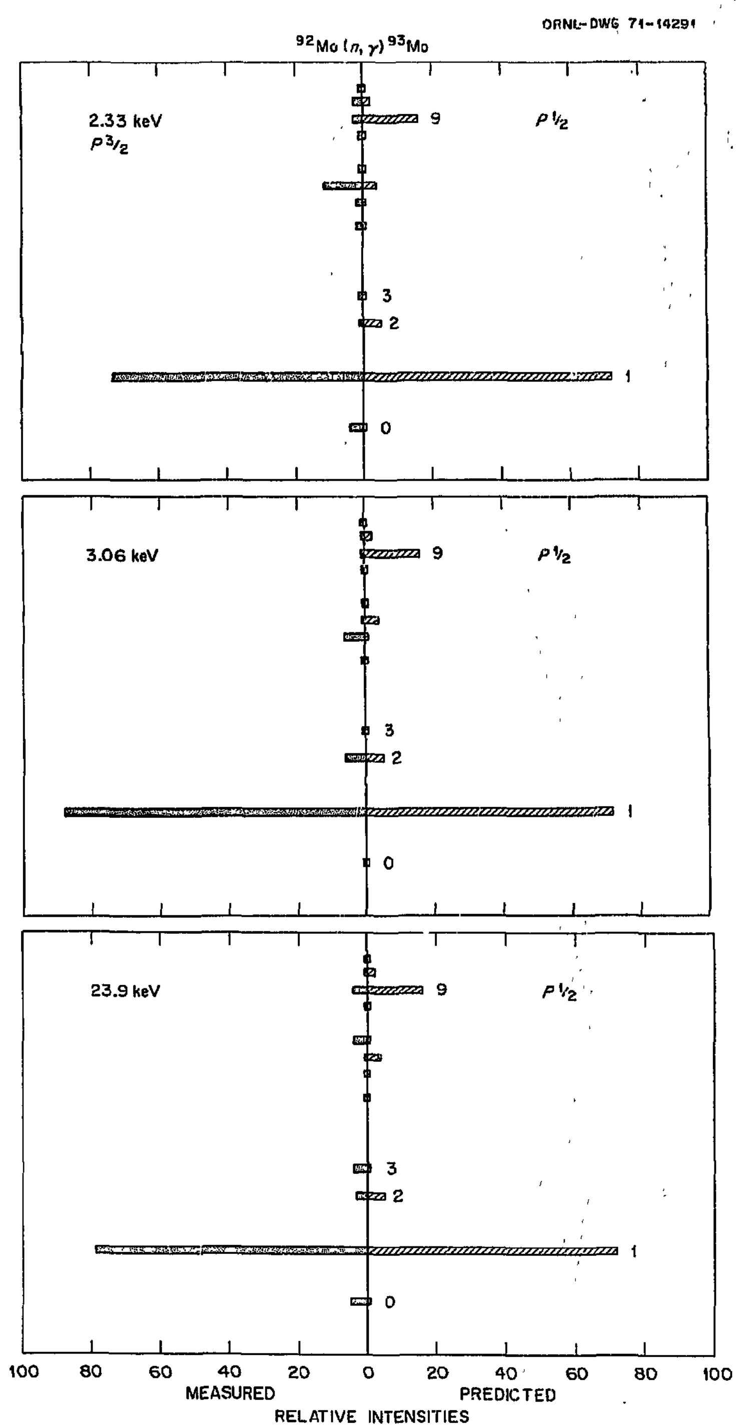

Fig. 4. A comparison of the measured gamma-ray intensities (left), normalized to the sum of 12 high-energy primary transitions, to the predictions of the valency neutron model (right), for $3p_{1/2}$ resonances.

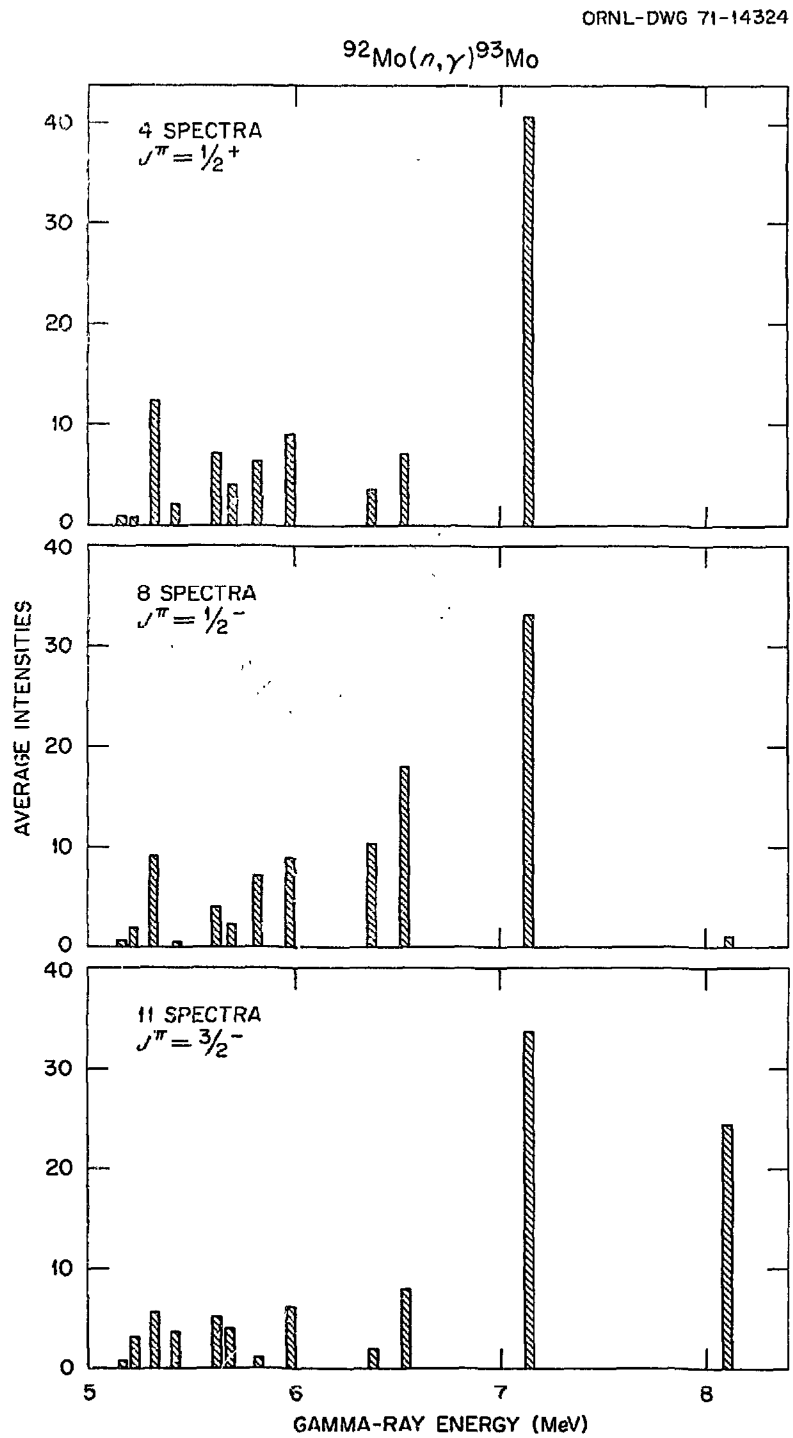

Fig. 5. Intensities averaged over resonances for $s_{1/2}^+$, $p_{1/2}^-$, and $p_{3/2}^-$ resonances.

STUDIES OF ^{95}Ru AND ^{94}Ru WITH THE ^{96}Ru(*p*, *d*) AND (*p*,*t*) REACTIONS[1]

J. B. Ball

NUCLEAR REACTIONS: ^{96}Ru(*p*, *d*), ^{96}Ru(*p*,*t*), E_p = 31.5 MeV; measured *Q*, $\sigma(E, \theta)$. ^{95}Ru deduced levels, l_n, *J*, π, spectroscopic strengths, ground-state mass excess. ^{94}Ru deduced ground-state mass excess. Enriched target.

The level structure of ^{95}Ru has been investigated with the ^{96}Ru(*p*, *d*) reaction at a proton energy of 31.5 MeV. Experimental angular distributions are compared with distorted-wave Born-approximation calculations to extract spin, parity, and spectroscopic-factor assignments for the levels observed up to about 3.5 MeV of excitation. The ground state of ^{95}Ru is observed to be reached by $l = 2$ transfer, which is consistent with the $5/2^+$ assignment expected from shell-model considerations. The measured *Q* values for the (*p*,*d*) and (*p*,*t*) reactions result in a new value for the mass of ^{95}Ru and a determination of the previously unmeasured mass of ^{94}Ru.

1. Abstract of published paper: *Nucl. Phys.* **A160**, 225 (1971).

TWO-NEUTRON TRANSFER REACTIONS FROM ODD-SPIN TARGETS: ^{91}Zr(*p*,*t*)^{89}Zr

J. B. Ball C. B. Fulmer

NUCLEAR REACTIONS: ^{91}Zr(*p*,*t*), *E* = 31 MeV; measured $\sigma(E_t, \theta)$. ^{89}Zr deduced levels, *J*, π. Enriched target.

In our previous work on the (*p*,*t*) reaction, we have concentrated on even-target nuclei largely because the simplifications introduced by proceeding from a 0^+ initial state allowed a clear test of the ability of the two-nucleon transfer DWBA calculations to reproduce our results. The selection rules governing the (*p*,*t*) reaction are such that with a 0^+ target only the natural parity states in the final nucleus will be observed and each of these final states will be populated with a unique *L*-transfer value. Thus the determination of the *L* value for the given final-state angular distribution gives directly both the spin and parity of the level observed.

For odd-spin targets, however, usually more than one *L*-transfer value will be allowed to a given level in the final nucleus, and the observed angular distributions will be a composite of all the allowed *L* transfers. To illustrate the problem of analyzing such mixed transition data, we have chosen the reaction ^{91}Zr(*p*,*t*)^{89}Zr, where the low-lying levels of both initial and final systems are thought to have fairly simple shell-model descriptions.

Previous studies of one-neutron transfer reactions have shown that the neutron part of the ^{91}Zr ground-state wave function is almost entirely described by a single $2d_{5/2}$ neutron outside a closed $N = 50$ major shell closure. Similarly, the first four levels in ^{89}Zr can be described as due to creating a single neutron hole in the four shell-model orbitals comprising the major shell between $N = 28$ and 50 (i.e., the $1g_{9/2}$, $2p_{1/2}$, $2p_{3/2}$, and $1f_{5/2}$). The $9/2^+$ (ground state), $1/2^-$ (0.588 MeV) level, $3/2^-$ (1.095 MeV) level, and $5/2^-$ (1.452 MeV) level would thus be populated in the (*p*,*t*) reaction on ^{91}Zr by removal of the single $d_{5/2}$ neutron and one of the neutrons from these filled orbitals.

If these descriptions of the initial and final states are valid, then a straightforward derivation gives an expression for the expected *L*-transfer mixture as

$$\sigma_{\exp}(\theta) \propto \sum_L \frac{2L+1}{6} \sigma_{\mathrm{DWBA}}(\theta, L),$$

where the weighting factor is independent of the participating orbital from the closed core.

For the transition to the ground state (pickup of a $d_{5/2}$, $g_{9/2}$ pair), the allowed *L* transfers are 2, 4, and 6. The predicted angular distributions for each of these *L* values from the DWBA code JULIE are shown in the lower portion of Fig. 1 weighted by the $2L + 1$ factor.

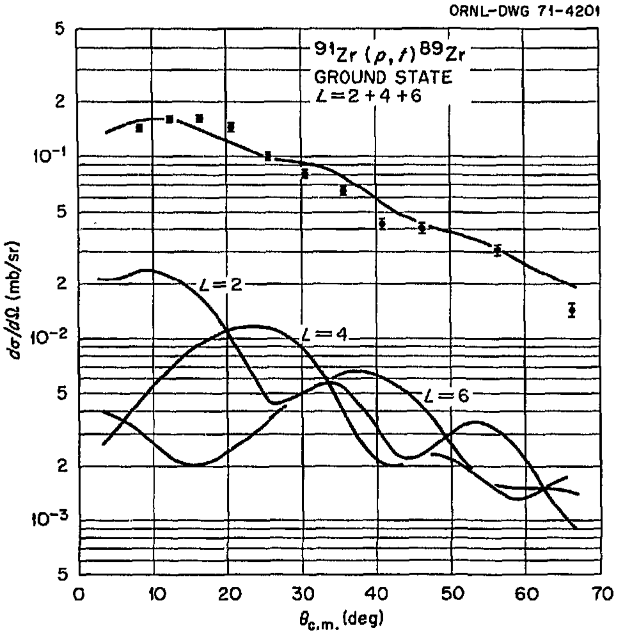

Fig. 1. Calculated and experimental angular distributions for the $^{91}Zr(p,t)^{89}Zr$ reaction to the $9/2^+$ ground state showing the relative contributions predicted for the allowed L transfers.

The sum of these three contributions is shown normalized to the experimental data in the upper portion of the figure. Although the individual L-transfer distributions show significant angular structure, the sum curve is rather featureless and is in good agreement with the experimental results.

Another example is shown in Fig. 2 for the 1.450-MeV, $5/2^-$ level. Here, $L = 1, 3$, and 5 are allowed, but both the reaction dynamics and the $2L + 1$ weighting enhance the $L = 5$ transfer sufficiently to make it dominate the composite angular distribution. The data for this level agree well with the predicted shape. Similar agreement is found for the other levels in ^{89}Zr. Data for higher-lying levels are being analyzed in a similar fashion to provide new information on spin-parity assignments.

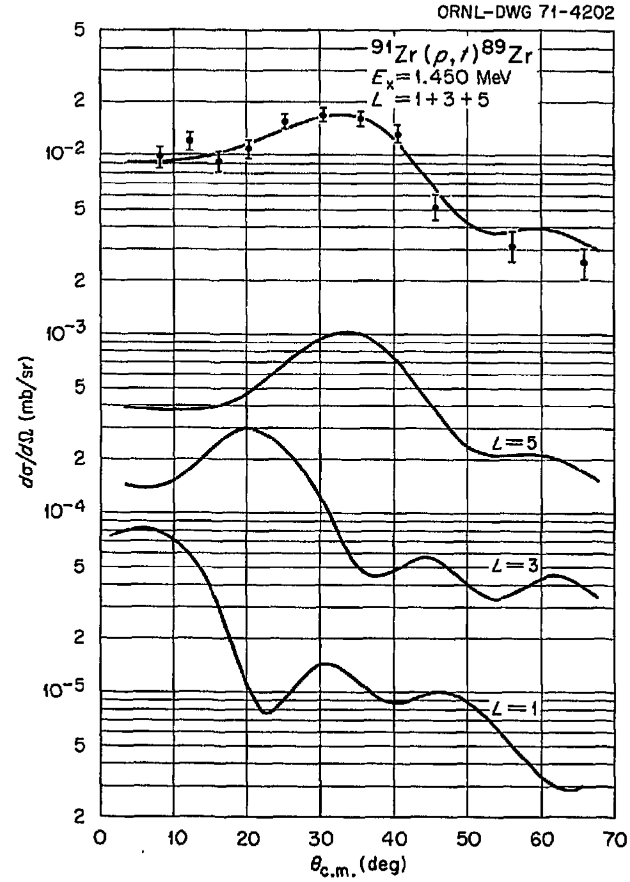

Fig. 2. Calculated and experimental angular distributions for the 1.450 MeV, $5/2^-$ level in ^{89}Zr, populated by the $^{91}Zr(p,t)$ reaction, showing the relative contributions predicted for the allowed L transfers.

The good agreement between the predicted and observed angular distributions suggests not only that our simple description of these nuclei has some validity but that the two-nucleon DWBA calculations can now be done with enough confidence to provide meaningful analysis of mixed L-transfer data.

P-WAVE NEUTRON CAPTURE SPECTRA FROM ^{98}Mo[1]

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R. E. Chrien[2] G. G. Slaughter

NUCLEAR REACTIONS: $^{98}Mo(n,\gamma)^{99}Mo$, E = 0.005–5 keV; measured E_γ, I_γ. ^{99}Mo deduced J, π. Enriched sample.

Recent measurements of radiative neutron capture with a ^{98}Mo target[4] by the BNL fast chopper group have demonstrated the validity of the valency neutron model[5] at resonance neutron energies below 1.0 keV. The energy region has been extended to ~5 keV using the Oak Ridge Linear Accelerator (ORELA), with a nominal time-of-flight resolution of 2.5 nsec/m. Capture gamma-ray spectra from resonances have been analyzed and compared to the valency neutron model.

The success of the model for resonances below 1 keV in ^{98}Mo is related to the large reduced widths of these resonances. If the final state has a strong single-particle component, then for these resonances a simple description of the capture process may reasonably be expected to apply. Above 1 keV in ^{98}Mo, the resonances have significantly smaller widths, and statistical processes are expected to dominate the capture reaction.

The results of the present work, in which 21 resolved resonances were studied, confirm these expectations. Spectra for the 12-, 429-, 612-, and 818-eV resonances are in substantial agreement with the previously reported values for the widths of six primary transitions to low-lying *s* and *d* states in ^{99}Mo.

However, the regularities expected from the valency neutron model are not observed in the spectra obtained from resonances between 1.0 and 4.0 keV, and the widths predicted by the model are not in agreement with experiment.

Above 4 keV an increase in the *P*-wave neutron strength function is observed.[6] Agreement with the model is obtained for the $p_{3/2}$ resonance at 4842, with $\Gamma n^{(1)}$ = 0.71 eV. The observed ground-state radiation width of 11.8 ± 3 meV compares to a predicted value of 11.0. Other transitions of this resonance are not in such good accord with the model.

Examination of the primary gamma-ray spectra has led to spin and parity assignments for previously unassigned resonances of ^{98}Mo, as indicated in Table 1.

Table 1

E_r(eV)	l	j
401	1	3/2
1122	1	3/2
2170	1	1/2
2623	1	(3/2)
2950	1	(1/2)
3260	1	(1/2)
3792	1	(1/2)
4013	1	3/2
4571	1	(1/2)
4842	1	3/2

1. Abstract of paper to be published in *Proceedings of International Conference on Statistical Properties of Nuclei, August 23–27, 1971*, State University of New York, Albany.
2. Brookhaven National Laboratory, Upton, N.Y.
3. Guest Assignee from Brookhaven National Laboratory.
4. S. F. Mughabghab, R. E. Chrien, O. A. Wasson, G. W. Cole, and M. R. Bhat, *Phys. Rev. Lett.* 26, 1118 (1971).
5. J. E. Lynn, *The Theory of Neutron Resonance Reactions*, p. 330, Clarendon Press, Oxford, 1968.
6. H. Weigmann, G. Rohr, and J. Winter, Third Neutron Cross Section Technology Conference, Knoxville (1971), CONF. 710301, vol. 2, pp. 749–56.

3d. $A > 100$

SEARCH FOR WEAK TRANSITIONS IN THE DECAY OF ^{108m}Ag[1]

J. H. Hamilton[2] S. M. Brahmavar[3] J. B. Gupta[2] R. W. Lide[4] P. H. Stelson

RADIOACTIVITY: ^{108m}Ag [^{107}Ag(n,γ)]; measured E_γ, I_γ; deduced isomeric branching. Ge(Li) detectors. Sources produced in 1950s and 1960s.

The decay of ^{108m}Ag ($T_{1/2}$ > 5 years) has been studied with large-volume (60 cm^3) Ge(Li) detectors to search for weak transitions in this decay. The ^{108m}Ag sources were prepared from neutron capture on natural silver in the early 1950s and 1960s. In addition to the well-known 723.0-, 614.4-, 434.0-keV (100%) triple cascade in ^{108}Pd, only the (0.15 ± 0.01)% 633-keV transition in ^{108}Cd was observed from the decay of ^{108}Ag via the isomeric decay of ^{108m}Ag. Evidence for a very weak (0.005%) 836.5-keV transition was found. Upper limits were placed on the intensity of any other transitions in this decay. The isomeric branching is (7.7 ± 0.8)%.

1. Abstract of published paper: *Nucl. Phys.* A172, 139–44 (1971).
2. Physics Department, Vanderbilt University, Nashville, Tenn.
3. Present address: Wesson Memorial Hospital, Springfield, Mass.
4. Consultant from the University of Tennessee, Knoxville.

A STUDY OF (^{3}He,d) REACTIONS ON ^{107,109}Ag

R. L. Auble J. B. Ball F. E. Bertrand D. J. Horen

NUCLEAR REACTIONS: ^{107,109}Ag(^{3}He,d), E = 26 MeV. Measured $\sigma(\theta, E_d)$. ^{108,110}Cd deduced levels, l_p, J^π, S. Enriched targets.

A recent compilation[1] of nuclear structure data for A = 110 showed that there are essentially no particle-transfer data for ^{110}Cd. Thus most of the level properties for this nucleus have been deduced from radioactivity measurements. These latter studies suggested the presence of two possible $J^\pi = 5^-$ levels at 2.0042 and 2.1245 MeV, which were not reported in inelastic scattering[1] and are therefore not of collective character. One possible way of forming a noncollective 5^- state is through the proton coupling $(1g_{9/2})(2p_{1/2})$ which will form states with $J^\pi = 4^-$ and 5^-. If there are two $1g_{9/2}$ proton holes in the ^{109}Ag ground state, which has $J^\pi = 1/2^-$, such states should be populated in the (^{3}He,d) reaction by l = 4 stripping. Data from the ^{109}Ag(^{3}He,d) reaction at E = 26 MeV have been taken and are partially analyzed. A spectrum is shown in Fig. 1. Two features are immediately obvious. First, the levels mentioned above are not excited, and second, the first excited 2^+ level at 0.6577 MeV is quite strong. The latter observation shows that there are appreciable vacancies in the $2p_{3/2}$ orbits and, consequently, fewer $1g_{9/2}$ vacancies than originally anticipated. This could account in part for our failure to excite the proposed 5^- levels. However, several states at higher excitation may be excited by l = 4 transfer, although definite assignments cannot be made until the data are fully analyzed. Similar measurements are being made on ^{107}Ag, where, again, there is an essentially complete lack of reaction data. Data have been taken at several angles, and we are currently awaiting the scanning of the photographic plates.

1. F. E. Bertrand and S. Raman, *Nucl. Data* B5, 487 (1971).

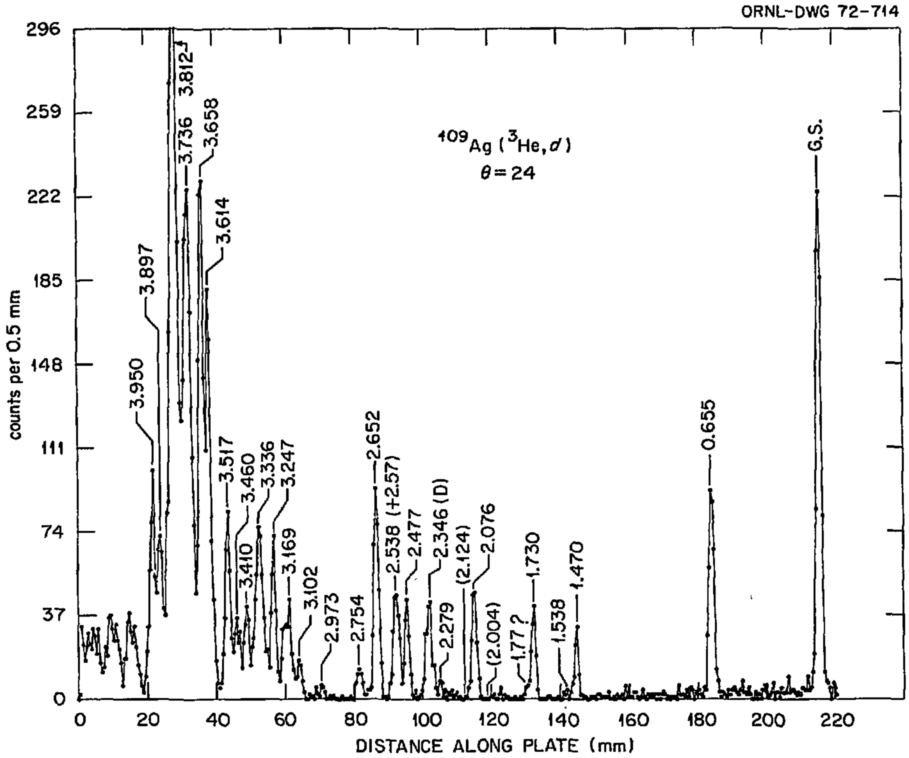

Fig. 1. Deuteron spectrum from the ^{109}Ag(^{3}He,d)^{110}Cd reaction.

HINDERED $E2$ TRANSITION IN ^{113}Cd

S. Raman H. J. Kim W. T. Milner

NUCLEAR REACTIONS: ^{113}Cd($p,p'\gamma$), E = 3.8 MeV; measured $p\gamma$ delay. ^{113}Cd level deduced $T_{1/2}$.

Hindered $E2$ transitions of energies 59.9 and 245.4 keV are known in ^{109}Cd and ^{111}Cd respectively (see Table 1). We have observed the analogous hindered $E2$ transition in ^{113}Cd. The measurements were carried out with a 3.8-MeV pulsed proton beam. The outputs from a time-to-pulse-height converter and a 30-cm^3 Ge(Li) detector were displayed in a 64 X 256 two-dimensional mode.[1] The 315.8-keV gamma ray from the 5/2$^+$, 316-keV level in ^{113}Cd was observed to decay with $T_{1/2}$ = 11.0 ± 0.6 nsec (see Fig. 1).

It is well known that pairing correlations can inhibit $E2$ transitions between quasi-particle states near the Fermi surface. The recent calculations by Reehal and Sorensen[2] predict such $E2$ hindrances only for ^{109}Cd. Experimentally, the increase in $B(E2)$ going from ^{109}Cd to ^{113}Cd is much smaller than that predicted by these calculations.

1. H. J. Kim and W. T. Milner, *Nucl. Instrum. Methods* **95**, 429 (1971).
2. B. S. Reehal and R. A. Sorensen, *Phys. Rev.* **C2**, 819 (1970).

Table 1. Hindered $E2$ transitions in Cd isotopes

Nucleus: $J_i \to J_f$, gamma energy (keV)	$T_{1/2}$ (level)	Hindrance factor (Moszkowski units)	$B(E2)$ ($e^2 \times 10^{-50}$ cm^4)	
			Experiment	Calculation[a]
^{109}Cd: $1/2^+ \to 5/2^+$, 59.9	11.7[b] μsec	16	0.059	0.246
^{111}Cd: $5/2^+ \to 1/2^+$, 245.4	84.5[c] nsec	4	0.075	1.136
^{113}Cd: $5/2^+ \to 1/2^+$, 315.8	11.0[d] nsec	2	0.163	6.52

[a]B. S. Reehal and R. A. Sorensen, *Phys. Rev. C* 2, 819 (1970).
[b]F. E. Bertrand, *Nucl. Data Sheets* B6, 1 (1971).
[c]S. Raman and H. J. Kim, *Nucl. Data Sheets* B5, 181 (1971).
[d]Present results.

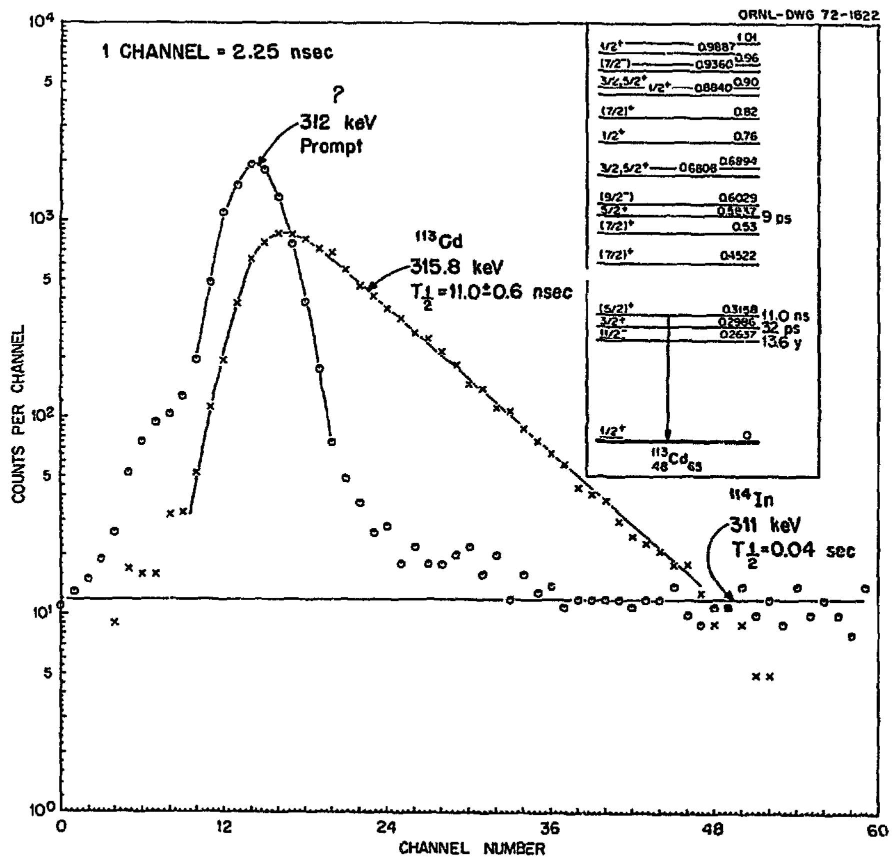

Fig. 1. Results of lifetime measurements with a pulsed proton beam.

ELASTIC AND INELASTIC PROTON SCATTERING FROM ^{116}Cd[1]

J. A. Deye[2] R. L. Robinson J. L. C. Ford, Jr.

NUCLEAR REACTIONS: ^{116}Cd(*p,p*), ^{116}Cd(*p,p'*), E_p = 12 MeV; measured $\sigma(E_p, \theta)$, $\sigma(E_p', \theta)$. ^{116}Cd deduced levels, deformation parameters, β_λ. Enriched targets. DWBA and coupled-channel calculations.

The differential cross sections for elastically and inelastically scattered 12-MeV protons from ^{116}Cd have been measured for 18 groups to levels below ~2.8 MeV. The elastic scattering was fitted by searching for the best parameters of an optical model. The observed cross sections for excitation of the one-phonon 2^+ and 3^- states were compared with the predictions of both the DWBA and coupled-channel theories. Distortion parameters were extracted and compared with those determined from *E*2 transition probabilities. The coupled-channel theory was used to calculate cross sections for the one-octopole–one-quadrupole and two-quadrupole phonon states. States at 2.041, 2.115, and 2.296 MeV were fitted by means of the 1^-, 3^- or 5^-, and 3^- octopole-quadrupole coupled-channel calculations respectively. Fits to the two-quadrupole phonon-like states were obtained by assuming an admixture of the one-phonon state in their description. The amplitudes of these admixed wave functions were calculated from both the proton scattering and Coulomb excitation experimental results, and it was found that the one-phonon amplitudes, especially for the second 2^+ states, are large. The results for ^{116}Cd are compared with those obtained from inelastic proton scattering and Coulomb excitation of other nuclei in this mass region to determine systematic trends.

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

2. Present address: University of Dayton, Dayton, Ohio; this work was performed while this author was an Oak Ridge Graduate Fellow from Vanderbilt University under appointment from Oak Ridge Associated Universities.

THE ^{117,119}Sn(*p,n*)^{117,119}Sb REACTIONS NEAR 0^+ ANALOG STATE[1]

R. L. Kernell[2] H. J. Kim R. L. Robinson C. H. Johnson

NUCLEAR REACTIONS: ^{117,119}Sn(*p,n*)^{117,119}Sb, $E \cong 4.5$ MeV; $\sigma(E; E_n, \theta)$. ^{117,119}Sb deduced levels, *J*, π. Enriched target.

Differential cross sections were measured for the ^{117,119}Sn(*p,n*)^{117,119}Sb reactions in the vicinity ($E_p \approx$ 4.5 MeV) of 0^+ analog states in the compound nuclei ^{118,120}Sb. Three techniques have been used to establish spin-parities of the states in ^{117,119}Sb: (1) the amount of on-resonant enhancement for the neutron groups, (2) the differential cross sections off resonance, and (3) the relative yields off resonance. Energies (in kilo-electron volts) and I^π assignments for levels in ^{117}Sb are 1085 ($I \geqslant 7/2$), 1165 ($I \geqslant 7/2$), 1300 ($I \geqslant$ 7/2), and 1355 ($1/2^-$). Those for ^{119}Sb are 644 ($1/2^+$), 700 ($3/2^+$), 975 ($5/2^-$, $\geqslant 7/2$), 1337 ($1/2^-$), 1416 ($3/2^-$), 1482 ($1/2^-$), 1547 ($5/2^-$,$\geqslant 7/2$), 1665 doublet ($1/2^+$ and $1/2^+$, $5/2^+$), 1745 ($3/2^+$), 1822 ($1/2^+$), 1880 doublet ($3/2^+$ and $5/2^-$, $\geqslant 7/2$), 1970 ($5/2^-$, $\geqslant 7/2$), and 2130 doublet (1/2 for one). It is suggested that the observed $1/2^-$ and $3/2^-$ states are due to coupling of $d_{5/2}$ and $g_{7/2}$ single particles to the 3^- core state. The ground-state *Q* values were found to be −2.525 ± 0.020 MeV for the ^{117}Sn(*p,n*) reaction and −1.369 ± 0.015 MeV for ^{119}Sn(*p,n*).

1. Abstract of published paper: *Nucl. Phys.* **A176**, 449 (1971).

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ENERGY LEVELS OF ^{122,124}Te POPULATED BY (^{3}He,d) AND (p,t) REACTIONS[1]

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NUCLEAR . ONS: ^{121,123}Sb(^{3}He,d), E = 25 MeV; ^{124,126}Te(p,t), E = 33 MeV; measured $\sigma(E_d, \theta)$, σ\ ,, ϑ). ^{122,124}Te deduced levels, J, π, l_p, L_{2n}, S.

The ^{121,123}Sb(^{3}He,d) and ^{124,126}Te(p,t) reactions were used to study the levels of ^{122,124}Te nuclei. The bombarding energies were 25 and 33 MeV respectively. Deuteron and triton spectra were analyzed with a broad-range magnetic spectrograph. Angular distributions for states up to approximately 4 MeV of excitation in ^{122}Te and ^{124}Te are compared with DWBA predictions to extract angular-momentum transfer values and single-proton transfer strengths. Level energies and J^π values are compared with previous measurements.

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

NUCLEAR SPECTROSCOPY OF NEUTRON-DEFICIENT La, Dy, and Er ACTIVITIES[1]

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RADIOACTIVITY: ^{131,132m,132g}La, ^{153,155}Dy, ^{158,161}Er [from (α,xn) reactions]; measured E_γ, I_{ce}. ^{131}Ba, ^{132}La, ^{153,155}Tb, ^{158,161}Ho deduced levels, J, π. Enriched targets.

A search was made for systematic properties of low-lying excited states at the edge of the rare-earth deformed region. Internal conversion spectra were analyzed for the following disintegrations: ^{131}La → ^{131}Ba, ^{132m}La → ^{132}La → ^{132}Ba, ^{153}Dy → ^{153}Tb, ^{155}Dy → ^{155}Tb, ^{158}Er → ^{158}Ho, and ^{161}Er → ^{161}Ho. More complete conversion electron results permit extension of the nuclear level structures of ^{153,155}Tb, which span the transition region of neutron numbers 88 and 90. The energy systematics of proton and neutron Nilsson particle states established in ^{159,161}Ho and in ^{155}Gd are correlated with the particle-coupled spectra in doubly odd ^{158}Ho. More evidence is presented on decay spectra of ^{131,132m}La, including transition multipolarity determinations.

1. Abstract of paper submitted for publication in *Nuclear Physics.*
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ANALYSIS OF 50.8-MeV PROTON SCATTERING FROM THE SAMARIUM ISOTOPES[1]

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NUCLEAR REACTIONS: ^{144,148,150,152,154}Sm(p,p), (p,p'), E = 50.8 MeV; measured $\sigma(\theta)$ for ground state and lowest 2$^+$ level, also lowest 4$^+$ level for ^{154}Sm. Deduced optical-model parameters, β^2 values. Collective-model DWBA and SCA analysis. Enriched targets, magnetic spectrograph, photographic plates.

An analysis was made of proton scattering from the ground and first 2$^+$ state of the stable even isotopes of samarium at 50.8 MeV. The analysis of the elastic scattering was in terms of the simple optical model and of the reformulation by Greenlees, Pyle, and Tang in terms of nuclear matter distributions and the nucleon-nucleon force. Angular distributions for the lowest 2$^+$ levels were fitted by using the collective model in the

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DWBA and by a coupled-channels analysis. Predictions are also presented to fit scattering data from the lowest 4^+ level of ^{154}Sm. The implications and conclusions of each type of analysis are compared to determine which effects are model dependent. Systematic trends depending on target mass were observed for the parameters of all the models used. In particular, both the volume integral and the depth of the real central potential decrease with increasing deformation, and the volume integral of the imaginary potential increases.

INVESTIGATION OF THULIUM ALPHA EMITTERS; NEW ISOTOPES, ^{155}Tm AND ^{156}Tm[1]

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RADIOACTIVITY: ^{155}Tm [from ^{144}Sm(^{14}N,3n)] and ^{156,156m}Tm [from ^{147}Sm(^{14}N,5n)]; measured E_α, $T_{1/2}$. Enriched targets.

In the present investigation the alpha decay of the previously unknown isotopes ^{155}Tm and ^{156}Tm was observed. These thulium nuclides were produced by bombarding targets of ^{144}Sm and ^{147}Sm with 103-MeV ^{14}N ions accelerated in the Oak Ridge Isochronous Cyclotron. Supplementary data were also obtained by irradiating ^{162}Er with 110-MeV ^{3}He particles. The experimental apparatus used in this study is based on the idea of stopping recoil products in helium gas. The stopped recoils are then swept out through a small orifice and deposited on a wheel, which, after bombardment, conveys the collected radioactivity to a position in front of an Si(Au) detector for the assay of alpha activity. Three new alpha emitters were observed. Their decay characteristics and mass assignments (made on the basis of yield curve measurements and parent-daughter relationships) are as follows: (1) ^{155}Tm, E_α = 4.45 ± 0.01 MeV, $T_{1/2}$ = 39 ± 3 sec; (2) ^{156}Tm (low-spin isomer), E_α = 4.23 ± 0.01 MeV, $T_{1/2}$ = 80 ± 3 sec; and (3) ^{156}Tm (high-spin isomer), E_α = 4.46 ± 0.01 MeV, $T_{1/2}$ = 19 ± 3 sec.

1. Abstract of published paper: *Phys. Rev.* C4, 2223 (1971).
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ALPHA DECAY FROM HIGH-SPIN ISOMERS IN ^{153}Ho AND ^{154}Ho[1]

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RADIOACTIVITY: ^{142,144}Nd(^{14}N,xn)^{153,154}Ho; measured E_α, $T_{1/2}$. Enriched targets.

Alpha-emitting high-spin isomeric states in ^{153}Ho and ^{154}Ho were found by bombarding targets of ^{142}Nd and ^{144}Nd with nitrogen ions accelerated in the Oak Ridge Isochronous Cyclotron. In the experiments, recoil nuclei ejected from the thin targets were stopped in helium gas, swept through an orifice, and deposited on the surface of a wheel. After bombardment, the wheel was turned by remote control to place the collected activity in front of an alpha-particle Si(Au) spectrometer for assay. The previously unreported high-spin isomer in ^{153}Ho was found to have a half-life of 2.0 ± 0.1 min and an alpha-decay energy of 3.91 ± 0.01 MeV. The beta decay of the 3.25-min ^{154}Ho high-spin isomer had been investigated earlier by Ward and Neiman.[3] In the present study it was found that the isomer also emits alpha particles with an energy of 3.72 ± 0.01 MeV. The nuclidic assignments of these two new alpha emitters were based primarily on: (1) a comparison of yield curves for their production with yield curves for the production of the known pairs of alpha-emitting isomers in ^{151}Ho and ^{152}Ho and (2) cross bombardments which demonstrated that the alpha groups could not be due to decay from previously unknown isomers in dysprosium and terbium nuclei in the investigated mass region.

1. Abstract of published paper: *Phys. Rev.* C3, 854 (1971).
2. Chemistry Division.
3. D. Ward and M. Neiman, *Nucl. Phys.* A115, 529 (1968).

DETERMINATION OF RESONANCE SPINS FOR $^{163}Dy(n,\gamma)^{164}Dy$

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NUCLEAR REACTIONS: $^{163}Dy(n,\gamma)^{164}Dy$, E = 16.5–726 eV; measured E_γ, I_γ. ^{164}Dy deduced J. Enriched target.

Preliminary data from a continuing measurement of the $^{163}Dy(n,\gamma)^{164}Dy$ reaction at ORELA were analyzed by the well-known method of ratios of intensities of low gamma rays to obtain the capturing state spins of resonances corresponding to incident neutron energies from 16.5 to 726 eV. The target nucleus, ^{163}Dy, has a spin of $(5/2)^-$, yielding capturing state spins of 3^- and 2^- for incident s-wave neutrons. The ground-state spin of the even-even final nucleus, ^{164}Dy, is 0^+. If the capture gamma-ray decay cascade is sufficiently complex, such that the low-energy radiation is relatively strong and free from Porter-Thomas fluctuations, then the intensity ratio of a transition from a state having a relatively high spin to a transition from a state having a low or intermediate spin should favor the higher spin, or 3^-, resonances. The high spin state is relatively inaccessible from the lower capturing state spin because of the large spin change involved. The transitions chosen were the 168.9-keV transition from the 242.2-keV (4^+) level to the 73.4-keV (2^+) level, and the 215.1-keV transition from the 976.9-keV (2^-) level to the 761.8-keV (2^+) level. Table 1 lists the resonance spins inferred from the gamma-ray intensity ratios. These results extend the measurements reported by Mughabghab et al.[2] to a higher energy, with better neutron resolution.

1. Guest Assignee from Brookhaven National Laboratory.

2. S. F. Mughabghab, R. E. Chrien, and O. A. Wasson, *Bull. Amer. Phys. Soc.* 15, 1667 (1970).

Table 1. Resonance capturing state spin assignments for ^{163}Dy

Resonance energy (eV) $J=3^-$		Resonance energy (eV) $J=2^-$		Resonance energy (eV) $J=3^-$		Resonance energy (eV) $J=2^-$
16.5						291
19.7						299
		36		325	Overlap	
51				333		
56				344	Overlap	
		59				351
66				371		
71	Unresolved			389	Overlap	
72.6						394
		76		403		
		79		413		
87						432
94				455		
106	Overlap			462	Overlap	
		108				468
121				481	Overlap	
128				488		
136						507
		144		518	Unresolved	
		146	Overlap	524		
		148		536	Overlap	
164				545		
178					Unresolved	566
186				574		
		190				584
	Overlap	204		597	Overlap	
207				605		
215				618	Unresolved	
225				624		
				635		
235				641	Unresolved	
253				651		
263				670		
270				689		
		277		700		
283				716		
						726

WIDTH CORRELATIONS IN ^{169}Tm

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NUCLEAR REACTIONS: ^{169}Tm$(n,\gamma)^{170}$Tm, E = 5–900 eV; measured E_γ, I_γ. ^{170}Tm deduced levels, J. Enriched target.

A significant correlation between partial radiation widths of gamma rays following neutron capture in resonances of ^{169}Tm (J = 1/2$^+$) and the reduced neutron widths of the resonances was found by the Brookhaven Chopper Group.[3] A value of 0.274 was determined for the partial-radiation-width–reduced-neutron-width correlation for a sample of eight J = 1 resonances and 15 final states. The 3.9-eV resonance, with strong transitions and a large reduced neutron width, was responsible for most of the correlation. Later, the 153-eV resonance was added to the set, which established the correlation more firmly. Even later, the Harwell group assigned J = 0 to the 153-eV resonance[4] (confirmed by the present experiment), thereby removing it from the data set. Measurements have been extended to higher neutron energies, including more resonances, by the higher neutron energy resolution made possible by ORELA. The correlation for 24 resonances (J = 1) and 15 final states is 0.046 ± 0.06, which is not significantly different from zero. A statistical analysis for the distribution of partial radiative widths for these 24 resonances in terms of the chi-square class of functions with ν degrees of freedom gives $\nu = 1.21^{+0.24}_{-0.18}$ for 10 to 90% limits. The correlation for five resonances with J = 0 and six final states is 0.15 ± 0.22.

A necessary adjunct to the calculation of the correlation between the partial gamma-ray widths and the reduced neutron widths is the determination of the resonance spins. This was done in the present experiment by the method of ratios of intensities of low-energy capture gamma rays.[5] The average of the intensity ratios of four pairs of gamma rays (two 3^- initial state/1^- initial state and two 2^- initial state/0^- initial state) which should be sensitive to the resonance spin is plotted in Fig. 1 as a function of neutron resonance energy. The ratios fall clearly into two groups, and the 153-eV resonance is definitely identified as having spin 0. As a control, the average of the ratios of two pairs of gamma rays ($2^-/2^-$) which should show no spin sensitivity is shown as a comparison. Table 1 lists the resonance spins found by this method.

1. Brookhaven National Laboratory.
2. Guest Assignee from Brookhaven National Laboratory.
3. Beer, Lone, Chrien, Wasson, Bhat, and Muether, *Phys. Rev. Lett.* **20**, 340 (1968); Lone, Chrien, Wasson, Beer, Bhat, and Muether, *Phys. Rev.* **174**, 1512 (1968).
4. B. Thomas, *International Conference on Statistical Properties of Nuclei, Albany, New York, 1971* (in press).
5. O. A. Wasson and G. G. Slaughter, "Determination of Resonance Spins for ^{163}Dy$(n,\gamma)^{164}$Dy," this report.

Table 1. ^{169}Tm(n,γ) spin assignments

E_n (eV)	J	E_n (eV)	J
3.9	1	297.2	1
14.5	0	319.9	(Doublet, 1 and 0)
17.5	0	325.1	1
28.8	1	333.6	1
34.9	1	346.8	1
37.6	1	358.2	0
45.0	1	378.1	1
50.8	1	391	0
59.3	1	400.5	1
63.2	1	409.2	1
66.2	0	416.2	(Doublet, 1 and 0)
83.6	1	441.4	1
94.2	1 } Incompletely	455.4	1
95.7	(0) } resolved	459.9	1
101.9	1	469	1
115.6	1	472.8	0
125.3	0	493.3	1
132.3	1	512.9	1
136.1	1	520.2	0
153.8	0	542.8	1
160.7	1	550.4	1
164.5	1	557.4	1
207.9	1	565.9	1
210.2	(Doublet, 1 and 0)	573.9	1
214.1	1	586.7	0
224.4	0	592.4	1
228.4	1	599.8	1
238.8	1	607.8	1
243.8	1	626.3	1
251.6	1	631.8	1
260.6	1	643	1
2[illegible]4.2	1	659.5	0
283.8	1	676.1	1
289	(Doublet, 1 and 0)	716	1

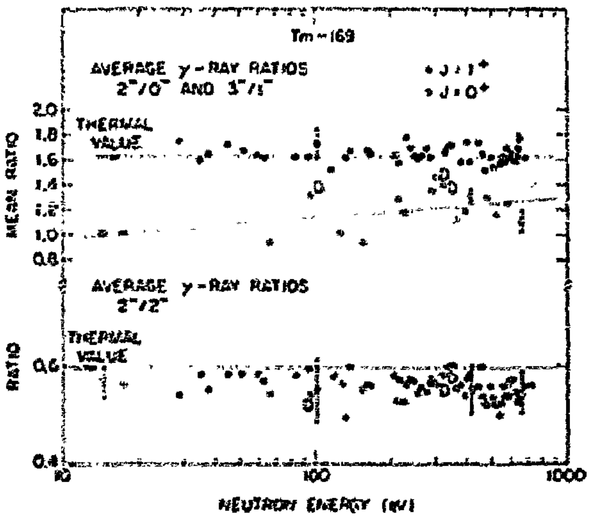

Fig. 1. (Above) Averaged intensity ratios for four pairs of low-energy capture gamma rays which should be sensitive to resonance spin, vs neutron energy; (below) averaged intensity ratios for two pairs of low-energy capture gamma rays which should *not* be sensitive to resonance spin, vs neutron energy.

COULOMB EXCITATION OF $^{182,184,186}W$, $^{186,188,190,192}Os$, AND $^{192,194,196,198}Pt$ WITH PROTONS AND ^{4}He AND ^{16}O IONS[1]

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NUCLEAR REACTIONS: $^{182,184,186}W(p,p'\gamma)$, E = 5 MeV; $^{182,184,186}W(\alpha,\alpha'\gamma)$, E = 14 and 15 MeV; $^{182,184,186}W(^{16}O,\ ^{16}O'\gamma)$, E = 45.5 MeV; $^{188,190,192}Os\ (p,p'\gamma)$, E = 4.56–5.08 MeV; $^{186}Os(\alpha,\alpha'\gamma)$, E = 3–5 MeV; $^{188,190,192}Os(\alpha,\alpha'\gamma)$, E = 15 MeV; $^{186,188,190,192}Os(^{16}O,\ ^{16}O'\gamma)$, E = 42, 45.1, and 45.5 MeV; $^{192,194,196,198}Pt(p,p'\gamma)$, E = 4.5 MeV; $^{192,194,196,198}Pt(^{16}O,\ ^{16}O'\gamma)$, E = 43.75 MeV. Measured I_γ, E_γ, ^{16}O-γ coin, deduced $B(E2)$, $B(M1)$, J. Enriched and natural targets.

Coulomb excitation of the first 2⁺ states was produced in ^{186}Os with 3- to 5-MeV ^{4}He ions, $^{188,190,192}Os$ with 4.56- to 5.08-MeV protons, and $^{192-198}Pt$ with 4.5-MeV protons and 43.75-MeV ^{16}O ions. Values of $B(E2,\ 0 \rightarrow 2)$ have been extracted with an absolute uncertainty of ±9% for ^{186}Os, ±7% for $^{188-192}Os$, and ±5–6% for $^{192-198}Pt$. Coulomb excitation of second 2⁺ states was produced in $^{182-186}W$ with 5-MeV protons, 14- and 15-MeV ^{4}He ions, and 45.5-MeV ^{16}O ions, and in $^{186-192}Os$ with 5-MeV protons, 15-MeV ^{4}He ions, and 42-, 45.1-, and 45.5-MeV ^{16}O ions. Excitation of higher 2⁺ states at 1257, 1386, and 1286 keV was effected in $^{182,184,186}W$ with 15-MeV ^{4}He ions. Values of $B(E2,\ 0 \rightarrow 2')$, $B(E2,\ 2 \rightarrow 2')$, $B(M1,\ 2' \rightarrow 2)$, $\delta = \langle 2\|E2\|2'\rangle/\langle 2\|M1\|2'\rangle$, and the transition branching ratio $T(2' \rightarrow 2)/T(2' \rightarrow 0)$ are reported for second and higher 2⁺ states. Values of $B(E2,\ 2 \rightarrow 4)$ have been obtained for $^{182-186}W$ and $^{186-192}Os$ from direct Ge(Li) spectra using 15-MeV ^{4}He ions and 42- to 45.5-MeV ^{16}O ions and from ^{16}O-γ coincident (NaI) spectra using 42- to 45.5-MeV ^{16}O ions, and for $^{194,196}Pt$ from direct Ge(Li) spectra using 43.75-MeV ^{16}O ions. Values of $B(E2,\ 4 \rightarrow 6)$ for $^{182,184,186}W$ were also extracted from the ^{16}O-γ data. Data analysis was carried out using first-order quantal perturbation theory in the case of proton and ^{4}He ion experiments. First- and second-order semiclassical perturbation theory and the multiple-Coulomb-excitation program of de Boer and Winther as augmented by Sayer were used in analyzing the ^{16}O ion data. The de Boer–Winther program was also used to estimate multiple excitation corrections for the ^{4}He ion data. The results are compared with recent results of other workers and with the pairing-plus-quadrupole model calculations of Kumar and Baranger, as well as with the predictions of the more simple phenomenological models.

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1. Abstract of published paper: *Nucl. Phys.* **A177**, 1 (1971).
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THE 5.5-MeV ANOMALOUS GAMMA RADIATION IN $^{205}Tl(n,\gamma)^{206}Tl$[1]

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NUCLEAR REACTIONS: $^{205}Tl(n,\gamma)^{206}Tl$, E = 0.005–250 keV; measured E_γ; measured $\sigma(E)$; measured $\sigma_{n\gamma}(E)$; ^{206}Tl deduced π, levels. Enriched target.

An enhancement at 5.5 MeV in the gamma-ray spectra following thermal and fast neutron capture[4] in the mass region $180 < A < 208$ represents a significant departure from the statistical model. Since this effect is strong in ^{206}Tl, we have studied its magnitude and variation with resonance energy in the $^{205}Tl(n,\gamma)^{206}Tl$ reaction.

Two complementary experiments were performed with the Oak Ridge Electron Linear Accelerator. (1) High-resolution gamma-ray spectra were recorded for the strong resonances up to 30 keV with a 36-cm^3 Ge(Li) detector at a 10-m station and with a neutron time resolution of 4 nsec/m. (2) The capture cross section, resonance parameters, and a measure of the relative intensity of gamma rays above and below ≈4 MeV for neutron energies up to 70 keV were studied with a "total energy detector"[5] at a 40-m station with approximately 0.2% energy resolution.

The magnitude and details of the 5.5-MeV gamma-ray anomaly are most clearly seen in the gamma-ray spectra from two strong *s*-wave resonances at 2.80 and 3.05 keV. The intensities of all observed gamma rays above 2.5 MeV from these resonances are shown in Fig. 1. Since the low-lying levels of ^{206}Tl are well known,[6] it can be shown that all these gamma rays >2.5 MeV are $E1$ primaries and that the only unobserved $E1$ primary in the anomalous region is at 5.852 MeV. Gamma rays to levels 2.5 → 4.5 MeV below the binding energy are not observed, although there are many states in this energy region.

Assuming that the target configuration is predominantly $\pi;\ \nu = s_{1/2}^{-1};\ p_{1/2}^{-2}$ and adopting recent calculations[7] of the ^{206}Tl low-lying state wave functions, we conclude that the gamma-ray intensity distribution is not consistent with a simple particle-hole neutron transition with unperturbed target. The data require that at least 2p − 1h neutron doorway states participate. The unobserved $E1$ primary is to an excited proton hole state at 0.652 MeV and implies that excited proton configurations do not have significant amplitudes in these two resonances. However, a strong transition to this state is observed from several other resonances which also exhibit a strong anomaly, indicating that excited proton configurations are important in these cases.

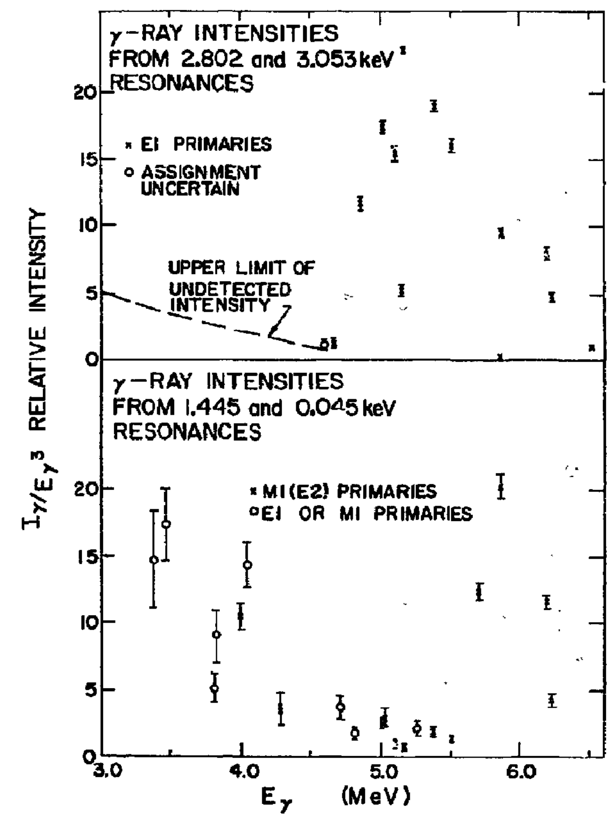

Fig. 1. Upper – Intensities of all gamma rays above 2.5 MeV for the 2.802- and 3.053-keV resonances in $^{205}Tl(n,\gamma)^{206}Tl$. Lower – Intensities of all gamma rays above 2.5 MeV for the 0.045- and 1.445-keV resonances in $^{205}Tl(n,\gamma)^{206}Tl$.

1. Abstract of paper to be published in *Proceedings of International Conference on Statistical Properties of Nuclei*, August 23–27, 1971, State University of New York, Albany.

2. Atomic Energy of Canada Ltd., Chalk River.

3. Guest Assignee from Australian Atomic Energy Commission.

4. G. A. Bartholomew, *Proc. Int. Conf. Neutron Capture γ-Ray Spectroscopy, Studsvik, 1969*, IAEA, p. 553 (1969).

5. R. L. Macklin and B. J. Allen, *Nucl. Instrum. Methods* 91, 565 (1971).

6. M. B. Lewis and W. W. Daehnick, *Phys. Rev.* C1, 1577 (1970).

7. G. H. Herling and T. T. S. Kuo, private communication from G. H. Herling.

Two weaker resonances at 0.044 and 1.44 keV are believed to be *p* wave because of their decay to known 3^- states, and therefore most of the observed transitions from these states are $M1(E2)$ primaries. The 5.5-MeV gamma-ray anomaly is much less evident from these resonances (Fig. 1), implying that the anomaly is predominantly due to $E1$ transitions after *s*-wave capture.

The neutron capture data taken with the total energy detector at the 40-m station provided accurate resonance energies and, for many resonances, a measure of the neutron and radiative widths. The ratio of intensity above a 4-MeV bias to that below was determined for all resonances. This ratio will be large for resonances with a large 5.5-MeV anomaly. Most of the observed resonances have ratios as large as the *s*-wave resonances shown in the figure, while a few have values lower than the two *p*-wave resonances. It is clear that the anomaly is present in most *s*-wave resonances in $^{205}Tl(n,\gamma)^{206}Tl$. Correlation coefficients between the reduced neutron width, the radiative width, and the relative strength of the anomaly are being determined.

INVESTIGATION OF THE $^{207}Pb(\alpha,d)^{209}Bi$ REACTION[1]

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NUCLEAR REACTIONS: $^{207}Pb(\alpha,d)$, E = 42 MeV; measured absolute $\sigma(E_\alpha;\ \theta)$. ^{209}Bi levels deduced configuration, reaction normalization. Spectrograph.

Energy levels and differential cross sections for the $^{207}Pb(\alpha,d)^{209}Bi$ reaction have been determined at an incident bombarding energy of 42 MeV. A two-nucleon distorted-wave Born-approximation (DWBA) analysis was performed for the ground and first excited levels of ^{209}Bi in order to obtain a normalization for the (α,d) and (d,α) reactions. The results of calculations using this normalization were compared with data for the 1.097-MeV 7^+ level of ^{48}Sc excited in the $^{50}Ti(d,\alpha)^{48}Sc$ reaction and for the first excited state of ^{206}Tl excited in the $^{208}Pb(d,\alpha)^{206}Tl$ reaction. This latter comparison confirmed an earlier argument that cross sections to the low-lying ^{206}Tl levels are considerably enhanced over pure two-hole configuration estimates. The normalized DWBA was then used to study higher-lying two-particle–one-hole excited states in ^{209}Bi.

1. Abstract of published paper: *Phys. Rev.* **C3**, 2027 (1971).

INVESTIGATION OF COLLECTIVE PROPERTIES OF ^{208}Pb BY THE $^{208}Pb(p,p')$ REACTION AT E = 55 MeV

F. E. Bertrand M. B. Lewis C. B. Fulmer

NUCLEAR REACTIONS: $^{208}Pb(p,p')$, E = 55 MeV; measured absolute $\sigma(E,\ \theta)$. ^{208}Pb levels, deduced L, β_L^2. Spectrograph.

The importance of understanding collective nuclear properties in spherical shell-model regions has prompted our investigation of the collective states in ^{208}Pb. We utilized the inelastic proton scattering reaction at a higher bombarding energy and over a larger excitation energy range than has been attempted heretofore.[1]

Targets of ^{208}Pb were bombarded with a 55-MeV proton beam from the Oak Ridge Isochronous Cyclotron. The inelastically scattered particles were detected with photographic plates utilizing the ORIC broad-range spectrograph facility. Spectra were obtained at laboratory angles between 9 and 58°, and the spectrum at θ_L = 45° is shown in Fig. 1. The energy resolution was typically 35 to 40 keV (FWHM). Excitation energies are shown for the peaks for which an angular distribution has been obtained. These angular distributions are currently being compared with those predicted by DWBA methods utilizing a collective-model form factor.

The primary purpose of the present experiment is to study the higher-lying ($E_x > 4$ MeV) collective states in ^{208}Pb. We have confirmed the location of the low-spin members of a sequence of positive parity states (2^+, 4^+, 6^+, ...), first identified in a 24-MeV (p,p') experiment.[2] However, we find that the 10^+ state suggested in ref. 2

1. M. B. Lewis, "Nuclear Data Sheets for A = 208," *Nucl. Data* **B5**, 243 (1971).
2. J. Saudinos, G. Vallois, O. Beer, M. Gendrot, and P. Lopato, *Phys. Lett.* **22**, 492 (1966).

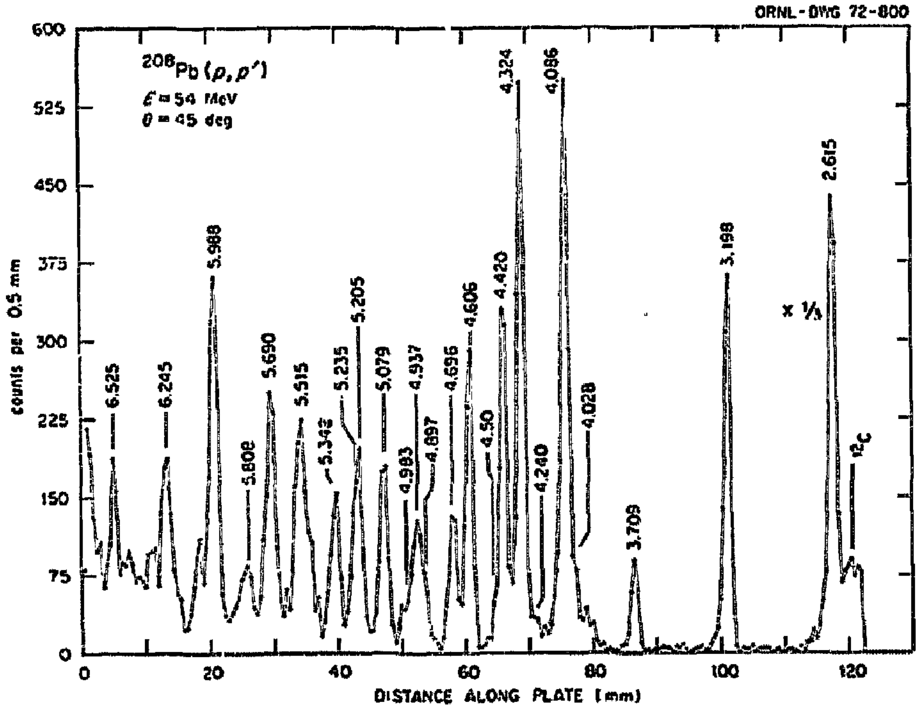

Fig. 1. Inelastic proton spectrum from ^{208}Pb bombarded by 54-MeV protons. $\theta_L = 45°$.

is, in fact, $L = 3$ and is probably the first collective fragment of the octopole state at 2.615 MeV.

In the region between 5 and 6 MeV, we found several collective fragments of the 2.615-MeV 3^- state and the 4.323-MeV 4^+ state. It is curious that these fragments are usually aligned (within admittedly rather large experimental uncertainties) with known[3] proton–proton-hole states. No quadrupole fragments have been found.

Although the DWBA calculations provide generally good agreement with the experimental angular distributions, some discrepancies have been noted. For example, the DWBA has consistently underestimated the forward-angle cross sections for large ($L \geqslant 6$) momentum transfers, suggesting the possibility that a different reaction mechanism or form factor is needed. In addition, for the more weakly excited states, it is sometimes difficult to distinguish between an $L = 3$ or $L = 4$ spin assignment based on the best fit to the experimental angular distributions. It appears probable that microscopic effects may be significant in describing the weakly collective levels.

Finally, it should be stressed that the collective strengths of the fragments for $L = 3, 4, 5, 6$, and >6 which we observe, although only a few single-particle units, are nevertheless much greater than those predicted by the random-phase approximation calculations[4] of Gillet et al.

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3. E. A. McClatchie, C. Glashausser, and D. L. Hendrie, *Phys. Rev.* C1, 1828 (1970).

4. V. Gillet, A. M. Green, and E. A. Sanderson, *Nucl. Phys.* 88, 321 (1966).

CROSS SECTIONS FOR HYDROGEN AND HELIUM PARTICLES PRODUCED BY 62- AND 39-MeV PROTONS ON ^{209}Bi[1,2]

F. E. Bertrand R. W. Peelle[3]

NUCLEAR REACTIONS: ^{209}Bi (p,xp), (p,xd), (p,xt), $(p,x^3\mathrm{He})$, $(p,x\alpha)$, E = 61.7 MeV; measured absolute $\sigma(\theta)$ for each exit particle type; secondary energy range ≈2–60 MeV. Solid-state counter telescope.

Tabulated differential cross sections are presented for the production spectra of proton, deuteron, triton, ^{3}He, and alpha particles from ^{209}Bi bombarded by 62-MeV protons, and for all particles but ^{3}He for incident 39-MeV protons. Continuum cross sections in ~1-MeV bins are listed for 18 angles for 62-MeV incident protons and for 4 angles for 39-MeV protons. The low-energy cutoffs range from 4 to 15 MeV for the different exit particle types. Angular distributions for 62-MeV incident protons are given for excitations in ^{209}Bi at 0, 1.62, 2.65, 3.15, 3.56, 3.96, 4.29, 5.20, and 5.49 MeV, and comparisons are made with DWBA theory. The energies, strengths, and angular momentum transfers obtained for the ^{209}Bi collective groups approximate those for the collective levels of ^{208}Pb. In ^{208}Bi, angular distributions are given for multiplets observed with 62-MeV protons at excitation energies of 0.030, 0.635, 1.02, 1.73, 2.42, and 3.48 MeV. Only elastic scattering cross sections are given for incident 38.8-MeV protons since there is an inadequate amount of data for angular distributions. Definite evidence is found for $(p,n\bar{p})$ reactions in the 90° proton spectrum for 39-MeV incident protons, and a value for the ^{209}Po-^{209}Bi Coulomb displacement energy of 18.9 ± 0.1 MeV is obtained from these data.

1. Work funded by National Aeronautics and Space Administration under order L-12, 186.
2. Abstract of ORNL-4638 (January 1971).
3. Neutron Physics Division.

EVIDENCE FROM 62-MeV PROTON SCATTERING FOR EXTENDING THE WEAK COUPLING MODEL IN ^{209}Bi[1,2]

F. E. Bertrand M. B. Lewis

NUCLEAR REACTIONS: ^{209}Bi(p,p'), E = 61.7 MeV; measured absolute $\sigma(E_p;\theta)$. ^{209}Bi levels deduced L, β_L. Ge(Li) detector.

The reaction ^{209}Bi(p,p') has been studied at a bombarding energy of 61.7 MeV. Differential cross sections were obtained between 15 and 75° for various groups of collective levels in ^{209}Bi and for the 1.62-MeV single-particle level. The data were compared with DWBA calculations, and the L values and deformation parameters so determined were compared with those for corresponding excitations in ^{208}Pb. The results are consistent with the excitation of at least six core (^{208}Pb) excitation multiplets in ^{209}Bi. The observed angular distribution for excitation of the 1.62-MeV level indicates a small $L = 3 + (5)$ admixture in this predominantly $i_{13/2}$ proton state.

1. Work sponsored partially by the National Aeronautics and Space Administration.
2. Abstract of published paper: *Nucl. Phys.* A168, 259 (1971).

PRECISE COULOMB EXCITATION $B(E2)$ VALUES FOR FIRST 2$^+$ STATES OF THE ACTINIDE NUCLEI[1]

J. L. C. Ford, Jr. P. H. Stelson C. E. Bemis, Jr.[2] F. K. McGowan
R. L. Robinson W. T. Milner

Precise transition probabilities have been measured for the first 2$^+$ states of ^{230,232}Th, ^{234,236,238}U, ^{238,240,242,244}Pu, ^{244,246,248}Cm, and ^{252}Cf by Coulomb excitation with 17- and 18-MeV alpha particles. Comparison is made with theoretical values. An excitation energy of 44.0 ± 0.5 keV was measured for the first excited level of ^{252}Cf.

1. Abstract of published paper: *Phys. Rev. Lett.* 27, 1232 (1971).
2. Chemistry Division.

ON THE REACTIONS OF PROTONS WITH ^{231}Pa AND ^{232}Th[1]

R. L. Hahn[2] K. S. Toth M. F. Roche[3]

NUCLEAR REACTIONS: ^{231}Pa(*p*,4*n*)^{228}U, (*p*,5*n*)^{227}U, (*p*,*p*4*n*)^{227}Pa, (*p*,*p*5*n*)^{226}Pa, (*p*,α3*n*)^{225}Th, E = 35–63 MeV; measured relative yields of recoil nuclei.

Yields of alpha-radioactive products from reactions induced in ^{231}Pa targets by protons from 35 to 63 MeV were measured by recoil-collection techniques. The results, as similarly observed by Lefort and co-workers for the reactions of ^{232}Th + p at energies ≤85 MeV, indicate that the yields of reactions involving charged-particle emission are comparable with or larger than those involving only neutron emission. In addition, the experimental yield curves exhibit high-energy tails. Results for both the ^{231}Pa and ^{232}Th targets are compared with the predictions of nuclear-reaction calculations[4] that take into account the competition between fission and particle emission. Bearing in mind the assumptions inherent in the calculations and the fact that no parameters were fitted to the data, we found that the compound-nucleus model, with fission, did not account for the experimentally observed trends. The intranuclear cascade model, including fission competition in the compound-nuclear deexcitation phase, on the other hand, predicted excitation functions that were reasonably consistent with the results for (*p*,*xn*) and (*p*,*pxn*) reactions. Neither model was successful in accounting for the (*p*,α3*n*) data. In the case of the ^{231}Pa results, it was found that recoil-range effects had to be included in the nuclear-reaction calculations.

1. Abstract of paper to be published in *Nuclear Physics* (1972).
2. Chemistry Division.
3. Present address: Argonne National Laboratory, Argonne, Ill.
4. R. L. Hahn, to be published in *Nuclear Physics* (1972).

POLARIZED-NEUTRON–POLARIZED-TARGET FISSION MEASUREMENTS AT ORELA

J. W. T. Dabbs G. A. Keyworth[1] F. T. Seibel[1]

NUCLEAR REACTIONS: ^{235}U(*n*,*f*), E = 0.7–50,000 eV; measured prompt *n*'s; test for future *J*, *K* measurements with polarized neutrons and polarized nuclei; enriched target.

Measurements of both J and K quantum numbers for neutron resonances in ^{235}U, ^{233}U, and ^{237}Np are planned at ORELA, using a neutron beam polarized by transmission through lanthanum magnesium nitrate and a polarized target. Variation in the total yield of fission neutrons as a function of relative direction of the neutron and nuclear spins will give a very direct determination of J. Time-of-flight separation of resonances is expected up to ~1 keV, based on detector test runs already completed. Variation in the angular distribution of fission neutrons relative to the nuclear polarization axis is expected to give a strong indication regarding K, the projection of J on the nuclear symmetry axis. The alignment required for the latter measurements is, however, obtained through a second-order effect and depends on the achievement of large nuclear polarization (60 to 90%). Preparation of 0.1- to 2.5-g targets of $NpAl_2$ and US is in progress at LASL (Clayton Olsen). These compounds are ferromagnetic at low temperatures and have extremely large internal fields (~3 × 10^6 Oe).

The polarized target cryostat is being constructed at LASL, as is a matching lanthanum magnesium nitrate polarizer cryostat. The data acquisition electronics have been tested on one of the fifteen 5 × 5 in. liquid scintillator systems, so that counting rates, backgrounds, and resolutions can be estimated for the uranium measurements. Good pulse-shape discrimination has been obtained (~500:1). A plot of a test run is shown in Fig. 1. The time-of-flight data-storage parameters of Fig. 1 are shown in Table 1 of another portion of this report.[2] A comparison of Fig. 1 with a truly low background fission run[2] shows that a further improvement in pulse-shape discrimination would be desirable to reduce the background. A 2-in. lead shield was required to achieve the results of Fig. 1; probably it will be necessary to exchange count rate for better discrimination, since the present γ:n ratio is ~10:1. This is particularly true for the case of ^{237}Np, since the subthreshold fission cross section is rather small. A similar test to the ^{235}U test is planned for ^{237}Np when accelerator time at high power becomes available.

1. Los Alamos Scientific Laboratory.
2. J. W. T. Dabbs et al., "Small-Sample Fission Cross-Section Measurements at ORELA," this report.

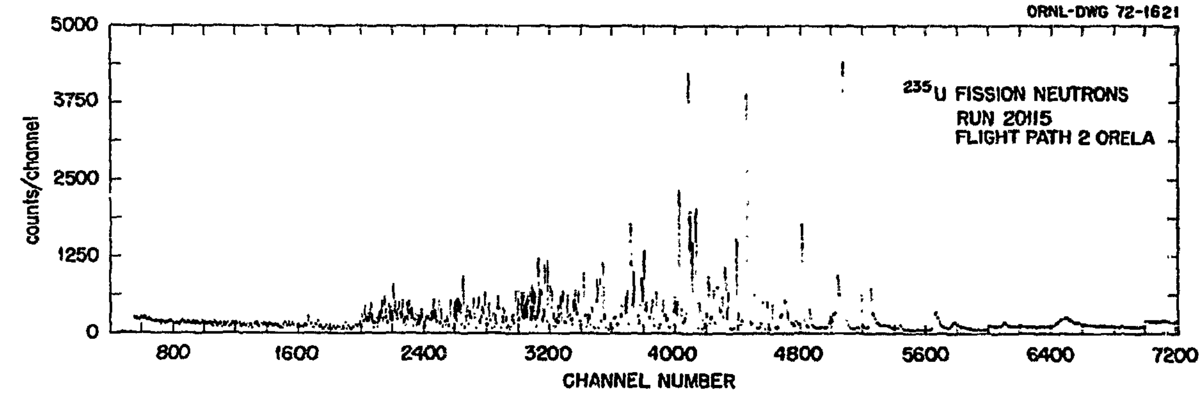

Fig. 1. ^{235}U fission neutrons – counts/channel vs channel number (time-of-flight spectrum). Steps in the plot occurring at channels 2000, 3000, etc., are caused by a doubling of the channel width at each step. The first 2000 channels are 16 nsec wide. 9-hr run at 20 kW average power, usual LASL pulse-shape discrimination. 5 × 5 in. NE 213 detector, 3.15 g of ^{235}U at 11.13 m, ^{10}B filter, time zero at channel 191.5 (3.064 μsec). The late timing is the result of the long "decision time" required by the P.S.D. system. Background is probably leakage from the high gamma-ray background through the P.S.D. system (compare Fig. 1 in "Small-Sample Fission Cross-Section Measurements at ORELA," this report).

EQUILIBRIUM QUADRUPOLE AND HEXADECAPOLE DEFORMATIONS IN ^{230}Th AND ^{238}U[1]

F. K. McGowan C. E. Bemis, Jr.[2] J. L. C. Ford, Jr. W. T. Milner
R. L. Robinson P. H. Stelson

NUCLEAR REACTIONS: ^{230}Th(α,α′), ^{238}U(α,α′), E_α = 17.0 MeV; measured $\sigma(E_{\alpha'}, \theta = 150°)$; deduced $B(E2, 0 \to 2)$, $B(E4, 0 \to 4)$, β_{20}, and β_{40}. Enriched targets.

Large contributions to the excitation of 4$^+$ rotational states from electric hexadecapole (*E*4) transitions have been observed in precision Coulomb excitation experiments with ^{4}He projectiles for even-even targets in the mass range 230 ⩽ 252. The values of $B(E4, 0 \to 4)$ deduced from an analysis of the Coulomb excitation probabilities for ^{230}Th and ^{238}U are 1.10 ± 0.44 e^2 b^4 and 1.26 ± 0.52 e^2 b^4 respectively. β_{40} deformation parameters are 0.110 ± 0.027 and 0.100 ± 0.028 for ^{230}Th and ^{238}U respectively.

1. Abstract of published paper: *Phys. Rev. Lett.* 27, 1741 (1971).
2. Chemistry Division.

GROUND-STATE ROTATIONAL BANDS IN EVEN-EVEN ACTINIDE NUCLEI[1]

M. Schmorak C. E. Bemis, Jr.[2] M. J. Zender[3] N. B. Gove[4] P. F. Dittner[2]

RADIOACTIVITY: ^{234}U, ^{236}U, ^{238}Pu, ^{240}Pu, ^{242}Pu, ^{246}Cm, ^{250}Cf; measured E_γ, I_γ. ^{230}Th, ^{232}Th, ^{234}U, ^{236}U, ^{238}U, ^{240}Pu, ^{242}Pu, ^{246}Cm deduced levels. Ge(Li) detector.

The gamma-ray spectra following the alpha decay of several even-even actinides were studied. The deduced level energies of the ground-state rotational bands were compared with the collective model and the VMI model. The VMI model gave an excellent fit to the experimental levels; no phase transitions were observed in the actinide region, in contrast to the situation in the rare-earth region.

1. Abstract of paper to be published in *Nuclear Physics.*
2. Chemistry Division.
3. Present address: Fresno State College, Fresno, Calif.
4. Mathematics Division.

IDENTIFICATION OF THE ATOMIC NUMBER OF NOBELIUM BY AN X-RAY TECHNIQUE[1]

P. F. Dittner[2] C. E. Bemis, Jr.[2] D. C. Hensley R. J. Silva[2] C. D. Goodman

RADIOACTIVITY: ^{255}No [from ^{249}Cf(^{12}C,$\alpha 2n$)]; measured $T_{1/2}$, E_α, E_x, α-x coin. Deduced Z. Enriched target.

A daughter x-ray identification scheme, in the original spirit of Moseley, has been applied to the identification of element 102, nobelium. The identification scheme is based on the coincident observation of K-series x rays from the daughter element, fermium in this case, with the alpha particle from the decay of the parent element, nobelium. We believe the technique provides an unequivocal identification of atomic number for the transfermium elements.

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1. Abstract of published paper: *Phys. Rev. Lett.* 26(17), 1037–40 (1971).
2. Chemistry Division.

4. Fission

SMALL-SAMPLE FISSION CROSS-SECTION MEASUREMENTS AT ORELA

J. W. T. Dabbs   C. E. Bemis[1]   M. S. Moore[2]   A. N. Ellis[2]   N. W. Hill[3]

NUCLEAR REACTIONS: $^{235}U(n,f)$ E = 0.25–50,000 eV; measured $\sigma_{n,f}$ for 100-μg sample; enriched target.

Preliminary tests of a new technique for measurement of fission cross sections, using 50-μg ^{235}U and 2-mg ^{235}U samples, have been made at ORELA. The technique uses specially radiation-resistant silicon solid-state detectors,[4] ~125 μm thick, located directly in the neutron flight path at ORELA, and nearly in contact with the sample. It was found that the gamma flash pulse was not substantially larger than a fission fragment pulse in these detectors. ORELA was operated at ~12 kW with a 30- to 40-nsec pulse width, and data were taken at 8.5 m in flight path 1.[5]

Figure 1 shows the results of a 14-hr measurement using the 2-mg sample. This is equivalent to a 112-hr run at 30 kW using 100 μg of sample. Such a run should be possible to obtain in approximately one week assuming good accelerator conditions. Thus we conclude that samples of ~100 μg and fission cross sections similar to ^{235}U can be reasonably measured at ORELA. Figure 1 also shows a commendably low background. (Note the effect of the cadmium overlap filter at the right side of the time-of-flight spectrum.) Table 1 gives the parameters of the time-of-flight spectrum shown in Fig. 1.

Plans are being made to carry out measurements on ^{249}Cf and ^{245}Cm when samples of adequate purity become available. The latter sample will require substantial improvements in the efficiency of the TRL isotope separator. The californium sample will require a very fast amplifier to reduce alpha-particle pileup. Such an amplifier is now under development.

1. Chemistry Division.
2. Los Alamos Scientific Laboratory.
3. Instrumentation and Controls Division.
4. Purchased by Los Alamos Scientific Laboratory from Solid State Radiations, Inc., 2261 S. Carmelina Avenue, Los Angeles, Calif. 90064 (model 600-PIN-125).
5. The loan of space in flight path 1 by J. A. Harvey is gratefully acknowledged.

Table 1

Starting time (μsec)	No. of channels	Channel width (nsec)	Starting channel
0	2000	16	0
32	1000	32	2000
64	1000	64	3000
128	1000	128	4000
256	1000	256	5000
512	1000	512	6000
1024	250	1024	7000
1280[a]			7249[b]

[a]Clock reset at 1245 μsec (1250 μsec between accelerator pulses).
[b]Ending channel of data storage.

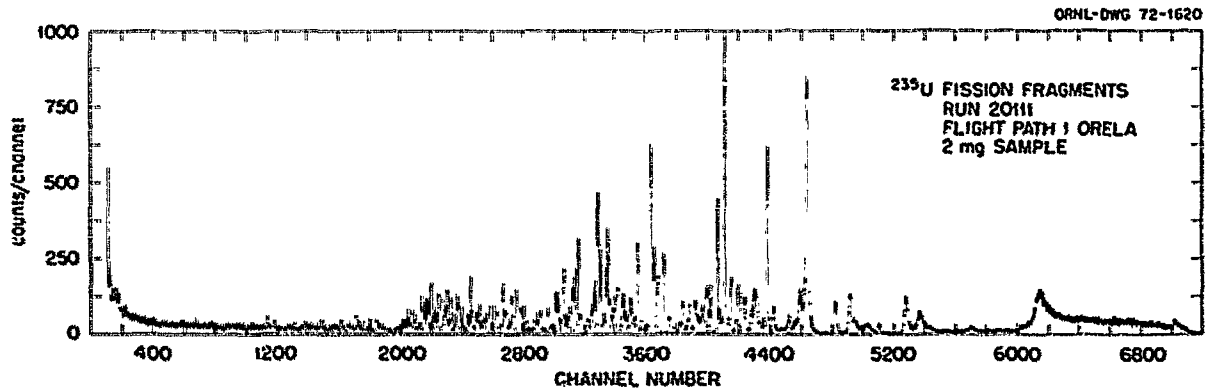

Fig. 1. ^{235}U fission fragments – counts/channel vs channel number (time-of-flight spectrum). Increases of a factor 2 in the channel widths occur at channels 2000, 3000, etc. The first 2000 channels are 16 nsec wide. 14-hr run at 12 kW average power, using special detectors and LASL fission chamber. 2 mg of ^{235}U at 8.517 m, 0.025-in. cadmium filter, time zero at channel 14 (295 nsec). Note the low backgrounds obtainable in this type of measurement.

PROMPT GAMMA RAYS EMITTED IN THE THERMAL-NEUTRON-INDUCED FISSION OF ^{235}U[1]

Frances Pleasonton   Robert L. Ferguson[2]   H. W. Schmitt

The average number and average energy of gamma rays emitted within ~5 nsec after fission have been determined as functions of fragment mass and total kinetic energy. In a four-parameter experiment, energies of coincident pairs of fission fragments were measured with surface-barrier detectors, and gamma-ray energies were measured with a large NaI(Tl) detector, which was located 89 cm from a thin ^{235}U target and positioned coaxially with the fragment detectors. The time difference between detection of a fission fragment and a gamma ray was measured to allow time-of-flight discrimination against fission neutrons. The gamma-ray data were analyzed with a "weighting method" proposed by Maier-Leibnitz to deduce average numbers and energies of gamma rays from measured pulse heights. The Doppler shift in the laboratory angular distribution of gamma emission from fragments traveling toward or away from the gamma detector was utilized to obtain the number and energy of gammas as functions of single-fragment mass.

Results are given for average number and energy of gamma rays emitted from single fragments as functions of fragment mass, and as functions of fragment mass and total kinetic energy in two-dimensional representations. The average total number and energy of gamma rays emitted from both fragments together are given as functions of fragment mass and of total kinetic energy.

The single-fragment results, both average number and average energy as functions of fragment mass, are characterized by a sawtooth behavior similar to that which is well known for neutron emission. The overall average number and energy of gamma rays emitted per fission were found to be 6.51 ± 0.3 and 6.43 ± 0.3 MeV, respectively, giving an average photon energy of 0.99 ± 0.7 MeV. Inferences are drawn concerning the vibrational and rotational characteristics of the deexcitation of the fragments by gamma-ray emission.

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

2. Chemistry Division.

NEUTRON EMISSION FROM THE FISSION OF ^{209}Bi INDUCED BY 36.1-MeV PROTONS

Franz Plasil Robert L. Ferguson[1] Frances Pleasonton H. W. Schmitt

NUCLEAR FISSION: ^{209}Bi(p,f), E_p = 36.1 MeV, calculated neutron emission function and pre-neutron-emission fragment mass and kinetic energy distributions.

In an earlier report,[2] we have presented the results of an experiment designed to search for an asymmetric component in the mass distribution from the fission of ^{209}Bi induced with 36-MeV protons. The experiment had been performed to check radiochemical results of Sugihara et al.[3] which indicated the presence of a side peak in the far wings of the fragment mass distribution. We did not confirm the existence of the asymmetric fission component. Figure 1 shows our experimental results and those of Sugihara et al. Our results were obtained by the standard correlated fragment energy technique, in which fragment masses were derived from measurements of kinetic energies of coincident fission fragments. As was discussed earlier,[2] due to the unavailability of neutron-emission results for our fissioning system, the fragment masses obtained in our work were provisional masses,[4] which are closely

1. Chemistry Division.
2. F. Plasil, R. L. Ferguson, H. W. Schmitt, and F. Pleasonton, *Phys. Div. Annu. Progr. Rep. Dec. 31, 1968,* ORNL-4395, p. 31 (1969).
3. T. T. Sugihara, J. Roesmer, and J. W. Meadows, Jr., *Phys. Rev.* **121**, 1179 (1961).
4. H. W. Schmitt, J. H. Neiler, and F. J. Walter, *Phys. Rev.* **141**, 1146 (1966).

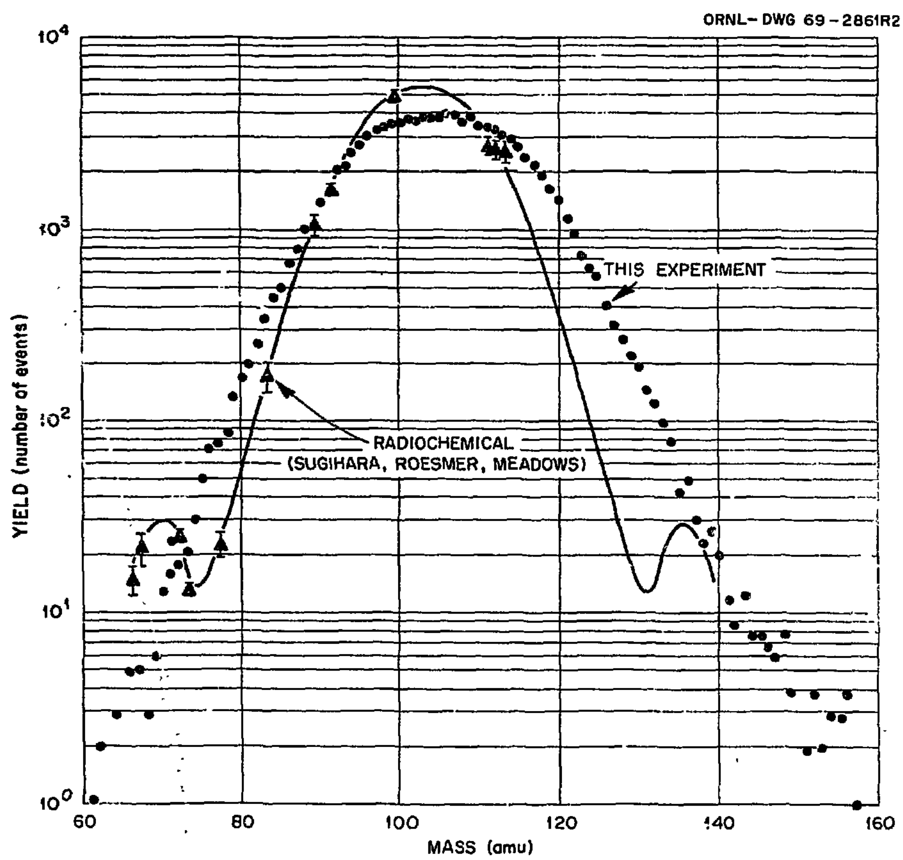

Fig. 1. Mass distribution from this experiment (closed circles, without error bars) and from radiochemical results of Sugihara et al. (triangles with error bars). The smooth curve was drawn through the radiochemical points. The areas under the two distributions are equal.

related to pre-neutron-emission masses. The radiochemical results of ref. 3 give post-neutron-emission masses.

In ref. 2, we tried to reconcile our results with those of Sugihara et al. by considering (*a*) the possibility that our experimental resolution was such that the small asymmetric component was washed out and (*b*) that neutron emission obscured the effect. We showed that neither of these two factors was responsible for the disagreement between our results and those of ref. 3. This conclusion is unchanged by the present work. There was, however, another problem which was pointed out in ref. 2: our mass distribution was considerably broader than that of ref. 3. In this work, we will show that this difference is explained by neutron emission from the fragments, and we will obtain neutron-emission results for the proton-induced fission of ^{209}Bi at 36 MeV.

The method we have used to generate the average number of neutrons emitted as a function of fragment mass is the cumulative yield method.[5] This method makes use of the difference between the mass distribution derived from the radiochemical post-neutron-emission data and a pre-neutron-emission distribution. When the two cumulative yields are plotted side by side, the horizontal displacement between them, aside from higher-order correction terms neglected here, gives the average number of neutrons emitted as a function of fragment mass. We have used the radiochemical data of ref. 3 and our provisional masses to obtain an approximate neutron emission function. Our provisional masses were then corrected for neutron emission, and the cumulative yield calculation was repeated to obtain a more accurate neutron emission function This iterative procedure was repeated several times, until no further changes in the neutron emission function were observed. At each stage of the iteration, our mass yield data were corrected for dispersion effects by folding into the data an arbitrary distribution with a negative variance equal in absolute value to the variance of all dispersion effects.[5] This dispersion variance was 5.85 amu^2, and consequently we undispersed our results by folding in a function with a variance equal to -5.85 amu^2. The final average neutron emission as a function of fragment mass is given in Fig. 2.

The rather steep nature of the neutron emission curve obtained in this experiment is consistent with earlier results in this region of relatively light fissioning nuclei. In addition to the ^{209}Bi + p results, Fig. 2 also gives neutron emission values from a more direct neutron emission measurement for the case of ^{4}He-induced fission of ^{209}Bi at a bombarding energy of 53.25 MeV.[6] The comparison between the results of ref. 6 and the results obtained in this work must be made with caution, because different compound nuclei are involved (^{213}At and ^{210}Po) and because the bombarding energies are different. Fortuitously, however, the excitation energies of the compound nuclei are nearly identical because the difference in bombarding energy is compensated, to within 1 MeV, by the difference in reaction Q values. The two sets of data in Fig. 2 are remarkably similar to each other.

As was discussed in ref. 6, the neutron emission function for the fission of bismuth is considerably steeper than is predicted by the liquid-drop theory. The

5. J. Terrell, *Phys. Rev.* **127**, 880 (1962).
6. F. Plasil, R. L. Ferguson, and H. W. Schmitt, *Proceedings of the Second Symposium on the Physics and Chemistry of Fission*, Vienna, 1969, p. 505.

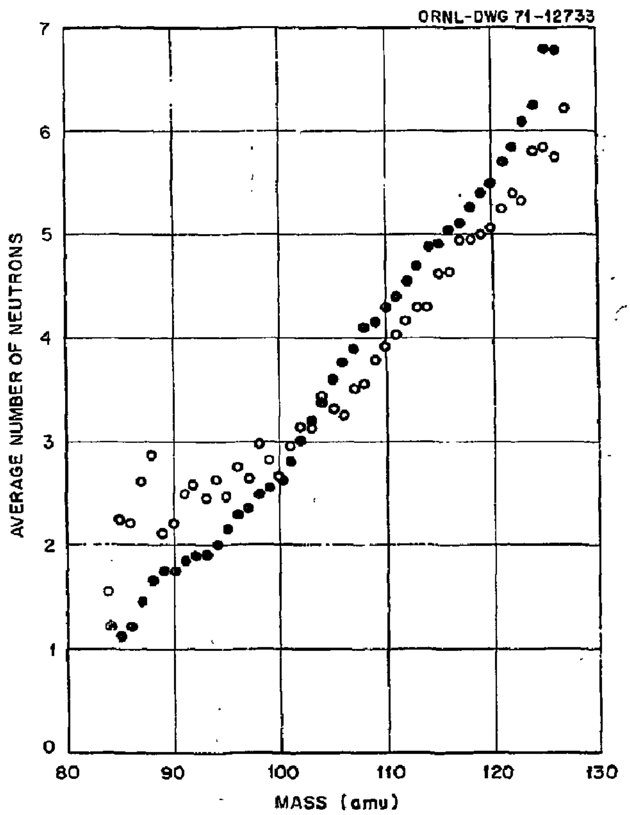

Fig. 2. Average number of neutrons emitted per fragment as a function of pre-neutron-emission fragment mass. The closed circles have been obtained in this work by the cumulative yield method for 36.1 MeV proton-induced fission of ^{209}Bi. The open circles are results of Plasil, Ferguson, and Schmitt for the 53.25-MeV ^{4}He-induced fission of ^{209}Bi.

neutron emission results obtained here are even steeper, though slightly, than those obtained earlier. The disagreement with liquid-drop theory, therefore, persists. A detailed discussion of comparisons with the liquid-drop model can be found in ref. 6, and the remarks given there also apply to the results obtained in this work.

The neutron emission function obtained in this work was used to convert our provisional masses to pre-neutron-emission masses. The final pre-neutron emission mass distribution is shown in the lower part of Fig. 3. As expected, there is still no indication of an asymmetric fission component in the wings of the mass distribution. Figure 3 also gives the average total fragment kinetic energy as a function of fragment mass, and the root-mean-square width of the kinetic energy distribution $\sigma_{E_K^*}$ as a function of mass. The results of Fig. 3 are consistent with similar results from fission of nuclei in the same compound nucleus mass region.[6] The overall average total kinetic energy before neutron emission is 148.8 MeV, the root-mean-square width of the kinetic energy distribution is 8.5 MeV, and the root-mean-square width of the pre-neutron-emission mass distribution is 9.2 amu.

To conclude, our data still do not confirm the presence of an asymmetric fission component in the wings of the mass distribution from the fission of ^{209}Bi induced with 36.1-MeV protons. Our experiment was carefully designed to search for this component, and we therefore suspect that the radiochemical results are in error. In Fig. 1 it can be seen that a change in only two measurements of Sugihara et al. would, in fact, result in a mass-yield curve with no side peak. The radiochemical data are rather sparse, and the width of the mass distribution derived from them depends on only three adjacent measurements near mass 115 amu. Nevertheless, the large difference in mass distribution width between our results and those of ref. 3 had to be reconciled. We found that neutron emission accounts for the difference in width, and we extracted the average number of neutrons emitted as a function of fragment mass. This neutron emission function was found to be consistent with earlier results of ref. 6 from about 85 to 125 amu. We conclude that in this mass region, the radiochemical results are accurate and that our experiment only casts doubt on the radiochemical data for fragments lighter than 80 amu, where the yield has dropped below 0.1% per amu. As a final bonus, we were able to use the neutron emission function generated in this work to correct our data for neutron emission and to obtain pre-neutron-emission distributions.

We are grateful for helpful discussions with Dr. H. W. Newson.

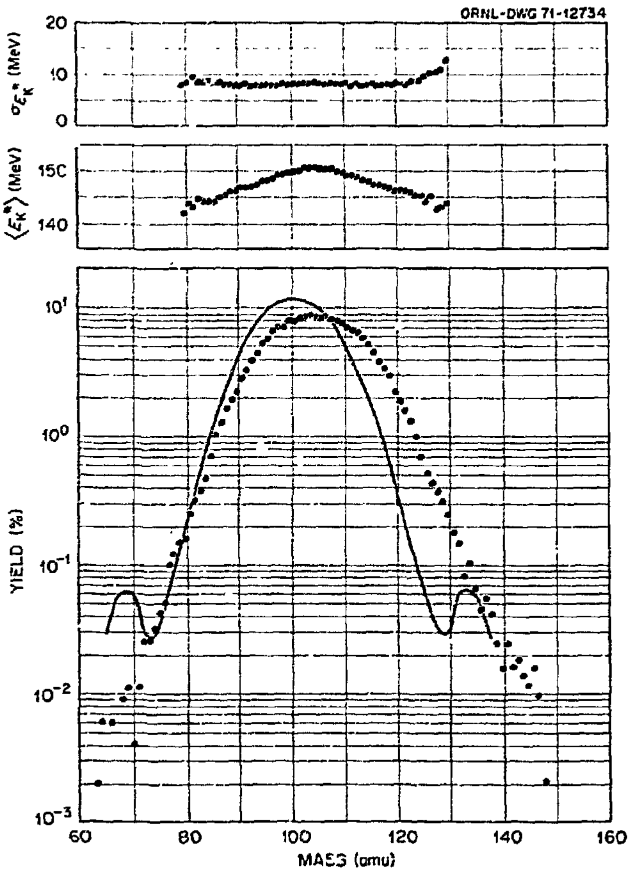

Fig. 3. The bottom section shows the pre-neutron-emission mass-yield distribution normalized to 200%. The solid line gives the radiochemical post-neutron-emission results of Sugihara et al. The middle section gives the average total pre-neutron-emission kinetic energy, $\langle E_K^* \rangle$, as a function of mass. The top section gives the rms width, $\sigma_{E_K^*}$, of the kinetic energy distributions as a function of mass.

MASS AND ENERGY DISTRIBUTIONS FROM 77.3-MeV-^{4}He-INDUCED FISSION OF ^{181}Ta, ^{209}Bi, AND ^{233}U; A TEST OF LIQUID-DROP MODEL PREDICTIONS[1]

F. Plasil H. W. Schmitt

NUCLEAR FISSION: ^{181}Ta(α,*f*), ^{209}Bi(α,*f*), ^{233}U(α,*f*), E = 77.3 MeV; measured correlated fragment energies, deduced fragment mass and total kinetic energy distributions, averages, and widths.

Thin targets of ^{181}Ta, ^{209}Bi, and ^{233}U have been bombarded with 77.3-MeV ^{4}He ions at the Oak Ridge Isochronous Cyclotron. Correlated measurements of kinetic energies of fission fragment pairs have been made, and mass and total kinetic energy distributions were obtained. The widths of the distributions were compared to predictions of the liquid-drop model for fission. The trends predicted by theory were observed, but the absolute magnitudes of the distribution widths were not in agreement with liquid-drop model predictions. It is concluded that the liquid-drop model describes fission of relatively light nuclei in general terms but that it must be used with caution when quantitative predictions are required.

1. Abstract of published paper: *Phys. Rev.* C5, 528 (1972).

FISSION FRAGMENT MASS DISTRIBUTIONS AND KINETIC ENERGIES FOR SPONTANEOUS FISSION ISOMERS[1]

R. L. Ferguson[2] F. Plasil G. D. Alam[3] H. W. Schmitt

NUCLEAR FISSION: ^{239m}Am, ^{237m}Pu, ^{236m}U, ^{238m}U(SF); measured fragment mass, energy distributions; deduced mean values, widths.

Fission fragment energy correlation experiments have been carried out for spontaneous fission isomers formed in the following reactions: ^{240}Pu(p,2n)^{239m}Am, ^{239}Pu(d,2n)^{239m}Am, ^{237}Np(d,2n)^{237m}Pu, ^{238}U(d,pn)^{238m}U, and ^{235}U(d,p)^{236m}U. The fragment mass distributions, total kinetic energies, and fragment distribution averages and widths are consistent with prompt, low-excitation fission systematics of the actinides. It is argued that fragment configurations, including mass and energy distributions, are determined in the same region of the multidimensional potential surface describing the fission process for both types of fission. Evidence which indicates that this region may begin in the neighborhood of the second barrier is discussed.

1. Abstract of published paper: *Nucl. Phys.* A172, 33 (1971).
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HIGH-RESOLUTION CROSS-SECTION MEASUREMENT FOR ^{236}U(n,f)[1]

Helmut Rösler[2] Franz Plasil H. W. Schmitt

NUCLEAR FISSION: ^{236}U(n,f), E = 0.5–2.6 MeV; measured $\sigma_{n,f}$.

The cross section for neutron-induced fission of ^{236}U has been measured in the neutron energy range 0.5 $\lesssim$ E_n $\lesssim$ 8 MeV. A resolution of 7 keV was achieved. Our results thus far confirm the existence of structure in the ^{236}U cross section superimposed on a smooth barrier-

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penetrability function. In addition to the structure previously observed at 0.95 and 1.4 MeV, we find maxima at 0.75 and 1.15 MeV. The peak at 1.4 MeV appears to be at least a doublet (peaks at approximately 1.3 and 1.4 MeV). It is possible that these peaks correspond to collective levels in the second minimum, for example, low-spin members of one or more vibrational bands.

FRAGMENT-SHELL INFLUENCES IN NUCLEAR FISSION[1]

Ulrich Mosel[2] H. W. Schmitt

Potential-energy surfaces and shell-correction-energy surfaces for nuclei in the $A \cong 200$ region and for actinides ($A \gtrsim 230$) have been calculated in the improved two-center model. These surfaces are shown in a two-dimensional representation as a function of the elongation and the constriction of the nuclear shape. Both the ground-state shell corrections and the fission barriers in the $A \cong 200$ region agree well with experiment. It is found that the saddle-point position in this region is shifted significantly towards smaller deformations compared with the liquid-drop-model prediction, this shift arising from a very pronounced valley in the shell-correction surface at the position of the liquid-drop-model saddle point. The implications of this finding for a nuclear mass formula and for the application of the liquid-drop model to fission of these nuclei are discussed. In both mass regions ($A \cong 200$ and $A \gtrsim 230$) the shell corrections alone show pronounced structure which changes slowly with mass number. At small deformations, up to the region of the second maximum in the potential, this structure is determined by the compound-nucleus shell structure. At larger deformations this structure is shown to arise from the shell structure of the nascent fragments, thus establishing the importance of fragment shells early in the fission process for the entire mass range $A \gtrsim 200$. As a consequence of these studies the regions of validity for the liquid-drop model in describing nuclear fission are explained. Finally, it is shown that the recently observed symmetry in the mass distribution of ^{257}Fm is due to the approach to the nucleus ^{264}Fm, which can split symmetrically into the two energetically strongly favored ^{132}Sn nuclei.

1. Abstract of published paper: *Phys. Rev. C* 4(6), 2185 (1971).
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FISSION BARRIERS FOR LIGHT ELEMENTS (A = 180–212)[1]

Ulrich Mosel[2] H. W. Schmitt

Fission barriers for elements in the mass range A = 180–212 have been calculated in the two-center shell model using the Strutinsky prescription. The theoretical predictions agree well with recent experimental results.

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ASYMMETRIC FISSION STUDIES IN THE TWO-CENTER MODEL

M. G. Mustafa[1] U. Mosel[2] H. W. Schmitt

Introduction

One of the most interesting results of calculations of collective potential energy surfaces (PESs) for heavy nuclei has been the instability of the second barrier against asymmetric deformations.[3–5] This result suggests that the mass asymmetry observed in low-energy nuclear fission of heavy elements may be due to static

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2. Department of Physics, University of Washington, Seattle, Wash. 98105.
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4. H. C. Pauli, T. Ledergerber, and M. Brack, *Phys. Lett.* 34B, 264 (1971).
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potential properties associated with the deformation behavior of these nuclei.

The two-center model provides a method for calculating the energy levels of a compound nucleus from its ground state, through successive stages of deformation, and finally to scission. It has been found in earlier two-center-model calculations,[6,7] carried out with reflection-symmetric shapes, that a level structure similar to that of the final fragments occurs quite early in the fission process, that is, in the region of the second saddle. Thus, we may say that the nuclear structure properties of the nascent fragments influence the potential surface, and hence the fission process, from the region of the second saddle point onward to scission.[6,7] The instability of the second saddle towards asymmetry[3-5] may also, in this sense, be due to the nuclear properties of the nascent fragments.

Our aim in this work is to examine the nuclear potential surface along the fission direction from the ground state of the compound nucleus across the barrier, and on to scission, to determine where the minimum-potential-energy path goes over to asymmetric shapes, and to determine the potential energy as a function of volume ratio (mass ratio) at a number of points along the fission path. We shall describe the calculations and results for the compound nucleus $^{236}_{92}U_{144}$. Then we shall proceed to a study of the two fermium isotopes, $^{252}_{100}Fm_{152}$ and $^{264}_{100}Fm_{164}$, carried out in view of the following observations: The fragment mass distribution for ^{254}Fm is asymmetric and peaks at heavy-fragment mass ≈ 140 amu,[8] similar to the distribution for ^{236}U. The mass distribution for ^{258}Fm, however, has been observed to peak at symmetry.[9] We speculate that this may be due to the approach to $^{264}_{100}Fm$,[10] where two double-magic nuclei may be formed at symmetry; if this is the case, symmetric peaks may be expected also for nuclei in the neighborhood of ^{264}Fm, for example, in ^{258}Fm, and the conclusion might be made that the extra stability effects of two approximately double-magic nascent fragment nuclei on the PES then override the deformation effects which lead to the $m_H \approx 140$ peak for the lighter actinides. The calculations reported here are a first attempt to understand these phenomena within the framework of a realistic model.

Model and Calculations

The model used for our calculation is a generalization of the two-center model[7,11] to asymmetric deformations. In a first paper,[12] it was shown that this model contains the correct asymptotic behavior of single-particle levels, both for the fissioning nucleus and for the two fragments formed. It also meets the physical requirement that the same potential depths are obtained for the two fragments regardless of their mass even for very large asymmetries, a necessary condition which, however, is violated in some other models.[13-15] In the present work, the Hamiltonian of ref. 12 has been changed to smooth out the neck. The Hamiltonian used in the present calculation is:

$$H = T + \frac{m}{2}\omega_{\rho i}^2(z)\cdot\rho^2 + \frac{m}{2}\omega_{zi}^2(z - z_i)^2 + V_{\text{corr}} + V(\text{l, s}), \quad (1)$$

with $i = 1$ for $z > 0$ and $i = 2$ for $z < 0$. The potential term V_{corr} is the same as in ref. 12 generalized to asymmetric deformations:

$$V_{\text{corr}} = -\frac{m}{2}\omega_{zi}^2\cdot\frac{(z - z_i)^4}{2z_i^2}\cdot\theta(z - z_i), \quad (2)$$

where θ is a step function: $\theta(x) = 0$ for $x > 0$, $\theta(x) = 1$ for $x < 0$. Equation (2) gives a smooth transition of the potential at $z = 0$ for $\rho = 0$, thus removing the sharp cusp of the original two-center-oscillator potential.[11,12] The frequency ω_ρ has been made z dependent in order to allow for a smooth transition of the potential for all ρ values. This dependence is given by:

$$\omega_{\rho i}(z) = \mathring{\omega}_{\rho i} + \alpha_i\left[(z - z_i)^2 - \frac{(z - z_i)^4}{2z_i^2}\right]\theta(z - z_i). \quad (3)$$

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The functional form is thus identical to the purely z-dependent part of the potential. Various conditions for smooth transitions of the potential and its derivative at $z = 0$, the physical condition that for large separations (large $z_1 + z_2$) two independent potentials must exist, and the usual constraint of volume conservation then leave us with four independent shape parameters, for which we choose the physically meaningful quantities:

D (radius of the neck in fermis),

λ (volume ratio of the two fragments,

$\lambda = 1$ for symmetry),

and:

$\alpha = a_2/a_1 - 1$ (see Fig. 1, $\alpha = 0$ for symmetry),

$\sigma = z_1/\sqrt{2c_1}$.

The choice of the last quantity has been suggested by the fact that for symmetric shapes, D is given by

$$D = a\sqrt{1 - \sigma^2} \quad . \tag{4}$$

Thus σ is directly connected with the relative neck thickness D/a.

An example of a nuclear shape describable by this single-particle potential is given in Fig. 1. The term $V(l,s)$ contains the usual spin-orbit and l^2 correction term of the Nilsson model generalized to a two-center model and is defined in the stretched coordinate representation.[7] The strength parameters of this term are given in the usual notation (see also ref. 7) by:[16]

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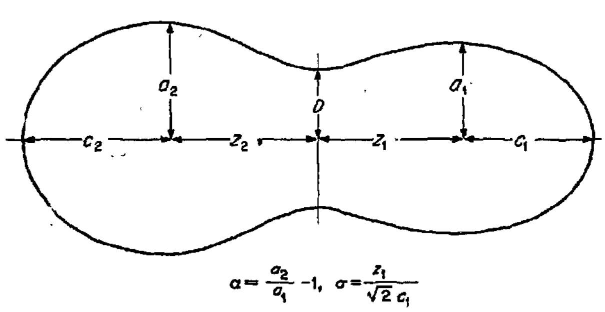

Fig. 1. Schematic diagram of the nuclear shape, showing quantities which describe it.

Mass Range	κ_p	μ_p	κ_n	μ_n
$A = 230–264$	0.058	0.645	0.0635	0.33
$A = 100–140$	0.0671	0.572	0.0638	0.493

and are interpolated between these two mass regions depending on the mass of the fragment formed in order to assure the correct asymptotic behavior.

The Hamiltonian has been diagonalized in a basis of asymmetric two-center states.[12] The shell corrections have then been calculated by using the Strutinsky prescription,[17] whereas pairing has been taken into account in the BCS formalism. The pairing strengths used are:

$$G_p = \frac{19.4}{A}\,\text{MeV} \quad \text{and} \quad G_n = \frac{13.8}{A}\,\text{MeV} .$$

These fit the empirical odd-even mass differences if Z levels for the protons and N levels for the neutrons are taken into account.[18] The liquid-drop parameters are taken from the Myers-Swiatecki mass formula,[19] except for the surface-symmetry coefficient, K_s, which we took from Seeger's work.[20] Johansson, Nilsson, and Szymanski[21] used Seeger's value for K_s to compensate for the use of constant pairing strengths G_p and G_n.

The calculations have been performed with D first fixed as a measure of the fission coordinate; a three-dimensional calculation of the total energy is then carried out as a function of λ, σ, and α. We minimize the energy with respect to σ and α to obtain the total energy E as a function of the asymmetry λ.

Results

The results of our calculations to date, for ^{236}U, ^{252}Fm, and ^{264}Fm, are shown in Figs. 2–5. It was found in the reflection-symmetric calculations[7] that the final stages of fission are predominantly in the constriction direction; therefore, we use the shape parameter D, the radius of the neck, as the variable which

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approximates the fission direction in presenting the present results for asymmetric shapes. (Note that this D is the same as the d_0 of refs. 6 and 7 and does not correspond to the constriction parameter d used there.

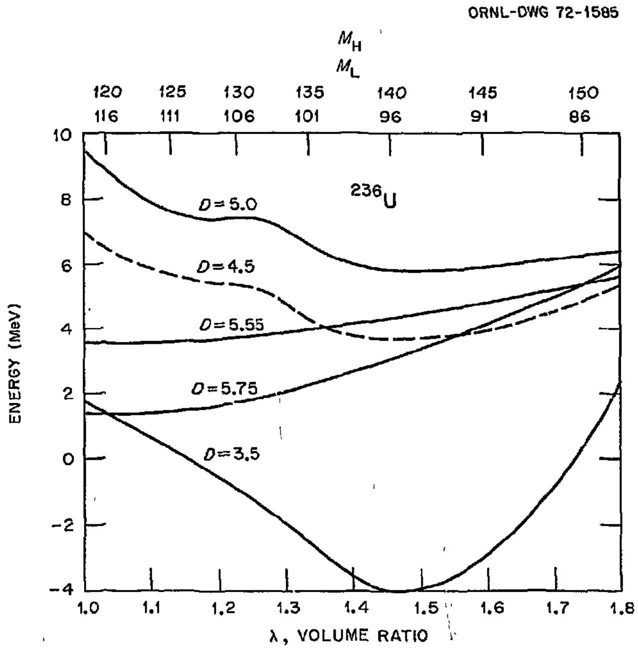

Fig. 2. Total potential energy for ^{236}U as a function of volume ratio of the two fragments, for several values of D, the radius of the neck in fermis. The energy has been minimized with respect to σ and α and normalized to the ^{236}U ground-state energy.

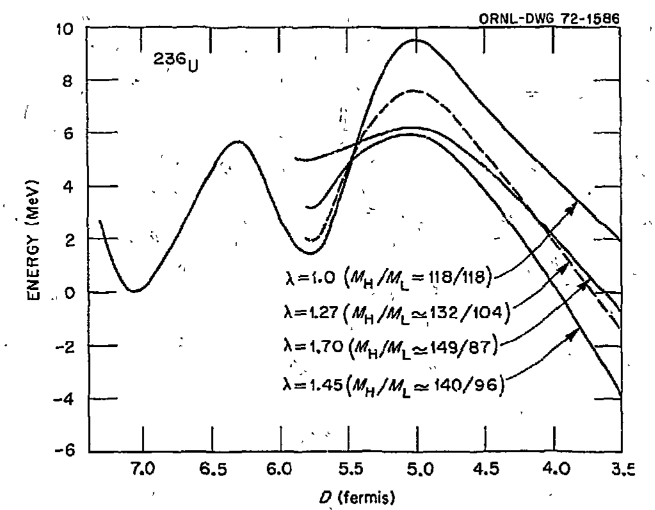

Fig. 3. Total energy (minimized with respect to σ and α) for ^{236}U as a function of D for selected values of λ. Note the rather sudden transition from symmetric to asymmetric shapes at $D \approx 5.5$ F. See text.

The constriction parameter d of refs. 6 and 7 was defined as $d = 1 - d_0/a$, where a is the maximum radius of the nuclear shape in a direction perpendicular to the symmetry axis. Thus, if there were no neck formed, d would remain zero while the nucleus elongates and d_0, or D, decreases. Use of the variable D to approximate the fission direction enables the qualitative study of the potential energy from the ground state to scission, as will be seen below.)

$^{236}_{92}U_{144}$. Figure 2 shows the deformation energy E as a function of the volume ratio λ, for various values of D. Zero on the energy scale corresponds to the ^{236}U ground state, for which $D \approx 7.05$ F (cf. Fig. 3). Symmetric shapes are seen to be preferred as D decreases, down to the 5.5 to 5.0 region, where asymmetries of about $\lambda \approx 1.5$ begin to be preferred. As D decreases further, through the second saddle point and beyond, the potential energy minimum continues to occur at about the same value of λ, shifting to a slightly smaller value, $\lambda \approx 1.46$. (Pauli et al.[4] have

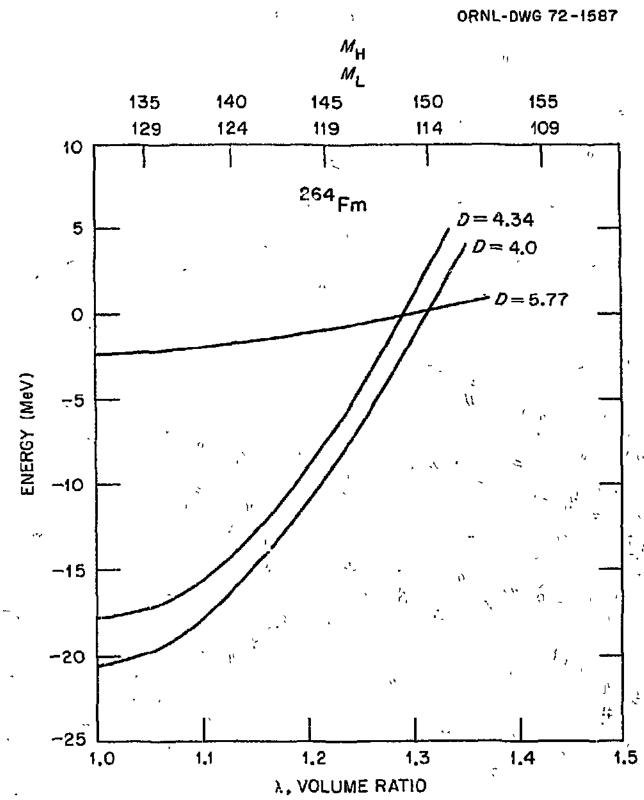

Fig. 4. Total potential energy for ^{264}Fm as a function of volume ratio of the two fragments, for several values of D, the radius of the neck in fermis. The energy has been minimized with respect to σ and α and normalized to the ^{264}Fm ground-state energy.

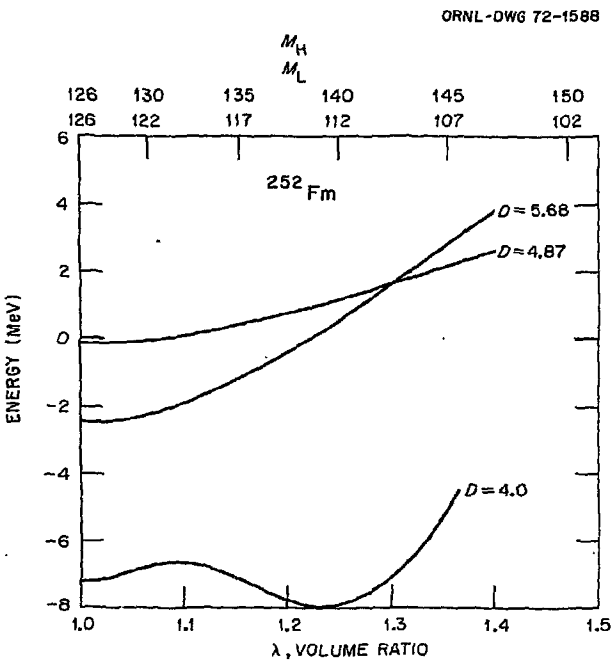

Fig. 5. Total potential energy for ^{252}Fm as a function of volume ratio of the two fragments, for several values of *D*, the radius of the neck in fermis. The energy has been minimized with respect to σ and α and normalized to the ^{252}Fm ground-state energy.

investigated the region of the second saddle and have also found the minimum potential energy to occur at $\lambda \approx 1.46$.)

We attach no particular significance to this small shift. Rather, it is significant that the transition from energetically preferred symmetric shapes to energetically preferred asymmetric shapes with values of λ very close to the final value occurs rapidly, that is, within a small region of $D \approx 5.5$ F.

Most significant, of course, is the strong energetic preference, as D decreases, for $\lambda \approx 1.46$, in excellent accord with the observed peak in the fragment mass distribution at $m_H/m_L = 140/96 = 1.46$.[22]

In Fig. 3 we show the deformation energy E plotted as a function of D, for selected values of λ. The minimum potential energy is seen here to correspond to symmetric shapes during the early stages of fission, through the second minimum, to $D \approx 5.5$ F. The sudden transition, indicated above, to $\lambda \approx 1.45$ then occurs, and this asymmetry appears to remain as the minimum potential energy value of λ.

A particularly important conclusion from these results is that the mass distribution is shown to be determined by that part of the potential energy surface beyond the second minimum, in agreement with recent experimental indications.[23]

$^{252}_{100}Fm_{152}$ and $^{264}_{100}Fm_{164}$. Figures 4 and 5 show preliminary results for ^{264}Fm and ^{252}Fm respectively. The deformation energy, on a scale the zero of which corresponds to the ground state of the fissioning nucleus, is plotted against the volume ratio λ for a few values of D beyond the saddle point. Although these results are still incomplete, we see a preference for symmetry in all of the curves for ^{264}Fm, with this preference increasing in strength with decreasing D. This result would seem to support the expectation suggested in the first section of this report, namely, that the production of two double-magic fragment nuclei at symmetry would be strongly preferred relative to asymmetric divisions, when that is possible.

Preliminary results for ^{252}Fm indicate that symmetric mass divisions are preferred for $D \gtrsim 4.8$ F. Between $D = 4.87$ F and $D = 4.0$ F a transition occurs in which asymmetric mass divisions become preferred. It is interesting that the minimum potential energy for $D = 4.0$ F occurs for $\lambda \approx 1.24$, corresponding to a mass ratio $m_H/m_L \approx 139/113$, again where the heavy-fragment mass is ~140 amu, as in the lighter actinides.

The assistance of M. J. Stephens in carrying out the computations is gratefully acknowledged.

22. See, for example, H. W. Schmitt, J. H. Neiler, and F. J. Walter, *Phys. Rev.* **141**, 1146 (1966), and references therein.

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FISSION PROPERTIES OF HEAVY AND SUPERHEAVY NUCLEI[1]

H. W. Schmitt   U. Mosel[2]

Calculations have been carried out to estimate the total fragment kinetic energies E_K, total fragment excitation energies E_X, and approximate total number of neutrons ν emitted in the binary fission of heavy and superheavy nuclei. The kinetic energy calculations are based on a static scission model reported earlier for fissioning nuclei in the actinide region. The total energy release Q is calculated from a recent mass formula of Seeger, and the total excitation energy is obtained from the difference $E_X = Q - E_K$. The results show a strong peak in $E_K(A)$ [A = compound nucleus mass number] and a corresponding minimum in $E_X(A)$ at $A \cong 264$, corresponding to fission into two nearly double-magic ($Z \sim 50, N \sim 82$) fragments. Our predictions of E_K, E_X, and ν disagree sharply with the liquid-drop predictions in the range $255 \lesssim A \lesssim 290$. It appears from these results that kinetic energy measurements do not provide an unambiguous test for superheavy nuclei, while measurements of ν, if $\nu \gtrsim 5$, seem to provide such a test.

1. Abstract of paper submitted for publication in *Nuclear Physics.*
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DIPOLE EXCITATIONS IN FISSION FRAGMENTS[1]

M. G. Mustafa[2]   H. W. Schmitt   U. Mosel[3]

Dipole excitations in fission fragments at the scission point have been studied in a classical model. These excitations correspond to a density fluctuation caused by the Coulomb repulsion between the fragments. A simple two-sphere approximation to the scission configuration is used for these studies. The dipole density distribution is obtained from a hydrodynamic picture of the fragment nucleus, and the dipole amplitude parameters are fixed by minimizing the total potential energy at the scission point. Calculations have been made for the symmetric and asymmetric scission configurations corresponding to the fission of ^{235}U by thermal neutrons. The dipole excitation energy is found to be about 0.5 MeV in one fragment, and, at the same time, the total energy is lowered by 1 MeV from its value calculated with a uniform density distribution.

1. Abstract of published paper: *Nucl. Phys.* A178, 9 (1971).
2. Visiting scientist from Pakistan Atomic Energy Commission, Karachi, Pakistan.
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5. Mössbauer Spectroscopy

MÖSSBAUER STUDIES OF ^{234}U, ^{236}U, AND ^{238}U

Paul G. Huray[1] J. A. Monard[2] J. O. Thomson[3]

The use of the 2+ → 0+ transition as a source of gamma rays for Mössbauer studies in the heavy even-even nuclei has been suggested for several years.[4] The availability of high isotopic purities of these elements and their parents and the relative toxicity of large quantities of heavy-element compounds has, until recently,[5] limited nuclear gamma resonance studies to recoil implantation techniques.[6] We have made use of the facilities of the Transuranium Research Laboratory as well as the Transuranium Processing Plant personnel to institute a Mössbauer program to study nuclear and solid-state properties of the uranium and plutonium compounds. This program emphasizes the use of the natural decay of parent isotopes to produce the Mössbauer gamma rays. Thus far we have established nuclear gamma resonance for ^{234}U, ^{236}U, and ^{238}U in the compound $(UO_2)Rb(NO_3)_3$ (uranyl rubidium nitrate) and have determined the ratio of the electric quadrupole moments of these isotopes. The absence of a measurable isomer shift has allowed us to place an upper limit on the change in nuclear radius between the excited and ground state. The $B(E2)$ measurements of the quadrupole moment of these isotopes have allowed us to accurately determine the electric field gradient, $\partial E_z/\partial z$, at the uranium site in $(UO_2)Rb(NO_3)_3$.

1. Ph.D. guest assignee from the University of Tennessee, Knoxville.
2. Student guest assignee with Chemistry Division from the University of Tennessee, Knoxville.
3. Consultant from the University of Tennessee, Knoxville.
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The alpha decay of ^{238}Pu, ^{240}Pu, and ^{242}Pu produces uranium isotopes in their first excited 2+ rotational state approximately 20% of the time. The subsequent transition to the 0+ ground state occurs with the emission of an ~45-keV gamma ray only about once in every 650 events, due to the large internal conversion coefficient of uranium. If the nuclear transitions occur in the absence of magnetic fields or electric field gradients, as is thought to be the case for the dioxide sources used, the excited and ground states form degenerate levels, and a single-energy gamma is available for absorption. By Doppler shifting this gamma, it is possible to survey the various transitions from the ground to the excited states of uranium absorber nuclei.

For these studies the nonmagnetic material $(UO_2)Rb(NO_3)_3$ has been employed to produce only electric multipole interactions with the absorber uranium nuclei. The electric monopole interaction leads to an isomer shift term which describes the electronic-nuclear charge density Coulombic interaction. This term has not been experimentally observed for any of the three isotopes studied. We have estimated the electronic charge density change at the origin between the chemical state of the source nuclei (4+) and that of the absorber nuclei (6+) through the Wigner-Seitz code of Tucker et al.[7] This value leads to an upper limit for the nuclear size change between the excited and ground state of $\Delta r/r = 2 \times 10^{-6}$.

The electric quadrupole interaction is described by the Hamiltonian

$$H_Q = \frac{eqQ}{4I(2I-1)}\left[(3I_z^2 - I^2) + \frac{1}{2}\eta(I_+^2 + I_-^2)\right], \quad (1)$$

7. Thomas C. Tucker, Louis D. Roberts, C. W. Nestor, Jr., and Thomas A. Carlson, *Phys. Rev.* **178**, 998 (1969).

where eQ is the nuclear quadrupole moment of the $I = 2$ excited state, q is the negative of the electric field gradient at the uranium nuclei in the absorber $(-\partial E_z/\partial z)$, I_z is the operator which determines the z component of angular momentum, and η is the asymmetry parameter

$$\frac{(\partial E_x/\partial x) - (\partial E_y/\partial y)}{\partial E_z/\partial z} .$$

Due to the high degree of axial symmetry at the uranium sites in $(UO_2)Rb(NO_3)_3$, the η term is thought to be negligible. The energy eigenvalues for the $I = 2$ excited states are thus given by

$$E_{\pm 2} = E_\gamma + \frac{2}{8} eqQ ,$$

$$E_{\pm 1} = E_\gamma - \frac{1}{8} eqQ ,$$

and

$$E_0 = E_\gamma - \frac{2}{8} eqQ$$

for the $I_z = \pm 2$, ± 1, and 0 substates respectively. The separation between the $E_{\pm 2}$ and $E_{\pm 1}$ states compared with that between the $E_{\pm 1}$ and E_0 states should thus be in the ratio 3:1. This ratio has been nominally observed for each isotope studied here and is indicated in Fig. 1 by the relative separation of the three theoretical component lines (solid curves). In this computer fit to the data, the line positions have been constrained to retain the 3:1 splitting ratio, and the intensities of the lines have been constrained to have the ratio 2:2:1 for the ± 2, ± 1, and 0 states respectively. The separation constant, $\frac{1}{4}$ eqQ, is seen from this figure to be of order -40.7 ± 0.7 mm/sec in terms of the Doppler shift velocity Δv for ^{234}U. This Doppler shift corresponds to an energy differential

$$\Delta E_{234} = \frac{\Delta v}{c} E_\gamma = 6.03 \pm 0.10\ \mu\text{eV}.$$

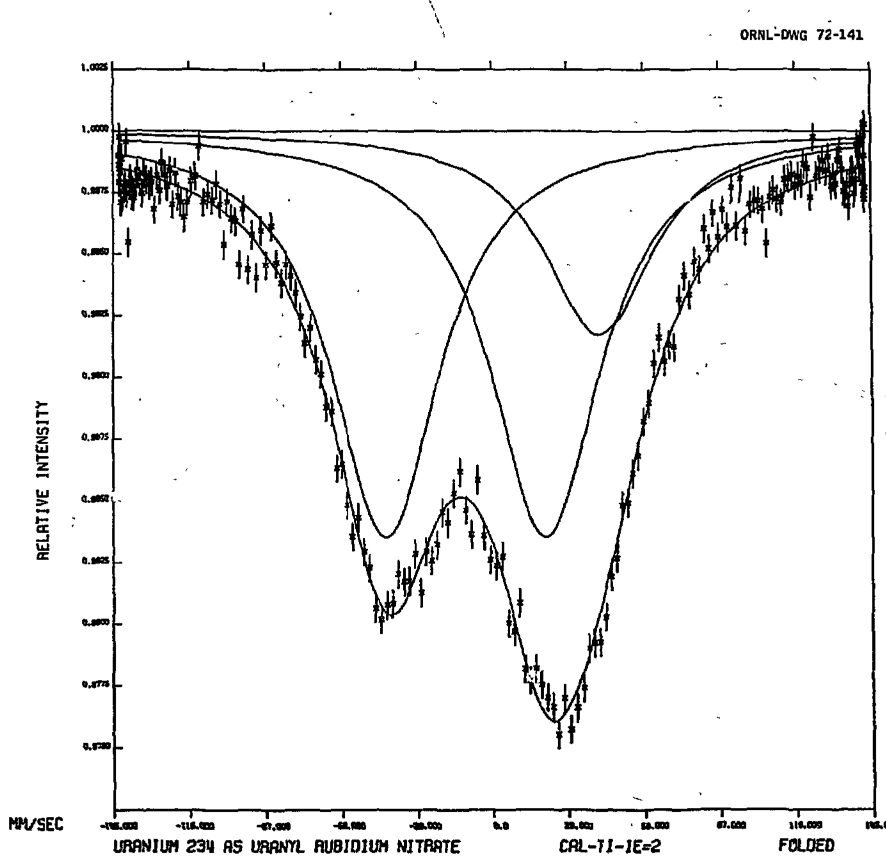

Fig. 1. Mössbauer spectrum of ^{234}U in $(UO_2)Rb(NO_3)_3$ following alpha decay of ^{238}Pu in PuO_2 at 4.2°K. The solid lines are a theoretical fit of a sum of three transmission integrals constrained in position and intensity ratios to represent the degenerate levels of a pure symmetric electric quadrupole interaction.

For each of the three isotopes fitted, in a similar manner

$$\frac{1}{4}eqQ_{234} = -40.7 \pm 0.7 \text{ mm/sec},$$

$$\frac{1}{4}eqQ_{236} = -38.5 \pm 1.7 \text{ mm/sec},$$

$$\frac{1}{4}eqQ_{238} = -42.2 \pm 2.2 \text{ mm/sec}.$$

Since the same absorber material was used for each isotope in the study, we shall presume that q is the same in each case. This leads to the ratios:

$$Q_{236}/Q_{234} = 0.98 \pm 0.05$$

and

$$Q_{238}/Q_{234} = 1.07 \pm 0.06.$$

McGowan et al.[8] have given a value of the intrinsic quadrupole moment for the ground state of ^{234}U as determined from $B(E2)$ measurements to be $Q_0 = 10.2 \pm 0.1$ b. This leads to a quadrupole moment for the 2+ state $Q_{234} = -2/7\, Q_0$ through the rigid rotor model and suggests that

$$q = -\frac{\partial E_z}{\partial z} = +(8.12 \pm 0.14) \times 10^{18} \text{ V/cm}^2.$$

This negative electric field gradient at the uranium nucleus along the crystalline z axis (the O-U-O axis) thus suggests a large concentration of electronic charge in the x-y plane and relatively less above and below the x-y plane. This distribution is in agreement with previous alpha-decay studies.[9]

For the case of the ^{238}U and ^{236}U spectra, relatively low count rates and hence fewer statistics have prevented any studies of a possible departure of the splitting ratio from the 3:1 value as discussed above. For the ^{234}U case, however, we have performed a computer fit in which the line positions were not constrained. In this fit, an optimum comparison between the data and the theoretical line shapes was found to occur for a splitting ratio of (3.42 ± 0.30):1.

8. F. K. McGowan, C. E. Bemis, Jr., J. L. C. Ford, Jr., W. T. Milner, R. L. Robinson, and P. H. Stelson, *Phys. Rev. Lett.* **27**, 1741 (1971).

9. L. D. Roberts, J. W. T. Dabbs, F. J. Walter, S. H. Hanauer, and G. W. Parker, pp. 329–40 in *Proc. Conf. on Use of Radioisotopes in the Physical Sciences and Industry (Copenhagen, Denmark, Sept. 1960)*, IAEA, Vienna, 1962.

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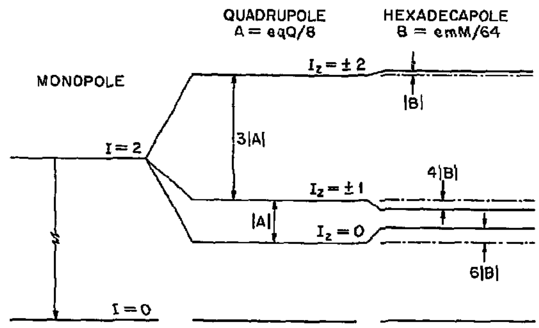

Fig. 2. Energy level diagram of 2± excited state under the influence of (*a*) a pure Coulombic monopole interaction, (*b*) the monopole interaction plus a pure symmetric quadrupole interaction, and (*c*) the monopole and quadrupole interactions plus a pure symmetric hexadecapole interaction.

Such energy eigenvalues would not naturally result from the symmetric part of the Hamiltonian given in Eq. (1) but might be caused by effects such as (*a*) a nonsymmetrical source distribution, (*b*) an asymmetry term η, or (*c*) higher terms in the multipole interaction. The next highest term in the electric multipole interaction is the hexadecapole term and is described by the Hamiltonian

$$H_M = \frac{emM}{128I(I-1)(2I-1)(2I-3)}(35I_z^4 - 30I_z^2I^2 + 3I^4 + 25I_z^2 - 6I^2), \quad (2)$$

where eM is the electric nuclear hexadecapole moment of the $I = 2$ excited state, m is the third derivative of the electric field $(-\partial^3E_z/\partial z^3)$, and I_z is again the operator which determines the z component of angular momentum. Asymmetry terms have been neglected in this equation. The energy eigenvalues of the $I = 2$ excited state would be therefore affected by this term and would be modified as is suggested in Fig. 2.

In order to account for the 3.42:1 splitting ratio suggested above, the value $emM/64$ = 0.217 mm/sec would be required. Even though ^{234}U is thought[10] to have the largest hexadecapole moment, M, of all nuclei, the value of m required would seem to be unreasonably high, even with a generous Sternheimer enhancement. Studies are presently being carried out with other sources and greater statistics in order to resolve this apparent discrepancy.

10. F. K. McGowan, C. E. Bemis, Jr., J. L. C. Ford, Jr., W. T. Milner, R. L. Robinson, and P. H. Stelson, unpublished.

HYPERFINE FIELDS AT NICKEL SITES IN HEUSLER ALLOYS[1]

John C. Love[2] Felix E. Obenshain

Mössbauer spectra of ^{61}Ni were measured for the ferromagnetic Heusler alloys Ni_2MnX (X = Ga, In, Sn, and Sb) at 4.2 and 78°K. Unsplit sources of ^{61}Co in ^{64}Ni-V (14 at. %) were produced by the reaction $^{64}Ni(p,\alpha)^{61}Co$. The Heusler alloy samples were prepared by induction melting, examined by x-ray diffraction for structure and impurity phases, and annealed in powdered form. The hyperfine fields (in kilo-oersteds) at 4.2°K are: X = Ga, 125 ± 3; X = In, 141 ± 3; X = Sn, −125 ± 3; and X = Sb, −60 ± 8. The value of H(Ni) in an unannealed sample of Ni_2MnSn, for which the x-ray spectrum indicated considerable disorder of nickel and tin atoms, is the same as that for the ordered (annealed) sample. The lattice structure of these alloys (type L21) may be described as four interpenetrating fcc sublattices (A, B, C, and D), where nickel occupies A and C sites and manganese and X occupy sites B and D respectively. The magnetic properties (e.g., Curie temperature) depend strongly on the degree of ordering. Since only the well-separated manganese atoms carry magnetic moments,[3] it is usually assumed that the ferromagnetism is due to a conduction-electron polarization (CEP) mechanism. We have calculated CEP hyperfine fields at nickel and X sites for the virtual-bound-state model, following the work of Caroli and Blandin[4] and Geldart.[5] The total CE polarization P(Ni) and P(X) at the nickel and X sites is calculated by summing over contributions due to manganese atoms within the first 50 shells of manganese neighbors. P depends upon the CE density n and the manganese moment M. For a range of reasonable values for these parameters (n = 1.5 to 2 electrons per atom and M = 3.6 to 4.4 μ_B), it is found that $P(\mathrm{Ni}) \approx P(\mathrm{X})$. This is consistent with the observation above that disorder of nickel and X sites does not affect H(Ni). In addition, we find that ξ = 0.2 to 0.3, where ξ is a factor specifying the s-wave character of the conduction electrons at the Fermi surface at nickel sites and where

$$H(\mathrm{Ni}) = \xi\,[H^{\mathrm{Ni}}_{\mathrm{atomic}}]\;\Omega(\tfrac{5}{8}\,\pi^2)P(\mathrm{Ni})$$

is derived within the context of the model, where Ω is the atomic volume.

1. Abstract of paper submitted for publication in the *Physical Review.*
2. Guest assignee from Clarkson College of Technology, Potsdam, N.Y.
3. P. S. Webster, *Contemp. Phys.* **10**, 559 (1969).
4. B. Caroli and A. Blandin, *J. Phys. Chem. Solids* **27**, 503 (1966).
5. D. J. W. Geldart and P. Ganguly, *Phys. Rev.* **B1**, 3101 (1970).

THE ^{61}Ni MÖSSBAUER EFFECT IN NICKEL-PALLADIUM ALLOYS[1]

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We have obtained nuclear gamma resonance (NGR) absorption spectra with the 67.4-keV transition from ^{61}Ni in nickel-palladium alloy absorbers throughout the concentration range 0 to 99.5 at. % Pd. The source contained the parent isotope ^{61}Co, produced by the reaction $^{64}Ni(p,\alpha)^{61}Co$, in a nonmagnetic ^{64}Ni-vanadium (14 at. %) foil. Both source and absorber were immersed in liquid helium. Values of the absorber recoilless fraction, energy shift, and absolute value of the ^{61}Ni hyperfine field were obtained for each concentration studied. In the ferromagnetic region, 0 to 98 at. % Pd, the spectra showed a partly resolved magnetic hyperfine splitting with a distribution of magnetic hyperfine fields. The average hyperfine field is negative in pure nickel (−76 kOe), changes sign near 50 at. % Pd, and rises to a large positive value (+173 kOe) at 90 at. % Pd. Qualitative agreement with these results is obtained with a model based on the assumption that $\langle H_{hf}\rangle$ in nickel-palladium has the same contributions from core polarization and bulk conduction-electron polarization as in other nickel-based alloys, *plus* a large positive contribution from palladium atoms on neighboring lattice sites. An external magnetic field was

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applied to alloys containing 50 to 99.5 at. % Pd, and from the behavior of the ^{61}Ni effective field as a function of applied field we have deduced: (1) the sign of $\langle H_{hf} \rangle$ is positive near the palladium-rich end, (2) at 50 and 60 at. % Pd the distribution width of hyperfine fields is $\Gamma = (80 \pm 9)$ kOe, and (3) at concentrations greater than 90 at. % Pd a long-range magnetic interaction exists down to 0.5 at. % Ni, the most dilute alloy studied. From a temperature-dependent study of the second-order Doppler shift, we have deduced the relative isomer shift between ^{61}Ni in palladium and in nickel to be $\delta_{IS}^{Pd} - \delta_{IS}^{Ni} = (-23 \pm 15)$ μ/sec.

ISOMER SHIFTS AND MAGNETIC HYPERFINE INTERACTION AT ^{61}Ni IN IONIC NICKEL COMPOUNDS[1]

John E. Tansil[2] Felix E. Obenshain J. C. Williams[3] Larry W. Houk[3]

Results of the analysis of ^{61}Ni nuclear gamma resonance absorption spectra in $Ni[P(OC_2H_5)_3]_4$, $Ni(NO_3)_2 \cdot 6H_2O$, $NiCl_2$, and $NiCl_2 \cdot 6H_2O$ are presented. Absorber recoilless fractions, energy shifts, and magnetic hyperfine fields were obtained from theoretical curves computer fitted to the experimental data. The deduced isomer shifts follow the general trend expected for the nickel formal charge states in these compounds. Electric quadrupole splitting of ^{61}Ni in $NiCl_2 \cdot 6H_2O$ gives a value for the ratio of the quadrupole moment of the first excited state to the ground state as $Q_e/Q_g = -0.5 \pm 0.4$.

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STUDY OF THE COPPER-GOLD AND SILVER-GOLD ALLOY SYSTEMS AS A FUNCTION OF COMPOSITION AND ORDER THROUGH THE USE OF THE MÖSSBAUER EFFECT FOR ^{197}Au[1]

Paul G. Huray[2] Louis D. Roberts[3] J. O. Thomson[4]

Mössbauer spectra for ^{197}Au and the alloy electrical resistivities have been measured for ordered and disordered phases of copper-gold and silver-gold alloys. The alloy compositions span the complete range (~0 to 100% Au). The change of isomer shift with pressure between ~0 and 65 kilobars has also been measured for ordered Cu_3Au. A theoretical model is given which describes the isomer shift in terms of the average atomic volume of the alloy, the short-range-order parameters, and the alloy composition. The agreement between the model and our measurements is good. Friedel oscillations are shown to be present in the electron charge distribution in these alloys. An estimate of the relative contributions of alloy-volume and short-range-order effects to the average electron charge density at the gold nuclei is given.

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MAGNETIC HYPERFINE STRUCTURE COUPLING AND MÖSSBAUER ISOMER SHIFT FOR ^{197}Au IN GOLD-NICKEL AND COPPER-NICKEL-GOLD ALLOYS[1]

J. W. Burton[2] J. O. Thomson[3] Paul G. Huray[4] Louis D. Roberts[5]

Mössbauer effect measurements have been made at 4.2°K for ^{197}Au in the Au_xNi_{1-x} and $Cu_{x-0.01}$-$Ni_{1-x}Au_{0.01}$ alloys systems over the full concentration range of noble metal. The effective magnetic field at the ^{197}Au nucleus is 272 ± 5 kG for 1 at. % Au in nickel. With increasing concentration of noble metal, this field decreases in direct proportion to the alloy magnetization. For Au_xNi_{1-x} and $Cu_{x-0.01}Ni_{1-x}$-$Au_{0.01}$ alloys, the isomer shift is approximately a linear function of composition. These isomer shift measurements are discussed in terms of a model developed previously to describe the charge density distribution in concentrated copper-gold alloys. A good description of the gold isomer shift in the nickel alloys is obtained using the parameters of this model determined previously for the copper-gold system. The similarity of the electron scattering contribution to the isomer shift by copper and by nickel is discussed.

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LEAST-SQUARES FIT TO A MÖSSBAUER TRANSMISSION INTEGRAL

John Burton[1]

In a Mössbauer experiment, gamma rays are emitted by a source, passed through a resonant absorber, and detected by a suitable detector. The energy of the gamma rays is Doppler shifted by relative motion of the source with respect to the absorber, and the variation of the counting rate vs this energy shift is recorded. In order to compute the theoretically expected counting rate, the energy distribution of the emitted gamma rays must be multiplied by the fraction of gamma rays which will be transmitted through the absorber, and this product must be integrated over all energies. The resulting expression is called the transmission integral, given by Eq. (1) below. To analyze a Mössbauer spectrum, a least-squares fit to the data must be obtained for the transmission integral, by appropriate choice of the various parameters. In this report, a computer program is described which determines the least-squares fit of the transmission integral to a set of data and computes the standard errors for the parameters.

The energy distribution of the gamma rays emitted by a source is given by the Lorentzian function[2]

$$dN = \frac{N_s\,(2/\pi\Gamma_s)\,dE}{[(E_s - E)/(\Gamma_s/2)]^2 + 1}\,,$$

where E is the energy of the gamma ray, E_s is the most probable energy of the source (with Doppler shift included), Γ_s is the full width at half maximum for the source, and N_s is a normalization factor. (A single-line source is assumed here, but a multiple-line source has been accounted for in the program by summation over the subscript s.) Of these gamma rays, a fraction f_s will undergo recoilless emission and, of all radiations detected, a fraction α will be due to the particular nuclear transition under study. Hence, the net fraction of recoillessly emitted gamma rays, among all radiations detected, is αf_s.

In passing through an absorber, some of these gamma rays will be resonantly absorbed at various energy levels, E_j. For each energy level, there will be a corresponding line width, Γ_j, and an effective thickness,[3] $T_j = f_A \sigma_0 n_j t$. Here, f_A is the recoilless fraction for the absorber, σ_0 is the Mössbauer absorption cross section at resonance in square centimeters, n_j is the number of atoms per cubic centimeter which may absorb at the jth energy level, and t is the thickness of the absorber in centimeters. The fraction of gamma rays of energy E which will be transmitted is given by

$$\exp\left\{-\sum_j \frac{T_j}{[(E_j - E)/(\Gamma_j/2)]^2 + 1}\right\}\,,$$

1. Consultant from Carson-Newman College, Jefferson City, Tenn.

2. Hans Frauenfelder, *The Mössbauer Effect,* W. A. Benjamin, New York, 1962.

3. S. Margulies and J. Ehrman, *Nucl. Instrum. Methods* **12**, 131 (1961).

where the summation over j includes all energy levels in the absorber. Hence, the net counting rate will be[3]

$$N(E_s) = N_0 \left[(1 - \alpha f_s) + \alpha f_s \frac{2}{\pi \Gamma_s} \int_{-\infty}^{\infty} \frac{dE}{[(E - E_s)/(\Gamma_s/2)]^2 + 1} \exp \left\{ - \sum_j \frac{(\Gamma_0/\Gamma_j)\, T_j}{[(E - E_s)/(\Gamma_j/2)]^2 + 1} \right\} \right], \quad (1)$$

where N_0 is the counting rate which corresponds to E_s being infinitely displaced from the E_j and the term $(1 - \alpha f_s)$ is due to all nonrecoilless background radiations which are detected. T_j is multiplied by Γ_0/Γ_j in order to allow for small extraneous broadening to be included in Γ_j. Γ_0 is the natural width.

Since the integral expression in (1) has not been evaluated in closed form, it is usually approximated by considering the first two terms of a power series expansion of the exponential function. The approximate integral can then be evaluated and results in the following approximate expression:

$$N_{app} = N_0 \times \left\{ 1 - \alpha f_s \sum_j \frac{T_j \Gamma_0/(\Gamma_s + \Gamma_j)}{[(E_s - E_j)/(\Gamma_j/2 + \Gamma_s/2)]^2 + 1} \right\} . \quad (2)$$

This is a Lorentzian distribution, but with an observed width equal to the sum of the source and absorber widths. Numerical integration of (1) has been carried out for single-line absorbers over a wide range of values for the effective thickness. The resulting distributions do not differ appreciably from a Lorentzian shape, but saturation near the peaks causes the function to be somewhat flattened. The result is that the full width at half maximum is increased as T increases. Thus single lines or well-resolved lines may be treated like broadened Lorentzians, and the widths may be interpreted in terms of the known behavior of the transmission integral.

For greatly overlapping lines or when a detailed analysis of the shape of Mössbauer transmission data is required, it is necessary to fit the data with Eq. (1) rather than to use the approximation.[3] A computer program has been developed which performs a least-squares fit with the transmission integral, Eq. (1), and gives the errors of the fitted parameters.

The Mössbauer spectra data are fitted with a function in the form of Eq. (1). The first-order approximation is evaluated from the closed form, Eq. (2), leaving only higher-order terms to be evaluated by numerical integration:

$$\Delta N = N_0\, \alpha f_s \frac{2}{\pi \Gamma_s} \int_{-E_{max}}^{E_{max}} \frac{dE}{[(E - E_s)/(\Gamma_s/2)]^2 + 1} \left[e^{-g(E)} - 1 + g(E) \right] , \quad (3)$$

where E_{max} is chosen so that the neglected part of the integral is smaller than the desired integration accuracy and

$$g(E) = \sum_j \frac{(\Gamma_0/\Gamma_j)\, T_j}{[(E - E_i)/(\Gamma_j/2)]^2 + 1} .$$

By eliminating the first two terms of the power series expansion from the numerical integration, the necessary range of integration was greatly reduced.

The integration of (3) is performed by Gauss-Legendre quadrature[4] and must be evaluated for each value of E_s in the data and for every iteration of the least-squares fitting procedure. The value of the integral is computed from the following equation:

$$I = \sum_{i=1}^{N} f(E_i)\, W_i\, \Delta E ,$$

where $f(E_i)$ is the integrand, W_i are weighting factors, E_i are selected values of the integration variable, and ΔE is the integration interval. The values of W_i and E_i are such that systematic errors in evaluating the integral are due only to residuals from an N-degree polynomial expansion of $f(E)$. Sufficient accuracy was obtained using 96-degree quadrature.

4. Anthony Ralston, *A First Course in Numerical Analysis*, McGraw-Hill, New York, 1965.

Since the second factor in the integrand of Eq. (3) is independent of the data variable, E_s, it is expedient to evaluate and store the values of this factor for each value of E_i. Then, for each data point, the remaining factor is computed and multiplied by the appropriate stored factor. Thus some computer time was saved in the repeated evaluations of the integrand. If a Lorentzian approximation is adequate for fitting a set of data, a function in the form of Eq. (2) may be used in place of the transmission integral.

With a given set of the parameters Γ_s, T_j, E_j, and Γ_j, the integral portion of Eq. (1) is evaluated. By standard least-squares fitting, the best fit of the linear parameters, N_0 and αf_s, is then computed. Then the value of χ^2 is computed:

$$\chi^2 = \sum_s \left[\frac{N_s - N(E_s)}{\delta_s}\right]^2 ,$$

where N_s is the observed counting rate at an energy E_s and δ_s is the statistical error of N_s. The values of the parameters Γ_s, T_j, E_j, and Γ_j are varied, and the resulting variations of χ^2 are noted. Further variations in the parameters are performed, which reduce χ^2, until a minimum value of χ^2 is reached (within the prescribed accuracy desired for the parameters).

An error analysis of the fitted parameters is performed by computing the error matrix, M, given by[6]

$$M_{jk}^{-1} = \sum_s \frac{\Delta N_j(E_s)}{\Delta P_j} \frac{\Delta N_k(E_s)}{\Delta P_k} \frac{1}{\delta_s^{\,2}} , \qquad (4)$$

where $\Delta N_j(E_s)$ is the change of the computed transmission [Eq. (1)] resulting from a variation ΔP_j of one of the fitted parameters. This matrix, Eq. (4), is then inverted to find M_{jk}. The statistical errors of the parameters are computed from[6]

$$\delta P_j = \left(\frac{M_{jj}\chi^2}{n_D - n_P}\right)^{+1/2} ,$$

where $n_D - n_P$ is the number of data points less the number of free parameters, that is, the number of degrees of freedom.

For the nonlinear function N [Eq. (1)], the value of ΔP_j should be the statistical error, δP_j. Therefore, the error matrix is initially computed using the desired parameter accuracy for ΔP_j; then the process is repeated, using the above results of δP_j for ΔP_j. This process is reiterated until less than 10% variation in the statistical errors is achieved. The resulting matrix is the error matrix corresponding to a linear approximation for N, which agrees with N at points separated by δP_j, centered at P_j.

Instead of working with all of the possible parameters for a least-squares fit, various constraints may be imposed. The values of Γ_s, αf_s, T_j, E_j, or Γ_j may be either fixed or free independent parameters, or they may be computed as a linear function of some other independent parameters. For example, the widths may all be made equal to one independent variable, the T_j may be made proportional to one total effective thickness parameter, and the E_j may be determined from isomer shift and splitting parameters. In such cases, the error analysis is performed on the independently variable parameters, and then the statistical errors for the dependent variables are found from the appropriate correlation terms in the error matrix.[6]

Plotting of the data, with error bars, and the fitted curve is performed on a Calcomp plotter. A curve corresponding to each component of a multiple-line spectrum is also plotted. The curves are smoothed out between data points by third-order interpolation.

The program is written in FORTRAN IV and has been successfully utilized on IBM 360/75 and 360/91 and CDC 1604 computers. A typical 400-data-point Mössbauer spectrum of ^{57}Fe in copper vs ^{57}Fe in iron can be fitted and analyzed with three independent variables (excluding N_0 and αf_s) in about 1 min of 360/91 computer time.

Various versions of the program have been written, providing for several modes of data acquisition: pulse-height mode (with or without time normalization and standard error computation), multiscaler-time mode, card input, tape input, etc. A special variation features a nonlinear constraint on the effective absorber width due to a distribution of hyperfine fields. Further modification has provided for proper treatment of split-source spectra.

5. M. J. D. Powell, *Comput. J.* 7, 303 (1965).
6. A. H. Wapstra, G. J. Nijgh, and R. Van Lieshout, *Nuclear Spectroscopy Tables*, North-Holland, Amsterdam, 1959.

6. Atomic and Molecular Physics

SELF-BROADENED ABSORPTION LINE WIDTHS FOR THE KRYPTON RESONANCE TRANSITIONS[1]

P. M. Griffin J. W. Hutcherson[2]

The total absorption, A_G, was measured as a function of absorbing gas pressure, P, and an absorption path length of 2 m for the $^1S_0 - {}^3P_1$ (λ1236 Å) and $^1S_0 - {}^1P_1$ (λ1165 Å) resonance transitions in krypton. For pressures between 0.006 and 0.06 torr, self-broadening was negligible compared with the natural width. In the pressure range 0.06 to 0.75 torr, self-broadening contributed significantly to the line width, and the line shape was symmetrical. For pressures between 1.0 and 7.0 torrs, the asymmetric van der Waals broadening was apparent. The component of the line width due to self-broadening, Γ_{SB}, was calculated from the measurements of A_G for pressures from 0.06 to 0.75 torr and was found to vary linearly with the number density of the absorbing gas, N, as predicted by theory.[3] The ratio Γ_{SB}/N was found to be in good agreement with theoretical predictions.[3]

1. Abstract of paper submitted for publication in the *Journal of the Optical Society of America.*
2. University of Tennessee at Chattanooga.
3. R. G. Breene, *The Shift and Shape of Spectral Lines,* Pergamon, New York, 1961.

LIFETIMES OF THE METASTABLE AUTOIONIZING $(1s2s2p)\ ^4P_{5/2}$ STATES OF LITHIUM-LIKE F^{6+} AND O^{5+} IONS[1]

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Electrons emitted from foil-excited beams of F^{6+} and O^{5+} ions (2.5 to 20 MeV) have been energy analyzed and their number measured vs distance from the foil. Lines associated with the $(1s2s2p)\ ^4P_{5/2}$ level and with higher quartet levels are observed to decay at various rates. Lifetimes for the $(1s2s2p)\ ^4P_{5/2}$ state in F^{6+} and O^{5+} are found to be (1.5 ± 0.1) and $(2.5 \pm 0.3) \times 10^{-8}$ sec respectively. The latter disagrees with earlier experimental work and with theoretical estimates.

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SPECTRA OF AUTOIONIZATION ELECTRONS EMITTED BY FAST METASTABLE BEAMS OF HIGHLY STRIPPED OXYGEN AND FLUORINE IONS[1]

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Unidentified metastable autoionizing states of highly stripped and excited oxygen and fluorine ions have been observed and their energies measured. Possible assignments are discussed. Appreciable populations of identifiable lithium-like states of high electronic spin and high excitation energy have also been observed and their energies compared with the results of variational calculations. The lifetime of a level identifiable as either $(1s2p3p)\ ^4P^e$ or $(1s2s4s)\ ^4S^e$ has been measured to be 1.00 ± 0.04 nsec.

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AUTOIONIZATION ELECTRONS EMITTED BY HIGHLY STRIPPED ION BEAMS

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Improvements in the apparatus[5] we use to study the electrons emitted by fast beams (2 to 30 MeV) of foil-excited oxygen and fluorine ions have permitted us to examine peaks in the spectrum of emitted electrons in more detail than previously.[6] It is clear that a number of highly energetic metastable states of high spin are produced, and we have been able to identify many of these with quartet states of lithium-like ions [e.g., $(1s2s5s)\ ^4S$ states and even more highly excited states have been observed]. In addition, new, as yet unidentified autoionizing states of such ions have been found and recently reported.[7] We suspect they may arise from (metastable) quintet levels of beryllium-like ions whose existence is not known. Figures 1 and 2 show electron spectra obtained at a separation of the target from the spectrometer viewing region of about 2 cm. The unidentified features *A* and *B* are shown. [Examples of rotation: $^4S^e(1) \to (1s2s3s)\ ^4S^e$, $^4S^e(2) \to (1s2s4s)\ ^4S^e$, $^4P^o(1) \to (1s2s2p)\ ^4P^o$, etc.]

Very recently, we have learned how to accumulate electron spectra with the target directly in view of the spectrometer. Figure 3 shows such a spectrum. From the marked change in the appearance of the spectrum, we conclude that there are a lot of new autoionizing levels appearing, some of which are metastable (e.g., *A* and *B*), since their appearance at 2-cm target separation indicates lifetimes far longer than typical 10^{-14} (see autoionization lifetimes). Further apparatus improvements are under way to permit experiments to be done with higher electron energy resolution and at variable target positions near the boundary of the viewing region. A substantial amount of information concerning previously unknown autoionizing states of simple atomic systems (those containing just a few electrons) is expected to emerge from this work. Measurements of the yield of the $(1s2s2p)\ ^4P_{5/2}$ metastable state vs target material have also been made in order to try to understand the collision mechanisms that are responsible for the production of this state when the oxygen and fluorine ion beams traverse thin foil targets. Our preliminary yield results for carbon targets[8] have been extended to include the effects of changing target material. At the same meeting, a group from the Moscow State University[9] reported a surprisingly high

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5. See ORNL-4659, p. 86.
6. I. A. Sellin et al., *Phys. Rev.* A2, 1189 (1971).
7. I. A. Sellin et al., *Phys. Rev. Lett.* 27, 1108 (1971).
8. W. W. Smith, I. A. Sellin, M. Brown, D. J. Pegg, and Bailey Donnally, "Collisional Excitation of Metastable Autoionizing States of Lithium-Like Ions in Fast Beams: Spectra and Yields," p. 513 in *Book of Abstracts*, International Conference on the Physics of Electronic and Atomic Collisions, North-Holland Publishing Co., Amsterdam, 1971.
9. I. S. Dmitriev, V. S. Nikolaev, and Y. A. Teplova, *Book of Abstracts*, p. 510, Seventh International Conference on the Physics of Electronic and Atomic Collisions, North-Holland Publishing Co., Amsterdam, 1971.

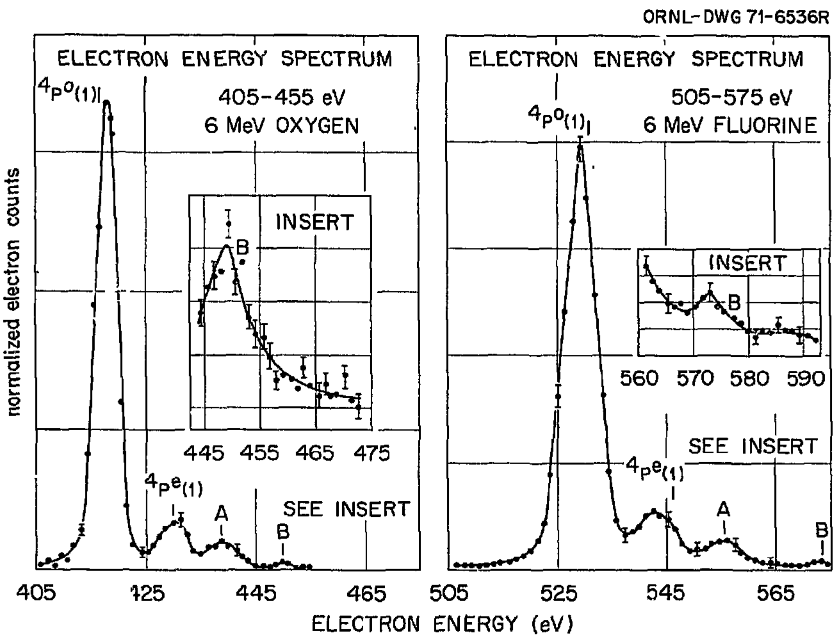

Fig. 1. Spectra of electrons from fast oxygen and fluorine beams. Features near the lowest quartet states of the three-electron ions $(1s2s2p)\ ^4P$ and $(1s2p^2)\ ^4P$.

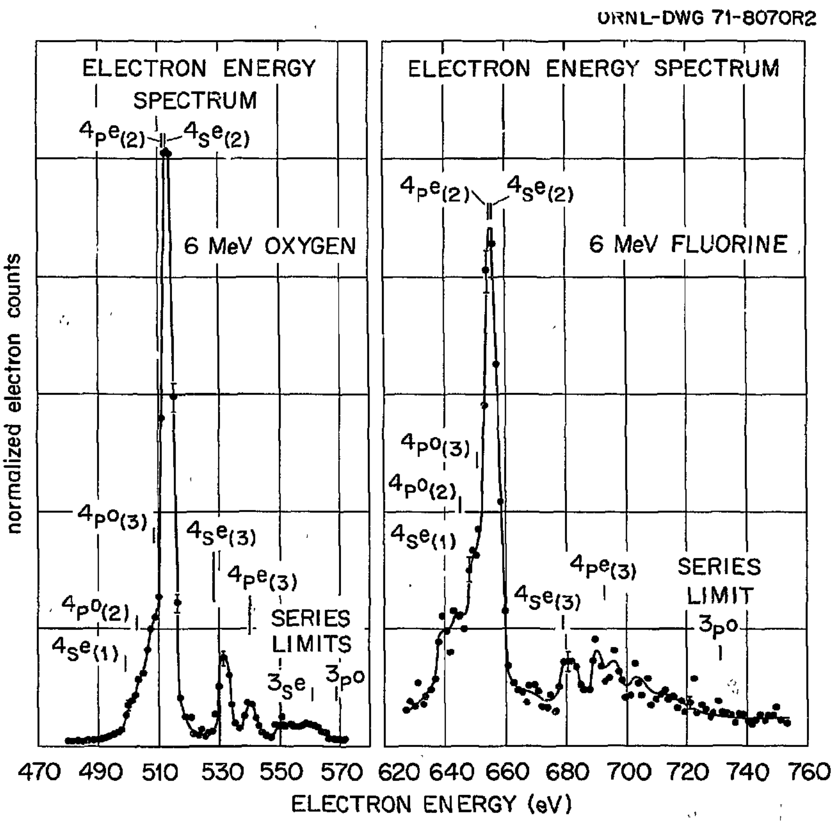

Fig. 2. Spectra of electrons from fast oxygen and fluorine beams. Higher excited quartet states of the three-electron ions.

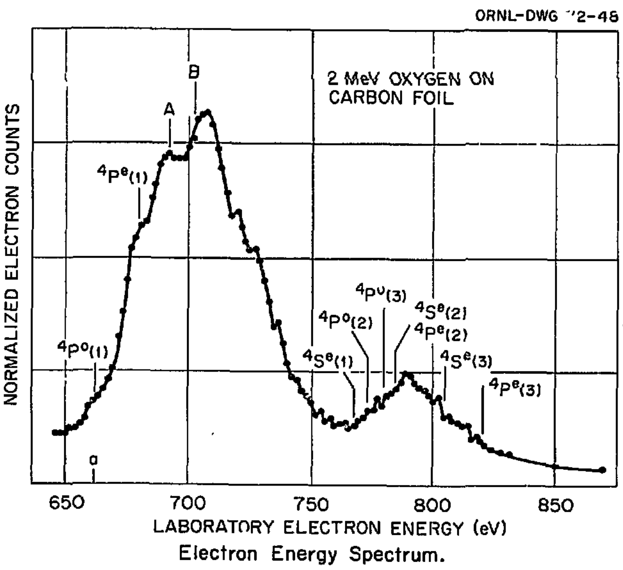

Fig. 3. As in Figs. 1 and 2, except that the target was directly in view of the spectrometer. a represents the comparative scale height for the $^4P^o(1)$ state.

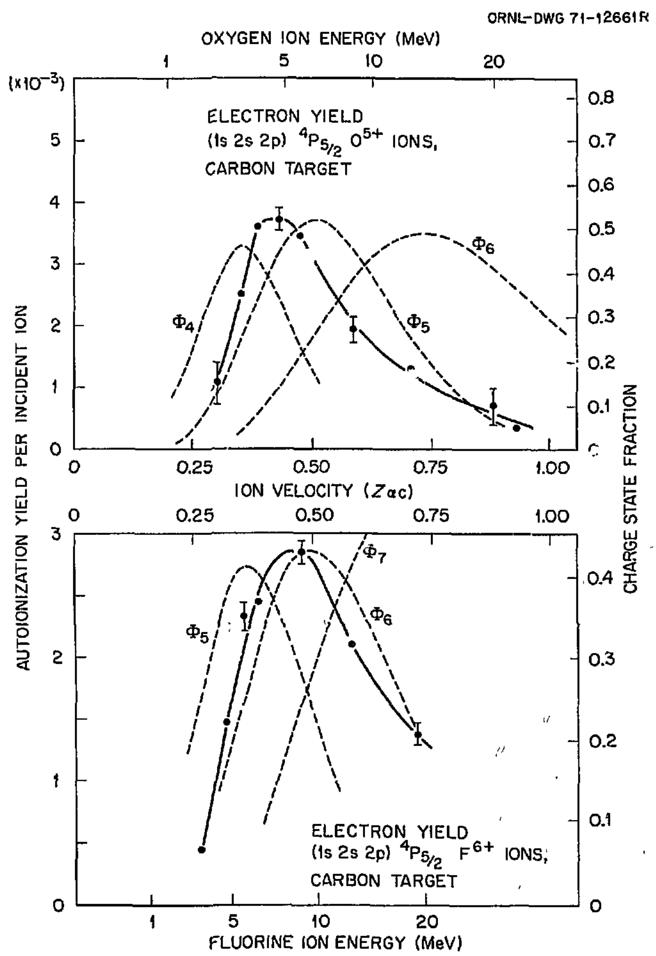

Fig. 4. Production yields of the $(1s2s2p)$ $^4P_{5/2}$ state as a function of energy.

maximum yield for the production of the $(1s2s2p)$ $^4P_{5/2}$ state in oxygen of approximately 1%. Our recent results indicate a lower figure, of approximately 0.2%, as can be seen from Fig. 1. This number is the fraction of *all* oxygen ions emerging from the foil target that are in the $(1s2s2p)$ $^4P_{5/2}$ excited metastable autoionizing state. The energy dependence of this yield can be seen in Fig. 4, from which one can see that the yield is only appreciable over a rather narrow range of energies. Also indicated in Fig. 4 are the oxygen and fluorine charge state fraction curves (dotted lines). It is noted that the yield curve peaks at approximately the same energy as does the charge state fraction curve for the three-electron oxygen and fluorine ions. One might have anticipated the peak would fall on the high-energy side of the corresponding charge state fraction, since the electronic energy of the metastable state lies above that for the two- and three-electron ground states. The yield work using oxygen ions has been extended to other target materials (Al, Ni, Ag, Au), and preliminary results indicate that the yield for production of the $(1s2s2p)$ $^4P_{5/2}$ state is greatest for aluminum targets and lowest for gold targets. Further analysis of these results is being done. Since the very highly excited ions have large radii (they grow as n^2), it may turn out that surface interactions affect them more strongly than ground-state ions.

THEORETICAL TREATMENT OF THE ENERGY DIFFERENCES BETWEEN $f^q d^1 s^2$ AND $f^{q+1} s^2$ ELECTRON CONFIGURATIONS FOR LANTHANIDE AND ACTINIDE ATOMIC VAPORS[1]

L. J. Nugent[2]   K. L. Vander Sluis

The differences between the lowest energy level of the $f^q d^1 s^2$ electron configuration and the lowest energy level of the $f^{q+1} s^2$ electron configuration for the metal vapors of nine members of the lanthanide series and four members of the actinide series are shown to be neatly and simply correlated by an adaptation of Jørgensen's refined electron-spin-pairing energy theory. The theory is also used to extrapolate the corresponding energy differences for those lanthanide and actinide metal vapors for which this information was previously undetermined. The results will be helpful as a guide in making spectral assignments, and they are generally useful in correlating the thermodynamic properties of the chemical compounds of the lanthanide and actinide series. The theoretical basis of the treatment should also be applicable for correlating the relative energies of other electron configurations in these metal atoms and ions.

1. Abstract of published paper: *J. Opt. Soc. Amer.* **61**, 1112 (1971).
2. Chemistry Division.

RELATIVISTIC HARTREE-FOCK-SLATER EIGENVALUES, RADIAL EXPECTATION VALUES, AND POTENTIALS FOR ATOMS, $2 \leqslant Z \leqslant 126$[1]

C. C. Lu[2]   T. A. Carlson[3]   F. B. Malik[4]   T. C. Tucker[2]   C. W. Nestor, Jr.[2]

Relativistic Hartree-Fock-Slater wave functions have been calculated for all elements with $Z = 2$ to $Z = 126$. From these wave functions we have obtained, and present in tables, the eigenvalues and expectation values of r, $1/r$, $1/r^3$, r^2, and r^4 for each orbital, the total energy of the atom, and the total potential as a function of radius.

1. Abstract of published paper: *At. Data* **3**, 1 (1971).
2. Mathematics Division.
3. On loan from Chemistry Division.
4. Consultant from Indiana University, Bloomington.

COMPREHENSIVE CALCULATION OF IONIZATION POTENTIALS FOR MULTIPLY CHARGED IONS FROM $Z = 104$ TO 126[1]

Thomas A. Carlson[2]   C. W. Nestor, Jr.[3]   J. D. McDowell[3]

Ionization potentials have been calculated for elements from $Z = 104$ to 126 for all states of ionization. The calculations are based on a simple spherical shell model using eigenvalues and mean radii from relativistic Hartree-Fock solutions for the neutral atoms.

1. Abstract of ORNL-4721.
2. On loan from Chemistry Division.
3. Mathematics Division.

CALCULATION OF THE *K* X-RAY INTENSITIES FOR ELEMENTS FROM $Z = 92$ TO 126[1]

C. C. Lu[2]   F. B. Malik[3]   Thomas A. Carlson[4]

Calculations of the radiative transition rates have been made for filling a *K*-shell vacancy from electrons in the *L, M, N, O,* and *P* shells for each element from $Z = 92$ to 126. With the help of these values and the previously calculated x-ray energies, one may use x-ray spectra arising from *K* vacancies of the heavy and superheavy elements as an unambiguous means for identifying these elements. The calculations are relativistic and utilize relativistic Hartree-Fock-Slater wave functions. From the radiation rates, the natural widths have also been computed; and a listing of binding energies and x-ray energies is given for elements $Z = 121$ to 126.

1. Abstract of published paper: *Nucl. Phys.* **A175**, 289 (1971).
2. Mathematics Division.
3. Consultant from Indiana University, Bloomington.
4. On loan from Chemistry Division.

PHOTOELECTRON SPECTRUM OF CHLORINE MONOFLUORIDE[1]

C. P. Anderson[2] G. Mamantov[3] W. E. Bull[3] F. A. Grimm[3] J. C. Carver[2] Thomas A. Carlson[4]

The photoelectron spectrum of ClF was taken with the helium I (21.22 eV) resonance line. Adiabatic ionization potentials were obtained and assignments made to the three observed bands. Spin-orbit splitting in the first band was found to be in good agreement with theory.

1. Abstract of published paper: *Chem. Phys. Lett.* 12, 137 (1971).
2. Student guest assignee from the University of Tennessee, Knoxville.
3. University of Tennessee, Knoxville.
4. On loan from Chemistry Division.

THE PHOTOELECTRON SPECTRA OF THE TETRAFLUORO AND TETRAMETHYL COMPOUNDS OF THE GROUP IV ELEMENTS[1]

Arthur E. Jonas[2] George K. Schweitzer[3] F. A. Grimm[3] Thomas A. Carlson[4]

The photoelectron spectra of CF_4, SiF_4, GeF_4, $C(CH_3)_4$, $Si(CH_3)_4$, $Ge(CH_3)_4$, $Sn(CH_3)_4$, and $Pb(CH_3)_4$ have been obtained using a double-focusing electron spectrometer with a helium I (21.22 eV) photon source. In addition, studies of the angular distributions of photoelectrons have been made on the tetramethyl compounds. Analyses of the spectra allowed electron ionization energies to be obtained. With the aid of CNDO/2, MINDO, and SCCMO semi-empirical calculations, the band shapes, vibrational fine structure in the spectra, and the angular distribution data, the ionization energies have been assigned to specific valence-level molecular orbitals. The splitting of degeneracies was observed throughout the tetramethyl series, the mechanism being chiefly Jahn-Teller in the early members and chiefly spin-orbit in the later members. Stabilization of certain molecular orbitals in both series of compounds was in accord with the presence of back bonding into vacant *d* orbitals and its increasing importance as the atomic number of the central atom is increased.

1. Abstract of paper submitted for publication in the *Journal of Electron Spectroscopy.*
2. Student guest assignee from the University of Tennessee, Knoxville.
3. University of Tennessee, Knoxville.
4. On loan from Chemistry Division.

ANGULAR DISTRIBUTION OF THE PHOTOELECTRON SPECTRA FOR Ar, Kr, Xe, H_2, N_2, AND CO[1]

Thomas A. Carlson[2] A. E. Jonas[3]

The distribution of photoelectrons as a function of the angle θ between the direction of the incoming photon and outgoing photoelectron has been measured for Ar, Kr, Xe, H_2, N_2, and CO. The experiments have been carried out with a double-focusing electrostatic electron spectrometer to which has been attached a chamber containing a gas discharge lamp that can be freely rotated. The He I (584 Å) and Ne I (736, 744 Å) resonance lines were used as photon sources. For each of the photoionization bands studied, the angular distribution could be fitted to the general shape predicted from theory: $1 + (\beta/2)(\frac{3}{2}\sin^2\theta - 1)$. In addition, the values of the parameter β experimentally determined were in good agreement with theoretically determined values for H_2 and for the rare gases but only partially satisfactory agreement for the first ionization potential of N_2. The Π state of N_2^+ and CO^+ gives lower values of β than the Σ state according to expectations. In general, the vibrational structure for a given band was independent of θ, but several exceptions were found for both N_2 and CO, which have been discussed in terms of the presence of autoionization states and possible breakdown in the Born-Oppenheimer approximation.

1. Abstract of published paper: *J. Chem. Phys.* 55(10), 4913 (1971).
2. On loan from Chemistry Division.
3. Student guest assignee from the University of Tennessee, Knoxville.

ANGULAR DISTRIBUTION OF THE PHOTOELECTRON SPECTRUM FOR BENZENE[1]

T. A. Carlson[2] C. P. Anderson[3]

The angular distribution of photoelectrons ejected from benzene using 21.22-eV radiation has been measured and the results applied to the analysis of the ionization bands.

1. Abstract of published paper: *Chem. Phys. Lett.* **10**(5), 561 (1971).
2. On loan from Chemistry Division.
3. Graduate student, University of Tennessee, supported by NSF Fellowship.

COMPREHENSIVE EXAMINATION OF THE ANGULAR DISTRIBUTION OF PHOTOELECTRON SPECTRA FROM ATOMS AND MOLECULES[1]

Thomas A. Carlson[2] G. E. McGuire[3] A. E. Jonas[3] K. L. Cheng[4]
C. P. Anderson[3] C. C. Lu[5] B. P. Pullen[6]

Photoelectron spectra have been measured as a function of angle between the incident photon and ejected photoelectron for the following gases: Ar, Kr, Xe, H_2, N_2, O_2, CO, NO, HCl, N_2O, CO_2, COS, CS_2, H_2O, H_2S, CH_4, CH_3F, CH_3Cl, CH_3Br, CH_3I, CH_2F_2, $C(CH_3)_4$, $Si(CH_3)_4$, $Ge(CH_3)_4$, $Sn(CH_3)_4$, $Pb(CH_3)_4$, C_2H_4, and C_6H_6. Each gas was studied with the He I resonance line (21.22 eV) and in a few selected cases the Ne I (16.85 and 16.67 eV) lines. An angular parameter β was determined for most of the photoelectron bands seen in the spectrum. The experimental data are examined for the information they offer on the nature of the molecular orbitals. Agreement with the few theoretical calculations that have been made is generally good. The nature of the angular parameter β has been generalized with regard to the importance of the final electronic state, its systematic behavior in a homologous series of molecules, and the behavior of the vibrational structure.

1. Abstract of paper to be published in the *Proceedings of International Conference on Electron Spectroscopy*, Asilomar, California, September 1971, North-Holland Publishing Company.
2. On loan from Chemistry Division.
3. Student guest assignee from University of Tennessee, Knoxville.
4. University of Missouri, Kansas City.
5. Mathematics Division.
6. Southeastern Louisiana State College, Hammond.

THE ν_2 FUNDAMENTAL VIBRATION-ROTATION BAND OF T_2O[1]

Raymond A. Carpenter[2] Norman M. Gailar[3] Henry W. Morgan Percy A. Staats

The ν_2 fundamental vibration-rotation band of T_2O vapor has been measured at grating resolution, and the rotational structure has been analyzed. The band center and the values of the rotational constants *A*, *B*, and *C* for the ground state and excited state have been determined. These values are consistent with the data for *J* through 6 and with extrapolations from H_2O and D_2O.

1. Abstract of paper to be published in *Molecular Spectroscopy*.
2. U.S. Atomic Energy Commission, Washington, D.C.
3. University of Tennessee, Knoxville.

VIBRATIONAL SPECTRA AND CRYSTAL STRUCTURE OF $POBr_3$[1]

E. Huler[2] A. Burgos[2] E. Silberman[2] H. W. Morgan

The infrared spectrum (200 to 4000 cm^{-1}) of phosphoryl bromide, sublimed and recondensed in a low-temperature cell, was examined with 0.3 to 0.6 cm^{-1} resolution. Strong orientation effects were observed in crystals deposited on CsI windows. The spectrum of molecules isolated in an argon matrix at liquid-helium temperature was also obtained. Raman shifts of crystals at room temperature and at −190°C were measured with a laser Raman spectrometer. The density of the solid was determined near the freezing point. Analysis of the band splittings and polarization, completed by packing considerations, leads to D_{2h}^{16} as the most probable structure of crystalline $POBr_3$.

1. Abstract of paper to be published in the *Journal of Molecular Structure*.
2. Infrared Spectroscopy Laboratory, Fisk University, Nashville, Tenn.; and Department of Physics, Vanderbilt University, Nashville, Tenn.

VIBRATIONAL SPECTRA AND STRUCTURE OF SOLID $POCl_3$[1]

A. Burgos[2] E. Huler[2] E. Silberman[2] H. W. Morgan

The infrared spectrum (200 to 4000 cm^{-1}) of phosphoryl chloride, deposited and annealed in a low-temperature cell, was examined with 0.3 to 0.6 cm^{-1} resolution. Spectra of molecules isolated in argon, carbon oxide, and methane at liquid-helium temperatures were also obtained. Raman shifts of crystals at −190°C were measured with a laser Raman spectrometer. Orientation effects observed by deposition on CsI windows are discussed. The density of the solid was determined near the freezing point. Analysis of the band splittings and polarization, complemented by packing considerations, leads to D_{2h}^{16} as the most probable structure of crystalline $POCl_3$.

1. Abstract of published paper: *J. Mol. Struct.* 9, 283 (1971).
2. Infrared Spectroscopy Laboratory, Fisk University, Nashville, Tenn.; and Department of Physics, Vanderbilt University, Nashville, Tenn.

INFRARED SPECTRA OF THE METABORATE ION IN ALKALI HALIDE SOLID SOLUTION[1]

H. W. Morgan P. A. Staats

Published and unpublished data on the infrared absorption spectra of BO_2^- in alkali halide lattices have been collected and evaluated. Discrepancies have been resolved by additional experimental work. A review of the preparation and stability ot the solid solutions is given.

1. Abstract of paper to be published in *Spectrochimica Acta* (in press).

USE OF PHOTOELECTRON SPECTROSCOPY FOR APPLIED RESEARCH[1]

Thomas A. Carlson[2] Nils Fernelius[3]

The use of photoelectron spectroscopy in research is discussed with particular attention paid to applied problems. Specific examples are examined in the various fields of biological systems, environmental studies, surface studies, and industrial control.

1. Abstract of article to appear in *Industrial Research*.
2. On loan from Chemistry Division.
3. Research Consultants, Inc., Oak Ridge, Tenn.

STUDIES OF SULFUR COMPOUNDS ADSORBED ON SMOKE PARTICLES AND OTHER SOLIDS BY PHOTOELECTRON SPECTROSCOPY[1]

L. D. Hulett[2] T. A. Carlson[3] B. R. Fish[4] J. L. Durham[5]

Photoelectron spectroscopy as a means of air pollution monitoring and as a tool for smoke pollution research has been studied. Field samples of fly ash from a power plant and smoke particles from a home furnace have been analyzed. It is shown that the oxidation states of sulfur in compounds adsorbed on these solids can be determined. The use of photoelectron spectroscopy for studying the effects of combustion variables and downwind conditions on the oxidation state of sulfur on fly ash and smoke particles is discussed. The composition of the solid on which SO_2 is adsorbed was found to be an important variable in the rate at which oxidation to sulfate occurs.

1. Abstract of paper published in *Determination of Air Quality*, pp. 187–95, ed. by G. Mamantov and W. D. Shults, Plenum, New York, 1971.
2. Analytical Chemistry Division.
3. On loan from Chemistry Division.
4. Health Physics Division.
5. Environmental Protection Agency, Research Triangle Park, N.C.

USE OF X-RAY PHOTOELECTRON SPECTROSCOPY TO STUDY BONDING IN TRANSITION METAL SALTS BY OBSERVATION OF MULTIPLET SPLITTING[1]

J. C. Carver[2] Thomas A. Carlson[3] L. C. Cain[2] G. K. Schweitzer[4]

Multiplet splitting of the penultimate *s* level is studied by use of soft x-ray photoelectron spectroscopy on about 40 transition metal compounds. The splittings vary as the degree of participation of the *d* electrons in the bonding changes and as the number of unpaired electrons changes. Qualitative examples of these behaviors are demonstrated. Theoretical predictions based on Hartree-Fock free-ion calculations give the correct trend for the different metal ions.

1. Abstract of paper to be published in the *Proceedings of International Conference on Electron Spectroscopy,* Asilomar, California, September 1971, North-Holland Publishing Company.
2. Student guest assignee from University of Tennessee, Knoxville.
3. On loan from Chemistry Division.
4. University of Tennessee, Knoxville.

ELECTRON SPECTROSCOPY FOR CHEMICAL ANALYSIS[1]

Thomas A. Carlson[2]

The nature of electron spectroscopy is discussed with regard to its use in the study of chemical problems, and the current status of the field is evaluated. The article is derived for the most part from an introductory talk given at the International Conference on Electron Spectroscopy, held in Asilomar, California, September 1971 (see below). However, the article has been edited, and certain points have been amplified and explained for the general reader.

1. Abstract of published paper: *Phys. Today,* January 1972, pp. 30–39.
2. On loan from Chemistry Division.

GENERAL SURVEY OF ELECTRON SPECTROSCOPY[1]

Thomas A. Carlson[2]

The basic phenomena underlying the use of electron spectroscopy are presented, and a comparison is made between the photoelectron effect, the Auger process, and x-ray fluorescence as to the type of chemical information that can be derived. An evaluation of the current status of research in photoelectron and Auger spectroscopy is given, and specific examples of research are discussed which illustrate new developments in the field. Finally, a discussion is made of some of the major problems which still face electron spectroscopy and the possibility for their solution.

1. Abstract of paper to be published in the *Proceedings of International Conference on Electron Spectroscopy,* Asilomar, California, September 1971, North-Holland Publishing Company.
2. On loan from Chemistry Division.

PRIMARY PROCESSES IN HOT ATOM CHEMISTRY[1]

Thomas A. Carlson[2]

An examination is made of the initial excitation phenomena associated with atoms and molecules as the result of nuclear decay. The three principal sources of excitation are: (1) the recoil energy that is imparted to the hot atoms, (2) the readjustment to a vacancy in an inner shell of an atom by a series of Auger processes, and (3) electronic excitation and ionization that arises from electron shake-off. After these three sources have been analyzed, specific problems are discussed associated with the various modes of nuclear processes, namely, beta decay, positron decay, alpha decay, gamma transition, internal conversion, electron capture, nuclear reactions, and fission. A review of the literature is made for both experimental and theoretical contributions to the field of primary processes in hot atom chemistry.

1. Abstract of chapter to appear in *Nuclear Transformations in Solids,* ed. by Harbottle and Maddock, North-Holland Publishing Company.
2. On loan from Chemistry Division.

PHOTOELECTRON SPECTROSCOPY[1]

Thomas A. Carlson[2]

A brief evaluation of the uses of photoelectron spectroscopy for the study of chemical bonding is made. The field is broken into two parts: photoelectron spectroscopy of the outer shells (PESOS) and photoelectron spectroscopy of the inner shells (PESIS). PESOS, with the help of vacuum ultraviolet radiation, is used for obtaining the explicit binding energies of molecular orbitals. With PESIS, using x rays, one studies the atomic binding energies that are slightly shifted according to changes in the chemical environment. Both the present status and future expectations for the fields of photoelectron spectroscopy are given.

1. Abstract of article for the *McGraw-Hill Year Book of Science and Technology for 1971*, p. 400.
2. On loan from Chemistry Division.

EQUILIBRIUM CHARGE STATES OF FAST HEAVY IONS[1]

C. D. Moak

Measurements of equilibrium charge distributions for a wide variety of ions are being reported frequently in current literature. These measurements have improved the accuracy of various interpolations for velocity of ion species which may be needed in accelerator design or in planning experiments. Certain major effects and several minor ones have been identified, and these must be considered in making such estimates. The relative importance of some of the factors affecting equilibrium distributions is discussed.

1. Abstract of paper to be published in the *Proceedings of the International Conference on Multiply-Charged Heavy Ion Sources and Accelerating Systems, Gatlinburg, Tenn., Oct. 25–28, 1971.*

COLLISIONAL EXCITATION OF METASTABLE AUTOIONIZING STATES OF LITHIUM-LIKE IONS IN FAST BEAMS: SPECTRA AND YIELDS[1]

W. W. Smith[2] I. A. Sellin[3] M. D. Brown[4] D. J. Pegg[3] B. L. Donnally[5]

We have measured electron spectra and yields from long-lived autoionizing states of lithium-like O^{5+} and F^{6+} ions collisionally excited in a fast beam by passing the beam through a carbon foil target (~10 μg/cm^2). These states have been studied in lithium-like ions up to $Z = 8$ (oxygen) by Dmitriev et al. by observing the change of charge of the beam in flight. We report here the first emission spectroscopy of autoionization electrons from these states.

1. Abstract of published abstract: *Book of Abstracts*, International Conference on the Physics of Electronic and Atomic Collisions, p. 513, 1971.
2. Oak Ridge Associated Universities, Consultant from the University of Connecticut, Storrs.
3. Consultant from the University of Tennessee, Knoxville.
4. Present address: Department of Physics, Kansas State University of Agriculture and Applied Science, Manhattan, Kan.
5. Oak Ridge Associated Universities, Consultant from Lake Forest College, Lake Forest, Ill.

COMMENT ON RELATIVE MAGNETIC SUBSTATE AMPLITUDES IN FOIL EXCITATION OF FAST HYDROGEN ATOMS[1]

I. A. Sellin[2]

If the particle-foil interaction potential governing production of hydrogen atoms coherently excited by passage through thin foils obeys the *L-S* coupling scheme applied by Macek (conservation of *z* components of total orbital and spin angular momenta of the entire particle-foil system, and incoherence of final states of foil constituents), the ad hoc assumption that random phases prevail among the hydrogenic magnetic substate amplitudes invoked in the interpretation of certain recent experiments is avoided. Arguments concerning relative phases of states of different orbital angular momentum are unaffected.

1. Abstract of published paper: *Phys. Rev. A*, Comments and Addenda Section, 3 (4) (1971).
2. Consultant from the University of Tennessee, Knoxville.

DIFFERENTIATION IN *L*-SUBSHELL VACANCY PRODUCTION IN IODINE IONS BY ATOMIC COLLISIONS AT 15–60 MeV[1]

S. Datz[2] C. D. Moak B. R. Appleton[3] T. A. Carlson[4]

A study of the iodine *L* x-ray spectra arising from collisions of 15- to 60-MeV ^{127}I ions with target atoms ranging from carbon to lead (Z_2 = 6 to 82) shows large systematic variations in the relative number of vacancies produced in the $2p_{3/2}$ and the $2p_{1/2}$ subshells.

1. Abstract of published paper: *Phys. Rev. Lett.* 27(7), 363 (1971).
2. Chemistry Division.
3. Solid State Division.
4. On loan from Chemistry Division.

RELATIVE ABUNDANCES AND RECOIL ENERGIES OF FRAGMENT IONS FORMED FROM THE X-RAY PHOTOIONIZATION OF N_2, O_2, CO, NO, CO_2, AND CF_4[1]

Thomas A. Carlson[2] Manfred O. Krause[3]

A specially designed mass spectrometer has been used to study the fragment ions following x-ray photoionization of several simple gaseous molecules containing only first-row elements. Two photon sources were used: copper *Lα* (930 eV) and carbon *Kα* (280 eV). The higher-energy x-ray source produced initial vacancies primarily in the *K* shells of the different elements, while the lower-energy radiation produced ionization entirely in the valence shells. Data were obtained as a function of collection voltage, and relative abundances of the fragment ions were evaluated under conditions of equal collection efficiency. From the shape of the collection efficiency curve, the average recoil energies were estimated. The results are briefly discussed in terms of the effect of the *KLL* Auger processes and multiple ionization.

1. Abstract of paper to be published in the *Journal of Chemical Physics.*
2. On loan from Chemistry Division.
3. Chemistry Division.

COMMENT: REJUVENATION OF HELIUM-NEON LASERS[1]

P. A. Staats H. W. Morgan

Loss of helium by diffusion through glass is an unimportant factor in the lifetime of helium-neon lasers. Contamination of the gas mixture by degassing from the glass or metal electrodes is most frequently the reason for loss of output power.

1. Abstract of published paper: *Rev. Sci. Instrum.* 42, 1380 (1971).

STOPPING POWER OF SOME SOLIDS FOR 30- TO 90-MeV ^{238}U IONS[1]

M. D. Brown[2] C. D. Moak

Uranium ions of energies in the range 30 to 90 MeV from the Oak Ridge tandem accelerator were used to measure stopping powers for C, Al, Ni, Ag, and Au foils. Foil thicknesses were determined by alpha-particle energy-loss measurements. The results are compared with various theoretical predictions. Subtraction of an assumed nuclear stopping component leaves a residual electronic stopping power which is velocity proportional but does not appear to extrapolate to the origin, in disagreement with theory. Comparisons with other ions indicate that heavier ions exhibit larger discrepancies with theory in that the velocity-proportional stopping extrapolates to zero stopping at larger values of velocity.

1. Abstract of paper submitted for publication in the *Physical Review.*
2. Graduate student, University of Tennessee, Knoxville.

THE RESPONSE OF A SILICON SURFACE-BARRIER DETECTOR TO BROMINE, IODINE, AND URANIUM IONS[1]

M. D. Brown[2]

Multicomponent bromine, iodine, and uranium beams from the Oak Ridge tandem accelerator were used to measure the pulse-height response of silicon surface-barrier detectors in the ion energy range 20 to 100 MeV. The detectors were found to have pulse-height defects of 3.0 ± 0.5 MeV, 4.0 ± 0.5 MeV, and 6.3 ± 1.0 MeV corresponding to bromine, iodine, and uranium ions respectively. An energy-dependent correction larger than the pulse-height defect is needed for iodine and uranium response data over most of the energy range studied. Certain previously published theoretical explanations which attribute detector nonlinearities to atomic scattering at the end of the ion's range are in reasonable agreement with these results.

1. Abstract of paper to be submitted for publication in *Nuclear Instruments and Methods*.
2. Graduate student, University of Tennessee, Knoxville.

CHARGE STATES OF 29.2- TO 45.7-MeV URANIUM IONS EMERGING FROM SOLID FOILS[1]

M. D. Brown[2]

The equilibrium charge-state distributions of uranium ions have been measured in carbon at 29.2 and 45.7 MeV, in aluminum at 29.1 MeV, in silver at 29.7 MeV, and in gold at 29.6 MeV exit beam energy. Following the passage of monoenergetic uranium ions from the Oak Ridge tandem accelerator through each thin foil target, the charge states in the emergent beams were spatially separated in an electrostatic analyzer and measured with a position-sensitive surface-barrier detector. The foil thicknesses, derived from alpha-particle energy-loss measurements, were 34 $\mu g/cm^2$ for carbon, 51 $\mu g/cm^2$ for gold. Non-Gaussian charge-state distributions were observed. The most probable charge states are in reasonable agreement with published semiempirical formulas, although some deviations are noted.

1. Abstract of paper submitted for publication in the *Physical Review*.
2. Graduate student, University of Tennessee, Knoxville.

7. Instrumentation and Experimental Techniques

HIGH RESOLUTION ELECTRON MICROSCOPY PROGRAM

R. E. Worsham J. E. Mann E. G. Richardson N. F. Ziegler

During calendar year 1971, the development program for the instrumentation in High Resolution Electron Microscopy was concentrated in two major areas. The first one was the continued improvement for high resolution and the conversion for 150-kV high-coherence operation of Microscope I.[1] High coherence[2] means a value of transverse coherence length of the illuminating beam at the specimen >1000 Å. This figure compares with <50 Å in usual operation. The brightness of a field-emission gun is required for the exposure time to be but a few seconds rather than the order of hours. High-coherence operation of Microscope I will lead to micrographs in which the resolution will be limited by primary spherical aberration of the objective lens to ~3 Å. However, theory predicts that spatial information of ~1 Å exists in the image in this case that may be brought out by further analysis. The method of image analysis is being developed by Welton[3] and is reported separately. Scanning of the micrograph with a digitally recording microdensitometer and processing off-line are required.

All of the modifications and additions for high resolution were completed. The new illuminating system – including the field-emission gun, aperture, condenser lens, ultrahigh vacuum system, and high voltage terminal – was 80% designed, and most of the parts were being constructed. The target date for completion of all parts is March 15, 1972.

The second area of the program included the development of certain components, described below, for Microscope II – the 150-kV scanning column that will have correction for the primary spherical aberration of the objective lens. A resolution of <1 Å is theoretically possible directly on the micrographs. Scanning permits separation of the scattered from the unscattered beams and, also, separation of the inelastically scattered from the elastically scattered beam. An energy analyzer and apertures provide these three signals for each elementary area of the speciment. Thus, more information is available than in the conventional mode. Digital control and on-line digital recording simplify operation by eliminating the photographic output and its subsequent conversion to digital form. On-line analysis, also, becomes possible.

The following paragraphs summarize the work that was completed.

Microscope I

Specimen stage. This mechanism – located on the objective lens and operating at 4.2°K in 10^{-8} torr vacuum – was installed and tested at magnifications up to ~50,000. The motion is smooth, and there is no evidence of drift in the region of 20 Å resolution that was observed.

Specimen exchange mechanism. This device allows ten specimens to be loaded, pumped to 10^{-6}–10^{-8} torr, and cooled to 77°K prior to insertion into the stage mechanism. On insertion into the cryostat, the specimens are cooled in steps to ~30°K and to ~4.2°K before they are inserted and released in the holder of the stage. Total insertion time is ~30 min. Switching from one specimen to another during operation requires about 1 min. The precision of resetting a specimen appeared to be well within 25 μ.

Cryostat modifications, operation, thermal oscillations. The covers to shields I and II were replaced with new ones shaped to permit more effective cryopumping

1. R. E. Worsham et al., Oak Ridge National Laboratory report ORNL-4649, pp. 108–19 (Dec. 31, 1970).

2. T. A. Welton, Oak Ridge National Laboratory report ORNL-4659, pp. 6–13 (Dec. 31, 1970).

3. T. A. Welton, "Electron-Optical Factors Limiting Resolution in Transmission Electron Microscopes," this report.

by the colder surfaces. Experience showed that two of the four vents could carry the vapor under all conditions, allowing two vents to be removed. Reduction of possible volumes for thermal oscillation was the motivation. No difficulty is encountered in pumping the liquid helium to reach a temperature of 1.8°K. All of the electrical leads – the major heat leak – originating at the helium vessel (40, total) were routed through the vents. Baffles of cotton in the low-temperature ends of the vents and Teflon baffles added inside of the vents reduced the thermal oscillations. Rubber diaphragms and piezoelectric detectors located at the vent exits showed no oscillations after filling. These baffles increased the efficiency of heat exchange during cooldown so that only ~27 liters is required when cooling from 77°K. In regular daily operation, 14 liters is required for filling if one run per day is made. Immediate refill at the end of a run requires about 8 to 9 liters to get 7 liters into the helium vessel. The operating time available after each filling is 8 to 12 hr.

A tank that holds about 6 liters of liquid nitrogen was added to shield II. Its purpose is to assist cooldown and help hold the cryostat cold over periods between runs. The reduction in liquid helium boil-off rate that it produces is quite small.

Four heavy epoxy-glass posts held in compression by stainless steel rods replaced the existing posts. They clamp all of the cryostat parts rigidly to the tank base plate, thus fixing the position of the objective lens.

Objective lens. A new superconducting objective lens capable of operation to ~150 kV was added. The pole pieces are of Hiperco 50. Finish of the pole faces and the lens bores to 3–4 μin. was achieved. The Hiperco 50 forging has grain size of ASTM No. 8.

Alignment coils. Two pairs of coils were added to help guide the beam on the rather long flight path between the condenser and the objective lenses. The upper pair is used with the thermionic gun. The lower set, in the cryostat at ~4°K, is used with both the thermionic and field-emission guns. This set of coils may be driven for scanning. Eight current-regulated supplies furnish the bidirectional currents required.

Stigmator – illumination. An eight-coil stigmator – double quadrupole – was added in the cryostat region for use with either gun. Two current-regulated power supplies controlled by sine-cosine pots furnish the currents.

Stigmator – objective lens. A coil similar to that of the stigmator above but designed to fit in the 0.270-in. bore of the objective lens was added. The windings are superconducting. The stigmator power supplies are similar to the one above, but, in addition, two more power supplies permit driving the coil as an octopole.

Objective aperture. A carrier and adjusting mechanism was added for a molybdenum strip aperture. The apparatus, like the stage, is attached to the objective lens, so that operation at 4.2°K is required. The strip has 11 apertures.

Intermediate lens. This lens was constructed with 5-mm minimum focal length pole pieces for 150-kV operation. Overall magnification of ~770,000 is possible. Because of the limited brightness of the thermionic gun, magnification to about 50,000 has been the limit for testing.

Voltage focusing. The flux pump is inherently slow in adjustment because of the limited open-circuit resistance of the persistent current switches and the large inductance of the lens. It was found more staisfactory in focusing to set the flux pump as a coarse control and control the fine focusing by voltage variation. The Siemens 100-kV supply was modified for use with the thermionic gun. A highly stable 1500-V supply was built, to go in the high-voltage terminal for use with the 150-kV accelerating system.

Channeltron viewer. For operation at low beam currents or at very high magnification, a 25-mm-diam Channeltron electron multiplier with an integral phosphor screen may be inserted just above the regular viewing screen.

Vacuum system modifications. A titanium sublimator pump was added to the cryostat to reduce the time required to pump down. The buildup in the cryosorb pumps of helium and neon, it is believed, both of which are pumped slowly by ion pumps, led to the inclusion of a heavily trapped two-stage mechanical pump in the fore line. The valves between the three vacuum regions were enlarged and converted to nonsliding types to help ensure that no insulating material can be seen by the beam.

150-kV power supply. Replacement of the ceramic capacitors in the high-voltage divider with paper capacitors led to no significant change in the noise level under 1 Hz. A capacitor made of 25 ft of RG19/U that eliminates the potential dividing resistors was installed.

Field-emission tips. A program to make field-emission tips and to perfect the technique for forming and operating them was reinitiated. Two procedures – one involving voltage forming only and a second involving thermal cleaning and high-current forming – were developed, leading to large and relatively quiet beams of electrons emitted at small angles to the tip axis.

Field-emission gun. A computer study of the cardinal points and aberrations as a function of gun geometry was completed. The most significant result was that gun geometry is not critical. A simple two-electrode geometry, slightly reentrant, was adopted. Axial motion of the tip is required to hold the image in a fixed location for different tip operating voltages. For high-coherence illumination, the beam must approach the specimen plane with an aperture $<10^{-5}$ radian. A single condenser lens, with a minimum focal length of ~3 mm, can match the tip image formed by the gun to the second-zone objective lens.

A high-voltage terminal, mounted directly beside the gun, contains the 1500-V supply for focusing plus all of the supplies required for tip operation: positive 1 to 5 kV for accelerating voltage, negative 0 to 10 kV for forming, and current for tip flashing. A series resistance of 10^9 Ω may be inserted in the 150-kV line for high-voltage conditioning.

Microscope II

Energy analyzer. The electrons inelastically scattered by specimen occupy a beam aperture only slightly larger than that of the no-loss (noninteracting) beam. The beam elastically scattered occupies sufficiently larger angles that it may be separated by an aperture (a solid-state detector with a hole in the center) from the other two components. The no-loss and inelastic beams may be separated by an energy analyzer. For the ~1 ppm resolution required at 150 kV, a retarding-field filter was selected. The no-loss beam will be transmitted through the filter to a detector, while the inelastic beam will be reflected by the cylindrical retarding-field electrode. A good signal-to-noise ratio requires efficient capture of the reflected, or mirror, electrons. A computer study showed that efficient capture is possible here using a symmetrical einzel lens with a long electrode length-to-bore ratio. The inelastic electron detector is shaped like and located immediately behind the elastic electron detector.

Objective lens current supply. This current-regulated supply, capable of 15 A for loads up to 90 V, was constructed and tested. All of the critical components are maintained at constant temperature by an oven or by a 52°C oil bath. The current setting resolution is 2 parts in 10^7. Stability measurements with a 4-Ω load showed a drift of 2 ppm in 20 min. High-frequency noise (>0.1 Hz) was about 4 ppm peak to peak.

Computer control and digital recording. The driving of the microscope sweep circuits and the control of the recording and display can be handled by a minicomputer such as the PDP-8/E. The system designed uses an existing surplus CDC-606 magnetic tape unit. The elastic and inelastic signals would be recorded one per scan line. The maximum recording speed would be about 40,000 picture elements per second. The computer would, also, control the display equipment and permit some image analysis on-line. For more complex processing that requires a large fast memory, the tape would be carried to the ORNL IBM 360/91 computer.

Display system. All of the items required for display plus a sweep generator, permitting tests of the system without digital control, were received. The system includes: a Lithocon storage tube with 1400 TV lines resolution to record the scanned image, a Miratel monitor with 1100 TV lines resolution (for a 1029-line raster) for viewing the Lithocon image, and two Tektronix 602 monitors with P31 and P7 phosphors for immediate display, focusing, and adjusting the microscope.

ELECTRON-OPTICAL FACTORS LIMITING RESOLUTION IN TRANSMISSION ELECTRON MICROSCOPES[1]

T. A. Welton

The performance of electron-optical imaging equipment is best measured by computation of its information-gathering power. An excellent synthesis for the optical case has been given by Fellgett and Linfoot, and this serves as a most useful guide. The treatment is most simply given for the case of weak objects with phase contrast, a situation highly relevant to macromolecular studies. In this case the field illumination is nearly uniform, and relatively small fractional variations from the average level carry the information about the sample. The electron statistical noise and the detector noise can then be regarded (to good approximation) as being signal-independent, random, additive functions of position, completely specified by their power spectra as a function of k (=|k|, where k is the two-dimensional wave vector in the object space).

The illuminating beam is assumed to be approximately parallel and monoenergetic, with rms energy spread δE and angular spread β, with the distributions

1. Abstract of paper to be published in *Proceedings of Workshop Conference on Microscopy of Cluster Nuclei in Defected Crystals* (Chalk River, Canada, September 1971).

taken to be Gaussian and uncorrelated. The electron-optical system is characterized by a chromatic coefficient C_c, a defocus value C_1, an astigmatic focal length discrepancy δ, primary and secondary spherical aberration coefficients C_3 and C_5, objective aperture angle α, and magnification M. The detector is characterized by a lateral spread function, conveniently (but not necessarily) assumed Gaussian, with mean spread radius R, and by a noise enhance factor. The various forms of image degradation are then measured by various functions of k (actually k, except for astigmatism), the modulation transfer functions (MTF). $C(k)$ depends on k, C_c, and δE and describes chromatic aberration; H(k) depends on k, C_1, δ, C_3, C_5, and α and describes the monochromatic aberrations and diffraction; G(k) depends on k, β, C_1, δ, C_3, and C_5 and describes the effect of imperfect beam coherence; $D(k)$ depends on k, R, and M and describes the effect of detector spread. The product $CHGD$ multiples the Fourier transform of the object wave O(k) to convert it into the image wave I(k), assumed noise-free. The noise (electron statistics, random substrate, and detector statistics) is described by an ensemble of functions with power spectrum $N(k)$ which depends on total electron flux, substrate thickness, and detector properties. One of these random functions is to be added to I(k) to obtain the actual detector response. Finally, the set of possible objects among which the micrograph is to discriminate can be described by another power spectrum $S(k)$, if the possible objects are randomly located in two dimensions and randomly oriented.

The information content of a micrograph can then be simply computed in terms of an integral over k of a simple combination of these functions and yields a very convenient measure of performance capability, in conjunction with some standard choice for the object set spectrum. Detailed applications will be given to interesting systems.

HIGH VOLTAGE ELECTRON MICROSCOPY AS A MEANS OF ACHIEVING HIGH RESOLUTION WITH BIOLOGICAL SAMPLES

T. A. Welton

We have made extensive theoretical studies of the informational performance of various electron-optical systems when using macromolecular samples of biological interest. In all this work, sample damage by heating, contamination, and erosion has been neglected as being nonessential in a well-designed instrument. Radiation damage by breakage of covalent bonds has been considered to be the essential deleterious effect on the sample by the beam and has been estimated in as realistic a way as possible from available information for the interesting case of double-stranded DNA. The permissible sample damage determines an allowed dose of N electrons/Å^2, and the effect of statistical error (electron noise) arising from this figure has been carefully considered. Substrate noise has been estimated for a carbon film of given thickness, and its effect included. The actual assumed microscope is represented by an illumination angle, a mean beam energy, an rms energy spread, a chromatic aberration coefficient, coefficients of primary and (possibly) secondary spherical aberration, and a magnification value. The detector is described by an rms lateral spread and a detective quantum efficiency.

Several types of calculations have been performed with these general assumptions. Synthetic micrographs of interesting appearance have been constructed for a variety of instrumental assumptions and two types of sample. One standard sample is one repeat distance of double-stranded DNA (33.6 Å), stained in one of several ways and lying on a carbon film of adjustable thickness, while the other standard sample consists of a number of atoms of various species randomly located on a square of carbon film. In addition, the results of reconstruction of these micrographs by application of the Wiener optimum filter have been calculated and displayed. Some of these pictures will be shown, where relevant for this meeting. In general, they appear to support, in a very visual way, the more abstract calculations next to be described.

Simple formulas have been developed for computing the probability of error of stated magnitude in the determination of the atomic number and position of an atom on the sample film. The simplest case is that of the possible precision in determining the location of an atom of known identity, whose position is a priori known only to lie in a square of area A. The fraction of the area ($\delta A/A$) within which a micrograph allows localization is given by

$$\delta A/A = e^{-I}, \tag{1}$$

where I is the information concerning the question which can be obtained from the micrograph and can be written as a simple integral over all spatial frequencies of a properly defined signal-to-noise ratio:

$$I = 2\pi \left(\frac{\hbar}{mc}\right)^2 \int_0^\infty k\, dk \frac{T^2(k)\, F^2(k)}{\beta^2/N + \beta^2/N_s(k)}. \qquad (2)$$

The function $T(k)$ contains a rather full description of the electron optics and detector [$T(k)$ = overall modulation transfer function of the system], $F(k)$ is the scattering amplitude which characterizes the sample, and N/β^2 is the full dependence on electron dose and velocity ($\beta \equiv v/c$), once the instrumental resolution is fixed in the choice of $T(k)$. More precisely, once the resolution is specified, all the effect of contrast change with beam energy is contained in the factor N/β^2. The substrate noise is specified by $\beta^2/N_s(k)$ and can be simply estimated in terms of the film thickness and the carbon scattering.

This formulation opens a broad area of study to rather simple computation, and we have made some systematic comparisons of various electron-optical systems, as well as investigations of feasibility of various types of work with such systems. The instrumental assumptions made were designated by various combinations of phrases, namely, *conventional, high resolution, high coherence, low energy,* and *high energy. Low energy* means 150 keV, *high energy* means 750 keV. *Conventional* means standard round objective, *high resolution* means that the primary spherical aberration has been controlled by a multipole corrector system, and *high coherence* means that a field-emission source has replaced the usual thermionic cathode and the objective aperture has been removed to give full scope for image processing. A highly controlled high-voltage source ($\delta V/V \leqslant 2 \times 10^{-7}$ rms) has been assumed throughout, and a standard fixed cathode energy spread (δV = 0.2 V). Four types of atoms were assumed,

Table 1. Informational parameter I for various atoms and instrumental conditions

Optics	Beam energy (keV)	Substrate thickness (Å)	Informational parameter, I											
			N/β^2 = 200 electrons/Å^2				N/β^2 = 400 electrons/Å^2				N/β^2 = 800 electrons/Å^2			
			P	Br	Tl	Th	P	Br	Tl	Th	P	Br	Tl	Th
Conventional	150	0	0.57	1.13	3.41	6.78	1.14	2.25	6.81	13.56	2.27	4.51	13.62	27.12
		5	0.31	0.62	1.89	3.75	0.44	0.87	2.63	5.23	0.55	1.09	3.29	6.56
		10	0.22	0.43	1.32	2.62	0.27	0.54	1.65	3.28	0.31	0.62	1.89	3.78
		20	0.14	0.27	0.82	1.64	0.16	0.31	0.95	1.89	0.17	0.34	1.03	2.06
	750	0	0.79	1.83	5.42	9.05	1.58	3.66	10.84	18.10	3.16	7.32	21.69	36.20
		5	0.53	1.24	3.69	6.14	0.81	1.90	5.65	9.39	1.11	2.60	7.77	12.88
		10	0.41	0.95	2.83	4.69	0.55	1.30	3.88	6.44	0.68	1.62	4.82	7.99
		20	0.28	0.65	1.94	3.22	0.34	0.81	2.41	4.00	0.39	0.92	2.76	4.57
High resolution	150	0	0.71	2.12	7.07	9.74	1.42	4.23	14.14	19.49	2.84	8.46	28.27	38.98
		5	0.61	1.84	6.21	8.50	1.08	3.30	11.20	15.23	1.78	5.54	19.02	25.63
		10	0.54	1.65	5.60	7.62	0.89	2.77	9.51	12.82	1.36	4.33	15.09	20.09
		20	0.45	1.38	4.75	6.41	0.68	2.17	7.55	10.05	0.96	3.16	11.21	14.70
	750	0	0.40	1.50	5.68	7.01	0.79	3.01	11.35	14.03	1.58	6.01	22.70	28.06
		5	0.38	1.46	5.53	6.83	0.75	2.85	10.78	13.31	1.42	5.43	20.56	25.36
		10	0.37	1.43	5.39	6.65	0.71	2.71	10.28	12.68	1.29	4.98	18.92	23.29
		20	0.35	1.36	5.14	6.34	0.65	2.49	9.46	11.65	1.11	4.33	16.53	20.29
High coherence	150	0	0.93	2.20	6.95	11.66	1.86	4.40	13.90	23.32	3.72	8.81	27.81	46.64
		5	0.62	1.56	4.99	7.97	0.98	2.54	8.23	12.80	1.45	3.92	12.89	19.40
		10	0.49	1.27	4.11	6.40	0.73	1.96	6.45	9.70	1.02	2.83	9.67	14.04
		20	0.36	0.98	3.22	4.85	0.51	1.44	4.84	7.02	0.68	2.03	6.98	9.79
	750	0	1.03	2.75	8.85	13.29	2.07	5.51	17.71	26.59	4.13	11.02	35.41	53.18
		5	0.76	2.12	7.01	10.18	1.25	3.59	12.05	17.21	1.93	5.76	19.73	27.57
		10	0.62	1.80	6.02	8.60	0.96	2.88	9.87	13.78	1.41	4.43	15.58	21.15
		20	0.48	1.44	4.93	6.89	0.71	2.22	7.79	10.57	1.00	3.32	11.98	15.81

namely, phosphorus, bromine, thallium (or mercury), and thorium (or uranium), and four substrate thicknesses, 0, 5, 10, and 20 Å. Three values for N/β^2 were chosen, 200, 400, and 800 electrons/Å^2. The last we would consider to be a fairly high dose for DNA, the second would be a plausible dose, and the first would be a fairly mild dose. The arguments for these last assertions will be given. It should be emphasized that the damage to covalent bonds depends *strongly* on the parameter N/β^2, any further energy dependence in the range 50 to 1000 keV being quite weak.

A detailed table of results is appended (Table 1). The numbers are self-explanatory and show the great advantage to be derived from high Z in the sample, thin substrates, and compensation of spherical aberration. Surprisingly, high coherence (with sophisticated image processing) gives results quite comparable in precision to the high-resolution results. It will appear that high energy will give an important further gain, but it will be seen that almost all of the computed gain over low energy arises from the strongly decreased importance of the cathode energy spread.

The microscope which is now essentially complete at Oak Ridge is characterized as low energy and high coherence, with the added bonus of liquid helium operating temperature and *very* good vacuum. We accordingly anticipate excellent performance, with more *convenient* use later as we pass to a scanning system with computer control, but no anticipated performance gain. A planned instrument will be high energy (750 keV) in addition to the above features, with accordingly enhanced performance.

MEASUREMENT SYSTEM FOR SUPERCONDUCTING RF RESONANT CAVITIES[1]

P. Z. Peebles, Jr.[2] C. M. Jones[3] R. F. King[4] J. P. Judish

Special considerations must be given to measurement techniques when making measurements on superconducting rf resonant cavities. A system is described that is especially designed to overcome most problems associated with narrow bandwidth (Q's of 10^8 or more), high field levels, and instabilities.

1. Abstract of paper accepted for publication at IEEE Region 3 Conference, April 1972.
2. Consultant from the University of Tennessee, Knoxville.
3. Presently on leave to Institut für Experimentelle Kernphysik, Kernforschungszentrum Karlsruhe, Germany.
4. ORNL retiree.

TRAPPED MAGNETIC FLUX IN A SUPERCONDUCTING RESONANT CAVITY

J. P. Judish C. M. Jones[1] F. K. McGowan J. A. Martin

Because trapped magnetic flux is detrimental to the performance of superconducting devices operating at high electrical frequencies, great care is taken to shield them from ambient magnetic fields. For instance, in our helically loaded lead-plated resonant cavity[2] a combination of high-permeability shields and trimmer coils is used to reduce the field to less than a milligauss before the cavity is cooled and made superconducting. It has been suggested[3] that the benefits derived from such a procedure may be nullified by the thermal gradients developed during the process of cooling down to superconducting temperature. The presence of dissimilar metals (in our case, Pb, Cu, In, Al) in a thermal gradient gives rise to emfs. In the closed electrical circuit, currents flow and generate a magnetic field which becomes trapped when the superconductor has cooled to its critical temperature.

We have constructed a cylindrical copper well which lies along the axis of the transmission line leading to the cavity and reaches down to within a few centimeters of its bottom surface. The well, which is kept near room temperature, is separated from the cooled transmission line and cavity by a vacuum. The well is prevented from radiating thermal energy directly into the lead-plated surfaces of the cavity by a copper cylinder in thermal contact with the neck of the cavity. This cylinder is axial with the well but separated from it by a vacuum. The inside of the well is at atmospheric pressure and is accessible at all times to a magnetometer probe which may be moved freely along the well's axis and also rotated about it.

1. Presently on leave to Institut für Experimentelle Kernphysik, Kernforschungszentrum Karlsruhe, Germany.
2. *Phys. Div. Annu. Progr. Rep. Dec. 31, 1970*, ORNL-4659, p. 89.
3. John Morley Pierce, HEPL report No. 514 (June 1967).

With this apparatus we have measured the magnitude and direction of the magnetic field along the axis of our resonant cavity at room temperature, liquid nitrogen temperature, and liquid helium temperature. The magnetic flux measured at room temperature and liquid nitrogen temperature is of the same magnitude and is less than 1 mG. After cooling the cavity from liquid nitrogen temperature to liquid helium temperature the measured magnetic flux increases by about a factor of 100. This trapped flux was measured after each of several cooldown cycles, and a large increase was always found.

Since the cavity and magnetometer well assembly are made of materials which, from available specifications, are nonmagnetic at liquid helium temperature, the increased magnetic flux appears to be generated by the thermal gradients present during the cooling-down process. The presence of the flux measuring apparatus does, of course, alter the electrothermal environment from that which the cavity has when it is operated as a superconducting resonator. It is possible that, in the absence of the magnetometer apparatus, the thermal gradients present during cooldown may be smaller. In any case, thermal gradients are expected to exist during a typical cooldown, resulting in an increase and then trapping of the magnetic flux.

PRELIMINARY MEASUREMENTS ON A LOW-PHASE-VELOCITY SUPERCONDUCTING RESONANT CAVITY[1]

C. M. Jones[2] R. F. King[3] W. T. Milner
J. P. Judish F. K. McGowan P. Z. Peebles, Jr.[4]

Preliminary measurements are described on a low-phase-velocity superconducting helically loaded lead-plated resonant cavity operated in its fundamental mode at 136 MHz. The following approximate fields were obtained at a power consumption of 320 mW/m:

Maximum magnetic field	187 G
Maximum electric field	4.75 MV/m
Axial accelerating field	0.7 MV/m

Axial electric field distributions in the fundamental and first two harmonic modes were measured.

1. Abstract of paper accepted for publication in *Particle Accelerators* during 1972.
2. Presently on leave to Institut für Experimentelle Kernphysik, Kernforschungszentrum Karlsruhe, Germany.
3. ORNL retiree.
4. Consultant from the University of Tennessee, Knoxville.

FAST FREQUENCY TUNING OF SUPERCONDUCTING RESONANT RF CAVITIES FOR PROTON LINEAR ACCELERATORS[1]

Peyton Z. Peebles, Jr.[2]

Superconducting resonant radio-frequency cavities which utilize helices for producing "slow" wave velocities are prime candidates for creating the large accelerating electric fields needed in linear proton accelerators. Because such structures are subject to mechanical vibrations, these vibrations may cause fast shifts in the cavity resonant frequency. The result of such shifts is to cause undesirable phase modulation of the accelerating field. This report describes results of a study of an all-electronic method of fast tuning of the cavity to compensate for the vibration.

Two types of control are discussed. The first employs only two electrical entrance points (ports) to the cavity. It is mechanically simpler than the second type, which uses three ports, but suffers some undesirable features not present in the three-port method.

1. Abstract of ORNL-TM-3654 (December 1971).
2. Consultant from the University of Tennessee, Knoxville.

NEUTRON MULTIPLICITY COUNTER[1]

R. L. Macklin F. M. Glass[2] J. Halperin[3] R. T. Roseberry[2]
H. W. Schmitt R. W. Stoughton[3] M. Tobias[4]

A neutron multiplicity counter assembly has been constructed to enable a search for superheavy elements in natural samples and in accelerator targets. The detector consists of 20 ^{3}He counters placed in a paraffin moderator. These counters surround a central sample cavity with a capacity of about 20 liters, capable of accommodating samples up to 100 kg in weight, depending on the density. A particular feature of this counter is its relative insensitivity to gamma rays. The efficiency for detecting a single neutron is ~30%. An estimate of $\bar{\nu}$, the number of neutrons emitted per fission in a sample, may be obtained from the observed multiplicity distribution $P(n)$, where n is the number of neutron counts in an event. More accurate values of $\bar{\nu}$ may be obtained for small isolated samples of spontaneously fissioning isotopes, where the neutron counters may be gated by a fission fragment detector. The design of the counter and an analysis of its properties are presented.

1. Abstract of paper submitted for publication in *Nuclear Instruments and Methods.*
2. Instrumentation and Controls Division.
3. Chemistry Division.
4. Reactor Division.

FAST TIMING FROM A FISSION IONIZATION CHAMBER[1]

H. Rösler[2] J. K. Millard[3] N. W. Hill[3]

The timing resolution of a ^{252}Cf-loaded fission ionization chamber connected to a new current preamplifier has been tested by looking at coincident fission fragment pulses and pulses from fission gamma rays which are detected in a plastic scintillator. A time resolution of 1 nsec FWHM could be achieved.

1. Abstract of paper submitted for publication in *Nuclear Instruments and Methods.*
2. Visiting scientist from Reaktorstation Garching, Germany. Present address: Universität of München Abteilung Kernphysik, 8046 Garching, Germany.
3. Instrumentation and Controls Division.

ATTEMPT TO MEASURE *J* VALUES USING BACKSCATTERED POLARIZED NEUTRONS AT ORELA

J. W. T. Dabbs W. W. Walker[1]

NUCLEAR REACTIONS: ^{55}M, W(n,n), E = 2–50,000 eV; measured $\sigma_{n,n}$ (E); test of feasibility of polarized neutron backscatter method to deduce J; natural targets.

Apparatus modifications required to test the method described in the last annual report[2] were completed and tests made at ORELA. A schematic drawing is shown in Fig. 1. It was found that a much lower signal-to-background ratio existed than had been expected. The background was largely caused by scattering from the front of the final beam collimator (shown at the extreme left of Fig. 1); however, "room background" from other flight paths in the electron room at ORELA was at least equal to the signal as well. Difference measurements (sample in minus sample out) were therefore required.

Analysis of the results disclosed a need for a much more complex and expensive collimator system and the construction of a shielded "room" around the apparatus, if the method is to be useful. A recalculation of the expected intensities also revealed an incorrect expansion in one of the integrals over sample thickness. Thus sample self-shielding reduced the counting rates below those originally expected.

In view of the cost of a redesigned collimator and shield system, the original plan for measuring J values has been reactivated.[3] The cost of the redesigned collimation and shielding system was estimated to be at

1. Summer Research Participant from University of Alabama.
2. *Phys. Div. Annu. Progr. Rep. Dec. 31, 1970,* ORNL-4659, p. 32.
3. J. W. T. Dabbs et al., "Polarized-Neutron–Polarized-Target Fission Measurements at ORELA," this report.

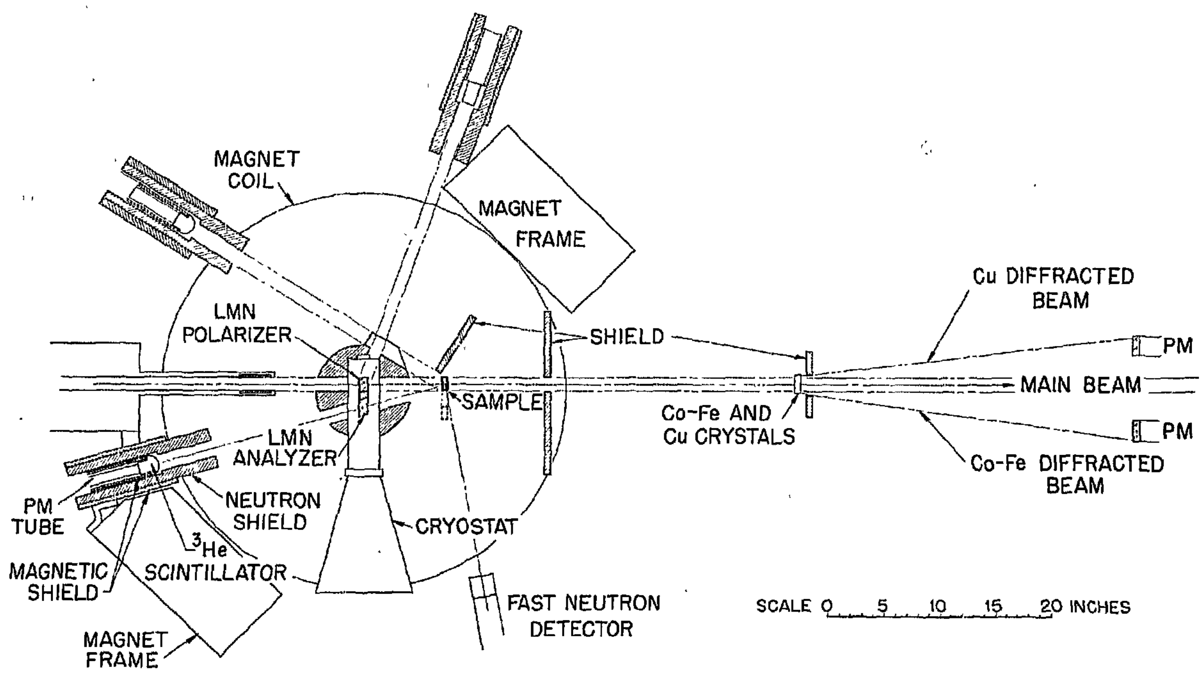

Fig. 1. Schematic drawing of polarized proton target apparatus. The neutron beam enters through the collimator at left, is polarized in passing through a polarized (LMN) proton target, then backscattered from the unpolarized nuclear sample through a second LMN crystal, where it is analyzed. The upper detector is a beam monitor. At right is a polarization measuring apparatus.

least equal to that of the polarized-target cryostat and magnet required for the more conventional approach originally planned. The backscatter method was attempted as a way to avoid the cost of the polarized target, although the polarized-neutron–polarized-target method is clearly superior in many ways to the backscatter method.

In the course of this work, a number of problems related to data acquisition and computer control of the cryostat system were solved. The work on the latter will be the subject of a report after final adjustments and definitive long-term operation have been accomplished. All of this work will be applicable to the final ORELA neutron polarizer system and its control.

The data acquisition system was completed and has proved to be extremely reliable in actual use. Figure 2 shows a block diagram of the detector timing and identifaction system as presently set up for up to 7 independent detectors. The system is capable of expansion to 15 detectors if desired; however, interactions related to clock (time digitizer) dead time probably would then be rather undesirable. The system shown in Fig. 2 has also been used for two fission measurements[3,4] with simple and rapid modification possible for each. The scaler system is also tied in to the computer controller mentioned above.

The assistance of W. B. Dress and P. D. Miller is gratefully acknowledged.

4. J. W. T. Dabbs et al., "Small-Sample Fission Cross-Section Measurements at ORELA," this report.

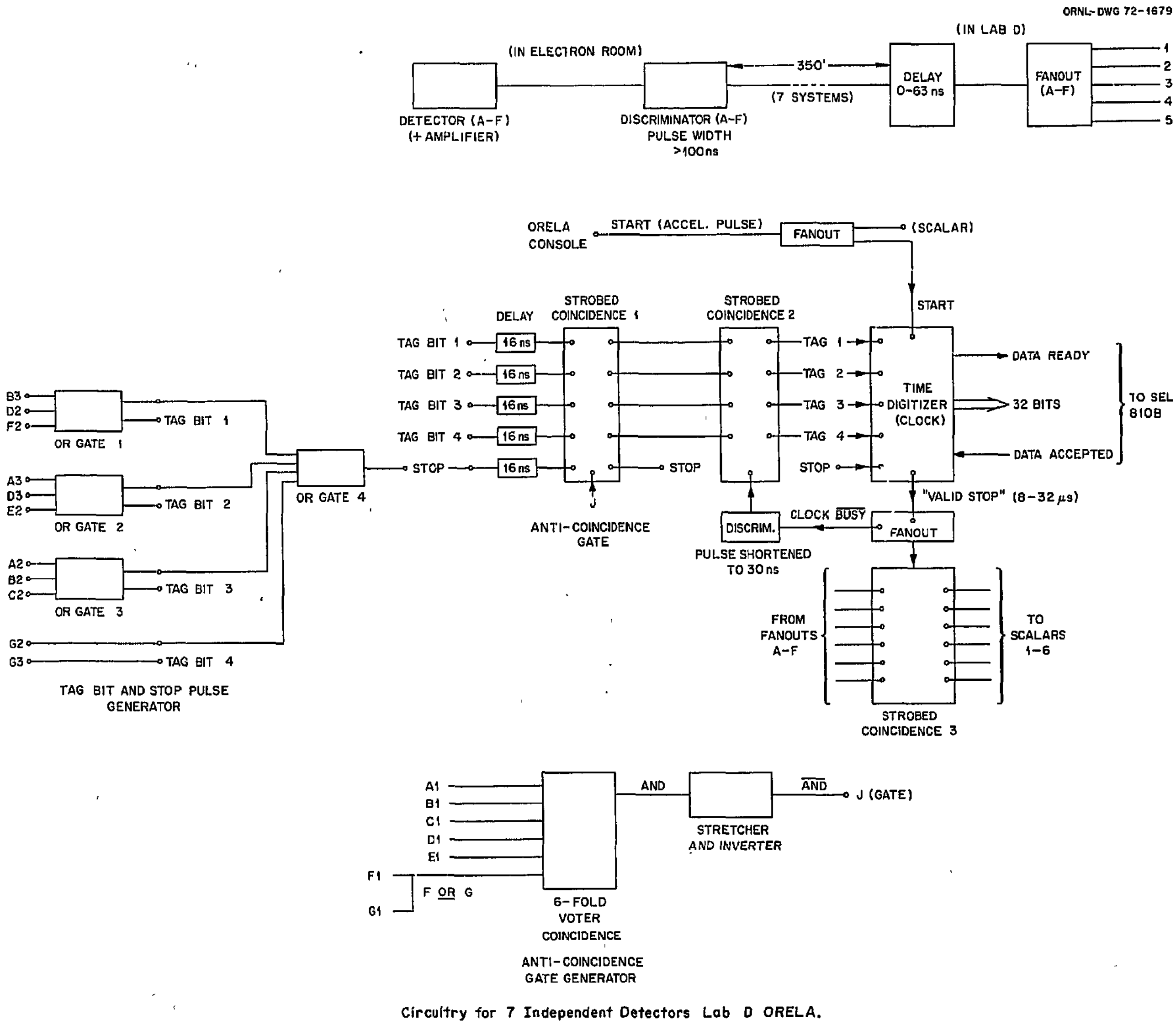

Fig. 2. Block diagram of a seven-detector system for event timing and detector identification. The time digitizer is an EG&G model 1040 which can digitize the time between a "start" pulse and multiple "stop" pulses to the nearest 0.5 nsec over a range of 67 msec. The system is primarily constructed of NIM fast logic modules and is easily modified by rerouting interconnecting cables.

SHORT NUCLEAR LIFETIME MEASUREMENTS VIA THE PULSED-BEAM DELAYED-COINCIDENCE TECHNIQUE[1]

H. J. Kim W. T. Milner

Lifetimes in the 10^{-10} sec range were determined by simultaneously observing the time as well as energy distributions of gamma rays detected by a large-volume coaxial Ge(Li) detector. This simultaneous observation was accomplished by the use of a two-parameter analyzer operated in the 512 X 32 channel mode. The fiducial time for the time distribution was provided by the pulsed beam initiating (p,p'γ) and (p,nγ) reaction on enriched Cd targets. Observed time distributions of delayed gamma rays ranging from 300 to 700 keV were analyzed using three different methods: centroid shift, shape fitting, and area analyses. Half-lives determined by these methods are mutually consistent. It is shown that the half-life corresponding to an observed shift as small as 1/140 of the prompt distribution width (FWHM) may be reliably determined from the data.

1. Abstract of published paper: *Nucl. Instrum. Methods* 95, 429 (1971).

SOME GAMMA-RAY SHIELDING MEASUREMENTS MADE AT ALTITUDES GREATER THAN 115,000 FEET USING LARGE Ge(Li) DETECTORS[1]

G. T. Chapman[2] R. P. Cumby[3] J. H. Gibbons[4] R. L. Macklin H. W. Parker[5]

RADIOACTIVITY: cosmic environment; measured γ's, γ spectrum.

A series of balloon-flight experiments at altitudes greater than 115,000 ft has been conducted to gain information relative to the use of composite shields (passive and/or active) for shielding large-volume lithium-drifted germanium [Ge(Li)] detectors used in gamma-ray spectrometers at these altitudes. The measurements were made in the gamma-ray energy region 60 keV $\leqslant E_\gamma \leqslant$ 2 MeV and clearly illustrate the necessity of using a dense gamma-ray shield protected by an active charged-particle shield for effective shielding of these detectors in the primary cosmic-ray environment. Data showing the pulse-height spectra of the environmental gamma radiation as measured at 5.3 and 3.8 g/cm^2 residual atmosphere with an unshielded diode detector are also presented.

1. Abstract of paper to be published in *Proceedings of National Symposium on Natural and Man-Made Radiation in Space* (Las Vegas, Nevada, March 1971).
2. Neutron Physics Division.
3. Instrumentation and Controls Division.
4. Director, ORNL-NSF Environmental Program.
5. Space Sciences Laboratory, G. C. Marshall Space Flight Center, Huntsville, Ala.

A HIGH-RESOLUTION SPECTROMETER SYSTEM WITH PARTICLE IDENTIFICATION FOR 1- THROUGH 60-MeV HYDROGEN AND HELIUM PARTICLES[1,2]

F. E. Bertrand W. R. Burrus[3] N. W. Hill[4] T. A. Love[5] R. W. Peelle[5]

A coincidence semiconductor spectrometer system based on a Ge(Li) total absorption detector has been applied to the simultaneous spectroscopy of all charge 1 and 2 particles from targets bombarded with protons with energy up to 62 MeV. Output spectra cover the range from the full energy down to a 1- to 5-MeV threshold which depends on particle type. The method for choosing the thicknesses for the two ΔE detectors is discussed, and unusual features of the system are described. Particles too slow to penetrate the first ΔE counter were sorted according to mass using flight time vs E discrimination, while the more energetic particles were separated using two sets of $\Delta E \times E$ discrimination. Germanium detectors thick enough to stop 60-MeV protons were used, with particles entering perpendicular or parallel to the field lines, and in either case the only significant inactive region in the path of the detected particles was the protective foil over the Ge(Li) detector. The typical pulse-height resolution of the system was about 200 keV for 60-MeV protons, although a germanium detector used alone gave 55 keV resolution at this energy. Analysis was performed after the experiments using magnetic tapes written by an on-line computer; corrections to the pulse-height spectra for reaction and collimator tails are discussed. The electronic logic system is described, including portions for event characterization, for use of an "active" detector collimator, and for pileup pulse rejection based on timing information.

1. Work funded by National Aeronautics and Space Administration under order L-12, 186.
2. Abstract of paper submitted to *Nuclear Instruments and Methods.*
3. Present address: Tennecomp, Inc., Oak Ridge, Tenn.
4. Instrumentation and Controls Division.
5. Neutron Physics Division.

ON THE Z^2 DEPENDENCE OF THE X-RAY PRODUCTION CROSS SECTION BY 5-MeV/amu HEAVY IONS

A. van der Woude M. J. Saltmarsh C. A. Ludemann R. L. Hahn[1] E. Eichler[1]

Theoretical predictions for the cross section σ_I of ionization of inner-shell electrons by fast ions indicate that σ_I is proportional to Z^2, where Z is the projectile charge, as long as the electrons are not polarized by the projectile during the interaction.[2,3] Recently, a few tests using helium and lithium ions have been made which indicate that appreciable deviations of this simple scaling law can occur in the K x-ray production cross section.[4,5] In order to test this further, we measured the cross section for the production of K x rays, σ_x, of Ti, Fe, Co, Zr, Sn, and Nd and for L x rays of Sn, Nd, and Au by 5-MeV/amu He, C, O, and Ne ions. We also measured σ_x for 10-MeV/amu carbon ions on the same targets. The 5-MeV/amu projectiles were obtained by accelerating He^{1+}, C^{3+}, O^{4+}, and Ne^{5+} ions in the Oak Ridge Isochronous Cyclotron. By this particular choice of ions, only minor adjustments in the cyclotron are necessary in order to switch from one ion to another, while the energy per mass unit will be the same for each ion.

An absolute value of the x-ray production cross section σ_x can be obtained by comparing the yield Y_x of the x rays with the yield Y_c of Coulomb-scattered particles according to the relation:

$$\sigma_x = \sigma_c Y_x \epsilon_c / Y_c \epsilon_x \,, \qquad (1)$$

where σ_c is the Coulomb cross section of the scattered particles at the angle of observation and ϵ_c and ϵ_x are the efficiencies of the x-ray detector and the scattered-particle detector respectively. In our case, the Coulomb cross section is independent of the nature of the projectiles at small angles of observation. This method eliminates the need to measure target thickness and beam current and thus enables one to perform accurate absolute measurements.

The x-ray yield was measured at an angle of 135° with respect to the incoming beam by using an Si(Li) detector with a resolution of about 250 eV at 5.9 keV. The target thicknesses ranged from 200 to 1000 $\mu g/cm^2$, and Y_x was corrected for self-absorption effects in the target. The scattered-particle yield Y_c was measured with two surface-barrier counters at angles of +11° and −11° with respect to the beam, so that corrections could be made for small changes in beam direction and position. For most cases the absolute uncertainty in σ_x is ±6%, which is mainly due to an uncertainty of ±5% in ϵ_x. The uncertainty in the ratio between σ_x for different projectiles is, in most cases, better than ±2%. The titanium results have an uncertainty of ±10% in the absolute cross section because the elastic scattering is not pure Coulomb scattering. For the same reason the absolute cross sections for the 10-MeV/amu carbon ions were obtained from target thicknesses and the integrated beam current, again resulting in an estimated uncertainty in σ_x of ±10%.

A well-known phenomenon of heavy-ion-induced x rays is the shifting of x-ray energies, which is presumably due to the creation of multiple inner shell vacancies.[6,7] We measured these shifts for the $K\alpha$ lines of Fe, Co, Zr, and Sn and for the $K\beta$ lines of Fe and Co by fitting the observed spectra with a function consisting of Gaussian peaks superposed on a quadratic background. It was found empirically that for the bombarding energies of 5 and 10 MeV/amu the observed energy shift for each target is a nearly linear function of the stopping power of the bombarding ion. This is shown in Fig. 1; the stopping powers were obtained from Northcliffe and Schilling.[8] The energy shift of the $K\alpha$ line of iron due to 80-MeV oxygen ions is about 50 eV, which is very close to the shift of 45 ± 15 eV reported in ref. 6 for 30-MeV oxygen ions on iron. Since the energy shift is reported to increase with bombarding energy up to 50-MeV oxygen ions,[7] this suggests that the shift at 80 MeV bombarding energy is slightly lower than the shift at 50 MeV. A comparison of the energy shifts induced by 60- and 120-MeV carbon ions, moreover, indicates that this latter trend continues as the energy of the ions is increased further.

Figure 2 shows the quantity $U_K{}^2 \; \sigma_I{}^K/Z^2$ as a function of $E/\lambda U_K$ for the 5-MeV/amu helium ions and

1. Chemistry Division.
2. J. D. Garcia, *Phys. Rev.* A1, 280 (1970); *Phys. Rev.* A4, 955 (1971).
3. E. Merzbacher and H. W. Lewis, *Encyclopedia of Physics*, vol. 34, p. 166, Springer-Verlag, Berlin, 1958.
4. G. Basbas, W. Brandt, R. Laubert, A. Ratkowski, and A. Schwarzschild, *Phys. Rev. Lett.* 27, 171 (1971).
5. C. W. Lewis, J. B. Natowitz, and R. L. Watson, *Phys. Rev. Lett.* 26, 481 (1971).
6. D. Burch and P. Richard, *Phys. Rev. Lett.* 25, 983 (1970).
7. D. Burch, P. Richard, and R. L. Blake, *Phys. Rev. Lett.* 26, 1355 (1971).
8. L. C. Northcliffe and R. F. Schilling, *Nucl. Data* A7, 233 (1970).

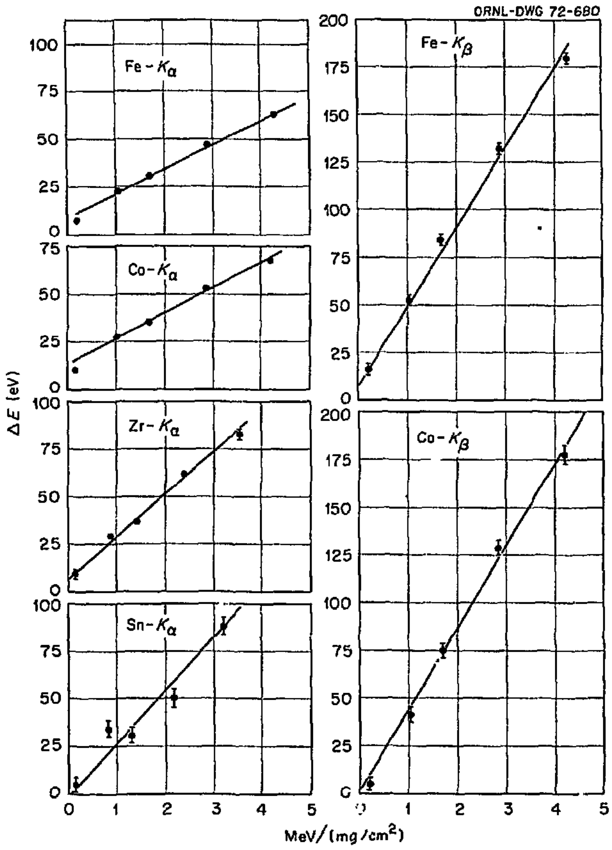

Fig. 1. The energy shift ΔE observed in the K x-ray spectra produced by 5-MeV/amu He, C, O, and Ne ions and 10-MeV/amu carbon ions vs the stopping power of the ions S. The curves illustrate the empirically observed nearly linear relation between ΔE and S.

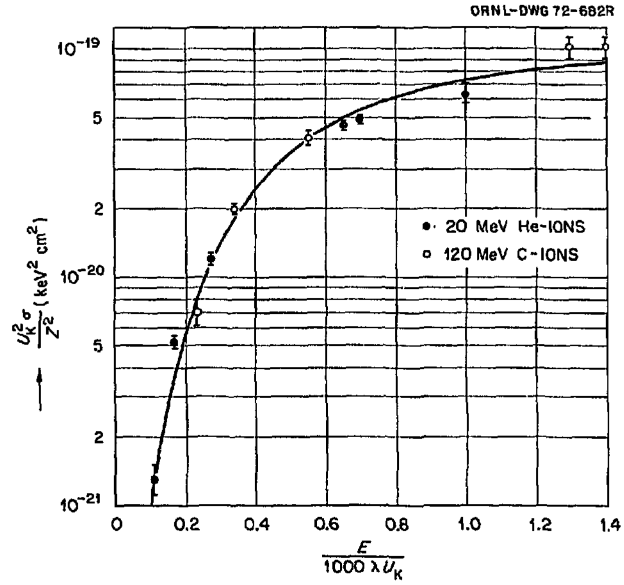

Fig. 2. Comparison of the experimentally observed ionization cross sections σ with the theoretical results of ref. 2. The values of σ are deduced from the experimentally measured x-ray production cross sections σ_x by using the fluorescence yields of Table 1.

Table 1. Fluorescence yields

Element	ω_K
Ti	0.221
Fe	0.344
Co	0.366
Zr	0.737
Sn	0.86
Nd	0.91

the 10-MeV/amu ^{12}C ions. The quantity E/λ is the energy per nucleon, and U_K is the binding energy of the K-shell electron. The $\sigma_I{}^K$ are calculated from the relation $\sigma_x{}^K = \omega_K \sigma_I{}^K$. The fluorescence yields that were used are summarized in Table 1. The curve is the prediction of the binary-encounter model of ref. 2. In general, there is a reasonable agreement between the predicted and experimental values for the helium ions. The somewhat low value of the titanium K cross section could be due to the fact that the elastic scattering cross section at 11° is not pure Coulomb scattering. The values for the 10-MeV/amu carbon ions for iron and cobalt are about 10 to 15% above the predicted values.

In order to illustrate the Z^2 dependence of the x-ray production cross sections, we define the quantity

$$R^x(Z_1, Z_2) = [\sigma_x(Z_1)/\sigma^x(Z_2)](Z_2/Z_1)^2 .$$

Figure 3 shows $R^x(Z_1, Z_2)$ for $Z_2 = 2$ and $Z_1 = 6, 8,$ and 10 as a function of $\xi = (E/1000\lambda U)$, where U is the binding energy of the K shell or a suitable average of the binding energy of the L shells. The experimental data suggest the following systematic trends: (1) For each projectile, R^x changes from values >1 to values <1 at $\xi \sim 0.45$. (2) For each value of ξ, the value of $|R^x - 1|$ increases with increasing Z_1. (3) The behavior of R is approximately the same for K and L x rays. It is interesting to note that the same systematic trend can be observed in the data reported in ref. 4, obtained with quite different projectiles, targets, and energies. Also, the data reported in ref. 5 agree with the observed systematics in the sense that $R^x > 1$ for $\xi > 0.5$.

The fact that $R^x \neq 1$ can be due to a Z_1 dependence of the fluorescence yield ω, or it can indicate that σ_I does not scale as $Z_1{}^2$. Most probably both effects have to be taken into account. However, in the case of Zr,

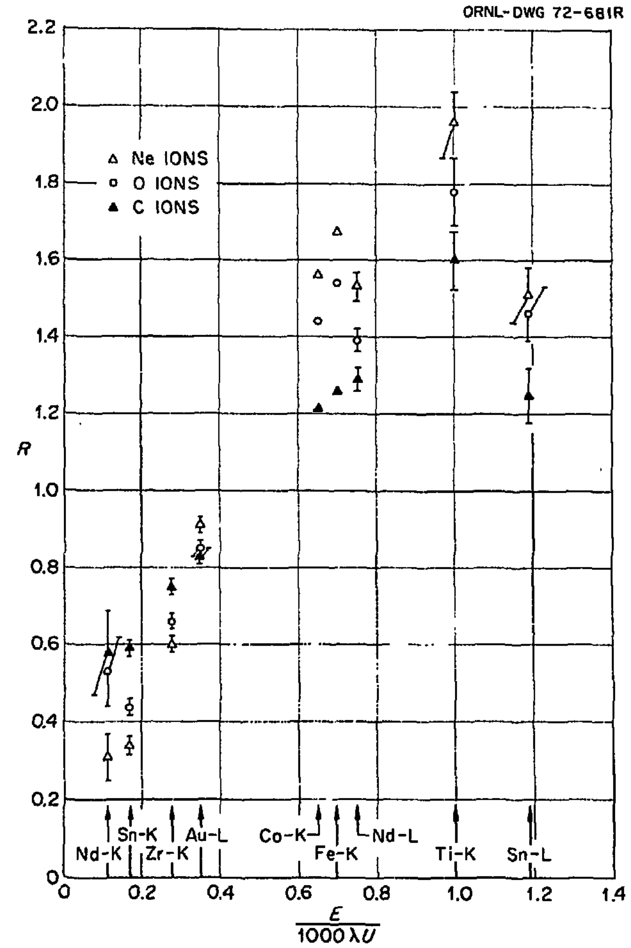

Fig. 3. The ratio $R^x(Z_1, Z_2) = [\sigma_x(Z_1)/\sigma_x(Z_2)](Z_2/Z_1)^2$ for K and L x rays with $Z_2 = 2$ and $Z_1 = 6, 8,$ and 10 vs $E/1000\lambda U$, where E/λ is the energy of the projectile per atomic mass unit and U the appropriate electron binding energy.

Sn, and Nd it is reasonable to assume that the fluorescence yield is not very Z dependent, since the energy shifts indicate that the number of additional L vacancies created is only about one[9] and the fluorescence yield of the undisturbed atoms is already large.

9. T. A. Carlson, private communication.

Table 2. $|R(Z_1, Z_2) - 1|Z_t/(Z_1 - Z_2)$ with $Z_2 = 2$ for the K x-ray cross section

Target	Value for specified projectile		
	C	O	Ne
Ti	3.3 ± 0.1	2.9 ± 0.1	2.6 ± 0.1
Fe	1.7 ± 0.1	2.34 ± 0.1	2.2 ± 0.1
Co	1.4 ± 0.1	2.0 ± 0.1	1.4 ± 0.1
Zr	2.5 ± 0.2	2.3 ± 0.2	2.0 ± 0.1
Sn	5.1 ± 0.1	4.6 ± 0.2	4.1 ± 0.2
Nd	4.2 ± 1.0	4.7 ± 0.9	5.2 ± 0.5

Thus the observed discrepancy of a Z^2 dependence for the x-ray production cross section σ_x very likely reflects in these cases the behavior of the ionization cross section σ_I.

If we assume that the ionization cross section σ_I can be written as

$$\sigma_I = \sigma_I^0 \,[1 + \delta(Z_1/Z_t) + O(Z_1/Z_t)^2] \, ,$$

where σ_I^0 is the cross section as can be calculated without taking polarization effects into account[2,3] and Z_t is the charge of the target atom, then the quantity

$$|R(Z_1, Z_2) - 1|Z_t/(Z_1 - Z_2)$$

should be independent of Z_1. Table 2 shows that this is approximately true for the Zr, Sn, and Nd targets. This suggests that for small ξ values the effects of polarization of the electron orbits by the projectile can to a large extent be described by adding a Z_1^3 term in the ionization cross section. For the lighter elements, one first would have to establish either experimentally or theoretically the effect of multiple vacancies on the fluorescence yield before such an evaluation can be made. A similar remark can be made with respect to the L x rays of Sn, Nd, and Au, although it might be meaningful that all the data indicate the same trend of R vs $E/\lambda U$.

A MEASUREMENT OF SURFACE CONTAMINATION USING HEAVY-ION-INDUCED X RAYS

M. J. Saltmarsh   A. van der Woude   C. A. Ludemann

Salt mines have recently been proposed as radioactive waste depositories.[1] It is therefore necessary to evaluate the risks of radioactive leakage from such storage areas. One possible leakage mechanism, which provided the motivation for the present work, involves the diffusion of plutonium oxides along the surface of NaCl crystals. Earlier measurements performed at ORNL using La_2O_3 as an analog for Pu_2O_3 had yielded equivocal results due to the difficulty of detecting very low surface concentrations of La_2O_3 on salt crystals. To resolve these difficulties, we have used the technique of heavy-ion-induced x-ray fluorescence to lower the threshold of detectability of the La_2O_3 layer.

An acceptable diffusion distance was taken to be approximately 10 m in 10^6 years, implying an upper limit for the diffusion coefficient of about 10^{-8} cm^2/sec. As the radioactive wastes generate heat, the coefficient was to be determined for a temperature of 250°C. The samples were prepared using pure NaCl crystals approximately 2 × 0.6 × 0.4 cm. One of the large faces was cleaned and polished, and tape was used to mask half of the surface. A layer of La_2O_3 approximately 160 Å (10 $\mu g/cm^2$) thick was then evaporated onto this face. After removal of the mask the samples were annealed for two weeks at 250°C.[2] With a diffusion coefficient of 10^{-8} cm^2/sec, one would expect to see appreciable concentrations of La_2O_3 at a distance of 2000 μ from the original boundary. Measurements with an electron microprobe showed that the La_2O_3 concentration had dropped to $\lesssim 1$ $\mu g/cm^2$ at a distance of 60 μ from the boundary. Unfortunately, the same data also suggested the presence of a layer 0.2 to 0.4 $\mu g/cm^2$ thick extending to the edge of the crystal, which is about 1 cm from the lanthanum boundary. Such a profile would imply the existence of some other diffusion mechanism with a diffusion coefficient higher than 10^{-8} cm^2/sec. As the thickness of the possible layer was at the limit of the sensitivity of the electron microprobe, a more sensitive technique was required to check the results.

There has recently been considerable interest in the use of heavy-ion-induced x-ray fluorescence as a tool

1. Oak Ridge National Laboratory report ORNL-4751 (December 1971).

2. These samples were prepared by B. K. Annis.

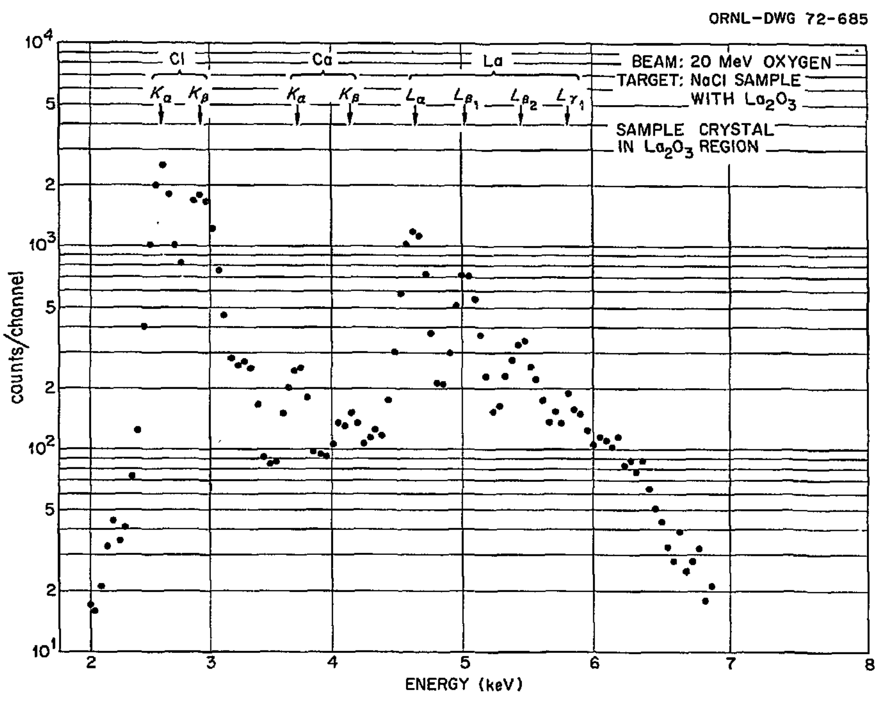

Fig. 1. An x-ray spectrum obtained from the NaCl crystal in the region of the 10-$\mu g/cm^2$ La_2O_3 coating. Total counting time was 5 min at a beam intensity ≈2.5 × 10^{10} particles/sec.

for trace-element analysis.[3] The choice of ion species and bombarding energy is dependent on the precise nature of the problem to be investigated. For this case, a small concentration of lanthanum was presumably present only on the surface of a large bulk of NaCl, so that an ion of low penetrating power was desirable to avoid excessive background from the bulk of the crystal. In the available energy region of about 1 to 10 MeV/amu, both the background from electron bremsstrahlung and the cross section for the excitation of lanthanum *L* x rays increase rapidly with increasing bombarding energy. Our choice of 20-MeV oxygen ions represents a compromise between the requirements of high cross section and low background.

Figure 1 shows a spectrum obtained by bombarding the 160-Å layer of La_2O_3 for approximately 5 min. The chlorine *K* x rays and the lanthanum *L* x rays are clearly visible, together with calcium lines from impurities in the crystal or the beryllium slit. By using the chlorine *K* x rays as a relative monitor and assuming the thickness of the La_2O_3 at this point to be 160 Å, all further measurements could be placed on an absolute basis.

3. T. B. Johansson, R. Akelsson, and S. A. E. Johansson, *Nucl. Instrum. Methods* **84**, 141 (1970).

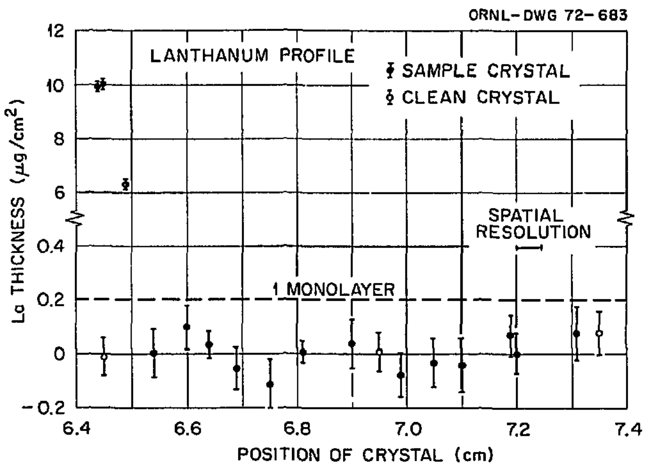

Fig. 2. The measured profile of lanthanum on the sample (solid circles) normalized to 10 μg/cm² for the deposited layer. The open circles represent values obtained from a clean NaCl crystal.

Figure 2 shows the lanthanum concentration profile obtained from a scan of the crystal. Also plotted are data points obtained from a clean NaCl crystal (open circles). There is no evidence for the 0.2- to 0.4-$\mu g/cm^2$ layer indicated by the microprobe data.

DETERMINATION OF HYDROGEN CONTAMINATION IN THIN METAL FOILS

M. J. Saltmarsh   A. van der Woude

We have made some preliminary measurements of the depth profile of hydrogen in thin metal foils using $p + p$ scattering, a technique previously reported by Cohen et al.[1] Standard techniques for assaying hydrogen can give incorrect results due to the presence of high concentrations of hydrogen on the surfaces of metallic foils. The present method combines a reasonably high sensitivity (≈1 ppm atomic) with a depth resolution sufficient to distinguish surface and interior effects.

Figure 1 illustrates the principle of the technique. A proton beam incident upon a foil induces $p + p$ scattering events. The scattered protons are detected in coincidence by two counter telescopes set at laboratory angles of +45° and −45°. As the energy of the scattered and recoil protons which are detected depends upon the depth at which the $p + p$ scattering occurs, a depth profile can be obtained by summing the energies deposited in the two telescopes.

For our measurements, we used a 23-MeV H_2^+ beam from the ORIC, the targets being 0.002 in. aluminum and 0.0005 in. stainless steel.[2] Each counter telescope comprised a ΔE detector approximately 300 μ thick, just sufficient to stop the 5.75-MeV protons from $p + p$ events, and a 1000-μ E detector. Most random coincidences were due to protons elastically scattered from the foil material, and could be eliminated by vetoing any event which triggered one of the E detectors. The solid angle subtended by each detector was approximately 4×10^{-3} sr, and beam currents were ≈10 nA. The resultant singles rates in the detectors were $\lesssim 10^4$/sec, requiring the use of pile-up rejection and fast coincidence techniques. Prompt and one-rf-cycle-delayed coincidence events were recorded simultaneously.

Figure 2 shows the spectrum obtained with a sample of stainless steel in which hydrogen had previously been

1. B. L. Cohen, C. L. Fink, and J. H. Degnan, *Bull. Amer. Phys. Soc.* **16**, 1171 (1971).
2. The samples were provided by J. Stiegler.

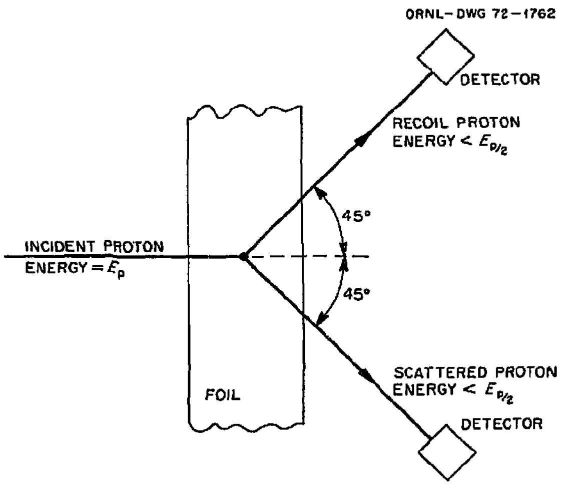

Fig. 1. An illustration of the detection of a $p + p$ event occurring in a metal foil.

injected, together with a nominally hydrogen-free foil. Large surface concentrations are evident. The counting time was approximately 15 min. The effective solid angle of the system was reduced by a factor ≈1.5 to 2.0 for events occurring on the upstream surface of the foils due to multiple scattering losses. This effect may be partially eliminated by reversing the foils.

The sensitivity achieved in these experiments (≈10 ppm atomic) was limited by two factors. The first of these, the random coincidence rate, was important only in the case of the aluminum samples. Due to the pulsed nature of the cyclotron beam, the effective coincidence resolving time could not be reduced below 100 nsec, but a considerable improvement can be expected by using a beam from a tandem Van de Graaff accelerator, for example. The second factor was presumed to be due to poor charge collection in one of the ΔE detectors and had the effect of adding a low-energy tail to any peak observed in the energy spectrum. One of the peaks corresponding to the foil surface therefore contributed to the background in the central region. A suitable choice of detector will reduce this background, the limit being due to protons which interact with the detector material before stopping in the detector.

From our results we estimate that, for counting times ≃15 min, a sensitivity of 1 ppm atomic can be achieved with a depth resolution of approximately one-tenth of the foil thickness if the incident beam energy is tailored to the sample thickness.

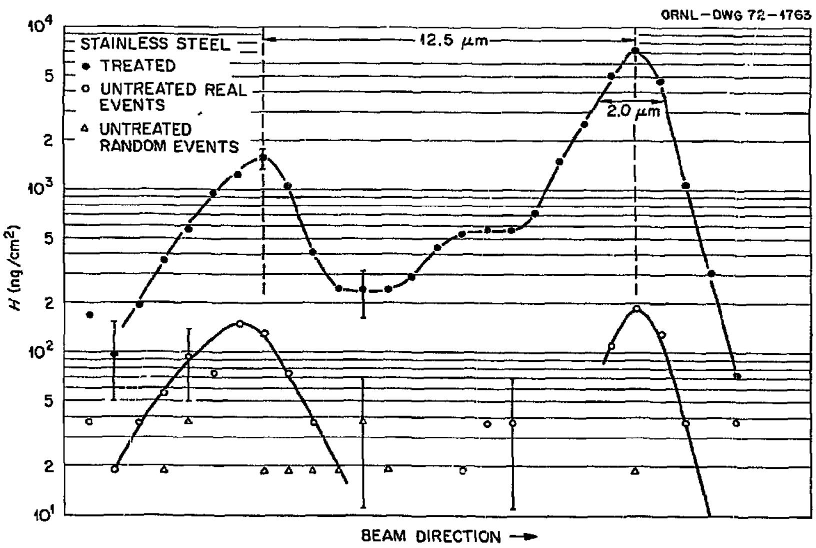

Fig. 2. Data obtained from a sample of a stainless steel foil. Open circles indicate a nominally hydrogen-free sample. The data have not been corrected for the decrease in sensitivity to events occurring on the upstream side of the foils. Representative uncertainties are indicated.

A PROTON-RECOIL NEUTRON DETECTOR FOR NEUTRONS OF A FEW KILO-ELECTRON VOLTS OF ENERGY

N. W. Hill[1] J. A. Harvey G. G. Slaughter A. St. James[2]

The Oak Ridge Electron Linear Accelerator (ORELA) was designed specifically for neutron cross-section measurements, especially in the neutron energy range from a few kilo-electron volts to a few hundred kilo-electron volts. Although suitable efficient detectors are available for low-energy neutrons less than a few kilo-electron volts and fast plastic scintillators are acceptable for million-electron-volt-energy neutrons, a good detector for neutrons from a few kilo-electron volts to 100 keV was not available. For transmission measurements at ORELA, ^{6}Li glass scintillators were chosen for measurements with low-energy neutrons and have been used for measurements up to ~400 keV. However, the largest ^{6}Li scintillation glass commercially available (4½ in. in diameter, ½ in. thick) has a neutron detection efficiency of only 5.3% at 10 keV, a minimum of 2.2% at 120 keV, and a maximum of 7.3% at the 250-keV ^{6}Li resonance, as shown in Fig. 1. Since only 22% (by atoms) of a glass scintillator is ^{6}Li, many neutrons are scattered (~30%) by the other constituents of the glass, which produces a tail about the same width as the neutron burst, which is annoying in time-of-flight neutron measurements. Also, ^{6}Li glass scintillators are sensitive to gamma rays and have a long 75-nsec decay component in addition to a short 5-nsec decay component.

In the process of testing plastic detectors for million-electron-volt neutron total cross-section measurements, it was discovered that a new plastic scintillator, NE 110, when suitably mounted on a selected RCA 4522 5-in. phototube with a special base, was capable of detecting neutrons whose energies were only 1 keV. The voltage divider used in this base was essentially the RCA type C, recommended by RCA for high-peak-current applications. The grid adjustment is made for optimum pulse-height resolution for the ~3-in.-diam scintillators with a gamma source remote from the scintillators. The dynode 14 to anode potential is adjusted to give maximum gain at the anode, consistent with the photomultiplier tube noise level, with some dynode 14 saturation. The scintillators, machined with a concave spherical curvature, were coupled directly to the phototube with Dow Corning optical coupling compound.

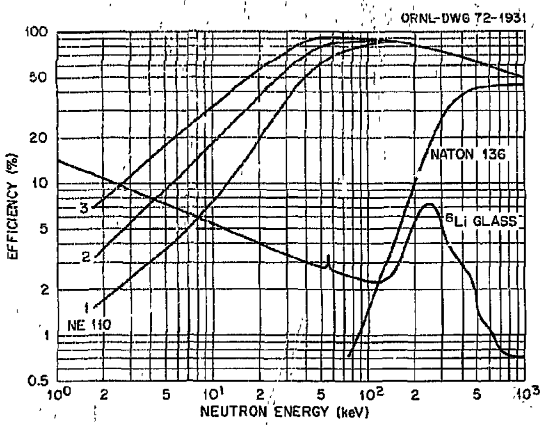

Fig. 1. The efficiencies of a ^{6}Li glass scintillator (½ in. thick) and of NE 110 (1 in. thick) and Naton 136 (1 in. thick) plastic scintillators in the 1- to 1000-keV neutron energy range.

Three different pieces of NE 110 from the same ingot were used on separate photomultipliers, and further tests of a different batch are planned.

In order to determine the efficiency of this new detector as a function of neutron energy, two measurements were made at an 18-m flight path at ORELA. First, 29.5 in. of high-purity iron was inserted into the neutron beam, which produced many groups of essentially monoenergetic neutrons, due to the neutron "windows" in iron at 24.5, 82, 138, 167, 220, 313, 468, 704, and 954 keV. The second measurement was with a sample of copper 1 in. thick, which has many large resonances from ~1 to 50 keV. These two measurements were made with several NE 110 detectors mounted on different RCA 4522 phototubes, two Naton 136 detectors, and a ^{6}Li glass scintillation detector. The efficiencies of these plastic detectors were normalized to that of the ^{6}Li glass detector, correcting for their differences in areas; and some of the results are shown in Fig. 1. It is obvious that this NE 110 scintillator is superior in efficiency to ^{6}Li glass above a few kilo-electron-volts neutron energy by as much as an order of magnitude. The efficiency of the NE 110 scintillator for low-energy neutrons is very sensitive to the photomultiplier gain and discriminator bias. We expect that the efficiencies of these plastic detectors can be further improved using photomultipliers selected for high quantum efficiencies and optimizing the

1. Instrumentation and Controls Division.

2. Student participant in Great Lakes Colleges Association Program, fall 1971, from Denison University.

electronics. The NE 110 scintillator is not sensitive to low-energy neutrons, is very fast (3.3 nsec decay constant), and the tail produced by the gamma rays from neutron capture by hydrogen from the moderated neutrons is small (<0.1% for 10-keV-energy neutrons).

The light efficiency for the NE 110 scintillator, which has a light attenuation length nearly twice that of NE 102A, was determined by comparing the pulse-height distributions from four monoenergetic neutron groups (138 to 954 keV) using the thick iron filter, with measurements of the Compton edges for gamma rays from ^{137}Cs, ^{51}Cr, and ^{57}Co. These sources have gamma-ray energies of 662, 320, and 138 and 122 keV and Compton edges of 477, 178, and 48 and 39 keV. The light efficiency for proton recoils from neutrons relative to electrons for the NE 110 scintillator is about the same as that of an NE 213 liquid scintillator at 1 MeV, but the NE 110 has a relatively higher output for ~100-keV neutrons by about a factor of 3. It is interesting to note that the pulse-height distribution from 954-keV neutrons clearly shows recoil pulses from the carbon in the scintillator. These pulse heights are ~1/12 those of the proton recoils.

A SYSTEM FOR MULTIPARAMETER PULSE-HEIGHT ANALYSIS WITH REPEATED USE OF A SINGLE, FAST ADC[1]

C. D. Goodman C. A. Ludemann D. C. Hensley R. Kurz [2] E. W. Anderson[2]

In many nuclear physics experiments an event consists of correlated output pulses from several radiation detectors. We call each separate output pulse a parameter. The experiments with which we are dealing are multiparameter experiments. We have constructed a system in which a single ADC is interfaced to a general-purpose computer. Multiparameter experiments are handled by storing the several pulses in analog stretchers and using the ADC repeatedly to digitize the several pulses in sequence. This approach is made practical by the availability of a very fast ADC. The system includes features that give it unusual flexibility for handling complicated time relationships among the pulses. The use of one rather than several ADCs makes the system simpler, more compact, and less expensive than multiple ADC systems. Provisions are included for evaluating counting loss due to dead time of the system for random or nonrandom event distributions. The data-transfer logic incorporates the facility for including digital information from devices in addition to the ADC in each event datum.

1. Summary of published paper: *IEEE Trans. Nucl. Sci.* NS-18, 323–25 (1971).
2. Tennelec, Inc., P.O. Box D, Oak Ridge, Tenn. 37830.

THE USE OF ARRAYS SMALLER THAN IMPLIED BY THE RANGE OF DESCRIPTORS FOR MULTIPARAMETER PULSE-HEIGHT ANALYSIS[1]

D. C. Hensley C. D. Goodman

A program for use with multiparameter pulse-height analysis is described. The main purpose of the program is to permit reasonably rapid accumulation of data into arrays which are much smaller than implied by the range of descriptors. In addition, the method readily permits the use of descriptors which exceed the bit capacity of the computer word. Any grouping of zero and nonzero channels as is observed in most real spectra is especially exploited. In many cases, the data can be retained in a packed array in core memory until the actual number of nonzero channels becomes almost as large as the allotted core-memory space, at which time the array is transferred to another space in core (where it will be transferred onto disk as a background operation); the core array is reinitialized, and the data acquisition is continued. With this procedure, multichannel arrays as large as the available disk memory can be stored on disk without the data acquisition suffering from the very slow random access time of the disk. Methods of data handling and the resulting effective counting rates are discussed.

1. Summary of published paper: *IEEE Trans. Nucl. Sci.* NS-18, 312–16 (1971).

PERFORMANCE OF A PENNING ION SOURCE ON A CYCLOTRON[1]

M. L. Mallory[2] E. D. Hudson G. Fuchs[3]

Over one year of continuous operation of a heavy-ion Penning source on an isochronous cyclotron (ORIC) has resulted in the acceleration of a number of isotopes of 17 elements ranging from boron to xenon. Comparison of the measured ion beam intensity of a given charge accelerated with the calculated ionization potential for that charge has resulted in a systematic understanding of expected intensities for new ion beams. In particular, shell effects and the total ionization potential must be taken into consideration. The total ionization potential is defined as the sum of the ionization potentials of each charge state up to and including the charge state of interest. A gas proportional counter was used to detect low-energy x rays from the Penning source. The x-ray spectrum observed characterizes the two modes of Penning source operation. Also, x rays with an energy of 2 kV have been detected with the source operating at 600 V.

1. Abstract of paper to be published in *IEEE Transactions on Nuclear Science* NS-19(2) (1972).
2. Chemistry Division.
3. Visiting scientist from the University of Marburg, West Germany; sponsored by the Bundesforschungministerium and GSI Darmstadt.

HIGH-PERFORMANCE HEAVY-ION SOURCE FOR CYCLOTRONS[1]

E. D. Hudson M. L. Mallory[2] S. W. Mosko

A cold-cathode Penning discharge source developed for the Oak Ridge Isochronous Cyclotron has produced external focusing beams of 140-MeV $^{16}O^{5+}$ (15 μA) and 205-MeV $^{40}Ar^{10+}$ (5×10^4 particles/sec). A water-cooled copper source chimney mounted on a single source stem is radially inserted into the cyclotron. The power supply operates in a constant-current mode and can deliver arc currents up to 12 A and arc voltages up to 6 kV. Typical operating parameters are 650 V at 5 A, yielding a source power input of ~3 kW. Other external beams obtained in microampere quantities are $^{12}C^{4+}$ and $^{20}Ne^{5+}$. Nanoampere quantities of $^{40}Ar^{8+}$ and $^{63}Cu^{9+}$ have been obtained. The intensities of 180-MeV $^{40}Ar^{9+}$ and 98-MeV $^{132}Xe^{12+}$ are 10^8 and 10^7 particles/sec respectively.

1. Abstract of paper published in *IEEE Trans. Nucl. Sci.* NS-18(3) (1971).
2. Chemistry Division.

POWER SUPPLIES FOR COLD-CATHODE PENNING DISCHARGE ION SOURCES[1]

S. W. Mosko

For the generation of heavy ions at high charge states, the cold-cathode Penning discharge ion source requires a power supply capable of both the high potential required for striking an arc and the high current for sustaining it. A series-regulated power supply developed at Oak Ridge provides up to 6 kV of striking voltage and up to 12 A of arc current. The power supply operates in a constant-current mode with the arc voltage dependent on ion source gas pressure. With this source in ORIC, the typical operating conditions are 5 to 10 A arc current, 600 to 2000 V arc potential, and 5 to 20 kW power dissipation in the arc. A larger power supply is planned for extending the arc current range to about 25 A. Various configurations, including preregulators and multiple power supplies, are under consideration to reduce power dissipation in the series regulator tubes.

1. Abstract of paper to be published in *IEEE Transactions on Nuclear Science* NS-19(2) (1972).

LIFETIMES OF CARBON FOILS AS HEAVY-ION STRIPPERS

P. H. Stelson E. D. Hudson M. L. Mallory[1] R. S. Lord

Large currents of 37-MeV Ar^{4+} ions are accelerated by ORIC. This beam was used to measure lifetimes of carbon foil strippers. The carbon foils were about 20 $\mu g/cm^2$ thick and were ¾ in. in diameter mounted on aluminum frames. By putting a collimator hole directly in front of the foil, we confined the beam to the central $^5/_{16}$-in.-diam area of the carbon foil. After stripping, the beam was passed through a 153° analyzing magnet. The magnet could be smoothly cycled in field strength so that we obtained a charge-state distribution of the stripped ions. We could then monitor any changes in the stripping ability of the foil as a function of time. In particular we could observe the intensity of the primary 4+ peak, which is far removed from the centroid (centered at +11) of the stripped beam. Any increase in the barely detectable 4+ intensity would indicate the development of pinholes in the foil.

We bombarded a carbon foil for 5 hr with 10 μA (or 2.5 particle microamperes) of 37-MeV Ar^{4+} ions. No detectable change in the stripping spectrum was observed. Figure 1 shows the charge-state spectra at the beginning and end of the bombardment. The physical appearance of the foil was little changed except for a darkening where the beam had hit, indicating a thickening of the foil in that area. We are quite encouraged by this result, since it shows that a carbon foil stripper will last for 12 particle microampere-hours. Put in another

1. Chemistry Division.

ORNL-DWG 72-1766

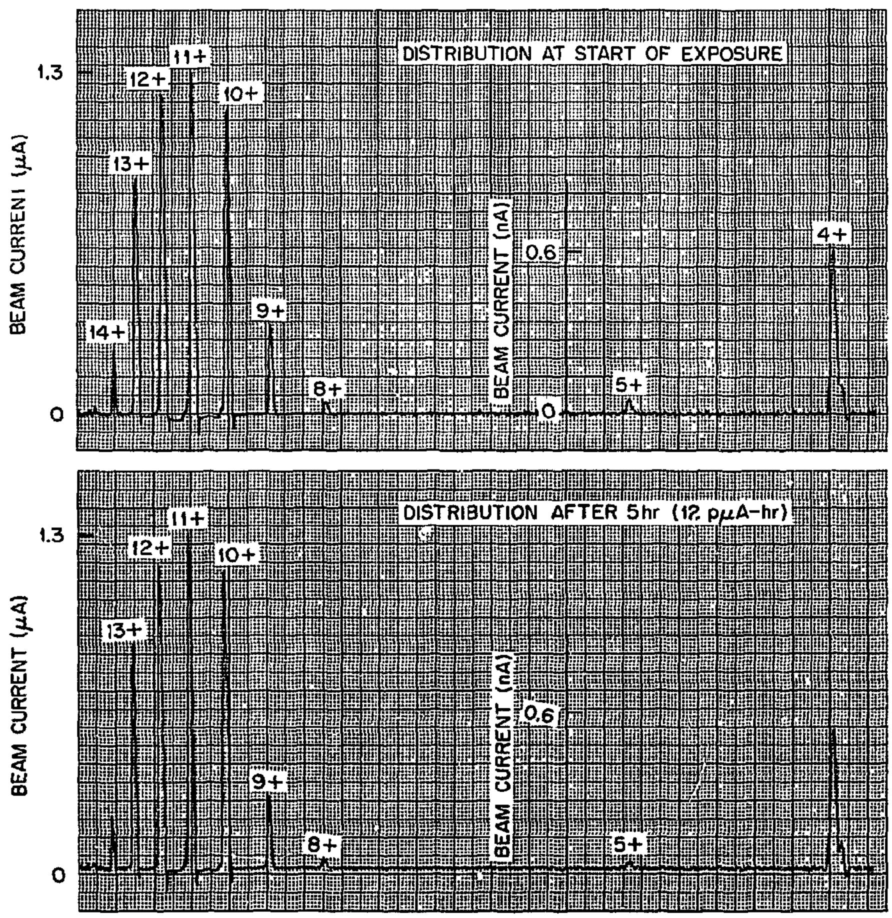

Fig. 1. Charge-state spectra observed at beginning and end (after 12 particle microampere-hours) of 37-MeV argon beam stripped by a 20-$\mu g/cm^2$ carbon foil.

way, the foil lasted perfectly as a stripper for 5×10^{17} particles/cm^2 incident on the foil. This is an order of magnitude longer life than the value suggested by Purser[2] for 40-MeV argon ions.

If we take the area occupied by a carbon atom as 5×10^{-16} cm^2, we find that the foil lasts for at least 200 argon ion traversals of an atomic area.

It is also interesting to compare our result with those of Yntema.[3] Yntema found that 4-MeV nickel ions destroyed carbon foils in about 1.7×10^{-2} particle microampere-hour, or about 7000 less flux per unit area than we observed. (Both experiments used areas of about 0.5 cm^2.) This suggests that damage may be strongly energy dependent. In an attempt to study this, we tried using the 13-MeV Ar^{3+} beam from ORIC. Unfortunately this beam is not very intense, because it must be accelerated on a high harmonic. In this case, we observed no detectable change in the stripping pattern after a total bombardment of 0.3 particle microampere-hour, which is still about 20 times longer than Yntema's results.

2. K. H. Purser, *Some Recent High Energy Heavy Ion Cyclotron Projects*, UR-NSRL-38, University of Rochester (1971).

3. J. L. Yntema, ANL Physics Division, *Physical Research Monthly Report for December, 1971.*

TANDEM ENERGY CALIBRATION

J. K. Bair W. B. Dress C. H. Johnson
C. D. Moak G. F. Wells[1]

During August 1971 an effort was made to redetermine the tandem *downstairs* energy calibration with improved accuracy taking into account the effects of saturation of the 90° magnet. The "absolute" calibration is based on the (p,n) reactions in ^{27}Al and ^{58}Ni. The threshold of the $D(^{16}O,n)^{17}F$ reaction was measured, using charge states 2 through 5, to obtain relative calibration points over a range of from 5 to almost 13 kG.

We define K_{eff} by the usual expression

$$k_{eff}B^2 = \left(1 + \frac{E}{1822\,M}\right)\frac{ME}{Q^2} .$$

Our experimental values of K_{eff} are then fitted by

$$K_{eff} = 0.35972 \text{ for } B < 4.0 \text{ kG} ,$$

$$K_{eff} = 0.3575 + 0.0010381\,B - 0.000137626\,B^2 + 0.000003665\,B^3 \quad \text{for } B \geq 4.0 \text{ kG} ,$$

with a maximum deviation of 0.01%.

1. Instrumentation and Controls Division.

A POSITION-SENSITIVE PROPORTIONAL DETECTOR FOR A MAGNETIC SPECTROGRAPH[1]

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

A position-sensitive detector has been constructed for use at the focal plane of an Enge split-pole spectrograph. The detector is a single-wire gas proportional detector of the Borkowski-Kopp type which derives the position information from the rise time of the pulses from the two ends of a high-resistance wire anode. A position resolution of 0.7 mm was obtained for the 20-cm-long detector operated with the magnet. Spectra are presented which were obtained from the Coulomb excitation of transuranic elements by alpha particles.

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

DETERIORATION OF LARGE Ge(Li) DIODES CAUSED BY FAST NEUTRONS[1]

P. H. Stelson J. K. Dickens[2] S. Raman R. C. Trammell[3]

The large Ge(Li) gamma-ray detector has become a powerful tool for the investigation of nuclear reactions. Unfortunately, these detectors are quite susceptible to fast-neutron damage, and this makes it difficult to decide whether or not to risk using a detector to study reactions at accelerators where fast neutrons are inevitably present. After ruining several detectors, we decided to study the problem in a controlled way. A 30-cm^3 true coaxial diode was systematically irradiated by neutrons from a plutonium-beryllium source. An increase in the width of the 2.614-MeV gamma ray from thorium C'' was first detected after an irradiation of 5×10^7 neutrons/cm^2. When the total irradiation had reached 6×10^8 neutrons/cm^2, the peak width had increased by more than 50%. The irradiated detector was then reprocessed to remove the damage. The diode was again subjected to neutron irradiation. The second curve of resolution deterioration as a function of neutron flux was quite similar to the first one. The procedure was repeated a third time with similar results. Thus reprocessing a detector effectively removes the neutron damage at a cost of only about 10 to 15% of the original price. A method was also developed for using the gamma-ray spectrum to evaluate the amount of neutron flux incident on the detector. The number of counts in the 693-keV peak [from (n,n') reaction with the ^{72}Ge in the detector] can be multiplied by 20 to get a rough measure of the neutron flux in neutrons per square centimeter.

1. Abstract of paper to be published in *Nuclear Instruments and Methods.*
2. Neutron Physics Division.
3. ORTEC, Inc., Oak Ridge, Tenn.

THE ORIC COMPUTER SYSTEM

C. A. Ludemann

The major portion of the activity concerned with upgrading the ORIC computer system this past year has been concentrated in the design and procurement of hardware. Figure 1 shows the data acquisition and processing network as it will appear in early 1972. All equipment is either in house or scheduled for delivery.

Core storage capacity of the system has been increased primarily due to the requirements of the fast-multiplexed-input ADC system (MUX ADC). Data are acquired from this device in random, word-by-word transfers which "steal" machine cycles from the programs that are processing stored information. Since each transfer of a data word takes $\lesssim 5$ μsec and data rates are typically $\lesssim 3000$ sec^{-1}, processing proceeds essentially uninterrupted by data acquisition. The only requirement that must be met in order that data not be lost is that resident dedicated computer memory buffers be readily available.

Because of the increased dimensionality of the data base to be handled in experiments planned for the near future, the size of the dedicated data buffers needed to be increased. In addition, data processing techniques are far more complex than have been used in the past. These complex processing routines have become too large to be loaded into the computer when the large data buffers are in core. The increase in memory size from 24K to 32K words will make it possible for both data acquisition and processing to take place simultaneously in our most complex experiments – a situation which must be achieved if cyclotron time is to be used efficiently.

The new general-purpose interface (INTERFACE No. 2) permits more than one data acquisition device to be connected to the computer at one time. Consequently, the bulk storage capacity of the system had to be increased to provide room for data files from all devices. A second moving head disk, providing one million words of additional storage, has been installed to alleviate this problem.

Three block transfer controls (BTCs) have been added to handle the data transfer requests from the devices that have been added to the system. The BTC hardware permits external devices to steal machine cycles as mentioned earlier. Each has a specific priority level in being able to acquire memory cycles. Generally, high-speed devices such as disk units are attached to the highest-priority BTCs. In this way a slower random access device, such as the ADC system, cannot interfere

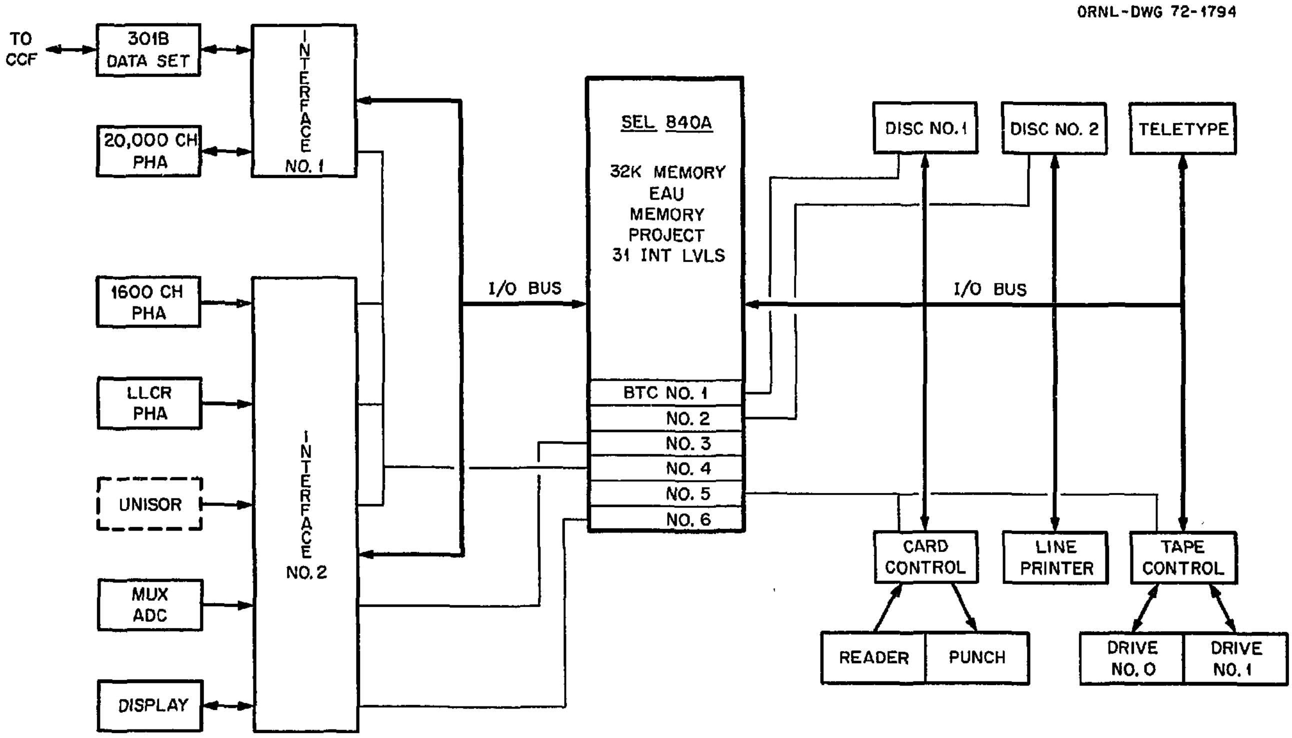

Fig. 1. The data acquisition and processing equipment at ORIC.

with disk reading or writing. While it is possible for several devices to share a BTC, it is desirable to do so only when there will be no competition for its usage. The four devices that share BTC No. 4 do not compete, because each is connected to a separate priority interrupt level. Transfers of data from these "external" memories, through the 840A, and on to disk storage are accomplished on a "core swap" basis, and only one device is serviced at a time. The ADC system, on the other hand, is attached to a separate BTC with priority just below that of the disk units and above all other devices. This permits the ADC to acquire data with a minimum amount of dead time even when the external memories are on line.

The new interface provides unit decode and synchronization logic for eight channels of input and eight channels of output communication with the SEL 840A. It includes signal conditioning and control electronics for the Victoreen 1600-channel pulse-height analyzer, the ADC system, and the storage tube display in the counting room, as well as for the Canberra 4096-channel dual-parameter analyzer in the low-level counting room (LLCR) 150 ft away. With a minimum of circuitry, additional devices such as the UNISOR data acquisition system can be interfaced to the computer.

The display is a Tektronix 4002A Graphic Computer Terminal complete with keyboard, joy stick, and hard-copy unit. It contains a storage cathode ray tube which permits spectra to be drawn once without the need for refreshing by the computer. The experimenter points to peak positions in spectra by means of the joy-stick controller. The position information is transmitted to the main frame for processing. Hard copies of the generated displays can be produced either under computer or manual control.

Finally, it should be pointed out that greater flexibility has been provided in communication with the central computer facility (CCF), a half mile away. Communications from ORIC no longer go directly to the IBM 360/75 but rather to a Digital Equipment Corporation PDP-10. By means of this new system it is possible to talk not only with the 360/75 but with the PDP-10 and the 360/91 as well.

STATUS REPORT OF THE 6.0-MV VAN DE GRAAFF ACCELERATOR

R. L. Robinson W. T. Newton[1]

During 1971 the 6.0-MV Van de Graaff accelerator, operating without any major problems, was utilized 3334 hr for research in a variety of programs. These are summarized in Table 1.

Our inexpensive column resistors,[2] which were fabricated from conventional Allen-Bradley carbon resistors (total cost of $200), have performed their role excellently. After nearly 5000 hr of service, there has been no failure, and their resistance is still within 5% of the original value.

The new terminal, which is expected to increase our pulsed beam intensity by a factor of 2 to 3 and at the same time reduce its energy spread, is nearing completion. All electrical components are built, wiring of the terminal is about half finished, and machining of the accelerator and buncher electrodes, einzel lens, deflectors, and housing is approximately 90% completed.

1. Instrumentation and Controls Division.

2. R. L. Robinson, W. T. Newton, and W. C. H. White, ORNL-4659, p. 95 (1971).

Table 1. Research activities on the 6.0-MV Van de Graaff accelerator

Type	Investigators	Percent of research time
	Dc beam	
(n,n) reaction	Fowler, Johnson	3
$(p$, x ray) and $(\alpha$, x ray) reactions	Duggan,[a] Lin,[b] Liu,[b] Humphrey,[c] Carlton,[d] Beck,[e] Ferree,[f] Cipola,[g] Robinson,[h] McCoy[i]	16
Trace element	Baglan,[j] Lubozynaki,[j] Lin[b]	1
Teaching	ORAU summer institute faculty members[k]	4
Coulomb excitation	Stelson, Raman	3
$[\alpha,\alpha'\gamma\gamma(\vartheta)]$	Robinson, Grabowski	22
Radiohalo studies	Gentry[l]	0.4
	Pulsed beam	
(n,n') and $(n,n'\gamma)$ cross sections	Perey,[m] Dickens,[m] Kinney[m]	32
$(n,n'\gamma)$ spectroscopy	Raman, Dickens,[m] Walkiewicz[n]	4
(α,γ) reaction	Jaszczak	8
(p,n) and $(p,n\gamma)$ reactions	Kim, Raman, Horen, Bertrand, Walkiewicz[n]	7

[a]Oak Ridge Associated Universities.
[b]Tennessee Technological Institute.
[c]Western Kentucky University.
[d]Middle Tennessee State University.
[e]University of Tennessee.
[f]Y-12 Plant.
[g]Creighton University.
[h]University of Alabama.
[i]University of Tulsa.
[j]Vanderbilt University.
[k]Participants from 23 different colleges.
[l]Chemistry Division.
[m]Neutron Physics Division.
[n]Edinboro College.

The 6-ft extension of the pressure vessel required by the new terminal has been fabricated and delivered. Now that more space will be available, it is also possible to consider other types of large terminals. One under serious consideration is for heavy-ion sources to be employed in studies of radiation effects on structural material for thermonuclear reactors.

As can be seen from Table 1, a large amount of the research employing the 6.0-MV accelerator was performed by groups not in the Physics Division. Since their work will not be discussed elsewhere in this annual report, we will briefly summarize their programs here.

Duggan et al. observed x rays from ionization induced with protons (energies of 1 to 6 MeV) and alpha particles (2 to 12 MeV) from 14 different elements ranging in mass from cobalt to thallium. They found that the ionization cross sections agree with theoretical values predicted by the plane-wave Born approximation theory proposed by Merzbacher and Lewis.[3] In the case of gold, they deduced the relative cross sections for ionization of the $2s_{1/2}$, $2p_{1/2}$, and $2p_{3/2}$ subshells.

The feasibility of using charged-particle-induced ionization for trace analysis is also being investigated by Duggan et al. Preliminary results show that it is possible to observe concentrations as low as 1 part in 10^{12}. One specific application of this technique was examined by Baglan, Lubozynski, and Lin. They measured x rays following charged-particle irradiation of blood samples doped with small amounts of various elements. It is possible that this technique might provide a rapid and reliable method for some types of medical laboratory work. A problem here is how to fabricate, quickly and simply, blood samples into targets suitable for charged-particle irradiation.

Since 1964, Perey, Dickens, and Kinney have used the accelerator as a source of monoenergetic neutrons via the $D(d,n)^3He$ reaction. They have measured cross sections for neutron scattering which are given as high-priority requests in the report LA-4652-MS. During 1971, this program was completed with the determination of (n,n') and $(n,n'\gamma)$ cross sections for targets, both enriched and with normal abundance, of C, N, O, Na, Ca, Ti, Fe, Ni, Cu, Zn, Zr, Pb, and U.

Ranges of 1- to 10-MeV alpha particles in mica samples have been determined by Gentry using helium ions from the accelerator. Comparison of the widths of the resulting discoloration with those of radiohalos found in the sample establishes the energy of the naturally occurring alpha particles. Besides those halos expected from uranium and thorium, he has observed ones which correspond to alpha-particle energies of ~1 and 10 to 15 MeV. At present, the origin of these is unknown. The helium beam is also being used to establish the integrated flux required for discoloration.

Finally, the accelerator served for two weeks as a training tool for faculty members from 23 universities. This was done in conjunction with an NSF-AEC-sponsored summer institute held at ORAU.

3. E. Merzbacher and H. W. Lewis, "X-Ray Production by Heavy Charged Particles," ed. by S. Flugge, vol. 34, *Encyclopedia of Physics*, Springer-Verlag, Berlin, 1958.

STATUS REPORT ON THE 3-MV VAN DE GRAAFF ACCELERATOR

J. P. Judish

In 1971 the Van de Graaff was used entirely by the Health Physics Division for studies of atomic excitations of some noble gases. A pulsed proton beam from the Van de Graaff strikes a target cell containing the gas and excites it to states which may decay by photon emission. The observed decay time is a function of target gas pressure and must sometimes be observed for time intervals greater than 32 μsec, the longest interval between pulses previously available from the ion source pulser.[1] A precountdown module was constructed and installed. It allows the interval between proton pulses to be set at 2, 4, 8, 16, 32, 64, 128, or 256 μsec by adjusting a switch at the control console.

The accelerator tube installed in October 1970 began to deteriorate and was replaced by a new one in May 1971. The new tube continues to perform well and shows no signs of deterioration.

1. R. F. King, *Instrumentation and Controls Div. Annu. Progr. Rep. Sept. 1, 1964*, ORNL-3782, p. 147.

CYCLOTRON LABORATORY ACCELERATOR DEVELOPMENT PROGRAM

E. D. Hudson R. S. Lord C. A. Ludemann M. L. Mallory[1] M. B. Marshall
J. A. Martin S. W. Mosko W. R. Smith A. van der Woude G. Fuchs[2]

The major effort in accelerator development was again applied to improvement of heavy ion capabilities.[3] The number of beams available was greatly expanded (Table 1), and new techniques of obtaining metal ions resulted in beams of $^{63}Cu^{3+}$, $^{58}Ni^{5+}$, $^{58}Ni^{6+}$, $^{181}Ta^{6+}$, $^{181}Ta^{8+}$, and $^{181}Ta^{9+}$. The nickel beam was obtained by introducing metallic nickel vapor directly into the arc, a technique first successfully used at the Harwell V.E.C. At ORIC, nickel wires were embedded in a small block of graphite. The graphite block was placed in the arc chamber behind the exit slit in such a way that it was heated to incandescence by the arc. The resulting nickel vapor readily ionized. Beams of $^{58}Ni^{5+}$ up to 1 μA were obtained in this manner. The copper and tantalum beams were produced by a different technique. Chlorine gas fed into the arc reacted with the hot source components to form volatile chlorides, which were then ionized in the plasma.[3] The first method, vaporizing material in the arc, appears to offer more promise of success in the long run.

Experience has shown that for heavy ions a separate arc chamber should be used for each source gas. Higher beam intensities are achieved in shorter bakeout times, and arc conditions are more stable with an "uncontaminated" source. Contamination due to previous operation persists for long periods of time. For example, during a $^{20}Ne^{6+}$ run one week after a boron run, nanoampere beam levels of $^{10}B^{3+}$ could be extracted by making a small change in magnet current. When using an "uncontaminated" source it is possible to obtain stable operation with oxygen gas. Previously, stable operation was possible only with carbon monoxide, with a consequent reduction in intensity.

Additional pumping on the beam line to station 7 has improved heavy ion transmission by a factor of 2. Further improvement is still possible, since only 60% of the available external beam reaches the target.

A program for replacement of the ORIC 6949 power amplifier with a new amplifier using an RCA 4648 was approved, and design work is under way. The new power amplifier will have improved hum and noise level, it will be easier to tune, and tube replacement will be easier and much less expensive than for the 6949. The new tube costs about $8000, vs $29,000 for the 6949. Replacement will be possible without lowering the entire rf system from the support crane, as is currently necessary with the 6949.

The polarized ion source has been used in experiments at energies up to 30-MeV protons. Maximum extracted beam current is ~30 nA. Proton polarization from either the low-frequency or high-frequency transitions is approximately 60%. A continuously monitoring polarization indicator has been developed and has proved useful in optimizing polarization.

The possible use of a microwave-heated plasma as a source of multiply charged heavy ions is being studied. The Thermonuclear Division of ORNL has developed such a device (ELMO) for the purpose of studying a plasma with a high density of relativistic electrons.

1. Chemistry Division.
2. Visiting Scientist from University of Marburg, West Germany; sponsored by the Bundesforschungministerium and GSI Darmstadt.
3. M. L. Mallory, E. D. Hudson, and G. Fuchs, *IEEE Trans. Nucl. Sci.* NS-19(2) (April 1972) (unpublished).

Table 1. ORIC extracted beams

Particle	Radio frequency (MHz)	Harmonic	Maximum ORIC energy[a] (MeV)	External beam current	Source feed
*$^{10}B^{2+}$	17.3	3	36	15 enA[b]	BF_3
*$^{10}B^{3+}$	20.16	3	81	8 eμA[c]	BF_3
*$^{10}B^{4+}$	9.32	1	96	>10 enA	BF_3
*$^{11}B^{3+}$	7.59	1	73.6	22 eμA	BF_3
*$^{12}C^{1+}$	11.00	5	7.5	12 enA	CO
$^{12}C^{3+}$	21.9	3	67	>10 eμA	CO
$^{12}C^{4+}$	9.2	1	120	>12 eμA	CO
*$^{12}C^{5+}$	11.25	1	187	40 enA	CO
*$^{12}C^{6+}$	13.67	1	270	~1 epA[d]	CO
$^{14}N^{2+}$	12.4	3	26	>20 eμA	N_2
$^{14}N^{4+}$	7.9	1	103	>20 eμA	N_2

Table 1 (continued)

Particle	Radio frequency (MHz)	Harmonic	Maximum ORIC energy[a] (MeV)	External beam current	Source feed
*$^{14}N^{5+}$	9.9	1	161	2 eμA	N_2
*$^{15}N^{3+}$	17.3	3	36	1 enA	N_2
$^{15}N^{4+}$	22.2	3	96	3 eμA[e]	N_2
*$^{16}O^{1+}$	8.25	5	5	1.3 eμA	O_2
*$^{16}O^{2+}$	10.81	3	22.5	5 eμA	O_2
*$^{16}O^{3+}$	14.85	3	50	300 enA	O_2
$^{16}O^{4+}$	20.7	3	90	>4 eμA	O_2
$^{16}O^{5+}$	8.6	1	140	20 eμA	O_2
*$^{17}O^{1+}$	7.77	5	4.7	2.2 enA	O_2
*$^{18}O^{2+}$	9.62	3	20	10 enA	O_2
$^{18}O^{5+}$	7.7	1	125	20 eμA[e]	O_2
*$^{19}F^{2+}$	11.79	5	18.9	1.5 eμA	BF_3
*$^{19}F^{6+}$	8.8	1	170	150 enA	BF_3
*$^{20}Ne^{1+}$	9.24	7	4.5	8 enA	Ne
*$^{20}Ne^{3+}$	19.8	5	36.6	1.3 eμA	Ne
$^{20}Ne^{4+}$	16.7	3	72	>1 eμA	Ne
$^{20}Ne^{5+}$	20.7	3	112	>1 eμA	Ne
*$^{20}Ne^{6+}$	8.3	1	162	3 eμA	Ne
*$^{21}Ne^{1+}$	8.8	7	4.3	0.7 enA	Ne
$^{22}Ne^{2+}$	7.9	3	16	800 enA	Ne
$^{22}Ne^{5+}$	18.9	3	102	80 enA	Ne
*$^{28}Si^{3+}$	9.26	3	29	0.1 enA[f]	
*$^{29}Si^{3+}$	11.59	5	27.9	100 particles/sec[f]	Ne
*$^{30}Si^{6+}$	17.3	3	108	1 epA	SiF_4
*$^{32}S^{6+}$	14.85	3	101	100 enA	H_2S
*$^{34}S^{2+}$	7.77	5	9.4	300 enA	H_2S
*$^{35}Cl^{3+}$	17.3	7	23	10 enA	Cl_2
$^{35}Cl^{5+}$	12.4	3	64	>1 enA	Cl_2
*$^{35}Cl^{7+}$	17.3	3	126	200 enA	Cl_2
$^{36}Ar^{9+}$	20.7	3	202	~5 × 10^5 particles/sec	Ar
*$^{40}Ar^{3+}$	8.40	5	20.2	250 enA	Ar
*$^{40}Ar^{4+}$	8.648	3	36	10 eμA	Ar
$^{40}Ar^{8+}$	16.7	3	144	300 enA	Ar
$^{40}Ar^{9+}$	18.8	3	182	~1 enA	Ar
$^{40}Ar^{10+}$	20.7	3	225	~5 × 10^4 particles/sec	Ar
*$^{52}Cr^{2+}$	9.13	9	6.9	1 enA[f]	
*$^{56}Fe^{6+}$	9.26	3	58	0.1 enA[f]	
*$^{58}Ni^{5+}$	7.46	5	38.8	~1 eμA	Ni + Ne
*$^{58}Ni^{6+}$	11.59	5	55.8	8 enA	Ni + Ne
*$^{63}Cu^{3+}$	8.8	7	12.9	15 enA	Cu + Cl_2
$^{63}Cu^{9+}$	12.4	3	116	1 enA[f]	
$^{66}Zn^{6+}$	7.9	3	49	0.1 enA[f]	
*$^{78}Kr^{3+}$	9.13	9	10.4	10 enA	Kr
*$^{84}Kr^{3+}$	8.48	9	9.6	32 enA	Kr
*$^{84}Kr^{9+}$	9.26	3	87	20 enA	Kr
$^{132}Xe^{12+}$	7.9	3	98	~1 × 10^7 particles/sec	Xe
*$^{181}Ta^{6+}$	7.87	9	17.9	1 enA	Ta + Cl_2
*$^{181}Ta^{8+}$	8.17	7	31.8	0.2 epA	Ta + Cl_2
*$^{181}Ta^{9+}$	9.19	7	40.3	0.5 epA	Ta + Cl_2

[a]Based on $90\,q^2/A$.
[b]Electrical nanoamperes.
[c]Electrical microamperes.
[d]Electrical picoamperes.
[e]Enriched isotopic abundance gas as source feed.
[f]From ion source material of construction.
*New beam in 1971.

Extraction and analysis of ion beams from ELMO are complicated by strong magnetic fields and low ion momentum. Consequently, ions are extracted along the magnetic axis through a 1-mm aperture and accelerated into a "time of flight" (T.O.F.) tube for charge-state analysis. A schematic of the analysis system is shown in Fig. 1*a*. The beam is switched on and off at the entrance to the T.O.F. tube by fast rise-time/fall-time pulses about 2 kV in amplitude. The entire T.O.F. tube is biased at high potential (up to about 5 kV). Beam current, collected in the Faraday cup, is differentiated and amplified with about a 10-μsec window and with a progressively incremented delay, so that the differentiated signal from the Faraday cup is integrated and reconstructed with an *x-y* recorder. The Faraday cup and wide-band amplifier are at T.O.F. tube potential, but the boxcar detector and pulse generator are at ground potential. The dotted line between the pulse

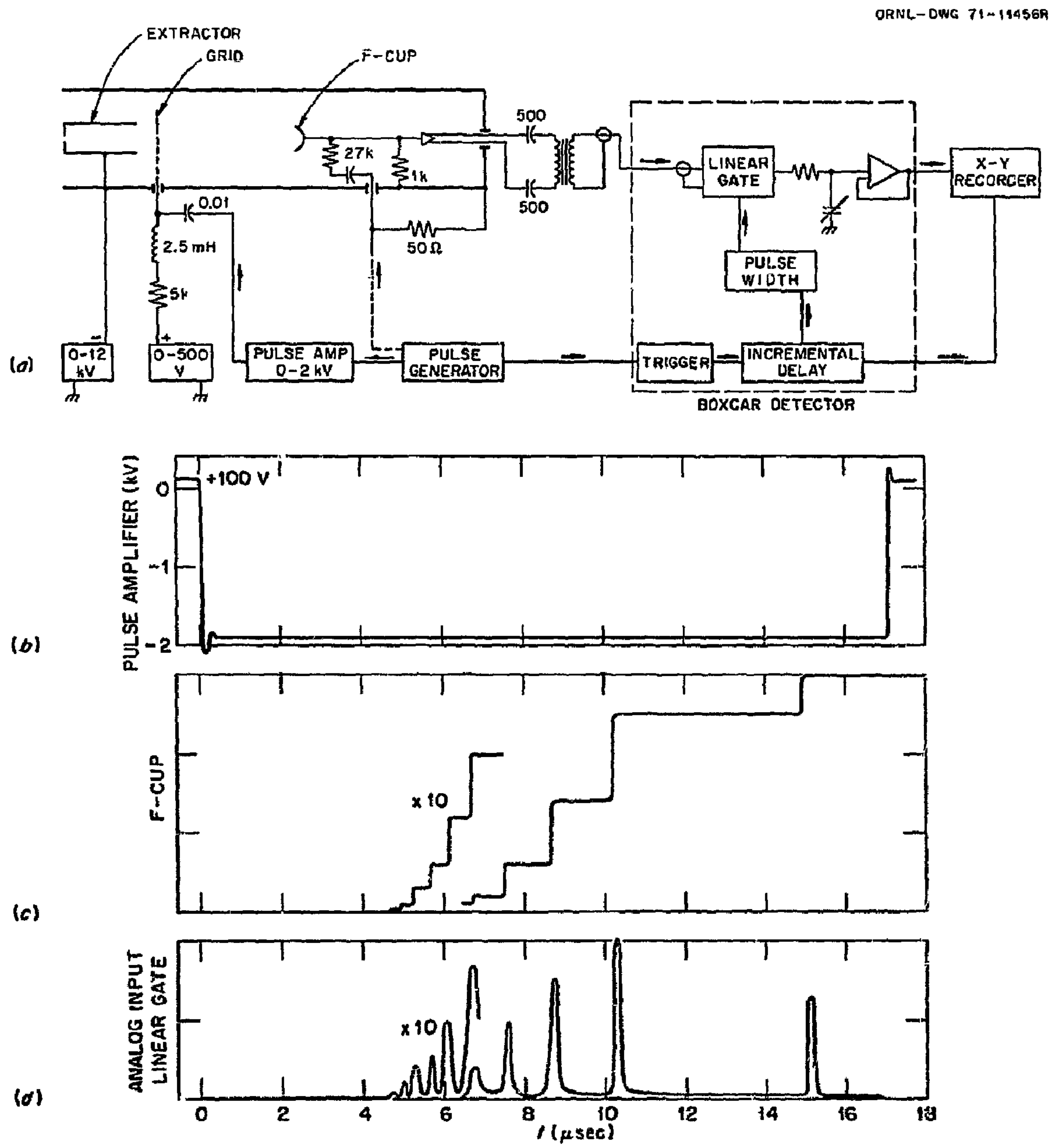

Fig. 1. (*a*) Diagram of time of flight analyzer with boxcar detector. (*b*) Typical control grid pulse. (*c*) Typical beam current as seen at Faraday cup during pulse. (*d*) Differentiated output from wide amplifier as seen by boxcar detector.

generator and Faraday cup (Fig. 1*a*) represents a method for inserting a test pulse (Fig. 2). The noise amplitude (Fig. 2) shows the signal-to-noise ratio improvement attainable with the boxcar detector. The system is capable of measuring ion currents as low as 1 nA with time resolution of about 10 nsec. It is expected that charge states such as $^{40}Ar^{12+}$ can be detected if present in the extracted beam.

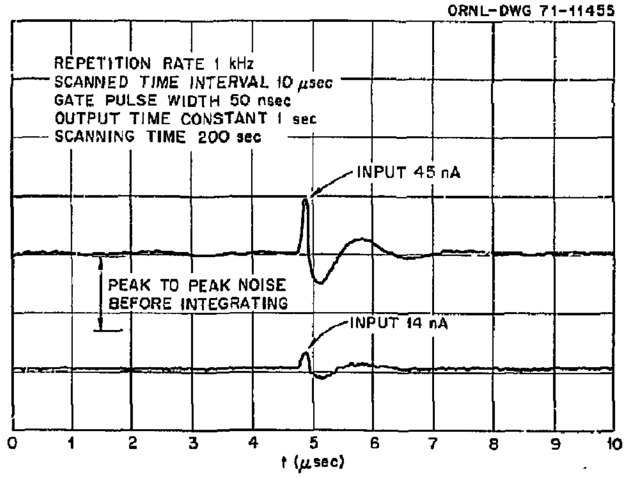

Fig. 2. Reconstructed pulses on *x-y* recorder corresponding to 100 μsec test pulses at Faraday cup.

OAK RIDGE ISOCHRONOUS CYCLOTRON OPERATIONS

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Introduction

The Oak Ridge Isochronous Cyclotron (ORIC) has continued to be operated on the 15-shift/week schedule which started in December of 1970. Nuclear research programs used about 56% of the total hours available. Usage of heavy particles continued to increase in the research programs, rising from approximately 26% in 1970 to about 56% in 1971.

Research Bombardments in 1970

A total of 6016 hr was the scheduled available time for ORIC operations in 1971 (see Table 1). Research bombardments were assigned about 3378 hr, or about 56% of the total time available. A usable beam was on target for 2321 hr, or about 39% of the total time. Distribution of the research bombardments for 1971 is shown in Table 2. A total of 268 bombardments were made with the various particle types and energies noted in Table 3.

Operations Summary

Operations continued on a 15-shift/week, 120-hr-week schedule. Beam lines with their associated quadrupoles, bending magnets, and shielding to the chemistry area in the South Research Extension to the ORIC facility were about 90% completed in 1971. Beam to the new chemistry station in the new addition was obtained in late December. The chemistry area will be used for experiments early in 1972.

Table 1. ORIC operations: operation analysis

	Hours	Percent
Beam on target	2321.3	38.5
Beam adjustment	374.3	6.2
Target setup	25.1	0.4
Startup and machine shutdown	657.6	11.0
Machine research	908.7	15.1
Total machine usable time	4287.0	71.2
Source change	271.2	4.5
Vacuum outage	175.0	3.0
Rf outage	235.7	4.0
Power supply outage	69.0	1.1
Electrical outage	44.2	0.7
Component failure outage	358.9	6.0
Miscellaneous outage	19.8	0.3
Total unscheduled outage	1173.8	19.6
Scheduled maintenance	369.7	6.1
Scheduled installation	185.5	3.1
Total scheduled outage	555.2	9.2
Total time available	6016	100

1. Health Physics Division.
2. Instrumentation and Controls Division.

Table 2. ORIC research bombardments in 1971

Affiliation	Reactions	Investigators	Hours	Percent of total available time (approx)
Physics Division	($^{14}N,3n$), ($^{3}He,p8n$), (d,p), ($^{14}N,6n$)	Toth, Hahn, Ijaz, Bingham, Hillis	319	5.3
	($^{3}He,t$), ($^{3}He,p$), ($d,^{6}Li$), ($d,^{6}He$), ($^{10}B,^{10}B^{*}$)	Goodman, Hensley, van der Woude, Raman	268	4.5
	($^{3}He,^{4}He$), ($^{2}H,^{3}H$), ($^{3}He,n$)	Newman, Gross, Greenfield, Roberts, Bingham, Ludemann, Saltmarsh	498	8.3
	($\alpha,\alpha\beta$), ($^{3}He,7n$)	Hasmatz, Handley	22	0.4
	^{16}O-induced particle reactions, (p,d) (p,t) recoils, ^{3}He-induced reactions	Ball, Toth, Eichler, Hahn, Stelson, Ford, Fulmer, Auble, Raman, Larsen, Williams, Palmer	170	2.8
	($^{12}C,\alpha$), x-ray production and tracer element analysis	Halbert, Saltmarsh, Ludemann, van der Woude	303	5.0
	Ternary fission research	Plasil, Schmitt	16	0.2
		Total hours	1716	28.5
In collaboration with universities				
Fulmer, Ball	Excitation functions	Hafele – Washington University, St. Louis, Mo.	44	0.7
	(p,d)	Miller – Redstone Arsenal	68	1.2
Halbert, van der Woude	^{3}He, excited state	O'Fallon – University of Missouri	112	1.8
Newman	($d,^{3}He$)	Kern, Chenervert – University of Kentucky	32	0.5
		Total hours	256	4.2
Other ORNL divisions				
Chemistry	($^{3}He,d$), ($\alpha,2n$), Coulomb excitation – Ar, Ne, O, ($^{3}He,3n$), ($p,2n\gamma$), ($^{16}O,4n$), ($^{12}C,\alpha xn$), ($p,5n$), ($^{18}O,\alpha 3n$), ^{20}Ne – search for ^{157}Hf, $^{157,158}La$, $^{170,171}Os$, x-ray identification of $Z = 103, 104, 106$	Ketelle, Brosi, Silva, Dittner, Keller, Bemis, Hahn, Eichler, Johnson, Schmorak, O'Kelley, Singhal, Mallory, Sayer	956	15.9
Metals and Ceramics	^{4}He, surface bubbling, study of voids in stainless steel	King, Wiffen	56	1.0
Nuclear Data	($p,2n\gamma$), (p,p'), ($^{3}He,d$)	Horen, Bertrand, Auble, Raman, Lewis	178	3.0
UNISOR	$^{141}Pr(^{15}N,5n)^{150}Dy$	Schmitt-Ott, Rester, Bingham, Toth	16	0.2
		Total hours	1203	20.1
Outside users				
Medical College of Virginia	Dosimetry calibration and animal irradiations	Lippincott	128	2.1
University of Kentucky	($\alpha,4n$), ($^{3}He,xn$)	Hofstetter, Stickler	32	0.5
University of Georgia	(p,p')	Scott, Whitten, Owais	40	0.7
		Total hours	200	3.3
		Total research bombardments	3378	56.1
		Total machine research	909	15.1
			4287	71.2

Table 3. Analysis of beam usage by types

Particle	Energy (MeV)	Hours	Percent (approx)
Protons	10–65	794	18
^{3}He	25–108	633	15
Alphas	20–91	286	7
Deuterons	20–46	150	4
Total light particles		1863	44
Carbon	31–270	683	16
Oxygen	5–140	650	15
Neon	4–167	475	10
Nitrogen	100–120	124	3
Argon	13–184	152	4
Boron	50–72	151	4
Chlorine	75–126	99	2
Sulfur	9–90	42	2
Tantalum	14	16	
Fluorine	12–168	16	
Nickel	36–48	16	
Total heavy particles		2424	56
Total research hours		4287	

Unscheduled outage increased from 14.8% to 19.6% of the total available time (Table 1). The major contributor to this increase was component failure, which rose from 2.8% to 6%. Rf outage rose from 2.0% to 4.0%. Deflector problems in late June and early July plus several coax water leaks in October were the primary causes for excessive component failure outage.

Scheduled installation was up from 0.4% to 3.1%. This was primarily used to complete installation of beam lines, associated quadrupoles, and shielding to the South Research Extension.

The rf outage resulted from a siege of power amplifier tuning capacitor failures starting in October and lasting into December. This circuit contains four vacuum tuning capacitors, which originally were of the glass envelope type rated at 55 kV. During the past two years we began substituting 35-kV capacitors, and very recently we began using 30-kV capacitors with ceramic envelopes. Failures were experienced with all three types of capacitors. It was long believed that tuning capacitor failure (which formerly occurred about every three months) was due to excessive rf current. Consequently, the ceramic envelope units were installed, since their current rating is 12% higher than for the glass envelope units. A study of the problem now indicates that most, if not all, failures were initiated by extremely high voltage transients. Modification of transient protection circuitry and installation of spark gaps in critical locations have at least temporarily eliminated the capacitor failure problem. Further, the 30-kV ceramic capacitors are quite adequate for this application. A study of the transient problem is continuing.

The power amplifier tube (6949) was replaced the latter part of December. The tube was still being used, but it was felt it was approaching a marginal condition where the maximum nonshorting value of the filament voltage would be too low for useful thermionic emission.

Because of the increased usage of heavy particles, as noted above, source change outage showed a substantial increase. This is attributable to more frequent source cathode changes required when running heavy ions.

Since the operating schedule was cut from 21 shifts/week to 15 shifts/week, the experience this year in the startup and shutdown category has shown a considerable increase. Having to shut the machine off for weekends has resulted in the loss of nearly one shift per week.

Scheduling

The scheduling of experiments on ORIC has continued on the same format adopted last year, where all ORNL users decide at scheduling meetings what experiments are to be done during any given scheduling cycle. These cycles are restricted to about 90 shifts. Unused shifts are still "banked" for future use, but no borrowing from subsequent cycles is permitted. As in the past, the feature of a "sliding schedule" in case of machine failures is still being followed.

Radiation Safety

The state of radiation safety at ORIC during 1971 remained good. There were no personnel exposures beyond permissible limits, and there were no radioactivity releases which resulted in a spread of contamination beyond zoned areas. The maximum integrated dose received by any individual associated with cyclotron operations was 0.95 rem, with the average for the group being 207 millirems. The cyclotron operators, who receive the highest exposures, had doses which averaged 430 millirems, with the highest single exposure being that indicated above. Continuously operating air monitors in and around the facility indicated effective containment of particulate radioactive materials, as no responses significantly above background variance were observed.

A number of features designed to improve the quality of radiation safety were added and/or initiated during the year. They were: (1) an improved safety checklist for periodic testing of all safety circuits (interlocks, scram switches, etc.), (2) the addition of a fresh air supply station, safety shower, and eye bath fountain near the vault for protection against possible releases of toxic gases used in ion sources (chlorine, boron trifluoride, etc.), (3) use of a ventilated hood for the storage of the toxic gases mentioned above, (4) the installation of a fast-closing valve in the beam line used during heavy element irradiations (the function of the valve is to limit the spread of contamination should a target rupture or target vaporization occur), and (5) the addition of absolute (HEPA) filters on the discharges of the pumps for the beam line to the transuranium target station. Testing of the filters at three-month intervals has been adopted.

STATUS OF THE UNISOR PROJECT

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Introduction

In February 1970, nuclear scientists from several Southeastern universities, ORAU, and ORNL formed a group for the purpose of jointly building and using an isotope separator facility on line with ORIC (the Oak Ridge Isochronous Cyclotron). From this beginning, rapid progress has been made on the construction of the UNISOR laboratory. In addition, UNISOR research workers are already using heavy-ion beams from ORIC in developmental research. This report briefly outlines from a technical viewpoint the progress which has been made on the UNISOR project during the past year. Reports published elsewhere[1,2] give more general coverage.

The UNISOR Annex

The construction of an addition to the ORIC building for the purpose of housing the isotope separator was essentially completed on schedule in February of 1972. Figure 1 is a general floor plan of ORIC, showing the UNISOR annex. A heavy-ion beam from the cyclotron will terminate in a small 150-ft^2 room, which will house the target–ion-source configuration. The ion source will be connected to the isotope separator by a 3-mm-long drift tube, which will pass through the shielding. The rest of the laboratory is shielded from the target–ion-source room by 3½-ft-thick concrete walls. Approximately 1870 ft^2 of laboratory floor space is designated for housing the isotope separator itself and such auxiliary equipment as the control console, a moving tape isotope collector system, off-line ion sources, counting equipment, and associated electronics. A large crane is provided for the movement of heavy material inside the laboratory. The entire annex is air conditioned, and the humidity inside the target–ion-source room is regulated as well.

The Isotope Separator

An isotope separator with a 90° homogeneous-field sector magnet was ordered from the commercial firm DANFYSIK in Denmark. Delivery of the instrument is expected in the spring of 1972. The separator has been specified to have a dispersion of 0.6 cm for mass 250, a mass resolution $m/\Delta m$ of at least 2000 for ion currents at the collector of 1 to 50 μA, a useful ion current range of 1 to 500 μA, and a mass range at the collector of ±7.5%. The instrument will operate off line as a conventional laboratory isotope separator as well as an on-line facility. Figure 2 depicts some of the general features of the instrument.

Ion Source Development

Because of the central importance of the target–ion-source configuration in the successful operation of an on-line isotope separator, considerable effort is being invested by UNISOR workers in ion source development. Sidenius[3] hollow cathode and Nielsen[4] oscillating electron ion sources will be delivered with the isotope separator. On-line experiments with heavy-ion reactions at ORIC indicate that reasonably efficient transfer of reaction products from a target chamber to one of the ion sources should be possible with a helium gas-jet system. Other UNISOR experiments confirm that one can rapidly extract low-melting-point reaction products from high-melting-point targets by thermal diffusion. More quantitative measurements of diffusion times under more realistic experimental conditions are

1. *Oak Ridge Associated Universities 25th Annual Report*, p. 8 (1971).
2. J. J. Pinajian, *ORNL Review*, fall 1971, p. 6.
3. G. Sidenius, *Nucl. Instrum. Methods* 38, 19 (1965).
4. K. O. Nielsen, *Nucl. Instrum.* 1, 289 (1957).

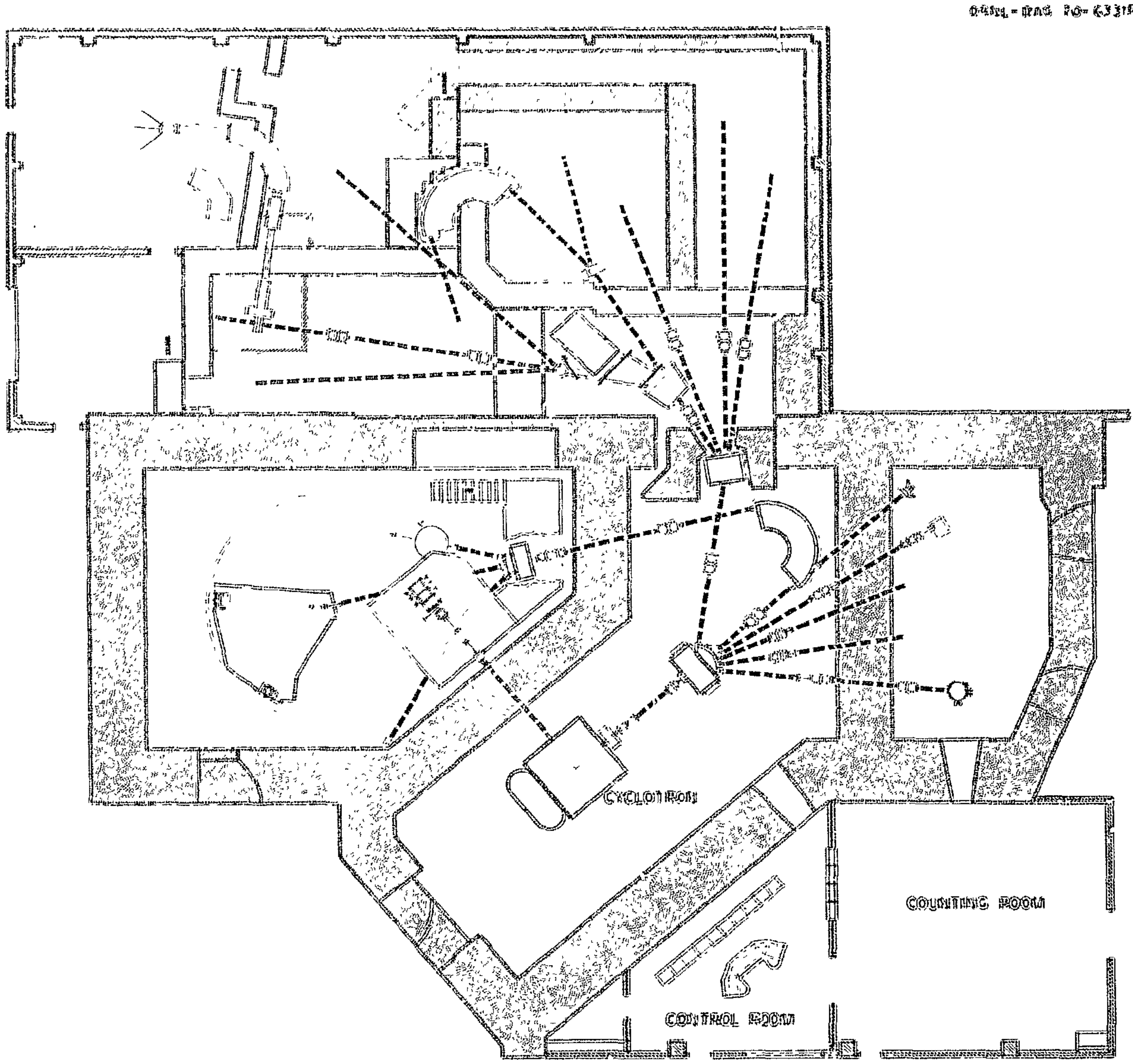

Fig. 1. General floor plan of the ORIC building. The area in the upper left corner is the UNISOR annex.

under way. Some less conventional ideas for ion sources are also being investigated with the goal of increased efficiency and decreased ion source holdup time in mind. One such idea is a side extraction Penning ion gage source[5] coupled to a thermal diffusion target arrangement. Such a source should be relatively efficient, as it can have a rather dense plasma in a small volume. It would also have the advantage of being easily accessible for beam input, ion extraction, changing targets, etc. Another approach under consideration is a modification of the inverse magnetron ion source with a catcher for recoiling reaction products which is employed by the project EMSOMHIB[6] group at Dubna.

Auxiliary Equipment

Preliminary design work on a moving tape isotope collector system has been completed. The UNISOR system will combine the best features of the TRISTAN

5. M. L. Mallory et al., International Conference on Multiply Charged Heavy Ion Sources and Accelerating Systems, Gatlinburg, Tenn. 1971: *IEEE Trans. Nucl. Sci.* NS-19(2), to be published April 1972.

6. N. I. Tarantin et al., *Proceedings of the International Conference on Electromagnetic Isotope Separators and the Techniques of Their Applications, Marburg, Germany*, p. 59, 1970.

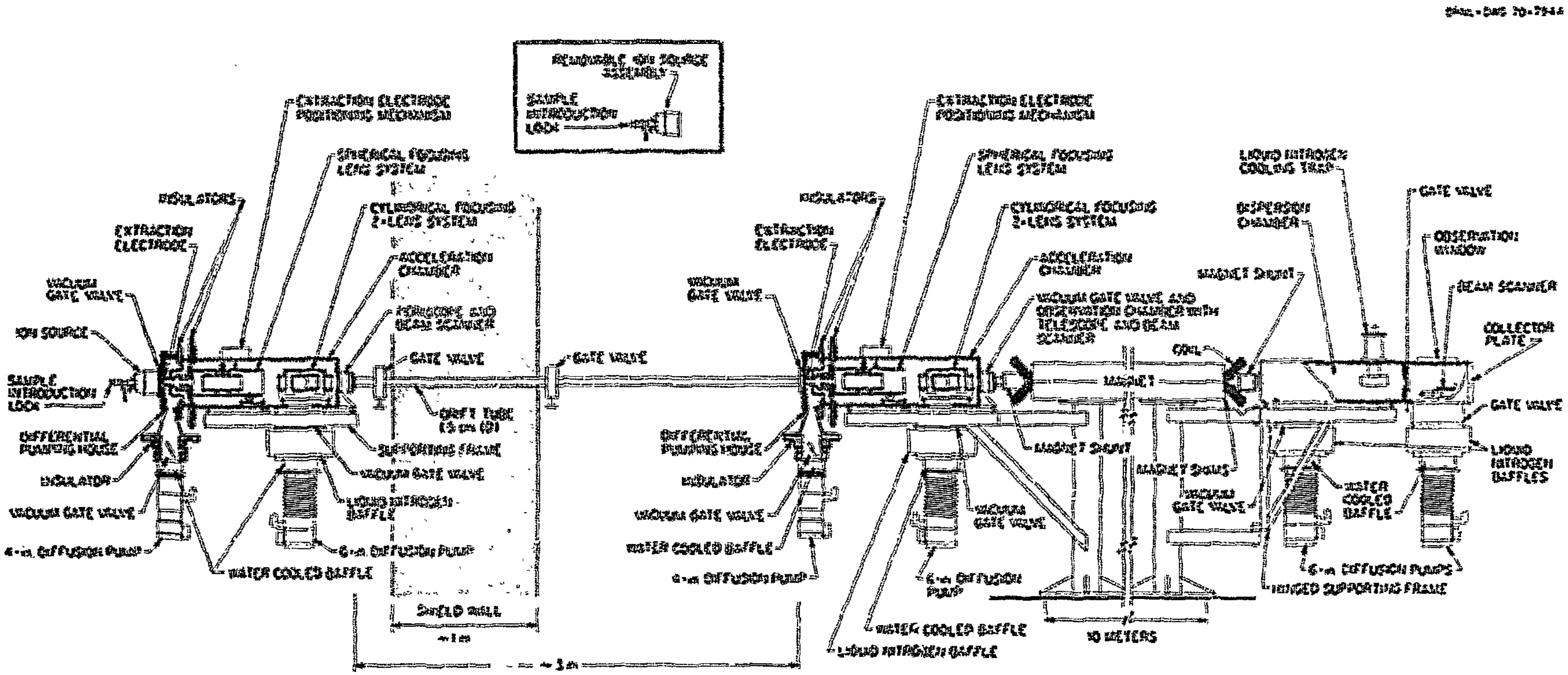

Fig. 2. The UNISOR on-line isotope separator.

and the POLARIS[7] systems. In particular, the UNISOR system will be built in modular form so that it can be adapted to many uses.

Specifications have been written for a computer-based multiparameter pulse-height analysis system and have been sent out to prospective bidders. The system will be capable of collecting a full 8K × 8K × 8K matrix of three-parameter time-correlated events at rates of 5000 events per second in the presence of single rates up to 100K per second. It will include a display and associated controls featuring a large-area oscilloscope and interactive light pen. The primary output will be via industry-compatible nine-track magnetic tape and DEC tape.

7. E. H. Spejewski et al., *Nucl. Instrum. Methods* 84, 237 (1970).

STATUS REPORT OF THE OAK RIDGE ELECTRON LINEAR ACCELERATOR (ORELA)

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Accelerator Operation

During 1971, ORELA was utilized for research by physicists from the Physics and Neutron Physics Divisions for a total of 5456 hr, an increase of 50% over 1970. Due to the failure of the closure clamp of the gun tank in December 1970 and the need to design, construct, test, and install a replacement gun tank, the accelerator did not operate until mid February. The accelerator is operated 24 hr a day seven days a week, except for holidays, with a two-day shutdown scheduled every two weeks for routine maintenance. The principal reasons for unscheduled shutdowns the past year were failures of electronics in the gun tank, time required to process new guns, and outgassing of new polyimide plugs used in the fast valves on the accelerator. To reduce downtime in the future, a new replacement gun tank with better cooling and modular electronics has been built and is being tested. Also, a facility to use the old gun tank has been assembled for processing and testing new guns off line. New polyimide plugs are prebaked and stored under vacuum. Additional cooling and filters were installed in the modulators to permit operation at 1000 pulses per second after the new gun tank has been installed. A new target positioner has been built to hold a new neutron-producing tantalum target which has beryllium walls instead of aluminum to eliminate the unwanted structure in the neutron beam caused by aluminum. A monthly breakdown of the ORELA operation for experimenters is shown in Table 1.

Two klystrons have operated for over 11,000 beam hours and are still on the accelerator. Since August 1969, only two klystrons have failed, after 3005 and 2325 hr of operation. One has been repaired, but the other one was not repairable and has been used for display purposes at ORELA. Only four electron guns have been used this past year, with two guns lasting over 2300 hr each. Details of the lifetimes of the electron guns and klystrons are given in Tables 2 and 3. Descriptions of the neutron time-of-flight experiments and results can be found in this progress report, last year's report (ORNL-4659), and the Neutron Physics Division annual reports (ORNL-4705 and ORNL-4592).

1. Instrumentation and Controls Division.
2. Neutron Physics Division.

Table 1. Electron beam hours for experimenters at ORELA, 1971

Date	Research hours
January	0
February	273.6
March	506.1
April	573.0
May	529.2
June	633.0
July	367.6
August	507.0
September	507.6
October	646.8
November	492.4
December	420.1
Total for 1971	5456.4

Table 2. Electron gun lifetimes for ORELA, 1971

Gun No.	Beam hours	Failure date
8-1	597.5	March 13, 1971
7-1	2397.2	July 26, 1971
4-3	2312.8	November 29, 1971
5-4	449.2	Still good on December 31, 1971
Total	5756.7	

Table 3. Klystron lifetimes at ORELA, 1971

Klystron No.	High-voltage hours	Date
2003	13,091	Original–Dec. 1971[a]
2006	11,686	Nov. 1969–Dec. 1971[a]
2007	7,850	Dec. 1969–Apr. 1971 (spare)
2010	4,509	Apr. 1971–Dec. 1971[a]
2009	3,106	Sept. 1970–Apr. 1971 (spare)
2011	2,327	Apr. 1971–Sept. 1971 (spare)
2004[b]	2,179	Sept. 1971–Dec. 1971[a]
2002	1,447	Original–Nov. 1969 (spare)

[a]Still in accelerator.
[b]Rebuilt klystron.

Data Handling System[3]

The ORELA data acquisition system has continued to perform exceedingly well, and usually five or six experimenters have taken data or performed preliminary experiments simultaneously. The maximum obtainable data rates for each computer were increased to ~5000 events/sec, new options were added to the display routines, new CRUNCH programs were written, and new routines were prepared to monitor the data collected by each experimenter. Interfaces were built for computer control of samples and filters during an experiment and to permit the monitoring of scalers which recorded neutron intensity, number of accelerator bursts, etc., for each phase of an experiment. To prevent electrical ground loops, electrical isolation has been installed on both the multiplexer and the scaler connections between experimenters and the computers.

The immediate analysis computer, a PDP-10 computer, arrived in April 1971. ORELA has three interactive displays, each containing a PDP-15 computer, and three remote Teletypes with hard-wired computer links allow for program debugging. The extended acceptance tests on all aspects of the system started in December and were completed on January 19, 1972. Preliminary programs for the processing of ORELA data have been written, have undergone some testing, and have been used by ORELA physicists. A link between the data acquisition computers and the PDP-10 has been installed and tested. This link permits rapid transmission of data from ORELA to the Computing Center in Building 4500 and sending computed results back to the line printer and plotter at ORELA. During 1972, experimenters will be able to do some of the processing and analysis of their data with this new system.

3. Details of the system may be found in the recent annual progress reports of the Instrumentation and Controls Division and the Mathematics Division.

APACHE CYCLOTRON DEVELOPMENT

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R. S. Lord
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M. B. Marshall
S. W. Mosko
W. R. Smith
P. H. Stelson

A new plan for the Accelerator for the Physics and Chemistry of Heavy Elements (APACHE) has been evolved from the 1969 concept. The new concept takes into account developments in tandem Van de Graaff design, the need for higher maximum heavy-ion energies, and the need for highest reliability. The accelerator system will be able to provide beams of the heaviest ions to 10 MeV/amu using only gas stripping. The nominal maximum energies of some representative ions are given in Table 1. The new design provides for acceleration of protons to 100 MeV, rather than 300 MeV formerly. It is assumed that accelerators at other laboratories can take care of the needs for the higher-energy protons.

The main injector accelerator of the new system is to be a 20-MV tandem, either a stretched version of the original 16-MV terminal TU concept of High Voltage Engineering Corporation or, alternatively, a model UD-20 vertical Pelletron-type tandem manufactured by the National Electrostatics Corporation. The terminal will be equipped for either gas or foil stripping; capability will be provided to add an ion source for multiply charged ions later.

1. General Engineering Division.
2. Chemistry Division.

The new cyclotron (see the plan section, Fig. 1, and specifications in Table 2) is, as before, a separated-sector design with four sectors but with the sector angle increased to 52° from the former value of 47°. Also, the maximum magnetic field has been increased from 15 to 16 kG. Model magnet measurements have shown that the use of a modified Rogowski pole-edge profile with a radius of 0.84 of the gap width without taper is effective in reducing the saturation effects by more

Table 1. APACHE beam energy for selected ions

For most probable charge states from gas stripping except for iodine and uranium

Ion	MeV	MeV/amu
^{238}U	2380	10
^{127}I	2400	19
^{81}Br	2400	30
^{35}Cl	2800	80
^{19}F	1850	97
^{12}C	1200	100

Table 2. APACHE cyclotron characteristics (design goals)

Uranium energy, MeV/amu	10
Relativistic energy limit, MeV/amu	100
Minimum q/A ratio (for 10 MeV/amu)	0.15
$B\rho_{max}$, kG-cm	3010
Energy constant, K ($E = Kq^2/A$)	435
Maximum magnetic field, kG	16.0
Magnet fraction, f	0.58 (52° hills)
Number of sectors	4
Injection energy, uranium ions, MeV/amu	1.1
Energy ratio (E_f/E_i)	9 min, 18 max
Radius ratio (R_f/R_i)	3 min, 4.25 max
Injection mean radius, m, at $R_f/R_i = 3$	1.08
Extraction mean radius, m	3.26
Rf system frequency, 10 MeV/amu, MHz	12.72
Harmonic number	6
Rf system frequency range, MHz	6–14
Magnet weight, tons	2200

ORNL-DWG 71-5362

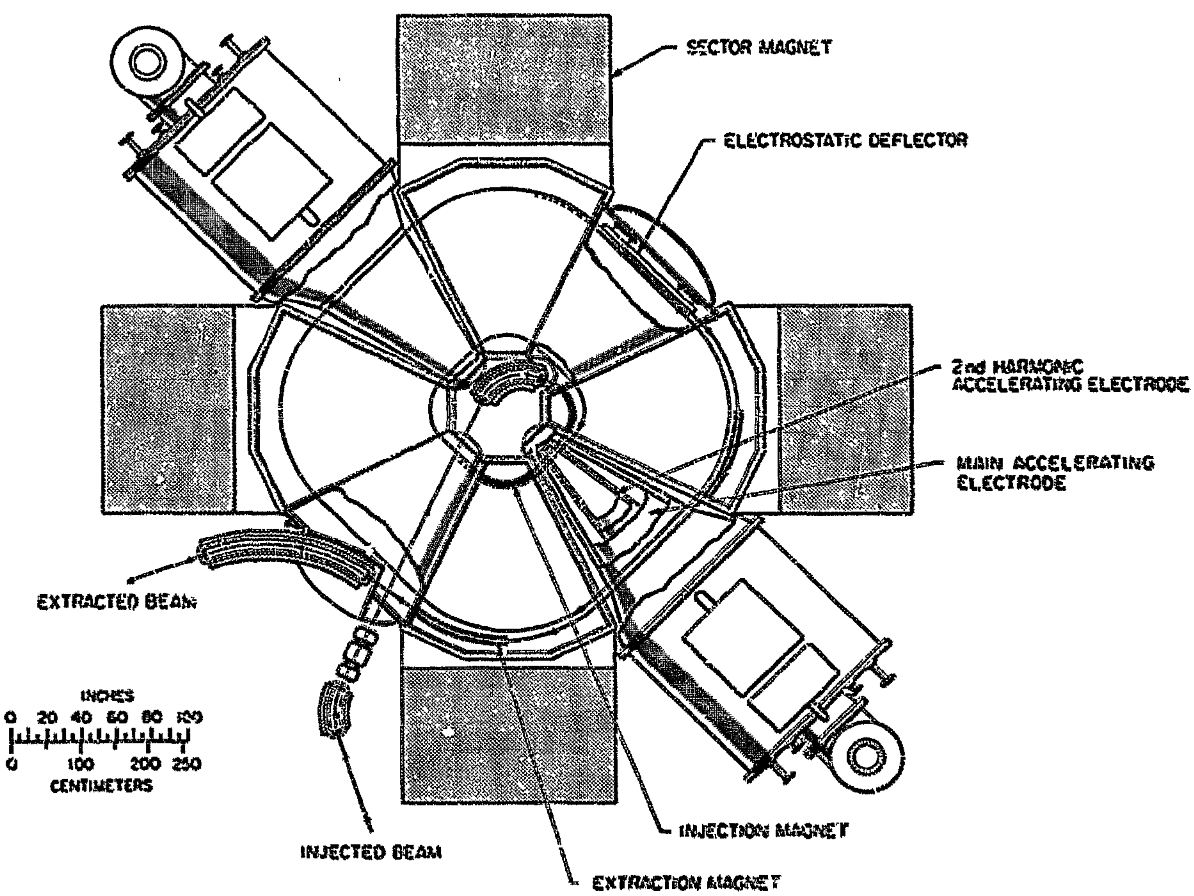

Fig. 1. Plan section of the APACHE cyclotron – an early version of the ion-injection system is shown.

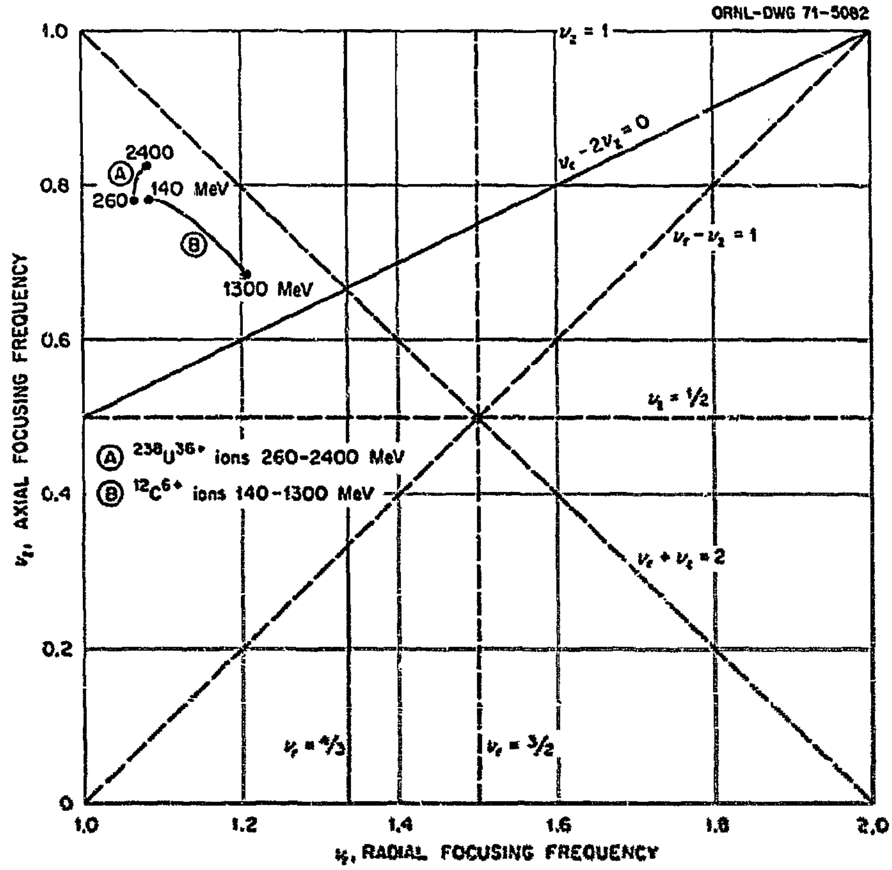

Fig. 2. The radial and axial focusing frequencies for 52° magnet sectors.

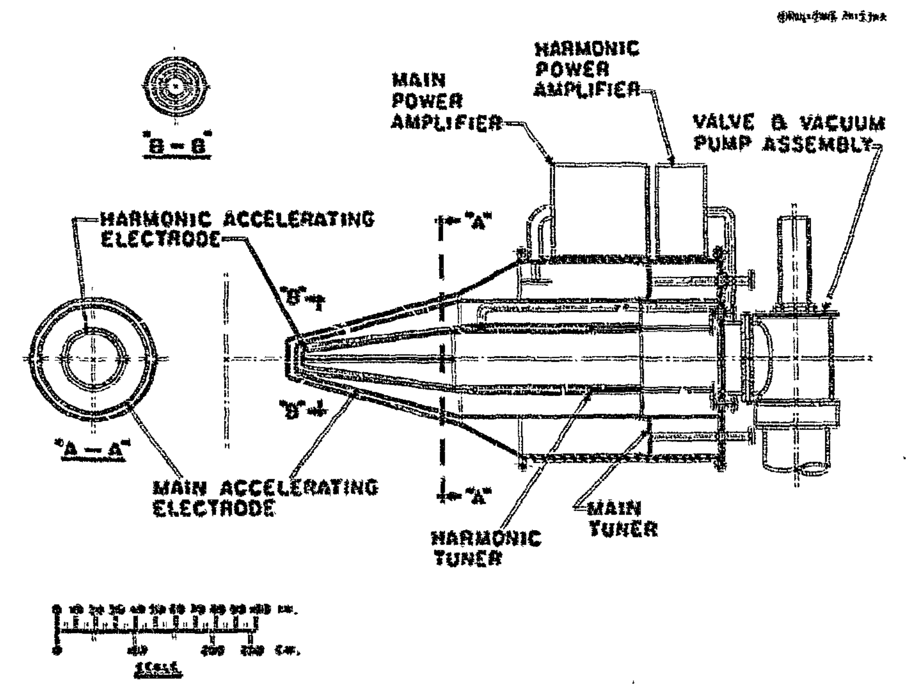

Fig. 3. The radio frequency resonators. The second harmonic resonators nest inside the main units.

than a factor of 2 at 16 kG. The combined effect of the increase in sector angle and magnetic field provides a $B\rho$ of 3010 kG-cm at a maximum mean radius of 3.26 m; the 1969 version provided 2600 kG-cm at 3.18 m radius.

The increased sector angle brings improvements in focusing as well as average field. Figure 2 illustrates how the axial and radial focusing frequencies will vary during acceleration for 10-MeV/amu (2380-MeV) uranium ions and 108-MeV/amu (1300-MeV) carbon ions. The region traversed is free of resonances and gives a high space charge limit. Another advantage is that the design is not critical and may be easily achieved.

The radio-frequency system of the new cyclotron is mechanically and electrically much simpler than the old design, which featured panel tuning to span the frequency range from approximately 10 to 30 MHz. The new system is more closely matched to the requirements of heavy-ion acceleration and enables the cyclotron to operate synchronously with the ORIC as the injector over a wide range of particle masses. The system tunes over the 6–14 MHz range with resonators of the conventional quarter-wavelength type (Fig. 3), with cone-shaped accelerating structures. Second-harmonic (double frequency) resonators are mounted inside the main resonators. These serve to effectively flattop the accelerating voltage waveform to improve the phase acceptance and energy resolution.

The beam injection system for the cyclotron is being designed to provide optimum conditions for the injection of beams from the ORIC as well as from the tandem. To satisfy the different requirements for variable energy and the use of various injectors, the injection mean radius of the cyclotron must be adjustable. The range required is from 0.75 m for ORIC injection to 1.08 m for uranium ions from the tandem using gas stripping.

STATUS REPORT OF THE TANDEM VAN DE GRAAFF ACCELERATOR

G. F. Wells[1]

The tandem Van de Graaff accelerator operated for 3452 hr during the period January 1, 1971, to January 1, 1972, apportioned as shown in Table 1. Aside from research activities, major attention was devoted to problems associated with the accelerator charging system, to completion of the polarized proton ion source, and to an energy recalibration.

During the first six months, three drive motors, one terminal generator, and a new belt were installed, continuing similar failures of the preceding year. The second half of the year has shown no such difficulties. We believe this improvement to be due to a change in motor and generator bearing lubricant, a change in tank gas constituency, and a new internal ground shield installed enclosing the motor housing and wiring at the high-energy end of the tank.

The bearing lubricant was changed from 1 oz per bearing of Dow Corning FS-1292 grease with 3% MoS_2 additive to ½ oz per bearing with 1% MoS_2 additive. Bearing temperature monitors are indicating an operating temperature of 150°F after an initial run-in period at 250°F with the reduced amount of lubricant, whereas previously bearing temperatures were 250°F and higher during the entire run life.

The tank gas constituency was changed from 60 psig total pressure of 50% SF_6, 40% N_2, 10% CO_2 to 100 psig of 20% SF_6, 65% N_2, 15% CO_2. The gas was thus of lower weight density, so that windage loading of the belt was reduced, while the particle density was increased to provide better heat transfer from drive motor to heat sink. It is to be noted that both gas constituencies were capable of maintaining adequate voltage insulation to 6.5 MeV.

An energy recalibration of the analyzer magnet was done utilizing the following nuclear reactions:

$$^{27}\mathrm{Al}(p,n)^{27}\mathrm{Si},\ E_{\mathrm{th}} = 5796 \pm 3.8\ \mathrm{keV}\,, \tag{1}$$

$$^{58}\mathrm{Ni}(p,n)^{58}\mathrm{Cu},\ E_{\mathrm{th}} = 9515.2 \pm 2.9\ \mathrm{keV}\,, \tag{2}$$

$$^{16}\mathrm{O}(d,n)^{17}\mathrm{F},\ E_{\mathrm{th}} = 1829.2 \pm 0.6\ \mathrm{keV}\,. \tag{3}$$

By utilizing the "inverse" of reaction (3) (oxygen beams on a deuterium target), several different magnetic field settings were possible corresponding to the various charge states of oxygen. Hence a measure of the variation of the magnet constant, K_{eff}, over a large

1. Instrumentation and Controls Division.

Table 1. Research activities on the tandem Van de Graaff

Ion	Experimenter	Percent of time
O^{n+}, F^{n+}, Cl^{n+}	Sellin,[a] Donnelly,[b] Smith,[c] Pegg,[a] Griffin	12.3
O^{n+}	Robinson, Kim, Ford	7.9
O^{n+}	Ford, Stelson, Robinson, Thornton,[d] Rapaport[e]	14.9
O^{n+} pulsed	Kim, Milner, Robinson	11.7
O^{n+}	Bair, Johnson, Wells	9.0
U^{n+}, I^{n+}	Moak, Appleton, Datz, Brown[b]	9.5
I^{n+}, Br^{n+}, O^{n+}	Muga,[g] Taylor,[h] Schmitt	7.9
N^{n+}	Toth, Gaedke[i]	1.3
O^{n+}	Jaszczak[j]	1.2
$^4He^{2+}$	Stelson, McGowan, Milner, Bemis, Robinson, Ford	17.5
$^3He^{2+}$	Hamilton,[k] Varnell,[k] Stelson	4.0
$^1H^+$, $^2H^+$	Raman	2.8
		100.0

[a]University of Tennessee, Knoxville, Tenn.
[b]Lake Forest College, Lake Forest, Ill.
[c]University of Connecticut, Storrs, Conn.
[d]University of Virginia, Charlottesville, Va.
[e]Ohio University, Athens, Ohio.
[f]Kansas State University, Manhattan, Kan.
[g]University of Florida, Gainesville, Fla.
[h]ORTEC, Inc., Oak Ridge, Tenn.
[i]Trinity College, San Antonio, Tex.
[j]Nuclear Chicago Corp., Chicago, Ill.
[k]Vanderbilt University, Nashville, Tenn.

range of field strength was made and is presented in Fig. 1. K_{eff} is related to the field and the energy by

$$K_{eff}B^2 = \left(1 + \frac{E}{1822M}\right)\frac{ME}{Q^2}.$$

This variation is now incorporated in energy vs kilogauss tables for use on the tandem, improving previous tables which assumed a linear relationship based on calibrations using reactions (1) and (2) only.

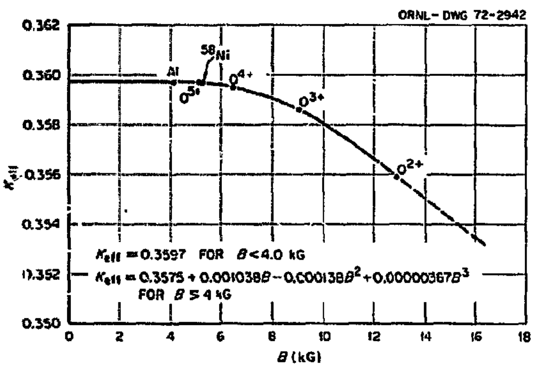

Fig. 1. K_{eff} vs B ORNL Tandem Van de Graaff, August 1971.

8. Omniana

PUBLICATIONS

The following listing of publications includes primarily those articles by Physics Division staff members and associates[1] *which have appeared in print during 1971.* It is not possible to include open-literature publications for the entire calendar year, however, as some journals for 1971 will be received only after this report has gone to press; thus four 1970 open-literature publications *not previously reported in an annual report* are included, and a few 1971 articles yet to be published will be listed in the next report for the period ending December 31, 1972.

NOTE: The following listing includes only publications in the open literature which appeared in print during 1971 or those for which references first became available during that year. The 84 articles now in preprint stage and pending publication are not included, nor are there any duplications of publications which were listed in last year's report (ORNL-4659).

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1. Associates include consultants, guest assignees, graduate students, members of other ORNL divisions, faculty member collaborators, etc.

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Chimin T. Chen M. M. El-Shishini Minal Jhaveri	Ph.D. theses
D. L. Hillis	M.S. thesis

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R. S. Livingston and J. A. Martin, "Trends in the United States for the Acceleration of Heavy Ions."

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E. D. Hudson, M. L. Mallory, and S. W. Mosko, "High Performance Heavy Ion Source for Cyclotrons."

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G. T. Chapman, "Some Gamma Ray Shielding Measurements Made at Altitude Greater Than 115,000 ft Using Large Ge(Li) Detectors."

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B. J. Allen and R. L. Macklin, "The Neutron Capture Cross Section of ^{207}Pb."

J. L. Fowler, C. H. Johnson, F. X. Haas, and R. M. Feezel, "The Neutron Total Cross Section of ^{16}O and ^{40}Ca."

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F. E. Obenshain, J. C. Love, G. Czjzek, W. A. Gläser, and J. E. Tansil, "Mössbauer Spectroscopy with ^{61}Ni in the Transition Metal Region."

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G. T. Chapman, "A Sightseeing Trip through the Milky Way Galaxy."

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W. B. Nielsen, H. W. Morgan, P. A. Staats, and R. G. Steinhardt, "Infrared Studies of Condensed Phases of CF_4."

45th National Colloid Symposium, Atlanta, Georgia, June 21–23, 1971

T. A. Carlson (invited paper), "Evaluation of the Use of Electron Spectroscopy for the Study of Surfaces."

Conference on Nuclear Three-Body Problem and Related Topics, Budapest, Hungary, July 8–11, 1971

A. van der Woude, "Observation of a $T = 1/2$ Resonance in ^{3}He by $H(d,^{3}He)\gamma$."

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W. W. Smith, I. A. Sellin, M. Brown, D. Pegg, and B. L. Donnally, "Collisional Excitation of Metastable Autoionizing States of Lithium-Like Ions in Fast Beams – Spectra and Yields."

Twenty-ninth Annual Electron Microscopy Society of America Meeting, Boston, Massachusetts, August 9–13, 1971

F. L. Ball, W. W. Harris, and T. A. Welton, "Computer Processing of Electron Micrographs."

T. A. Welton, "Computational Correction of Aberrations in Electron Microscopy."

R. E. Worsham, J. E. Mann, and E. G. Richardson, "A Superconducting Microscope."

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G. W. Cole, S. F. Mughabghab, M. Bhatt, O. A. Wasson, R. E. Chrien, and G. G. Slaughter, "P-Wave Neutron Capture Spectra from ^{98}Mo."

E. D. Earle, M. A. Lone, G. A. Bartholomew, B. J. Allen, G. G. Slaughter, and J. A. Harvey, "The 5.5 MeV Anomalous Radiation in $^{205}Tl(n,\gamma)^{206}Tl$."

W. M. Good and J. A. Harvey, "Neutron Total Cross Sections of ^{29}Si, ^{47}Ti, and ^{49}Ti."

H. Rösler, F. Plasil, and H. W. Schmitt, "High Resolution Cross Section Measurement for $^{236}U(n,f)$."

U.S.-Japan Seminar on Current Problems in Spectroscopic Studies, Tokyo, Japan, August 24–27, 1971

T. A. Carlson (invited paper), "Study of the Electronic Structure of Molecules by Photoelectron Spectroscopy."

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U. Mosel and H. W. Schmitt, "Fragment Shell Influence in Nuclear Fission"; *Bull. Amer. Phys. Soc.* **16**, 842 (1971).

International Conference on Polarized Targets, Berkeley, California, August 30–September 2, 1971

J. W. T. Dabbs (invited paper), "Neutron Physics Experiments with Oriented Nuclei."

International Conference on Electron Spectroscopy, Asilomar, California, September 6–10, 1971

T. A. Carlson (invited paper), "General Survey of Electron Spectroscopy."

T. A. Carlson, "Comprehensive Examination of the Angular Distribution of Photoelectron Spectra from Atoms and Molecules."

J. C. Carver, T. A. Carlson, L. C. Cain, and G. K. Schweitzer, "Use of X-Ray Photoelectron Spectroscopy to Study Bonding in Transition Metal Salts by Observation of Multiplet Splitting."

Gull Lake Symposium on the Two-Body Force in Nuclei, Gull Lake, Michigan, September 7–10, 1971

M. L. Halbert (invited paper), "Review of Experimental Information on Nucleon-Nucleon Bremsstrahlung."

J. B. McGrory (invited paper), "The Two-Body Interaction in Shell-Model Calculations."

Workshop Conference on Microscopy of Cluster Nuclei in Defected Crystals, Chalk River, Ontario, Canada, September 8–10, 1971

T. A. Welton (invited paper), "Electron-Optical Factors Limiting Resolution in Transmission Electron Microscopes."

Symposium on Heavy Ion Reactions and Many Particle Excitations, Saclay, France, September 8–14, 1971

R. L. Robinson, H. J. Kim, and J. L. C. Ford, Jr., "Heavy Ion Reaction Channels Determined from Induced Radioactivity Measurements."

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R. L. Hahn, P. F. Dittner, K. S. Toth, and O. L. Keller, "Studies of (Heavy Ion, αxn) Reactions on Actinide Targets."

R. L. Hahn, K. S. Toth, and M. F. Roche, "Interactions of Protons (<85 MeV) with ^{231}Pa and ^{232}Th."

F. Plasil (invited paper), "Experimental Studies of Double Barrier and Fragment Shell Effects in Fission."

H. W. Schmitt (invited paper), "Influence of Fragment Shells in Nuclear Fission."

P. H. Stelson (invited paper), "Coulomb Excitation of Nuclei."

Fourth North American Isotope Separator Symposium, Gaithersburg, Maryland, September 20–21, 1971

K. S. Toth (invited paper), "The UNISOR Project."

International Conference on Atomic Collisions in Solids, Gausdal, Norway, September 20–24, 1971

M. D. Brown and C. D. Moak, "Stopping Powers for 20–70 MeV Uranium Ions in Solids."

Eighth International Conference on High Energy Accelerators, Geneva, Switzerland, September 20–24, 1971

A. Citron, J. L. Fricke, H. Klein, M. Kuntze, B. Piosczyk, D. Schulze, H. Strube, J. E. Vetter, C. M. Jones, N. Merz, A. Schempp, and O. Siart, "Measurements on Superconducting Helices for the First Section of the Superconducting Proton Accelerator at Karlsruhe."

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T. A. Welton (invited paper), "High Voltage Electron Microscopy as a Means of Achieving High Resolution with Biological Samples."

Optical Society of America Meeting, Ottawa, Canada, October 5–8, 1971

K. L. Vander Sluis and L. J. Nugent, "Energy Differences between the $f^q ps^2$ and $f^{q+1}s^2$ Electron Configurations for Lanthanide and Actinide Neutral Atoms."

Ninth Rare Earth Research Conference, Blacksburg, Virginia, October 10–14, 1971

L. J. Nugent and K. L. Vander Sluis, "Theoretical Treatment of the Energy Differences between $f^{q+1}s^2$ and $f^q d^1 s^2$ Electron Configurations for Lanthanide and Actinide Atomic Vapors."

XVth Conference on Analytical Chemistry in Nuclear Technology, Oak Ridge, Tennessee, October 12–14, 1971

T. A. Carlson and N. Fernelius (invited paper), "Chemical Shifts Observed in Photoelectron Spectroscopy as a Function of the Periodic Table."

J. C. Carver, T. A. Carlson, G. K. Schweitzer, and F. A. Grimm (invited paper), "Photoelectron Spectroscopy of Transition Metal Compounds."

International Conference on Multiply Charged Heavy Ion Sources and Accelerating Systems, Gatlinburg, Tennessee, October 25–28, 1971

G. Fuchs, "Theoretical Calculation of Single and Multiple Impact Charge Distribution for Heavy Ion Sources."

G. Fuchs, J. Steyaert, and D. J. Clark, "Electron Cyclotron Resonance in a Penning Ion Source."

M. L. Mallory, E. D. Hudson, and G. Fuchs, "Performance of a Penning Ion Source on a Cyclotron."

C. D. Moak (invited paper), "Equilibrium Charge States of Energetic Heavy Ions in Solids and Gases."

S. W. Mosko, "Power Supplies for Cold Cathode Penning Discharge Ion Sources."

A. van der Woude (invited paper), "Microwave Heated Plasma (ELMO) as a Source of Multiply Charged Ions."

American Physical Society Meeting – Division of Nuclear Physics, Tucson, Arizona, November 4–6, 1971

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H. W. Schmitt and U. Mosel, "Fission Fragment Kinetic and Excitation Energies for Heavy and Superheavy Nuclei"; *Bull. Amer. Phys. Soc.* **16**, 1149 (1971).

M. Schmorak, "Alpha-Decay for Masses 210–260"; *Bull. Amer. Phys. Soc.* **16**, 1147 (1971).

K. S. Toth, R. L. Hahn, and M. A. Ijaz, "Further Investigation of Thulium Alpha-Emitters; New Alpha-Emitting Isomer in ^{156}Tm"; *Bull. Amer. Phys. Soc.* **16**, 1162 (1971).

C. Y. Wong, "Stability of Nuclei with New Types of Topology: Toroidal and Bubble Nuclei"; *Bull. Amer. Phys. Soc.* **16**, 1151 (1971).

Southeastern Section Meeting of the American Physical Society, Columbia, South Carolina, November 4–6, 1971

R. A. Carpenter, N. M. Gailar, H. W. Morgan, and P. A. Staats, "Analysis of the ν_2 Fundamental Vibration-Rotation Band in T_2O"; *Bull. Amer. Phys. Soc.* **17**, 197 (1972).

E. Collins, J. Lin, J. H. Hamilton, R. L. Robinson, H. J. Kim, and J. L. C. Ford, Jr., "Decay of ^{72}Br Produced by ^{58}Ni(^{16}O,*pn*)^{72}Br"; *Bull. Amer. Phys. Soc.* **17**, 192 (1972).

E. Huler, A. Burgos, E. Silberman, and H. W. Morgan, "Vibrational Spectra and Crystal Structure of $POBr_3$"; *Bull. Amer. Phys. Soc.* **17**, 203 (1972).

R. L. Macklin (invited paper), "Production of the Heavier Elements from Iron by Neutron Reactions in Stars"; *Bull. Amer. Phys. Soc.* **17**, 207 (1972).

J. Springer, Ch. Callis, and H. W. Morgan, "Vibrational Spectra of Solid and Matrix Isolated $PSCl_3$"; *Bull. Amer. Phys. Soc.* **17**, 203 (1972).

R. Wentz, E. Silberman, E. A. Jones, and H. W. Morgan, "Vibrational Spectra and Crystal Structure of $VOCl_3$"; *Bull. Amer. Phys. Soc.* **17**, 203 (1972).

17th Annual Conference on Magnetism and Magnetic Materials, Chicago, Illinois, November 16–19, 1971

J. C. Love and F. E. Obenshain, "Hyperfine Fields at Ni Sites in Heusler Alloys."

American Physical Society Meeting, Cambridge, Massachusetts, December 27–29, 1971

S. Raman, J. K. Dickens, N. B. Gove, and T. A. Walkiewicz, "Log *ft* Values for Second-Forbidden Beta-Transitions and the Decay of ^{24}Na"; *Bull. Amer. Phys. Soc.* **16**, 1433 (1971).

S. Raman, J. L. Foster, Jr., O. Dietzsch, and D. Spalding, "Energy Levels in ^{142}Nd"; *Bull. Amer. Phys. Soc.* **16**, 1433 (1971).

T. A. Welton, "Object Reconstruction in Phase-Contrast"; *Bull. Amer. Phys. Soc.* **16**, 1399 (1971).

ANNOUNCEMENTS

Merger of Divisions and Staff Appointments

A merger of Divisions took place June 1, 1971, wherein the Electronuclear Division became a part of the Physics Division. With J. L. Fowler serving as Director of the new Physics Division, two former Electronuclear Division staff members assumed posts – E. E. Gross was appointed Director of the Oak Ridge Isochronous Cyclotron (ORIC), and J. A. Martin was appointed Associate Director of ORIC. J. B. Ball, also a former Electronuclear Division staff member, assumed the post of Acting Director of ORIC during E. E. Gross' absence overseas (July 1971 through June 1972).

The Nuclear Data Project merged also with the Physics Division on June 1, 1971, with D. J. Horen continuing as Director and W. B. Ewbank as Assistant Director of the Project, reporting to the Director of the Physics Division.

As a result of the above-mentioned mergers, some 56 employees were welcomed to the Physics Division.

Associate Directors of the expanded Physics Division are G. R. Satchler and P. H. Stelson, the latter appointed to this post effective July 1, 1971. Effective also on July 1, 1971, was the appointment of C. D. Moak as Director of the Physics Division's Van de Graaff Laboratory.

FOREIGN TRAVEL AND ASSIGNMENTS

Participation in Conferences, Seminars, Lectures, and Institutes

A preceding section of this report lists 11 papers, authored and/or coauthored by Physics Division staff members, presented during 1971 at international conferences and symposia in seven countries outside the United States – Canada (2), France (1), Germany (1), Hungary (1), Japan (1), the Netherlands (1), Norway (1), Switzerland (1), and the U.S.S.R. (2). Participation in such meetings is primarily by special invitation; the opportunity to visit nearby atomic energy installations and educational institutions while abroad for discussions on scientific subjects directly related to the travelers' ORNL research interests and responsibilities has proved of substantial benefit via exchange of information. A later section of this report, entitled "University Seminars," lists additionally 16 seminar talks presented by Division personnel at universities outside the United States – Australia (1), Canada (1), England (4), France (2), Germany (3), and the Netherlands (5). Division staff members who took part in conferences, etc., abroad during 1971 included those mentioned in the following paragraphs.

J. A. Biggerstaff (Van de Graaff Program) has been on an 18-month assignment to the Australian Atomic Energy Commission, Lucas Heights Research Establishment, in Sutherland, New South Wales, Australia, since September 1970. While there, he presented a seminar talk March 12, 1971, entitled "New Uses of Particle Accelerators." He also presented a seminar-type talk at the University of Melbourne during the same month.

T. A. Carlson[1] (Electron Spectroscopy Program) attended the U.S.-Japan Seminar on Current Problems in Spectroscopic Studies, held August 24–27, 1971, in Tokyo, Japan, and presented an invited talk entitled "Study of the Electronic Structure of Molecules by Photoelectron Spectroscopy." On his return trip a stopover was made in Asilomar, California, where an invited paper and two contributed papers were presented at the International Conference on Electron Spectroscopy.

W. B. Ewbank (Nuclear Data Project), while on leave of absence to the Free University in Amsterdam, Netherlands, also attended the 21st All-Union Conference on Nuclear Spectroscopy and Nuclear Structure. The Conference was held January 27 through February 4, 1971, in Moscow, U.S.S.R.

J. L. C. Ford, Jr. (Van de Graaff Program) participated in the Symposium on Heavy Ion Reactions and Many Particle Excitations, held September 8–14, 1971, in Saclay, France. He presented a paper entitled "Heavy Ion Reaction Channels Determined from Induced Radioactivity Measurements." Visits were made following the Saclay symposium to three European laboratories which are involved in nuclear structure physics and with active heavy ion programs. Among the laboratories visited were the Max-Planck Institut in Heidelberg, Germany, the Atomic Energy Research Establishment in Harwell, England, and Oxford University in Oxford, England.

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1. Staff member of Chemistry Division on loan to Physics Division.

E. E. Gross (Nuclear Physics Program), while on a one-year assignment at the Niels Bohr Institute in Copenhagen, Denmark, additionally visited several European universities where he presented seminar-type talks. He also presented a seminar talk during November 1971, entitled "Violation of the Barshay-Temmer Theorem in the Reaction $^2H(^4He,^3H)^3He$," at the Research Institute for Physics in Stockholm, Sweden.

C. M. Jones (Van de Graaff Program), while on a one-year assignment at the Institut für Experimentelle Kernphysik of the Kernforschungszentrum Karlsruhe in Karlsruhe, Germany, attended by invitation the Eighth International Conference on High Energy Accelerators. The Conference took place September 20–24, 1971, at CERN in Geneva, Switzerland.

J. A. Martin (Electronuclear Systems Development Program) was also an invited attendee at the Conference mentioned in the preceding paragraph. Prior to the Conference in Geneva, he participated in a planning meeting which took place for the 1973 Particle Accelerator Conference to be held in San Francisco. Visits were made in Germany to the University of Frankfurt, the University of Heidelberg, the UNILAC heavy ion linear accelerator project at Darmstadt, and the Nuclear Research Center (Kernforschungszentrum) at Karlsruhe; and a visit was made in France to the Nuclear Physics Institute at Orsay. Discussions in both Germany and France concerned ion sources and the techniques and problems of heavy ion acceleration.

J. B. McGrory (Theoretical Physics Program) visited the Chalk River Nuclear Laboratories in Chalk River, Ontario, Canada, during the period of August 16–20, 1971. He presented a seminar talk in Chalk River entitled "Nuclear Spectroscopy in Light *f-p* Shell Nuclei" and spoke on the same subject at Queen's University at the Kingston Meeting on Nuclear Structure.

C. D. Moak (Director of the Van de Graaff Laboratory) was an invited participant in the International Conference on Atomic Collisions in Solids – Physics of Channeling and Related Phenomena, which took place in Gausdal, Norway, September 20–24, 1971. A paper by him, entitled "Stopping Powers for 20–70 MeV Uranium Ions in Solids," will be included in the conference proceedings. Following attendance at the Gausdal conference, he additionally visited the following installations for discussions regarding accelerator design: the University of Aarhus in Aarhus, Denmark; Oxford University in Oxford, England; and the Atomic Energy Research Establishment in Harwell, England.

F. Plasil (Physics of Fission Program), while assigned to the Pakistan Institute of Nuclear Science and Technology in Rawalpindi, Pakistan, additionally visited the following installations where discussions and/or lectures were conducted on the subject of "Fission Research at ORNL": Atomic Energy Research Institute in Tokai, Japan; Bhabha Atomic Research Centre in Trombay-Bombay, India; Technische Universität in Munich, Germany; and the International Atomic Energy Agency in Vienna, Austria.

G. R. Satchler (Associate Director of the Physics Division, and Theoretical Physics Program), while on a six-month leave of absence at Oxford University in Oxford, England, additionally presented several seminar talks at English universities. He also attended, and served as a session chairman, the Symposium on Heavy-Ion Reactions and Many Particle Excitations which took place September 8–14, 1971, in Saclay, France.

K. L. Vander Sluis (Atomic and Molecular Spectroscopy Program) attended the annual meeting of the Optical Society of America in Ottawa, Canada, October 5–8, 1971, and presented a paper entitled "Energy Differences between the $f^q ps^2$ and $f^{q+1}s^2$ Electron Configurations for Lanthanide and Actinide Neutral Atoms." He also attended a meeting of the Committee on Line Spectra of the Elements of the National Research Council–National Academy of Sciences which was held in conjunction with the Optical Society meeting; he has been a member of this Committee since 1961.

A. van der Woude (Nuclear Physics Program) attended the Conference on Nuclear Three-Body Problem and Related Topics, held July 8–11, 1971, in Budapest, Hungary, and presented a paper entitled "Observation of a $T = 1/2$ Resonance in ^3He by Radiative Capture." Following the Budapest conference he attended the VIIth International Conference on Physics of Electronic and Atomic Collisions, held July 26–30, 1971, in Amsterdam, Netherlands. Visits for technical discussions and seminars were made in Germany to the Max Planck Institute for Nuclear Physics in Heidelberg and to the Physics Institute of the University of Marburg; in France a brief visit was made to the heavy ion accelerator ALICE at Orsay; and in the Netherlands a visit was made to the University of Groningen.

T. A. Welton (High Resolution Electron Microscopy Program) attended the Chalk River Conference on Microscopy of Cluster Nuclei in Defected Crystals, held September 8–10, 1971, in Chalk River, Canada. He presented an invited paper entitled "Electron-Optical Factors Limiting Resolution in Transmission Electron Microscopes" and engaged extensively during the conference in discussions with other participants at the

Chalk River Nuclear Laboratories concerning the field of electron microscopy.

Exchange, Fellowship, Consultant, and Guest Assignments; Leaves of Absence

B. J. Allen (Guest Assignee with the Nuclear Geophysics and the Oak Ridge Electron Linear Accelerator Neutron Time-of-Flight Spectroscopy Programs) continued a 2½-year assignment which was begun in September 1969. As the first exchange assignee to the Physics Division from the Australian Atomic Energy Commission, Lucas Heights Research Establishment, in Sutherland, New South Wales, he is conducting measurements of neutron and charged-particle radiative capture cross sections.

G. A. Bartholomew and E. D. Earle (Guest Assignees with the Oak Ridge Electron Linear Accelerator Neutron Time-of-Flight Spectroscopy Program), both with Atomic Energy of Canada, Ltd., in Chalk River, Ontario, Canada, completed a three-month series of intermittent assignments with the Physics Division in January 1971. The purpose of their assignments was to collaborate on capture gamma-ray experiments at ORELA.

J. A. Biggerstaff (Van de Graaff Program) continued an 18-month assignment begun in September 1970 as ORNL's first Physics Division exchange assignee to the Australian Atomic Energy Commission, Lucas Heights Research Establishment, in Sutherland, New South Wales, Australia. His research there is concerned with nuclear capture gamma-ray spectrum measurements involving keV capture experiments using time-of-flight techniques on the 3-MeV accelerator; additionally, he is acting in a technical liaison capacity for the USAEC and AAEC groups having mutual interests in the research.

W. B. Ewbank (Nuclear Data Project) began a 13-month leave of absence in January 1971 to accept an appointment as temporary lecturer in physics at the Free University in Amsterdam, Netherlands. He has been engaged there in many activities of benefit, through enlarged communication with the European nuclear physics community, to the ORNL Nuclear Data Project.

G. H. Fuchs (Guest Assignee with the Nuclear Physics Program) completed a 13-month assignment with the Physics Division in November 1971 and has returned to the Physikalisches Institut der Universität Marburg in Marburg, Germany. His ORNL research involved a study of the feasibility of plasma devices for heavy ion research.

Jorge Gomez del Campo (Student Guest Assignee with the Van de Graaff and Theoretical Physics Programs) began a one-year assignment with the Physics Division in November 1971 to conduct Ph.D. thesis research in the field of heavy ion reactions. His educational affiliation and sponsor is the National University of Mexico in Mexico City, Mexico, where he received both the Bachelor of Science and Master of Science degrees.

E. E. Gross (Nuclear Physics Program) began a one-year assignment in August 1971 to the Niels Bohr Institute in Copenhagen, Denmark. In this first exchange of scientific personnel between ORNL's Physics Division and the Niels Bohr Institute, he is performing collaborative nuclear physics experiments on the tandem accelerator at Risø Laboratories and participating in the scientific program of the Institute. Instructive visits are planned to the CERN synchrocyclotron in Geneva, Switzerland, where pioneering work with on-line mass separators, of direct interest to a similar program planned for ORNL, is being conducted. Visits are planned to several other European laboratories, primarily for discussions on nuclear physics in the area of the few-nucleon problem; included are proposed visits in Saclay and Grenoble, France; Groningen and Amsterdam, Netherlands; Karlsruhe and Hamburg, Germany; and Harwell and Birmingham, England.

C. M. Jones (Van de Graaff Program) began in June 1971 a one-year assignment at the Institut für Experimentelle Kernphysik of the Kernforschungszentrum Karlsruhe in Karlsruhe, Germany. He is participating in work on superconducting rf accelerator elements. The acceleration of heavy ions to high energies is a subject of great interest at ORNL, and for a number of years staff members at Karlsruhe have been studying problems associated with building superconducting accelerator elements. C. M. Jones' assignment, similar to previous exchange assignments between ORNL and Karlsruhe, is expected to provide information which can be used in the present ORNL research program on superconducting accelerator elements and to provide insight into the ultimate feasibility of this technology. Extensive consultation during this assignment is also expected to take place in Germany with accelerator development groups at the University of Frankfurt, the University of Heidelberg, and the University of Munich, and with the Nuclear Physics Institute in Orsay, France.

J. S. Larsen (Guest Assignee with the Nuclear Physics Program) began a one-year assignment with the Physics Division in August 1971 as the first exchange assignee from the University of Copenhagen, Niels Bohr Institute, in Copenhagen, Denmark. He is conducting investigations of gamma-ray spectra of short-lived isotopes produced with the Oak Ridge Isochronous Cyclotron (ORIC).

Tove Larsen (part-time Guest Assignee with the Nuclear Physics Program) began an 11-month assignment with the Physics Division in September 1971. She is on leave from the Technical University of Denmark in Lyngby, Denmark, and is engaged during her stay at ORNL in the study of handling large amounts of measuring data and processing of on-line data.

M. G. Mustafa (Consultant with the Physics of Fission Program) continued a 1½-year assignment with the Physics Division which was begun in November 1970. His home affiliation is the Pakistan Atomic Energy Commission in Karachi, Pakistan, and he is the second assignee to the Physics Division through the ORNL and Pakistan Sister-Laboratory Arrangement. Theoretical studies of the fission processes are currently being conducted.

F. Plasil (Physics of Fission Program) spent two months early in 1971 engaged in research at the Pakistan Institute of Nuclear Science and Technology (PINSTECH) in Rawalpindi, Pakistan. His assignment there was sponsored by AID funds provided for the Sister-Laboratory Arrangement between ORNL and the Pakistan Atomic Energy Commission (PAEC). Work at PINSTECH involved an experiment on energy and mass distributions from fission of ^{239}Pu induced with resonance-energy neutrons as well as with thermal neutrons. The experiment was carried out in collaboration with Dr. G. D. Alam of PINSTECH, formerly a consultant (1969–1970) with the ORNL Physics Division. A visit to the PAEC establishment at Dacca was made during the assignment period for consultation with the Chairman and Secretary of the PAEC.

Helmut Rosler (Guest Assignee with the Physics of Fission Program) completed a 26-month appointment with the Physics Division in December 1971. His stay at ORNL was sponsored by a NATO Fellowship, and he is presently with the University of Munich in Garching, Germany. The principal research conducted at ORNL involved physics of fission experiments, some of which employed an on-line high-speed multiparameter analysis system.

G. R. Satchler (Associate Director of the Physics Division and Theoretical Physics Program) completed in December 1971 a six-month leave of absence from ORNL. He was engaged during this period as a Visiting Professor at the Nuclear Physics Laboratory of Oxford University in Oxford, England. His work at Oxford involved primarily collaboration with the nuclear physics computing group.

G. J. Vanpraet (Guest Assignee with the Nuclear Geophysics Program) completed a two-month assignment with the Physics Division in April 1971 and has returned to the State University of Antwerp in Antwerp, Belgium. His stay at ORNL was sponsored by the Belgian Fund for Scientific Research; his work involved assistance with neutron capture cross section experiments.

DOMESTIC ASSIGNMENTS AND LEAVE OF ABSENCE

Exchange Assignments

Edith C. Halbert (Theoretical Physics Program) and M. L. Halbert (Nuclear Physics Program) began in September 1971 a one-year exchange assignment at Brookhaven National Laboratory. Edith Halbert's work is part-time with the Low Energy Nuclear Theory Group; she is, additionally, spending part time with the State University of New York at Stony Brook engaged in work with their Nuclear Theory Group. M. L. Halbert's work is with BNL's Tandem Van de Graaff Group.

O. A. Wasson is the BNL exchange assignee to the ORNL Physics Division during the same period of time. He is conducting research with the Oak Ridge Electron Linear Accelerator Time-of-Flight Spectroscopy Program.

Mutual benefit is being derived by the laboratories concerned through this exchange of personnel.

Leave of Absence

A. Zucker (Nuclear Physics Program) continued throughout 1971 a two-year leave of absence, begun in August 1970, to serve as Executive Director of the Environmental Studies Board of the National Academy of Sciences in Washington, D.C. During this leave period, A. Zucker has acquired a broad view of the national and international activity in environmental problems.

RADIATION CONTROL AND SAFETY IN THE PHYSICS DIVISION

The Radiation Control and Safety Officers for the Physics Division report that there were no "unusual occurrences" in the Division during 1971, nor were there any minor incidents involving contamination or direct radiation exposures above normal levels.

The Oak Ridge Electron Linear Accelerator (ORELA), a joint Physics Division–Neutron Physics Division facility, has now completed its third year of operation and has had no "unusual occurrences" or direct radiation exposures above normal levels.

ORNL PHYSICS DIVISION SEMINARS

The normal day for weekly Divisional seminars, long a practice of the Physics Division, is Friday at 3:00 PM. Frequently, however, additional talks are scheduled for other days of the week in order to include on the seminar calendar topics of especial timeliness or interest. Advance Laboratory-wide announcement is made of these seminars, which are open to both employees and guests.

Seminar Chairman for the first six months of 1971 was G. G. Slaughter (Oak Ridge Electron Linear Accelerator Program); in July 1971 the duties of Seminar Chairman were assumed by S. Raman (Nuclear Data Project). Lectures arranged by these Chairmen during 1971 were as follows:

January 8 – C. C. Coutant, ORNL, "Coexisting with Nuclear Energy V: Thermal Effects Aspects of Nuclear Power Plant Siting"

January 14 – Nicolae Vilcov, Institute for Atomic Physics, Bucharest, Romania, "Isomeric Fission in Transuranium Nuclei"

January 15 – R. E. Blanco, ORNL, "Coexisting with Nuclear Energy VI: Reprocessing of Light Water Reactor and Liquid Metal Fast Breeder Reactor Fuels"

January 22 – C. E. Bemis, ORNL, "The Unequivocal Identification of Trans-Fermium Elements: Atomic and Nuclear Spectroscopy above $Z = 100$"

January 27 – B. R. Barrett, University of Arizona, "Progress Report on Effective Nuclear Interaction Calculations with Realistic Nuclear Forces"

January 29 – M. T. Robinson, ORNL, "Channeled Heavy Ion Energy Loss Spectra"

February 5 – J. O. Blomeke, ORNL, "Coexisting with Nuclear Energy VII: New Methods of Waste Management"

February 12 – M. Roberts, ORNL, "ORMAK – Progress, Program, and Promise"

February 16 – R. S. Berry, University of Chicago, "Charge Transfer and Curve Crossing in Atomic and Ionic Collisions"

February 26 – W. B. Cottrell, ORNL, "Coexisting with Nuclear Energy VIII: Nuclear Safety – Myth or Reality?"

March 5 – L. B. Hubbard, Furman University, "Gamma-Ray Dosimetry for Radiobiology"

March 11 – F. J. Dyson, Institute for Advanced Study, Princeton, "Black Holes"

March 11 – D. A. Atkinson, Tennessee Technological University, "Your State Universities: You Get What You Pay For"

March 12 – A. Marinov, Rutherford High Energy Laboratories, Chilton, Berkshire, England, "Evidence for the Possible Discovery of a Superheavy Element"

March 12 – F. J. Dyson, Institute for Advanced Study, Princeton, "Neutron Capture Levels"

March 19 – P. W. M. Glaudemans, University of Utrecht, Netherlands, "Simplicity versus Compexity in Shell-Model Calculations"

March 22 – R. G. Stockstad, Yale University, "Heavy Ion Studies of Highly Excited States in ^{24}Mg"

April 2 – R. J. Silva and C. Y. Wong, ORNL, "Production of Superheavy Nuclei by Secondary Reactions"

April 16 – T. Aberg, University of Chicago, "Koopman's Theorem and the Sudden Approximation"

April 23 – M. K. Kopp, ORNL, "Some Applications and Properties of One and Two Dimensional Position-Sensitive Proportional Counters"

May 7 – R. E. Chrien, Brookhaven National Laboratory, "Evidence for Simple Reaction Mechanisms in Neutron Capture"

May 11 – Joachim Frank, University of Munich, Munich, Germany, "Heavy/Light Atom Discrimination in Bright-Field Electron Microscopy"

May 14 – R. F. Zweifel, Virginia Polytechnic Institute, "Theory of Measurement and the EPR Paradox"

May 24 – B. Fricke, Northwestern University, "Chemistry of Superheavy Elements"

May 28 – R. Y. Cusson, Duke University, "Light Nuclei Systematics in the Unrestricted Hartree-Fock Approximation"

June 4 – E. P. Wigner, Princeton University, "Similarities and Differences in Chemical and Nuclear Reactions"

June 11 – F. Plasil, ORNL, "Nuclear and National Fission – a Pakistani Odyssey"

June 18 – R. E. Pace, Jr., Marshall Space Flight Center, "Summary of the Skylab Mission"

June 25 – I. A. Sellin, University of Tennessee, "Electrons Emitted by Fast Ion Beams: Spectra and Lifetimes"

June 28 – P. G. Hansen, CERN, Geneva, Switzerland, "Status Report on Isolde"

June 29 – J. R. Huizenga, University of Rochester, "Effects of Isospin on Statistical Nuclear Decay"

July 2 – R. E. Reed, ORNL, "How to Make Ultrapure Niobium for Use in Accelerators"

July 16 – R. C. von Borstel, ORNL, "Spontaneous Mutations"

July 23 – N. B. Gove, ORNL, "The 1971 Atomic Mass Adjustment"

July 30 – M. R. Schmorak, ORNL, "Rotational Bands in Nuclei and the Variable Moment of Inertia Model"

August 6 – P. H. Stelson, ORNL, "Zero-Phonon Transitions in Vibrational Nuclei"

August 13 – Z. W. Grabowski, Purdue University, "Magnetic Moments of 2^+ States in Transitional Nuclei"

August 18 – Rolf Wagner, University of Basel, Basel, Switzerland, "Nuclear Physics Research at the University of Basel"

August 20 – S. B. Kaufman, Argonne National Laboratory, "Pulse Height Response Characteristics for Heavy Ion Silicon Surface Barrier Detectors"

August 25 – K. E. G. Lobner, Technische Hochschule, Munich, Germany, "*E*1, *M*2, *E*3 Multipole Mixing in Nuclear Gamma-Ray Transitions"

August 27 – F. K. McGowan, ORNL, "Octopole and Quadrupole Vibrational States in the Actinide Nuclei"

September 1 – S. S. Kapoor, Bhabha Atomic Research Centre, Bombay, India, "Excitation Energy Dependence of Single Particle Effects in Fission"

September 2 – A. Chatterjee, Saha Institute of Nuclear Physics, Calcutta, India, "Energy Partition Processes in Prompt Fission Phenomena"

September 10 – R. V. Gentry, ORNL, "Radiohalos: Some Unique Lead Isotope Ratios and Unknown Alpha Radioactivity"

September 14 – F. M. Russell, Rutherford High Energy Laboratories, Chilton, Berkshire, England, "Polarized Targets and the Crystal Defect Mystery"

September 23 – W. L. Talbert, Jr., Iowa State University, "Nuclear Structure Studies with the Tristan On-Line Isotope Separator"

October 8 – Film (four showings), "Apollo 15 – in the Mountains of the Moon"

October 12 – G. Sletten, Niels Bohr Institute, Risø, Denmark, "Spontaneously Fissioning Isomers"

October 22 – J. L. Fowler, ORNL, "Mass, Mascons, and Magnetic Moments"

October 29 – C. Y. Wong, ORNL, "Stability of Nuclei with New Types of Topology"

November 1 – I. Zvara, Joint Institute for Nuclear Research, Dubna, U.S.S.R., "Heavy Ions and Heavy Elements at Dubna"

November 8 – Constance K. Cline, University of Rochester, "The Griffin Model: A Closer Look at the Mythology of Nuclear Reactions"

November 19 – J. L. C. Ford, Jr., ORNL, "Quadrupole and Hexadecapole Moments from Coulomb Excitation of Actinide Nuclei"

November 22 – W. R. Farkas, University of Tennessee Memorial Research Center and Hospital, "Should We Get the Lead Out?"

November 29 – F. G. Perey, ORNL, "Pleochroic Halos: Sweden and France Revisited"

December 6 – Sheldon Datz, ORNL, "Ion-Induced Inner-Shell Ionization"

December 10 – H. W. Meldner, University of California at San Diego, "*Z* Concept of Single-Particle Energies of Finite Fermion Systems"

December 17 – C. B. Fulmer, ORNL, "Helion Elastic Scattering and the Importance of Back-Angle Data"

MISCELLANEOUS PROFESSIONAL ACTIVITIES OF DIVISIONAL PERSONNEL

Staff members of the Physics Division are frequently requested or appointed to assume certain professional duties which are incident to their primary responsibilities at ORNL. Such duties may be in connection with scientific journals, societies, conferences, committees, institutes, etc. During 1971 such activities have included the following:

J. B. Ball – referee for *The Physical Review;* reviewer for *Nuclear Physics.*

R. L. Becker – member of the Technical Council of the Cooperative Science Education Center, Inc.; instructor for the Oak Ridge Resident Graduate Program of the University of Tennessee; reviewer for *The Physical Review* and *Physical Review Letters.*

T. A. Carlson[1] – reviewer for *The Physical Review;* member of the Organizing Committee for the International Conference on Electron Spectroscopy (Asilomar, California, September 1971); Joint Editor-in-Chief of the *Journal of Electron Spectroscopy,* published by Elsevier Publishing Company.

J. W. T. Dabbs – member of the Graduate Fellowship Evaluation Committee of the National Research Council.

W. B. Dress – reviewer for *Nuclear Instruments and Methods.*

J. L. Fowler – member of the Committee on Nuclear Data Compilations of the Division of Nuclear Physics of the American Physical Society (resigned during 1971); Divisional Councilor of the American Physical Society for the Division of Nuclear Physics (1970–1973); member of Executive Committee of the American Physical Society (1971); also, member of the Executive Committee of the Division of Nuclear Physics of the American Physical Society (1970–1973); member of Fellowship Committee of the American Physical Society (1971); member of the Publications Committee of the Council of the American Physical Society (1971); also, member of the Division of Nuclear Physics of the American Physical Society Publications Committee for *The Physical Review* and *Physical Review Letters;* member of the Committee on Meetings of the Council of the American Physical Society (1971); member of 1971 Nominating Committee of the Division of Nuclear Physics of the American Physical Society (appointed by Council); referee for *The Physical Review* and *Physical Review Letters;* Corresponding Member of the Commission on Nuclear Physics of the International Union of Pure and Applied Physics (1967–1971); lecturer for the Visiting Scientists Program in Physics of the American Institute of Physics (1958–1971).

C. B. Fulmer – member of the ORNL Accelerator and Radiation Sources Review Committee; reviewer for *The Physical Review;* reviewer for *Journal of Nuclear Energy.*

W. M. Good – member of the Program Committee for the Third Conference on Neutron Cross Sections and Technology (Knoxville, Tennessee, March 1971); reviewer for *The Physical Review;* member of the U.S. Atomic Energy Commission's Nuclear Cross Section Advisory Committee (appointment began July 1970); chairman of the Subcommittee on Stable Isotopes of the Nuclear Cross Section Advisory Committee.

C. D. Goodman – assistant chairman of the Technical Program Committee for the IEEE Nuclear Science Symposium (San Francisco, California, November 1971); member of President's Council of Clark University; reviewer for *Physical Review Letters.*

E. E. Gross – member of the Technical Advisory Panel (TAP) for the Los Alamos Meson Factory.

M. L. Halbert – reviewer for *The Physical Review* and *Physical Review Letters.*

J. A. Harvey – Secretary-Treasurer of the Division of Nuclear Physics of the American Physical Society (1967–1972); member of the Program Committee of the Division of Nuclear Physics of the American Physical Society; member of the Editorial Board of *Nuclear Data Tables,* a journal published by Academic Press; member of AEC Computer Index Neutron Data Steering Committee (CINDA); reviewer for the *The Physical Review* and *Nuclear Science and Engineering;* member of the ORNL Graduate Fellow Selection Panel; chairman of Organizing Committee and Program Committee for the Third Conference on Neutron Cross Sections and Technology (Knoxville, Tennessee, March 1971); member of the Subcommittee on Total Cross Sections and the Subcommittee on Stable Isotopes of the Nuclear Cross Section Advisory Committee.

D. J. Horen – member of the Committee on Nuclear Data Compilations of the Division of Nuclear Physics

1. On loan from the ORNL Chemistry Division to the Physics Division.

of the American Physical Society (1971–1972); member of Ad Hoc Panel on Nuclear Data Compilations of the National Academy of Sciences (1971–1972); U.S. member of IAEA International Working Group on Compilation, Evaluation, and Dissemination of Nuclear Structure and Reaction Data (1971–1972).

F. T. Howard[2] – member of the Program Committee for the 1971 Particle Accelerator Conference (Chicago, Illinois, March 1971); guest editor for the proceedings of the 1971 Particle Accelerator Conference (Chicago, Illinois, March 1971); guest editor for the proceedings of the International Conference on Multiply Charged Heavy Ion Sources and Accelerating Systems (Gatlinburg, Tennessee, October 1971).

C. H. Johnson – chairman of the ORNL Accelerator and Radiation Review Committee; reviewer for *The Physical Review.*

H. J. Kim – reviewer for *The Physical Review.*

C. A. Ludemann – Physics Division representative to the Union Carbide Nuclear Division Affirmative Action Program; Senior Scientific Secretary for the International Conference on Multiply Charged Heavy Ion Sources and Accelerating Systems (Gatlinburg, Tennessee, October 1971).

R. L. Macklin – member of the Oak Ridge Gaseous Diffusion Plant Nuclear Safety Committee; editor of the proceedings for the Third Conference on Neutron Cross Sections and Technology (Knoxville, Tennessee, March 1971); member of the Subcommittee on Gamma-Ray Production and Capture of the Nuclear Cross Section Advisory Committee; nuclear safety consultant to Goodyear Atomic Corporation in Portsmouth, Ohio; reviewer for *Nuclear Instruments and Methods, Astrophysical Journal, Nuclear Applications, Nuclear Science and Engineering, The Physical Review, Physical Review Letters,* and *Nuclear Science and Technology.*

M. B. Marshall – member of the ORNL Electrical Safety Committee.

J. A. Martin – Vice-President of the Nuclear Science Group of the Institute of Electrical and Electronic Engineers (1971–1972); member of the Administrative Committee of the Nuclear Science Group of the IEEE (1971–1975); member of the Technical Committee on Particle Accelerator Science and Technology of the Nuclear Science Group of the IEEE; member of Editorial Advisory Board of *Particle Accelerators;* reviewer for *Particle Accelerators;* consultant to the National Science Foundation Physics Section as a member of the Visiting Committee for the Indiana University Cyclotron Project; Program Chairman for the International Conference on Multiply Charged Heavy Ion Sources and Accelerating Systems (Gatlinburg, Tennessee, October 1971); member of the Organizing Committee and the Program Committee for the 1971 Particle Accelerator Conference (Chicago, Illinois, March 1971); member of the Organizing Committee for the 1973 Particle Accelerator Conference (San Francisco, California, March 1973).

F. K. McGowan – member of the Editorial Board of *Nuclear Data Tables,* a journal published by Academic Press; reviewer for *The Physical Review.*

J. B. McGrory – reviewer for *The Physical Review* and *Physical Review Letters;* Vice Chairman for the Gordon Research Conference on Nuclear Structure (Andover, New Hampshire, July 1971).

P. D. Miller – reviewer for *The Physical Review;* member of the ORNL Review Board on the Environmental Impact for the Surry Reactor.

C. D. Moak – reviewer for the *Review of Scientific Instruments* and *Physical Review Letters;* member of the Program Committee for the Symposium on Ion Sources and Formation of Ion Beams (Upton, Long Island, New York, October 1971).

H. W. Morgan – faculty member of Fisk University Infrared Spectroscopy Institute; on the Membership Committee for the Southeastern Section of the American Physical Society (1970–1971); member of the Program Committee for the Southeastern Section of the American Physical Society (Columbia, South Carolina, November 1971); consultant to the National Science Foundation, Office of International Programs (for science programs in India); member of the Board of Directors of the Tennessee Partners of the Alliance for Scientific Exchange between Universities in Tennessee, Brazil, and Venezuela.

S. W. Mosko – member of the Program Committee for the 1971 Particle Accelerator Conference (Chicago, Illinois, March 1971).

E. Newman – member of the ORNL Graduate Fellow Selection Panel; reviewer for *The Physical Review;* reviewer for *Physical Review Letters.*

F. E. Obenshain – part-time faculty member with the Department of Physics of the University of Tennessee; reviewer for *The Physical Review.*

2. Presently a consultant with the ORNL Physics Division.

S. Raman – reviewer for *The Physical Review.*

R. L. Robinson – reviewer for *The Physical Review.*

G. R. Satchler – reviewer for *The Physical Review, Physical Review Letters,* and *Nuclear Physics;* member of the Editorial Board of *Nuclear Data Tables,* a journal published by Academic Press; member of the Editorial Board of *Particles and Nuclei,* a journal published by F.U. Research Institute, Athens, Ohio; member of panel of "Contributors" to *Comments on Nuclear and Particle Physics,* a journal published by Gordon and Breach, Scientific Publishers, Inc.; member of Subpanel on the Development of Nuclear Physics of the National Academy of Sciences.

H. W. Schmitt – reviewer for *The Physical Review, Physical Review Letters,* and *Nuclear Science and Engineering;* member of Committee on ORNL Sister-Laboratory Arrangement with the Pakistan Atomic Energy Commission; consultant to the Nuclear Engineering Department of Catholic University of America; consultant to Tri-Universities Nuclear Laboratory of Duke University.

G. G. Slaughter – reviewer for *Nuclear Science and Engineering* and *The Physical Review.*

P. A. Staats – faculty member of Fisk University Infrared Spectroscopy Institute.

P. H. Stelson – part-time faculty member with the Department of Physics of the University of Tennessee; member of the Advisory Board to the Nuclear Data Group of ORNL; reviewer for *The Physical Review* and *Physical Review Letters;* member of the Subcommittee on Isotopes of the Nuclear Cross Sections Advisory Committee; referee for *Nuclear Physics;* member of the Executive Committee of the Southeastern Section of the American Physical Society; member of the Visiting Committee for the Texas A & M Cyclotron.

K. S. Toth – reviewer for *The Physical Review* and for *Physical Review Letters.*

K. L. Vander Sluis – member of the Committee on Line Spectra of the Elements of the National Academy of Sciences–National Research Council.

A. van der Woude – editor of the proceedings of the International Conference on Multiply Charged Heavy Ion Sources and Accelerating Systems (Gatlinburg, Tennessee, October 1971); referee for *Canadian Journal of Physics.*

T. A. Welton – part-time faculty member with the Department of Physics of the University of Tennessee; reviewer for *Science, Biophysical Journal,* and *Journal of Applied Physics.*

PERSONNEL ASSIGNMENTS

Listings are included in a later section of this report ("Activities Related to Educational Institutions") of Ph.D. and M.S. candidates engaged in thesis research, cooperative students, consultants under subcontract, guest assignees from university faculties, summer investigators, etc., who have been associated with the regular staff of the Physics Division during 1971. In addition, five assignments were begun and/or continued during the year by researchers from Australia, Denmark, Mexico, and Pakistan; and five assignments were completed by researchers from Canada, Belgium, and Germany. These and other assignees to and departees from the Division during 1971 were as follows:

Guest Assignees from Abroad

B. J. Allen (Exchange Assignee), Australian Atomic Energy Commission, Lucas Heights Research Establishment, Sutherland, New South Wales – Nuclear Geophysics and Oak Ridge Electron Linear Accelerator Neutron Time-of-Flight Spectroscopy Programs (continued $2\frac{1}{2}$-year assignment begun in September 1969)

G. A. Bartholomew (Guest Assignee), Atomic Energy of Canada, Limited, Chalk River, Ontario, Canada – Oak Ridge Electron Linear Accelerator Neutron Time-of-Flight Spectroscopy Program (completed three-month series of intermittent assignments in January 1971)

E. D. Earle (Guest Assignee), Atomic Energy of Canada, Limited, Chalk River, Ontario, Canada – Oak Ridge Electron Linear Accelerator Neutron Time-of-Flight Spectroscopy Program (completed three-month series of intermittent assignments in January 1971)

G. H. Fuchs (Guest Assignee), Physikalisches Institut der Universität Marburg, Marburg, Germany – Nuclear Physics Program (completed 13-month assignment in November 1971)

Jorge Gomez del Campo (Student Guest Assignee), National University of Mexico, Mexico City, Mexico – Van de Graaff and Theoretical Physics Programs (began one-year assignment in November 1971)

J. S. Larsen (Exchange Assignee), University of Copenhagen, Niels Bohr Institute, Copenhagen, Denmark – Nuclear Physics Program (began one-year assignment in August 1971)

Tove Larsen (part-time Guest Assignee), Technical University of Denmark, Lyngby, Denmark – Nuclear Physics Program (began 11-month assignment in September 1971)

M. G. Mustafa (Consultant), Pakistan Atomic Energy Commission, Karachi, Pakistan – Physics of Fission Program (continued 1½-year assignment begun in November 1970)

Helmut Rösler (Guest Assignee), University of Munich, Garching, Germany; ORNL assignment was through NATO Fellowship – Physics of Fission Program (completed 26-month assignment in December 1971)

G. J. Vanpraet (Guest Assignee), State University of Antwerp, Antwerp, Belgium – Nuclear Geophysics Program (completed two-month assignment in April 1971)

Guest Assignees – Students Not Engaged in Thesis Research at ORNL

H. J. Hargis, on leave of absence from the Mathematics Division; presently graduate student at the University of Tennessee – High Energy Physics Program (continued indefinite assignment begun in October 1970)

Karen M. Smith, employee of the University of Tennessee – High Energy Physics Program (continued indefinite assignment begun in October 1969)

V. E. Vandergriff, employee of the University of Tennessee – High Energy Physics Program (continued indefinite assignment begun in December 1968)

Staff Appointees – Temporary Status

R. J. Jaszczak, formerly an AEC Postdoctoral Fellow with Physics Division; presently with Nuclear Chicago Corporation – Nuclear Geophysics Program (completed 1½-year assignment in March 1971)

D. C. Kocher, Nuclear Information Research Associate under National Science Foundation Grant – Nuclear Data Project (began two-year assignment in September 1971)

Staff Appointees – Intralaboratory Transfer

J. P. Judish, formerly a staff member of Instrumentation and Controls Division – Van de Graaff Program (transferred to the Physics Division in November 1971)

Staff Appointees – Intralaboratory Loans

G. T. Chapman, staff member of Neutron Physics Division – NASA Gamma Ray Astronomy Program (completed loan assignment with the Physics Division in October 1971)

W. M. Good, staff member of Physics Division – Oak Ridge Electron Linear Accelerator Neutron Time-of-Flight Spectroscopy Program (began nine-month half-time loan assignment with the Environmental Reports Project in September 1971)

P. M. Griffin, staff member of Physics Division – Atomic and Molecular Spectroscopy Program (completed one-month loan assignment with Technical Information Division, Program of Declassification, in November 1971)

B. Harmatz, staff member of Physics Division – Nuclear Physics Program (completed three-month half-time loan assignment with the Environmental Reports Project in December 1971)

F. Plasil, staff member of Physics Division – Physics of Fission Program (began one-year loan assignment with the Director's Division, Program Planning and Analysis, in September 1971)

Staff Appointees – Terminations

C. A. Gault, staff member of Physics Division – Cyclotron Operations Program (retired in November 1971)

F. T. Howard, staff member of Physics Division; presently a consultant under subcontract – Accelerator Information Center (retired in November 1971)

E. L. Olson, staff member of Physics Division – Nuclear Physics Program (retired in August 1971)

ACTIVITIES RELATED TO EDUCATIONAL INSTITUTIONS

Summer Research Participants

The Research Participation Program of Oak Ridge Associated Universities is administered for the Division of Nuclear Education and Training of the U.S. Atomic Energy Commission. The program enables selected college and university faculty to participate in research and development, primarily during the summer months, at several major installations of the U.S. Atomic Energy Commission, including the Oak Ridge National Laboratory, Oak Ridge Associated Universities, Puerto Rico Nuclear Center, Savannah River Laboratory, University of Tennessee–Atomic Energy Commission Agricultural Research Laboratory, University of Georgia–Savannah River Ecology Laboratory, and the National Bureau of Standards. Of mutual benefit to the participant and to the laboratory where the research is conducted, the program has proved extremely important for over 20 years to the progress of nuclear energy research and development, not only in the South but throughout the nation. Approximately 1100 faculty members from more than 300 colleges and universities in nearly all states, Puerto Rico, and the District of Columbia have performed research under this program of university–government-laboratory cooperation.

During 1971, nine Research Participants received appointments at the Oak Ridge National Laboratory (seven ORAU-supported and two ORNL-supported); those listed below were engaged in research with three programs of the Physics Division:

W. W. Walker (ORAU-supported), Associate Professor, University of Alabama – Oak Ridge Electron Linear Accelerator (ORELA) Neutron Time-of-Flight Spectroscopy Program; also, Physics of Fission Program

R. R. Winters[1] (ORNL-supported), Assistant Professor, Denison University – Nuclear Geophysics Program

Summer Visitors

Additional investigators assigned to the Physics Division during the summer months of 1971 included faculty members and graduate and undergraduate students as listed by category below:

Faculty member – Ph.D. personnel.

G. T. Condo,[2] Associate Professor, University of Tennessee – High Energy Physics Program

Faculty members – Ph.D. Guest Assignees.

L. A. Galloway, Professor, Centenary College of Louisiana – Van de Graaff Program

R. M. Haybron, Associate Professor, Cleveland State University – Theoretical Physics Program

J. C. Love, Assistant Professor, Clarkson College of Technology – Mössbauer Experimental Program

Graduate student – consultant under subcontract.

C. M. Ko, State University of New York at Stony Brook – Theoretical Physics Program

Undergraduate student – Guest Assignee.

Keith Halstead, Furman University – Theoretical Physics Program

ORAU Undergraduate Research Trainees – Guest Assignees. The ORAU Undergraduate Research Trainee Program is administered for the Division of Nuclear Education and Training of the U.S. Atomic Energy Commission by Oak Ridge Associated Universities. Trainees are assigned to the Oak Ridge National Laboratory, Oak Ridge Associated Universities, the University of Tennessee–AEC Agricultural Research Laboratory, Savannah River Laboratory, the University of Georgia–Savannah River Ecology Laboratory, and the National Bureau of Standards. The program offers temporary (usually ten-week) summer appointments, on a competitive basis, to a limited number of students who are United States citizens and who have completed their junior year of college and are majoring in physical, life, and environmental sciences, engineering, and mathematics; appointments include a stipend and travel allowance. Students are given the opportunity, by working in a full-time research laboratory and with instruction and training, to gain a keener perception of the factors involved in selecting, planning, and executing research projects. The stimulus is offered toward encouraging graduate study after attainment by the student of the bachelor's degree; staff members of the Division strongly encourage and recommend that graduate study be undertaken by trainees who have displayed

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1. Continued appointment with the Physics Division throughout the fall of 1971 as a participant in the Great Lakes Colleges Association Science Semester Program; began in mid-December 1971 a five-month guest assignment while on sabbatical leave from Denison University.

2. Consultant to Physics Division, High Energy Physics Program.

the qualifications for same during their summer assignments. Since inception of the program in 1958, nearly 900 students have received appointments.

During 1971, 64 ORNL summer appointments were accepted; of this number, 11 students were assigned to the Physics Division:

G. S. Adams, Murray State University – Nuclear Physics Program

R. N. Coleman, University of California, Berkeley – High Energy Physics Program

J. E. Cunningham, University of Tennessee – Nuclear Physics Program

R. A. Dana, University of Wisconsin – Nuclear Physics Program

T. A. Degrand, University of Tennessee – Electronuclear Systems Development Program

S. R. Farmer, Phillips University – Nuclear Physics Program

J. L. Mitchell, Valdosta State College – Oak Ridge Electron Linear Accelerator (ORELA) Neutron Time-of-Flight Spectroscopy Program

R. F. Nelson, Ohio State University – Nuclear Physics Program

S. E. Skubic, New College – Theoretical Physics Program

P. K. Smith, Murray State University – Electronuclear Systems Development Program

L. W. White, Oklahoma Baptist University – Theoretical Physics Program

Guest Assignees – Ph.D.'s

In addition to faculty members of universities and colleges listed in preceding sections of this report (summer research participants and summer visitors), ten Ph.D.-level scientists have engaged in collaborative research projects with staff members of the Physics Division as guest assignees. During calendar year 1971, these scientists, their affiliations, and the research programs with which they were associated have included the following:

N. C. Fernelius, Research Consultants, Inc. – Electron Spectroscopy Program (began part-time assignment of one year in May 1971)

Z. W. Grabowski, Purdue University (sabbatical leave) – Charged Particle Cross Section Data Center (began seven-month assignment in July 1971)

E. L. Hart, University of Tennessee – High Energy Physics Program (continued part-time assignment begun in October 1969)

K. T. Hecht, University of Michigan (sabbatical leave and NSF fellowship – Theoretical Physics Program (completed one-year assignment in August 1971)

P. G. Huray, University of Tennessee – Mössbauer Experimental Program (continued part-time assignment begun in October 1969)

D. J. Pegg, University of Tennessee – Van de Graaff Program (completed part-time assignment of one year in December 1971)

C. A. Rester, Jr., Oak Ridge Associated Universities – University Isotope Separator Project (UNISOR) (began six-month assignment in October 1971)

O. A. Wasson, Brookhaven National Laboratory – Oak Ridge Electron Linear Accelerator (ORELA) Neutron Time-of-Flight Spectroscopy Program (began one-year assignment in September 1971)

R. M. White, Baker University (sabbatical leave) – Electron Spectroscopy Program (began nine-month assignment in September 1971)

R. R. Winters,[1] Denison University (sabbatical leave) – Nuclear Geophysics Program (began nine-month assignment in September 1971 following summer assignment as a Research Participant)

Guest Assignees – Undergraduate Students in the Great Lakes Colleges Association Program

In addition to undergraduate students with the Physics Division during the summer months, two undergraduate students took part in the Great Lakes Colleges Association (GLCA) Science Semester Program (explained in some detail in a later section of this report) and were assigned to the Division during the fall months of 1971. These students, their schools, and the programs with which they were associated were as follows:

A. R. St. James, Denison University – Oak Ridge Electron Linear Accelerator (ORELA) Neutron Time-of-Flight Spectroscopy Program

W. C. Palmer, Earlham College – Nuclear Physics Program

Cooperative Education Program for Undergraduate Students

Promising students in science and engineering (generally those 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. During calendar year 1971, nine co-op students were with the Physics Division; of these, one student resigned from the program, three completed their assignments in the program, and five are presently continuing their work association with the Division. These students, the schools they attend, and the research programs of the Division with which they have been assigned are as listed:

W. K. Bell, University of Tennessee – Theoretical Physics Program

S. D. Blazier, University of Tennessee – High Resolution Electron Microscopy Program

J. L. Brown, University of Tennessee – High Resolution Electron Microscopy Program

U. L. Brown, Jr.,[3] Georgia Institute of Technology – Theoretical Physics Program

W. H. Dragoset,[4] Auburn University – Physics of Fission Program

R. M. Feezel, Auburn University – Van de Graaff Program; also, Oak Ridge Electron Linear Accelerator (ORELA) Time-of-Flight Spectroscopy Program

R. W. McGaffey,[5] Auburn University – High Energy Physics Program

D. W. Smith,[6] Virginia Polytechnic Institute and State University – Van de Graaff Program; also, Oak Ridge Electron Linear Accelerator (ORELA) Time-of-Flight Spectroscopy Program

M. A. Stephens, Georgia Institute of Technology – Physics of Fission Program

Cooperative Program in Graduate Education between ORNL and the University of Tennessee

The University of Tennessee, through a grant originally established by the Ford Foundation and through special arrangements with the Oak Ridge National Laboratory, supports at present 45 ORNL staff members on the faculty as permanent members on a part-time basis. Their services are available for presenting seminars, teaching graduate and undergraduate courses, and discussing research in their special fields on the Knoxville campus. ORNL staff members now hold such faculty appointments with the Departments of Basic Engineering, Botany, Chemistry, Chemical and Metallurgical Engineering, Electrical Engineering, Engineering Mechanics, Mathematics, Nuclear Engineering, Physics, and Zoology and with the University of Tennessee–Oak Ridge Graduate School of Biomedical Sciences.

Three Physics Division staff members have engaged in this cooperative arrangement as Professors of Physics at the University of Tennessee during 1971: T. A. Welton continued an appointment begun in the fall of 1963, and F. E. Obenshain and P. H. Stelson continued appointments begun in the fall of 1968.

Laboratory Graduate Participation Program – Selection Panel

A Graduate Fellow Selection Panel, appointed by the Director of the Oak Ridge National Laboratory, reviews applications for graduate fellowships for a program sponsored by Oak Ridge Associated Universities. Two Physics Division staff members were engaged in panel membership responsibilities throughout 1971: J. A. Harvey continued membership begun in January 1969, and in January 1971 E. Newman was appointed to panel membership.

The Laboratory Graduate Participation Program (formerly known as the Oak Ridge Graduate Fellow Program) originated in 1950; since that time more than 225 graduate students have received their degrees, 210 at the doctoral level. Until recently the program emphasized predoctoral work almost exclusively; however, equal emphasis is now being given to candidates who seek appointments for full-time graduate thesis research at the M.S. and Ph.D. levels. During the past year, Laboratory Graduate Participants who conducted thesis research at ORNL totaled 37, and of this number four were assigned to the Physics Division; two appointees completed their appointments, with one of these receiving the doctoral degree, and two will continue their appointments with the Division into the coming year. The following section of this report includes the staff members and graduate students concerned.

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3. Resigned from the Cooperative Program after three work assignments in March 1971.

4. Completed work assignments in the Cooperative Program in June 1971.

5. Completed work assignments in the Cooperative Program in December 1971.

6. Completed work assignments in the Cooperative Program in March 1971.

Ph.D. Thesis Research

During 1971, 18 Physics Division staff members (including T. A. Carlson of the Chemistry Division on loan to the Physics Division) served in either an advisory or supervisory capacity for thesis research conducted by 23 candidates for the Doctor of Philosophy degree. For the most part, research by the students was carried out at the Oak Ridge National Laboratory through fellowship appointments or through guest assignment arrangements with the Laboratory.

Doctoral degrees were conferred during the year to six of the graduate students – one by the University of California at Riverside and five by the University of Tennessee. A listing of those concerned follows:

Ph.D. candidate	Staff member(s)	Field of research (thesis title listed if known)
Carol P. Anderson[7,8] University of Tennessee	T. A. Carlson	Determination of molecular orbitals by photoelectron spectroscopy
J. L. Blankenship[9] University of Tennessee	J. W. T. Dabbs	Semiconductor solid-state physics
M. D. Brown University of Tennessee	C. D. Moak and P. H. Stelson	"Interaction of Heavy Ions with Solids"
J. Carroll University of Tennessee	T. A. Welton	"The Classical and Relativistic Solutions of the Circular Restricted Problem of Three Bodies"
J. C. Carver[7,10] University of Tennessee	T. A. Carlson	"Photoelectron Multiplet Splitting and Chemical Shifts in Transition-Metal Compounds"
Chimin T. Chen[11] University of Tennessee	T. A. Welton	"Nonadditivity of Intermolecular Forces and the Radial Distribution Functions of Dense Fluids"
M. M. El-Shishini[12] University of Tennessee	F. E. Obensh[illegible]	"Average Magnetic Hyperfine Fields at ^{106}Pd Nuclei in Ni-Pd Alloys"
D. O. Galde[7] Tulane University	M. L. Halbert, C. A. Ludemann, and A. van der Woude	Proton-proton bremsstrahlung at 64.4 MeV
J. Gomez del Campo[7] National University of Mexico	J. L. C. Ford, Jr., and G. R. Satchler	Heavy ion reactions
M. B. Greenfield[7,13] University of Tennessee	E. Newman, M. J. Saltmarsh, and T. A. Welton	"A Study of the (^{3}He,n) Reaction at 25 MeV"
Minal Jhaveri[14] University of Tennessee	H. O. Cohn	"Pion Absorption in Neon"

7. Student guest assignee.
8. Terminated student guest assignment in spring 1971.
9. Instrumentation and Controls Division.
10. Presently with the Department of Chemistry of the University of Georgia. Doctorate expected in spring 1972.
11. Presently with the Department of Physics of the University of Tennessee. Doctorate received in summer 1971.
12. Presently with the Department of Physics of the University of Pennsylvania. Doctorate received in summer 1971.
13. Presently with the Department of Physics of Florida State University. Doctorate expected in spring 1972.
14. Presently with the Physical Research Laboratory in Ahmedabad, India. Doctorate received in winter 1971.

A. E. Jonas[7,15] University of Tennessee	T. A. Carlson	"Photoelectron Spectroscopy of the Tetrafluoro and Tetramethyl Compounds of Group IV Elements"
J. P. Judish[16] University of Tennessee	P. H. Stelson and C. M. Jones	Superconducting rf cavities
G. C. McGuire[7] University of Tennessee	T. A. Carlson	Photoelectron spectroscopy of inorganic complexes
Elizabeth C. Miller University of Tennessee	T. A. Welton	Ultrasonic waves in liquids
Joyce A. Monard[17] University of Tennessee	F. E. Obenshain and R. L. Becker	Mössbauer effect with uranium isotopes
C. L. Rao[18] University of Tennessee	G. R. Satchler, T. A. Welton, and R. L. Becker	Effective interactions for nuclear scattering
Rose Marie Rice[7,19] University of California at Riverside	H. O. Cohn	"A Study of the $\bar{K}N$ Channels in K^-p Interactions between 680 and 840 MeV/c"
W. J. Roberts[20] University of Tennessee	E. E. Gross, E. Newman, and P. H. Stelson	Isospin conservation
R. W. Rutkowski[20,21] University of Tennessee	E. E. Gross	"The ^{3}He(d,t)2p Reaction at a Center-of-Mass Energy of 23.5 MeV" (ORNL-TM-3484)
D. P. Spears[20] University of Oklahoma	T. A. Carlson	Study of systems of biological interest by use of x-ray photoelectron spectroscopy
John Springer Vanderbilt University	H. W. Morgan	Infrared spectroscopy of molecular solids
J. E. Tansil[7,22] University of Tennessee	F. E. Obenshain and R. L. Becker	Mössbauer effect with ^{61}Ni in Ni-Pd alloys

M.S. Thesis Research

Five students were advised or supervised by staff members of the Physics Division during 1971 while conducting thesis research leading to the Master of Science degree; two of these students were awarded the M.S. degree during the year. Students and staff members concerned are as follows:

M.S. candidate	Staff member(s)	Field of research (thesis title listed if known)
Linda C. Cain[23] University of Tennessee	T. A. Carlson	"The Use of X-Ray Photoelectron Spectroscopy to Study Compounds of the Second and Third Row Transition Metals"

15. Presently with the University of Tennessee Memorial Research Center and Hospital in Knoxville. Doctorate received in winter 1971.
16. Transferred to the Physics Division from the Instrumentation and Controls Division in November 1971.
17. Student guest assignee on loan from the Chemistry Division.
18. Consultant under subcontract (part time).
19. Presently with Control Systems, Inc., in Palo Alto, California. Doctorate received in summer 1971.
20. ORAU Laboratory Graduate Participant.
21. Presently with the U.S. Atomic Energy Commission in Oak Ridge. Doctorate received in fall 1971.
22. Completed appointment as ORAU Laboratory Graduate Participant in fall 1971 (presently a student guest assignee).
23. Completed student guest assignment in spring 1971. Master's degree received in summer 1971.

John Forrester University of Tennessee	K. S. Toth	Decay scheme of ^{148}Eu
Lawrence Hess Fisk University	H. W. Morgan	Infrared spectroscopy of solid solutions
D. L. Hillis[24] University of Tennessee	J. B. Ball and P. H. Stelson	"Neutron Single Particle States in ^{145}Nd"
D. U. O'Kain[25] University of Tennessee	K. S. Toth	Measurement of α/E.C. branching ratios for rare earth isotopes

24. Presently working toward doctorate at the University of Tennessee. Master's degree received in winter 1971.
25. Separations Systems Division of Union Carbide Nuclear Division, ORGDP.

Oak Ridge Resident Graduate Program

Graduate degrees at both the master's and doctoral levels may be earned in Oak Ridge through a cooperative program involving the University of Tennessee, Oak Ridge Associated Universities, and the Nuclear Division, Union Carbide Corporation. The Oak Ridge Resident Graduate Program was established initially in 1946 to provide graduate-level study for Union Carbide scientific and technical staff members whose formal studies had been interrupted by World War II. Today, the program continues to further the professional advancement of Union Carbide, AEC, and ORAU employees.

Graduate-level courses are presently offered in chemistry and physics; mathematics, statistics, and computer science; biology, genetics, radiation biology, ecology, microbiology, and zoology; chemical, electrical, mechanical, environmental and pollution, and metallurgical engineering; industrial management and economics; foreign languages; and other courses required for the M.S. and Ph.D. degrees in the nuclear sciences and related fields. Approximately half of the 400 students presently enrolled in the Program are candidates for the Ph.D. degree. About 25 courses are offered each quarter, scheduled in the late afternoons, evenings, and Saturdays to minimize conflicts with the students' work schedules.

R. L. Becker, of the ORNL Physics Division, served as an instructor in the Oak Ridge Resident Graduate Program during calendar year 1971; he taught courses in Nuclear Structure and Advanced Dynamics.

Consultants under Subcontract with Union Carbide Corporation Nuclear Division – ORNL

Faculty members of colleges and universities who served as consultants under subcontract to the Physics Division during the past year are listed below, along with the research program with which they were associated. Numerous other consultants (not under subcontract or not faculty members) have also been associated with the various physics programs of the Division, either as collaborators or as seminar speakers, during this report period. (See also the following section of this report.)

Michel Baranger, Massachusetts Institute of Technology – Theoretical Physics Program

J. R. J. Bennett,[26] Rutherford High Energy Laboratory, Chilton, England – Electronuclear Systems Development

C. R. Bingham, University of Tennessee – Nuclear Physics Program

Gregory Breit, State University of New York at Buffalo – Nuclear Physics Program

D. A. Bromley, Yale University – Nuclear Physics Program

W. M. Bugg, University of Tennessee – High Energy Physics Program

26. Subcontract closed during 1971.

J. W. Burton, Carson-Newman College – Mössbauer Experimental Program

R. W. Childers, University of Tennessee – High Energy Physics Program

G. T. Condo, University of Tennessee – High Energy Physics Program

R. M. Drisko, University of Pittsburgh – Theoretical Physics Program

J. B. French, University of Rochester – Theoretical Physics Program

H. F. Glavish,[26] University of Auckland, Auckland, New Zealand – Electronuclear Systems Development

J. H. Goldstein, Emory University – Atomic and Molecular Spectroscopy Program

L. B. Hubbard, Furman University – Theoretical Physics Program

S. J. Krieger, University of Illinois at Chicago Circle – Theoretical Physics Program

R. W. Lide,[26] University of Tennessee – Physics of Fission Program

F. B. Malik, Indiana University – Theoretical Physics Program, Charge Spectrometry Program, and Mössbauer Experimental Program

R. J. McCarthy, Carnegie-Mellon University – Theoretical Physics Program

U. B. Mosel,[26,27] University of Tennessee – Physics of Fission Program

G. H. Nussbaum, University of Tennessee – Van de Graaff Program

P. Z. Peebles, University of Tennessee – Van de Graaff Program

J. T. Sanderson,[28] Harvard University – Physics of Fission Program

I. A. Sellin, University of Tennessee – Van de Graaff Program

K. K. Seth, Northwestern University – Nuclear Data Project

J. O. Thomson, University of Tennessee – Mössbauer Experimental Program

Hendrik Verheul, Free University, Amsterdam, Netherlands – Nuclear Data Project

27. Presently with the Department of Physics of the University of Washington.

28. Presently with the National Science Foundation.

Katharine Way,[26] Duke University – Nuclear Data Project

Lawrence Wilets, University of Washington – Physics of Fission Program

I. R. Williams, Knoxville College – Nuclear Physics Program

Consultants under Contract Arrangement with Oak Ridge Associated Universities

Under arrangements with Oak Ridge Associated Universities ("S" contracts and "U" contracts), 68 university or college faculty members visited the Physics Division for consultation and collaboration during the past year. These individuals and the educational institutions with which they were affiliated at the time of their 1971 visits are as follows:

W. L. Alford, Auburn University

D. A. Atkinson, Tennessee Technological University

F. T. Avignone, University of South Carolina

W. T. Bass, Macon Junior College

C. R. Bingham, University of Tennessee

W. H. Brantley, Furman University

L. D. Bridwell, Murray State University

W. M. Bugg, University of Tennessee

R. F. Carlton, Middle Tennessee State University

H. K. Carter, Furman University

R. E. Clarke, University of Florida

W. E. Collins, Jr., Vanderbilt University

J. R. Cooper, Auburn University

Fred Culp, Tennessee Technological University

R. Y. Cusson, Duke University

R. H. Davis, Florida State University

B. L. Donnally, Lake Forest College

M. M. Duncan, University of Georgia

F. E. Dunnam, University of Florida

R. W. Fink, Georgia Institute of Technology

R. M. Gaedke, Trinity University

J. H. Hamilton, Vanderbilt University

B. O. Hannah, University of Alabama in Birmingham

K. J. Hofstetter, University of Kentucky

D. L. Humphrey, Western Kentucky University

M. A. Ijaz, Virginia Polytechnic Institute and State University

J. A. Jacobs, Virginia Polytechnic Institute and State University

R. W. Jones, University of South Dakota

B. D. Kern, University of Kentucky

Y. E. Kim, Purdue University

B. B. Kinsey, University of Texas

Juergen Lange, Vanderbilt University

Jung Lin, Tennessee Technological University

J. C. Love, Clarkson College

M. A. Ludington, Albion College

A. D. MacKellar, University of Kentucky

W. E. Maddox, Murray State University

M. T. McEllistrem, University of Kentucky

R. L. Mlekodaj, Florida State University

J. M. Palms, Emory University

B. P. Pullen, Southeastern Louisiana University

A. R. Quinton, University of Massachusetts

A. V. Ramayya, Vanderbilt University

N. F. Ramsey, Harvard University

P. V. Rao, Emory University

Jacobo Rapaport, Ohio University

R. B. Raphael, Emory University

L. L. Riedinger, Jr., University of Tennessee

P. J. Riley, University of Texas

E. L. Robinson, University of Alabama in Birmingham

R. O. Sayer, Furman University

W. D. Schmidt-Ott, Georgia Institute of Technology

Alan Scott, University of Georgia

Y. Y. Sharon, Temple University

Ming-liang Shen, Tusculum College

Enrique Silberman, Fisk University

R. D. Smith, Georgia Institute of Technology

W. W. Smith, University of Connecticut

E. H. Spejewski, Oberlin College

Willard Talbott, Iowa State University

S. T. Thornton, University of Virginia

H. A. Van Rinsvelt, University of Florida

George Vourvopoulos, Florida A & M University

J. C. Wells, Tennessee Technological University

B. H. Wildenthal, Michigan State University

J. C. Williams, Memphis State University

R. E. Wood, Emory University

E. F. Zganjar, Louisiana State University

Traveling Lecture Program

The Traveling Lecture Program, administered by Oak Ridge Associated Universities through its University Programs Office, provides an avenue for staff members of U.S. Atomic Energy Commission installations in Oak Ridge and Savannah River to contribute to the scientific life of colleges and universities by lecturing, presenting seminar-type talks, and participating in colloquia and other similar college- and university-sponsored activities. Funds for transportation of the lecturers are provided by ORAU; the institution requesting the lecturers, in turn, provides funds for their local expenses during the campus visits.

Two ORNL Physics Division staff members accepted invitations under the Traveling Lecture Program during 1971:

F. E. Obenshain – Clarkson College of Technology, October 14, 1971, "Mössbauer Spectroscopy of ^{61}Ni in NiPd Alloys"

S. Raman – Emory University, November 19, 1971, "Nuclear Spectroscopy in the Tin Region"

University Seminars

In addition to lectures presented under auspices of the Traveling Lecture Program (listed in the preceding section of this report), scientists with the Physics Division received numerous requests to present seminar-type talks both in this country and abroad. Thirty-four such invitations from 27 different universities and colleges were accepted by 18 Division affiliates during 1971; 18 talks were given in the United States, one in Australia, one in Canada, four in England, two in France, three in Germany, and five in the Netherlands. These included:

J. B. Ball – Ohio University, March 19, 1971, "Studies of Nuclear Structure with Direct Reactions"; Michigan State University, August 11, 1971 (MSU-NSF Program of Research Participation for College Teachers), "Nuclear Structure of Near Closed-Shell Nuclei"

R. L. Becker – Case Western Reserve University, September 14, 1971, "Separation Energies in Renormalized Brueckner Theory"

J. A. Biggerstaff – University of Melbourne, Melbourne, Australia, March 10, 1971, "Beam-Foil Spectroscopy"

T. A. Carlson (on loan from Chemistry Division – University of Oklahoma, March 11, 1971, "Multiple Ionization and Excitation in Atoms and Molecules"

G. T. Chapman[29] – University of Florida, April 2, 1971, "Experimental X-Ray and Gamma-Ray Astronomy"

E. E. Gross – University of Georgia, April 8, 1971, "Testing Time-Reversal Invariance in Nuclear Physics"; Free University, Amsterdam, Netherlands, October 12, 1971, and Institute of Nuclear Research, Amsterdam, Netherlands, October 13, 1971, "A Study of the Reaction ^{3}He(d,^{3}H)2p at 23 MeV c.m."; University of Groningen, Groningen, Netherlands, October 15, 1971, "A Test of the Barshay-Temmer Theorem with the Reaction ^{2}H(^{4}He,^{3}He)^{3}H"; University of Grenoble, Grenoble, France, November 1, 1971, "Violation of the Barshay-Temmer Theorem in the Reaction ^{2}H(^{4}He,^{3}H)^{3}He" and "A Study of the Reaction ^{3}He(^{2}H,^{3}H)2p at 24 MeV"

Edith Halbert – State University of New York at Stony Brook, October 21, 1971, "Hidden Configurations and Effective Interactions"; Rutgers University, November 29, 1971, "Shell-Model Calculations"

C. M. Jones – University of Frankfurt, Frankfurt, Germany, December 15, 1971, "Slow Tuning Elements for Superconducting Helically Loaded Cavities"

H. J. Kim – Ohio University, June 1, 1971, "Neutron Decay of Analog States"

J. B. McGrory – Queen's University, Kingston, Ontario, Canada, August 19, 1971, "Nuclear Spectroscopy in Light f-p Shell Nuclei"

C. D. Moak – University of Texas, March 24, 1971, "Atomic Interactions of Fast Heavy Ions in Solids and Gases"

H. W. Morgan – Mississippi State University, April 20, 1971, "Coherent Light and Holography" and "Lasers and Holography"

29. Completed loan assignment to the Physics Division from the Neutron Physics Division during 1971.

M. J. Saltmarsh – University of South Carolina, April 2, 1971, "^{3}He,n Reactions at 25 MeV"

G. R. Satchler – University of Georgia, April 15, 1971, "Optical Model of the Nucleus"; University of North Carolina, April 23, 1971 [Growth Point Meeting – Nuclear Scattering Potentials for Composite Projectiles ($A \leqslant 4$)], "Inelastic-Scattering Interactions"; University of Surrey, Guildford, Surrey, England, August 10, 1971, Oxford University, Oxford, England, October 27, 1971, University of Birmingham, Birmingham, England, November 3, 1971, and University of Manchester, Manchester, England, November 10, 1971, "A Microscopic Description of Scattering from Nuclei"

K. L. Vander Sluis – University of Louisville, April 16, 1971, "Atomic Spectroscopy"

A. van der Woude – Max Planck Institute, Heidelberg, Germany, July 12, 1971, and University of Marburg, Physics Institute, Marburg, Germany, July 14, 1971, "Radiative Capture of Deuterons by Protons"; Nuclear Accelerator Institute, Groningen, Netherlands, July 19, 1971, "Heavy Ion Sources and Reactions"; University of Groningen, Physics Institute, Groningen, Netherlands, August 2, 1971, "Recent Experimental Work on the Few Nucleon Problem at Oak Ridge"

T. A. Welton – University of California, Berkeley, California, October 1, 1971, "The Object Reconstruction Problem in Phase Contrast Electron Microscopy"

C. Y. Wong – Rutgers University, May 24, 1971, "Superheavy Nuclei and Strutinsky Renormalization"; State University of New York at Stony Brook, May 26, 1971, "Shells in Deformed Nuclei"; Notre Dame University, October 26, 1971, "Stability of Nuclei with New Types of Topology"

Participation in Varied Institutes and Symposia

Summer Institute on Low-Energy Accelerators for Teaching and Research, Oak Ridge, Tennessee. A summer institute on Low-Energy Accelerators for Teaching and Research was conducted in Oak Ridge, Tennessee, during the six-week period of July 5 through August 13, 1971. Sponsored by the Special Training Division of Oak Ridge Associated Universities, the institute was for science and engineering faculty members in the fields of physics, chemistry, and nuclear engineering and emphasized theory as well as experimental training in the uses of small accelerators.

Some 24 faculty members from 12 states participated in the institute. Staff members and affiliates of the ORNL Physics Division presented lectures and/or conducted tours as shown below:

J. B. Ball – tour of Oak Ridge Isochronous Cyclotron

W. M. Bugg (consultant, University of Tennessee) – tour of Department of Physics and facilities at the University of Tennessee

T. A. Carlson (on loan from Chemistry Division) – "Electron Spectra and Chemical Problems"

W. B. Dress, Jr. – "The Electronic Dipole Moment"

J. L. C. Ford, Jr. – "Transuranium Experiments"

J. L. Fowler – "Closed Shell Nuclei"

J. A. Harvey – tour of Oak Ridge Electron Linear Accelerator

P. D. Miller – "^{3}He-Induced Reactions"

D. J. Pegg (guest assignee, University of Tennessee) – "Atomic Lifetime Measurements"

S. Raman – "The Nuclear Data Project"

H. W. Schmitt – "The Physics of Nuclear Fission"

I. A. Sellin (consultant, University of Tennessee) – "Atomic Physics of Fast Ion Beams; Fine Structure Experiments"

Fisk University Twenty-second Annual Infrared Institute, Nashville, Tennessee. Two Physics Division staff members, H. W. Morgan and P. A. Staats (Atomic and Molecular Spectroscopy Program), served as visiting lecturers at the Fisk University Twenty-second Annual Infrared Institute, held on the Vanderbilt University campus in Nashville, August 16–20, 1971.

Included in the institute were sessions on infrared spectroscopy (basic and advanced), ultraviolet-visible spectroscopy, and gas chromatography. P. A. Staats directed laboratory sessions designed to train participants in the construction and renovation of liquid and gas absorption cells, the preparation of solid and solution samples, the calibration and operation of standard infrared spectrophotometers, and the use of newer infrared techniques for difficult sample materials. H. W. Morgan assisted in the planning of the institute and the organization of the lecture programs.

The ORNL participants presented a total of seven lectures on the topics listed below:

H. W. Morgan – "Solid State Infrared Techniques," "Laser Raman Spectroscopy," and "Laser Raman Instrumentation"

P. A. Staats – "Experimental Infrared Spectroscopy" (four lectures)

Summer Symposium on Fission, Stony Brook, New York. C. Y. Wong (Theoretical Physics Program) was an invited participant at an informal Fission Symposium held at the State University of New York (SUNY) in Stony Brook, New York, August 16 through September 30, 1971. He collaborated extensively on fission problems with other participants at the SUNY symposium and spoke on the subject "Stability of Nuclei with New Types of Topology."

Great Lakes Colleges Association Science Semester Program, Oak Ridge, Tennessee. The Great Lakes Colleges Association (GLCA), a consortium of 12 liberal arts colleges in Michigan, Ohio, and Indiana, and the Division of Nuclear Education and Training of the U.S. Atomic Energy Commission sponsor a Science Semester Program for students and faculty of GLCA member institutions. The need for students of the arts to extend the college experience to include off-campus studies has long been recognized by the liberal arts colleges. It has only recently been recognized that science students might also benefit from off-campus study programs. The justification for such experiences for the science students is essentially identical with that used to support the already-established off-campus programs for the arts. That is, liberal arts colleges are beginning to become sensitive to the need for every developing intellect to experience first-hand the unique atmosphere associated with any center of creativity, whether in the arts or the sciences.

The objectives of the GLCA-ORNL Science Semester Program are: (1) to give selected undergraduate science students the opportunity, by working full time in a research laboratory, to gain a more nearly complete understanding of how scientific research is planned and executed; (2) to provide the student, via his work experience, the judgment to make a better informed career choice; (3) to provide enrichment of the science faculty members of the participating schools by their involvement in research projects at ORNL; (4) to provide, via an interdisciplinary seminar program, an overview of some of the problems confronting society and particularly the scientific community; and (5) to facilitate student recognition of the interrelation between research and academic course work.

In 1971, the second year of the program, three faculty members and 16 students participated in the Science Semester. One faculty member, R. R. Winters,[1] an Associate Professor at Denison University, was engaged in research with the Nuclear Geophysics Program of the Physics Division. Two students, A. R. St. James, of Denison University, and W. C. Palmer, of Earlham College, were involved in research in the Physics Division during the fall. The former was engaged in total cross section measurements with the Oak Ridge Electron Linear Accelerator (ORELA) Neutron Time-of-Flight Spectroscopy Program, and the latter in excitation function measurements with the Nuclear Physics Program.

As a portion of the seminar component of the program, lectures were presented to the GLCA group by Physics Division staff members during the period of November 13 through December 7, 1971. Lecturers and their subjects were as follows:

J. L. Fowler – "Atoms with Toroidal Nuclei"

R. L. Macklin – "Production of the Heavier Elements from Iron by Neutron Reactions in Stars"

C. B. Fulmer – "The Oak Ridge Isochronous Cyclotron Program"

Additionally, the Physics Division supported the program by providing tours of its various research installations.

LABORATORY-SPONSORED CONFERENCES AND/OR MEETINGS

Annual Information Meeting of the Physics Division and Electronuclear Division, Oak Ridge, Tennessee

Advisory committees are attached to the majority of the research divisions of the Laboratory for the purpose of reviewing and offering advice on the cogency and effectiveness of the varied scientific programs under way.

The Annual Information Meeting of the Physics Division and the Electronuclear Division (including a report from the Nuclear Data Project) was held at ORNL during the week of May 17, 1971, just prior to a merger of these Divisions. During the combined sessions of the meeting, 93 topics in 34 main areas of research were covered by staff members in talks presented before Advisory Committee members, Laboratory attendees, and guests from the AEC and other installations; visitors were afforded the opportunity during one free day and afternoon of informal discussions with and/or tours by Division staff members at their work locations.

All members of the 1971 Advisory Committee were in attendance at the Information Meeting, and included:

Professor D. A. Bromley, Yale University

Professor J. J. Griffin, University of Maryland

Professor T. D. Lee, Columbia University

Dr. Joseph Weneser, Brookhaven National Laboratory

Third Conference on Neutron Cross Sections and Technology, Knoxville, Tennessee

The Third Conference on Neutron Cross Sections and Technology was held March 15, 16, and 17, 1971, at the University of Tennessee Carolyn P. Brown Memorial Center in Knoxville, Tennessee. Sponsorship was by the University of Tennessee, the Oak Ridge National Laboratory, the U.S. Atomic Energy Commission, the American Physical Society, and the American Nuclear Society.

Some 250 nuclear physicists and engineers attended the Conference and included representatives of laboratories and universities in France, Germany, Great Britain, Canada, Sweden, Austria, Belgium, Australia, the U.S.S.R., and the United States. All aspects of neutron cross section theory, present and future applications, and evaluation and handling of neutron cross section data were included on the program.

ORNL Physics Division staff members who participated actively in arranging the Conference were:

J. A. Harvey – Chairman of the Organizing Committee and the Program Committee

W. M. Good – Program Committee member

R. L. Macklin – Organizing Committee member; also Editor of the Proceedings

One evening was devoted to a tour of the Oak Ridge Electron Linear Accelerator facility of ORNL, taken by 70 of the Conference participants; an all-day tour of various ORNL facilities was conducted at the close of the Conference, with 25 of the participants remaining for this special event.

Proceedings of the Conference were published in two volumes (USAEC Conf-710301) and may be ordered directly from the National Technical Information Service, U.S. Department of Commerce, Springfield, Virginia 22151. Articles by three Physics Division staff members are included in the Proceedings.

UNISOR[1] Users Group Meetings, Oak Ridge, Tennessee

A general meeting of the University Isotope Separator at Oak Ridge (UNISOR) Users Group took place on September 23, 1971, at ORNL's Oak Ridge Isochronous Cyclotron Laboratory. Reports were given during the meeting on the Fourth North American Isotope Separator Symposium, held on September 20 and 21, 1971, at the National Bureau of Standards; also discussed in detail were the status of the isotope separator building, under construction, and the problems of equipment specifications and procurement.

K. S. Toth of the ORNL Physics Division (Nuclear and Theoretical Physics Program) handled, in cooperation with ORAU, the details of and arrangements for the meeting. Participants included 21 university members from 12 educational institutions and six ORNL staff members, four of whom are associated with the Physics Division.

The general meeting was then followed by a brief get-together of the Executive Committee to act on matters of staffing and personnel for the project. The members of the Executive Committee and their institutions are:

F. T. Avignone, University of South Carolina

W. M. Bugg, University of Tennessee

J. L. Duggan, Oak Ridge Associated Universities

R. W. Fink, Georgia Institute of Technology

J. H. Hamilton (Chairman), Vanderbilt University

K. J. Hofstetter, University of Kentucky

J. A. Jacobs, Virginia Polytechnic Institute and State University

R. S. Livingston, Oak Ridge National Laboratory

E. L. Robinson, University of Alabama, Birmingham

A. R. Quinton, University of Massachussetts

E. F. Zganjar, Louisiana State University

Another meeting of the UNISOR Users Group took place at the ORIC building on November 18, 1971. Thirty-eight persons, twenty-one of whom were university participants, attended the morning general session, which opened with the introduction of the new UNISOR employees: E. H. Spejewski, who will be the Director effective June 1972; A. C. Rester, Associate Scientist, who began work with the project in October 1971; and R. L. Mlekodaj, Scientist, who will begin work in January 1972. Reports were then heard concerning the results of some experiments done with the ^{12}C and ^{14}N beams available at the ORIC. Progress reports were also given concerning the UNISOR building, cyclotron beam-line elements, data-handling system, and the isotope separator. The morning session closed with a special report on the status of the Accelerator for Physics and Chemistry of Heavy Elements (APACHE), given by A. H. Snell, ORNL's Associate Director for Basic Physical Sciences.

In the afternoon, members of the Technical Committee met with the three new UNISOR employees to discuss various technical matters, such as the construction of a tape transport system, which will be used to collect isotopes of interest after mass separation. The UNISOR Executive Committee met in a separate session to discuss matters dealing primarily with the budget and with the makeup of two new committees. Members elected to these committees were as follows:

Scientific Program Committee: F. T. Avignone (Chairman), C. R. Bingham, K. J. Hofstetter, M. A. Ijaz, and N. R. Johnson

Scheduling Committee: K. S. Toth (Chairman), J. L. Duggan, R. W. Fink, R. O. Sayer, and E. F. Zganjar

1. Project UNISOR is a pioneer effort of public and private universities, state and federal governments, and a national laboratory, all of which are making contributions so that important and new research in nuclear physics and chemistry can be carried out. The universities have purchased an isotope separator, which is to be placed on line with the Isochronous Cyclotron at the Oak Ridge National Laboratory, hence the name UNISOR – Universities Isotope Separator at Oak Ridge.

Orientation Meeting at the ORNL Nuclear Data Project of NSF-Sponsored Nuclear Information Research Associates (NIRA), Oak Ridge, Tennessee

The Division of Nuclear Physics of the American Physical Society (DNP-APS) appointed in December 1969 a five-member Committee on Nuclear Data Compilations charged with presenting to the nuclear structure community plans for a "crash program" designed to get nuclear data information up to date within a period of three years. J. L. Fowler, Director of the ORNL Physics Division, served as a committee member and D. J. Horen, Director of the Nuclear Data Project, as a consultant during 1970–1971 (the latter became a committee member in 1971 following the resignation of J. L. Fowler).

The DNP-APS Committee formulated during 1970 a plan for the "crash program" and presented it in a letter sent to individuals at 23 of the leading nuclear structure centers in the United States. Overwhelmingly favorable response to the Committee's plan was received, which led to their recommendation, and subsequent approval during 1971, of the establishment of a nuclear information program to be funded by the Physics Research Division and the Office of Scientific Information Services of the National Science Foundation, supervised and administered by an ad hoc committee (one of whose members at present is D. J. Horen) appointed by the National Academy of Sciences.

By the fall of 1971 the Nuclear Information Research Associates (NIRA) Program was an actuality – 12 NIRA two-year postdoctoral appointments had been made, with sponsoring individuals selected for each appointee from 12 different universities and/or nuclear laboratories. The primary purpose of the NIRA Program is to assist existing centers in updating the nuclear data compilations by dividing the task among those organizations which generate most of the data. It was decided that the compilations would be published in *Nuclear Data Sheets,* the journal edited by the Nuclear Data Project. D. C. Kocher (Ph.D. 1970, University of Wisconsin) was the NIRA selected to work at the ORNL Nuclear Data Project, under the sponsorship of D. J. Horen, and was welcomed to the Laboratory in September 1971.

All Nuclear Information Research Associates and sponsors were invited to an Orientation Meeting which took place at ORNL during the week of October 4–8, 1971. The first day of the meeting was devoted to formal presentations regarding the overall aspects of the NIRA Program and an introduction to compilation methods used by the Nuclear Data Project, the latter presented by M. J. Martin and S. Raman. The second, third, and part of the fourth days gave the NIRA's an opportunity to read and extract information from a representative selection of scientific papers and to compare the results obtained by different people, as well as to discuss various aspects of the difficulties involved in extracting and evaluating information from some papers. Each NIRA was assigned to a Nuclear Data Project staff member, who provided assistance as well as moral support as the week progressed. The remainder of the week was devoted to scanning the Project files for unpublished references and discussions of formats, etc.

In addition to ORNL staff members in attendance at the Orientation Meeting, the following guests were present:

W. S. Rodney, National Science Foundation

G. Ward, National Science Foundation

C. K. Reed, National Academy of Sciences

H. Feshbach, Massachusetts Institute of Technology (DNP-APS)

F. Ajzenberg-Selove, University of Pennsylvania (DNP-APS)

Sponsors

G. T. Emery, Indiana University

E. T. Jurney, Los Alamos Scientific Laboratory

W. H. Kelly, Michigan State University

L. L. Lee, State University of New York, Stony Brook

C. W. Reich, Idaho Nuclear Corporation

G. M. Temmer, Rutgers University

NIRA's

K. R. Alvar, Rutgers University

A. Buyrn, Massachusetts Institute of Technology

S. Fiarman, Stanford University

G. E. Holland, Yale University

K. A. Kroger, Idaho Nuclear Corporation

C. Maples, Lawrence Radiation Laboratory, Berkeley

L. R. Medsker, Argonne National Laboratory

M. M. Minor, Los Alamos Scientific Laboratory

R. R. Todd, Michigan State University

J. K. Tuli, Indiana University

P. P. Urone, State University of New York, Stony Brook

D. C. Kocher, ORNL's NIRA appointee, was, of course, also in attendance at the meeting.

Advisory Committee Meeting on the Experimental Facilities of the Accelerator for Physics and Chemistry of Heavy Elements (APACHE), Oak Ridge, Tennessee

The Oak Ridge National Laboratory has for some time been proposing a facility for heavy-ion research known as APACHE (Accelerator for Physics and Chemistry of Heavy Elements). Staff members of the ORNL Physics Division and the Chemistry Division are closely involved with the APACHE proposal, which is periodically reviewed and update to reflect any advances in the state of the art, price c... ges, and shifts in program emphasis. Since such a facility (independent of its eventual location) will be national in character, it is important (1) that its planning receiv. maximum input from a broad representation of potential users throughout the country and (2) that within expected funding limitations a facility of maximum flexibility be designed to best serve the scientific community. Toward these goals, an Advisory Committee was appointed in the fall of 1971 to consult with ORNL management and staff concerned with the matter of experimental space required for a national heavy-ion accelerator facility. The first two-day meeting of the group took place at ORNL October 11 and 12, 1971, at which time Advisory Committee members included:

D. A. Bromley (Chairman), Yale University

J. H. Hamilton, Vanderbilt University

J. R. Huizenga, University of Rochester

R. B. Leachman, Kansas State University

R. A. Naumann, Princeton University

R. Vandenbosch, University of Washington

International Conference on Multiply Charged Heavy Ion Sources and Accelerating Systems, Gatlinburg, Tennessee

The International Conference on Multiply Charged Heavy Ion Sources and Accelerating Systems (acronym, ICOMCHISAAS) took place October 25–28, 1971, in Gatlinburg, Tennessee, with all sessions held in the Stephen Whaley Hall of the Riverside Motor Lodge. The Conference was organized by the Oak Ridge National Laboratory and the Lawrence Berkeley Laboratory and was sponsored by the following: the American Physical Society, the Nuclear Science Group of the Institute of Electrical and Electronic Engineers, the International Union of Pure and Applied Physics, the National Science Foundation, and the U.S. Atomic Energy Commission.

Some 137 specialists in the field of heavy-ion production attended the Conference, including U.S. participants and scientists from ten foreign countries – Austria, Canada, Denmark, England, France, Germany, Italy, Japan, Taiwan, and the U.S.S.R. The highly specialized area of nuclear technology covered in the Conference dealt with the instrumentation for studying the structure of matter and for the discovery of elements not found in nature.

ORNL Physics Division staff members took an active part in all phases of the Conference. C. D. Moak and A. van der Woude presented 2 of the 16 invited talks included in the eight sessions of the program; of the 31 contributed papers, 4 were by Division staff members; for Conference organization, J. A. Martin and R. S. Lord were, respectively, Program Chairman and Facilities and Arrangements Chairman; Scientific Secretaries for five sessions of the Conference included C. A. Ludeman, E. D. Hudson, R. S. Lord, and S. W. Mosko; and Special Activities were arranged by S. W. Mosko and A. W. Riikola. Additionally, coeditors of the Conference proceedings, to be published as *IEEE Trans. Nucl. Sci.* **NS-19**(2) (April 1972), are A. van der Woude and F. T. Howard, with C. A. Ludemann as Senior Scientific Secretary.

Immediately following the Conference, a one-day organized tour of the Oak Ridge National Laboratory was conducted for interested participants. The facilities visited included the Oak Ridge Isochronous Cyclotron (ORIC), the High Flux Isotope Reactor (HFIR), the Transuranium Laboratory (TRL), and the Van de Graaff Laboratory.

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