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FOR PERIOD ENDING JANUARY 31, 1964

OAK RIDGE NATIONAL LABORATORY
operated by
UNION CARBIDE CORPORATION
for the
U.S. ATOMIC ENERGY COMMISSION

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**PHYSICS DIVISION
ANNUAL PROGRESS REPORT
for Period Ending January 31, 1964**

J. L. Fowler
Director

H. B. Willard and E. O. Wollan
Associate Directors

JUNE 1964

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

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FOREWORD

This is the sixth Physics Division progress report made on an annual basis. As in previous years, the report contains the abstracts for papers which have been published or which have been prepared for publication. In such cases, reprints or preprints of the articles will be 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.

"Indexing words" or "key words" for experimental papers on nuclear structure have been supplied by Katharine Way. These appear in boxes just under the abstract or the authors' names. Comments on the usefulness of these terms to researchers and to those who collect data will be welcome.

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MAGNETIC ORDER IN RARE-EARTH INTERMETALLIC COMPOUNDS¹

J. W. Cable

W. C. Koehler

E. O. Wollan

Neutron diffraction measurements were made on a series of rare-earth intermetallic compounds to determine the type of magnetic order and its relationship to the number of valence electrons in the system. The compounds studied included TbCu, TbAg, ErCu, TbZn, and TbHg — all of which have the CsCl type of crystal structure. The first three compounds exhibit antiferromagnetism in which adjacent ferromagnetic (110) planes of moments are oppositely oriented. The

Néel temperatures are 115, 100, and 33°K, respectively. The last two compounds are ferromagnetic with Curie temperatures of 160 and 80°K. The lattice constant of ferromagnetic TbZn lies between those of TbCu and TbAg, both of which are antiferromagnetic. This shows that the different magnetic behavior is associated with the number of valence electrons rather than with interatomic separations. The Er moment in ErCu was observed to decrease with decreasing temperature from approximately $9\mu_B$ at 298°K to about $6\mu_B$ at 77°K. This moment reduction is probably associated with strong ligand field effects in this compound.

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

THE MAGNETIC STRUCTURES OF RARE-EARTH MANGANITES RMnO_3 ¹

W. C. Koehler

H. L. Yakel²

E. O. Wollan

J. W. Cable

The crystal structures and ferroelectric properties of the RMnO_3 compounds with R = Ho, Er, Tm, Yb, Lu, and Y have recently been reported. The magnetic configurations of the manganese ion moments in representative members of this series as well as in the newly prepared isostructural compound ScMnO_3 are described in this paper. Neutron diffraction data on polycrystalline samples have revealed transitions from a paramagnetic to

an antiferromagnetic state at temperatures ranging from 72°K for HoMnO_3 to approximately 120°K for ScMnO_3 . The magnetic configurations adopted by the moments in these compounds are "triangular" arrangements similar to those discovered by Corliss *et al.* in CrSe. The magnitudes of the moments are, in every case, slightly smaller than the expected value of 4 Bohr magnetons, and the moment directions are parallel or nearly parallel to the basal planes of the hexagonal structure, but they make various angles, depending upon the compound, with the hexagonal axes in the basal plane. A similar structural study has been independently reported by Bertaut and Mercier for YMnO_3 .

¹Abstract of paper to be published in *Proc. Fourth Rare Earth Conference, Phoenix, Arizona, 1964*.

²Metals and Ceramics Division.

THE MAGNETIC STRUCTURE OF NEODYMIUM¹

R. M. Moon

J. W. Cable

W. C. Koehler

Neutron diffraction measurements have been made on a single crystal of neodymium at temperatures below 20°K. The crystal structure is known to be hexagonal with a four-layer stacking sequence along the c axis of type ABAC. Thus, alternate layers have different near-neighbor environments, either hexagonal or fcc. Between 19 and 8°K, magnetic satellite peaks have been observed which are displaced from the nuclear peaks by reciprocal lattice vectors equal to $\pm\tau\mathbf{b}_1 + \mathbf{b}_3$ and $\pm\tau\mathbf{b}_1 - \mathbf{b}_3$. No satellites have been observed along the $\mathbf{b}_1$ direction, indicating that the moments are aligned in this direction. The structure may be described as an antiferromagnetic arrangement

of layers along the c axis with a sinusoidal modulation of the moments within each layer. The period of this modulation, described by the quantity τ^{-1} , increases from roughly seven to eight times the a_1 period as the temperature is lowered. Below about 8°K, the number of magnetic peaks doubles. Two closely spaced peaks appear in about the same reciprocal lattice locations as the single peaks in the higher temperature region. The ordered moments giving rise to both sets of satellites are in the $\mathbf{b}_1$ direction, as indicated by the absence of magnetic peaks along this direction. The structure in the low temperature region is similar to that of the higher temperature region except that there are two different values for τ occurring simultaneously. These two sets of satellites may be associated with the two types of sites present in the crystal structure.

¹Abstract of paper to be published in *Journal of Applied Physics, Supplement*.

ALIGNMENT OF RARE-EARTH MOMENTS IN DILUTE Pd-Fe ALLOYS

J. W. Cable

E. O. Wollan

W. C. Koehler

H. R. Child

Recently, Peter *et al.*¹ observed the paramagnetic resonance of Gd in the Pd-Rh and Pd-Ag alloy systems. They observed a negative g shift which was correlated with the magnetic susceptibility and electronic specific heat of the host lattice. This was interpreted as an antiferromagnetic exchange interaction between the Gd ion spin and the conduction electrons of the lattice. If such an interaction were strong enough to align the rare-earth moments in a "ferromagnetic Pd matrix" such as that produced by the introduction of Fe, then magnetization measurements should provide direct information regarding the inter-

action. This magnetic study of the ternary alloy system $\text{Pd}_{0.96}\text{Fe}_{0.03}\text{R.E.}_{0.01}$ was undertaken to explore this possibility.

A series of alloys having a composition of $\text{Pd}_{0.96}\text{Fe}_{0.03}\text{R.E.}_{0.01}$ were prepared by arc melting. The weight loss during the melting indicated a maximum 5% change in concentration of either dilute constituent, so that the nominal concentrations were accepted. Magnetic measurements were made by the ballistic method at sample temperatures between 4.2 and 150°K and in magnetic fields up to 5 kilo-oersteds. Saturation moments were obtained by extrapolation of magnetization vs $1/H$ curves. The relevant results, including those for the ferromagnetic host lattice, are given in Table 1. The Curie temperatures are all nearly

¹M. Peter *et al.*, *Phys. Rev.* 126, 1395 (1962).

Table 1. Magnetic Properties of $\text{Pd}_{0.96}\text{Fe}_{0.03}\text{R.E.}_{0.01}$ Alloys

R. E. (Rare Earth)	T_c ($^{\circ}\text{K}$)	μ_B per atom (4.2°K)	μ_B per R.E.	μ_B per R.E. (3+ ion)
La	118	0.230	0	0
Ce	108	0.223		2.1
Pr	120	0.232	+0.2	3.2
Nd	114	0.239	+0.8	3.3
Gd	108	0.173	-5.7	7
Tb	108	0.164	-6.6	9
Dy	106	0.169	-6.1	10
Ho	104	0.160	-7.0	10
Er	104	0.169	-6.1	9
Tm	104	0.198	-3.2	7
Yb	104	0.220	-1.0	4
$\text{Pd}_{0.97}\text{Fe}_{0.03}$	114	0.234		

the same, which indicates that the R.E.-Pd interaction is much weaker than the Fe-Pd interaction. There does appear to be a regular decrease in the Curie temperatures, but this is not correlated with the spin or total moment values of the rare earths. There are, however, significant variations in the average moment values, and these are correlated with the rare-earth moments. Assuming that all of the rare-earth ions are in plus three valence states (with the exception of cerium, which behaves anomalously and probably is in the plus four state) then the La alloy should furnish the standard for comparison with the other alloys. The Pr and Nd alloys have slightly higher moments and the other alloys have lower moments than this standard. Thus it appears that those rare-earth ions to the left of Gd ($J = L - S$) have their moments aligned parallel and those to the right of Gd ($J = L + S$) antiparallel to the ferromagnetic Pd-Fe lattice. This is in accord with a negative ionic-spin-conduction-electron interaction as suggested by Peter *et al.*¹ In column 4 of Table 1 the departure from the La standard is given in Bohr magnetons per rare-earth ion. These effective moments do not attain the maximum values for the tripositive ions, so that either the alignment is incomplete or there is some alteration of the moment associated with the host lattice. In order to investigate this aspect of the problem, neutron magnetic diffuse scattering measurements were made for the Dy alloy.

The differential cross section for the magnetic diffuse scattering from a ferromagnetic, disordered, ternary alloy can be written as:

$$\frac{d\sigma}{d\Omega} = q^2 [n_1 n_2 (p_1 - p_2)^2 + n_1 n_3 (p_1 - p_3)^2 + n_2 n_3 (p_2 - p_3)^2],$$

in which q is the magnetic interaction vector, the n 's are the mole fractions, and the p 's the magnetic scattering amplitudes of the constituent atoms. These magnetic scattering amplitudes are proportional to the ordered moments of the particular atoms. Of the three terms involving $(p_{Fe} - p_{Pd})^2$, $(p_{Dy} - p_{Pd})^2$, and $(p_{Fe} - p_{Dy})^2$, the magnitude of the first two will depend predominantly on the Fe and Dy moments since the Pd moment is so small in such alloys. The third term is negligible because of the small mole fractions of Fe and Dy.

A previous measurement² on $\text{Pd}_{0.97}\text{Fe}_{0.03}$ gave moment values of $3.0\mu_B$ per Fe and $0.15\mu_B$ per Pd. Because of the low Fe and Dy concentrations, it seems reasonable that the Fe moment would remain the same in this alloy, and that any changes in the average moment of the host lattice would be associated with the Pd moments. On that assumption, the contribution of the $(p_{Fe} - p_{Pd})^2$

²J. W. Cable, E. O. Wollan, and W. C. Koehler, *J. Appl. Phys., Suppl.* 34, 1189 (1963).

term to the cross section is $0.011 \text{ barn/steradian}$.³ The observed cross section at 16°K was $0.015 \pm 0.002 \text{ barn}$, which leaves $0.004 \pm 0.002 \text{ barn}$ for the $(p_{\text{Dy}} - p_{\text{Pd}})^2$ term. This is smaller than the value 0.018 calculated for a Dy moment of $6.1\mu_{\text{B}}$ as indicated by the magnetization data. However, the magnetic measurement is quite sensitive to small changes in the Pd moment while the neutron measurement is not. These results show that there is only partial alignment of the Dy moment, but they do not yield a unique value for that moment. The reason for this is that the cross section associated with the Dy term is approximately proportional to $n_{\text{Dy}} \mu_{\text{Dy}}^2$, so that in order to determine μ_{Dy} one must know the fraction of the Dy atoms which have their moments aligned. The observed cross section yields a moment of $3\mu_{\text{B}}$ per Dy if it is assumed that all of the Dy atoms have aligned moments. This moment is smaller than expected for Dy unless the ordering temperature is so low that there is a lack of saturation due to thermal agitation at 16°K . It seems more likely that the ordered moment is larger but that only a fraction of the Dy atoms have their moments aligned. For example, if the ordered moment is $10\mu_{\text{B}}$ per Dy, then the cross section allows only 9% of the Dy moments to be aligned.

Similar measurements were made on a sample for which the Dy content was increased to 2%. In this case, the differential cross section for magnetic diffuse scattering at 4.2°K was found to be $0.022 \text{ barn/steradian}$. After correction for the Fe term, the remaining Dy contribution of $0.011 \text{ barn/steradian}$ corresponds to $3.5\mu_{\text{B}}$ per Dy for alignment of all the Dy moments or to 12% alignment if the full moment of $10\mu_{\text{B}}$ per Dy is assumed. In order to help determine which of these alternatives is more nearly correct, magnetic measurements were made at several temperatures between 4.2°K and the Curie temperature of 100°K . The saturation moment at 4.2°K was $0.141\mu_{\text{B}}$ per alloy atom, but this increased with increasing temperature and reached a maximum of $0.162\mu_{\text{B}}$ per atom at about 35°K . This curve has the general character of the superposition of two Brillouin functions – one with a Curie temperature of 100°K and an extrapolated saturation value at 0°K of about $0.17\mu_{\text{B}}$ per atom, and the other with a Curie temperature of about 35°K and a saturation moment

of about $-0.029\mu_{\text{B}}$ per atom. If it is assumed that the former is associated with the Pd-Fe lattice and the latter with the Dy moments, then a unique Dy moment can be obtained. Thus, from the magnetization data:

$$n_{\text{Dy}} \mu_{\text{Dy}} = -0.029 ,$$

and from the neutron data:

$$n_{\text{Dy}} \mu_{\text{Dy}}^2 \approx 0.24 ,$$

so that $\mu_{\text{Dy}} = 8.3\mu_{\text{B}}$ and $n_{\text{Dy}} = 0.0035$. This indicates that only 18% of the Dy moments are aligned antiparallel to the Pd-Fe matrix. The ordered moment of $8.3\mu_{\text{B}}$ is in the range that has been reported for Dy in DyIr_2 (ref. 4) and DyNi_2 ,⁵ the latter having been interpreted by Bleaney⁶ in terms of crystal field effects. This observation of only a partial alignment of the Dy moments indicates that there is an overall reduction of the Pd moments relative to that in the alloy $\text{Pd}_{0.97}\text{Fe}_{0.03}$. The moment values for the two cases are $0.08\mu_{\text{B}}$ per Pd for the 2% Dy sample and $0.15\mu_{\text{B}}$ per Pd for the sample containing no Dy. The partial alignment of the Dy moments also implies that the interaction between the Dy atoms and the host lattice depends on the near-neighbor environment of the Dy. A possible interpretation is that only those Dy atoms which are located in the near-neighbor shell of an Fe atom are aligned, while the others remain paramagnetic. This interpretation gains support from the observation that a Pd–2.5% Dy alloy remains paramagnetic at temperatures as low as 4.2°K .

Neutron scattering data have not been obtained for the other 1% alloys of Table 1, but it seems likely that a similar situation exists for them also. Indeed, the same sort of interpretation is required to account for the observations on the 1% Dy alloy. The effective rare-earth moments in Table 1, then, do not actually represent the ordered rare-earth moments but, rather, the combined effect of an ordering of the rare-earth moments and a reduction in the average Pd moment of the system. The regular variation of these effective moments suggests that the Pd moment reduction is correlated with the moment of the rare-earth impurity, but the mechanism by which the reduction occurs is not understood.

⁴R. M. Bozorth *et al.*, *Phys. Rev.* 115, 1595 (1959).

⁵E. A. Skrabek and W. E. Wallace, *J. Appl. Phys.*, Suppl. 34, 1356 (1963).

⁶B. Bleaney, *Proc. Roy. Soc. (London)*, Ser. A (in press).

³The cross sections reported here apply to the forward direction, where the form factors are unity.

ANTIFERROMAGNETISM OF ORDERED Pd_3Cr

J. W. Cable

E. O. Wollan

W. C. Koehler

H. R. Child

This neutron diffraction study of the magnetic behavior of Pd_3Cr was undertaken as part of a general program inquiring into the distribution of magnetic moments in alloys of the 3d transition metals with palladium. The magnetic tendencies of these alloys are well illustrated by the paramagnetic Curie temperature (θ_p) data of Grestenberg.¹ The θ_p value of palladium increases rapidly with the addition of Fe or Co, and the alloys become ferromagnetic at very low 3d concentrations. With Mn, θ_p increases slowly to about 7% Mn and then decreases; while with Cr, θ_p decreases rapidly with Cr content. For the latter two alloys magnetization data cannot be obtained, and magnetic susceptibility data are difficult to interpret since the Pd lattice is so highly susceptible to changes induced by the magnetic impurities. It

seemed, then, that neutron diffraction techniques were required to better understand this system. The 25% Cr alloy was chosen as the best possibility for obtaining an ordered Cu_3Au type structure, for which it seemed more reasonable that antiferromagnetic order might occur.

The alloy was prepared by arc melting of the proper mixture of the constituents. Two samples were given slightly different heat treatments to induce positional order. The first sample, of 100 mesh particle size, was cooled from 800°C in 200° steps over a period of 12 days. The second, of 40 mesh particle size, was cooled from 900°C in 100° steps for a period of 33 days. Neutron data obtained for these two samples and for pure Pd are shown in Fig. 1. For the alloys, the reflections at the (100) and (110) positions include not only the superlattice reflections but also contributions from the second order of the (200) and

¹D. Gerstenberg, *Ann. Physik* 2, 236 (1958).

Fig. 1. Neutron Diffraction Patterns for Pd_3Cr and for Pd.

(220) normal lattice reflections. These intensities were corrected for this second-order contamination by comparison with the Pd data and internally calibrated with the (111) and (200) intensities. The observed F^2 values are given in Table 1 along with the values calculated for a perfectly ordered system. In neither case was a high degree of order attained, as indicated by the long-range order parameters (S) given in Table 1.

Also apparent in Fig. 1 are reflections at the $(\frac{1}{2} \frac{1}{2} \frac{1}{2})$ position. These reflections exhibit a Brillouin-type temperature dependence with a transition temperature of about 320°K. They are superpositions of the second-order (111) reflections and (111) antiferromagnetic reflections for a magnetic unit cell doubled in three dimensions. The magnetic intensities, corrected for the second-order contamination, were normalized to the nuclear intensities, and F^2 values are given in Table 2. As shown in Table 2, the magnetic intensities are proportional to the square of the long-range order parameter. This shows that the antiferromagnetic order is characteristic of the positionally ordered (Cu_3Au type) alloy and not of the disordered alloy.

Previous neutron diffraction studies²⁻⁴ of palladium alloys containing 25% Co, Fe, and Mn showed palladium moments of about 0.45, 0.40,

and $0.2\mu_B$, respectively. This decreasing Pd moment with increasing charge separation implies a filling of the Pd d band by electron transfer and suggests a very small Pd moment in Pd_3Cr . It seems reasonable, then, to attribute all of the magnetic scattering to the Cr atoms. The simplest antiferromagnetic structure which yields a (111) reflection is the (π, π, π) type⁵ in which adjacent ferromagnetic (111) planes of moments are oppositely oriented. The moment values given in Table 2 were obtained on the basis of these assumptions and the experimental Cr^{2+} form factor.⁶

These results indicate a strong antiferromagnetic interaction between next-near-neighbor Cr atoms in the face-centered cubic structure. It is not clear whether this interaction is sufficient to explain the antiferromagnetic tendencies of the more dilute alloys.

²E. O. Wollan *et al.*, *J. Phys. Soc. Japan* 17, suppl. B-III, 38 (1962).

³J. W. Cable *et al.*, *J. Appl. Phys., Suppl.* 33, 1340 (1962).

⁴J. W. Cable *et al.*, *Phys. Rev.* 128, 2118 (1962).

⁵H. A. Gersch and W. C. Koehler, *Phys. Chem. Solids* 5, 180 (1958).

⁶J. W. Cable, M. K. Wilkinson, and E. O. Wollan, *Phys. Rev.* 118, 950 (1960).

Table 1. Comparison of Observed and Calculated Nuclear Intensities for Pd_3Cr

hkl	F^2 (calcd.) ^a	F^2 (obs)	
		Sample 1	Sample 2
100	0.063	0.011	0.0022
110	0.063	0.010	0.0032
111	4.62	4.72	4.56
200	4.62	4.52	4.68
S^b		0.41 ± 0.02	0.21 ± 0.04

^aAssuming perfect order, $b_{\text{Cr}} = 0.35$, $b_{\text{Pd}} = 0.60 \times 10^{-12}$ cm.

^bLong-range order parameter.

Table 2. Magnetic Intensities of the Two Samples of Pd_3Cr

	Sample 1	Sample 2
$F^2(111)$	0.054 ± 0.003	0.017 ± 0.002
S^2	0.17 ± 0.02	0.043 ± 0.017
$F^2(111)/S^2$	0.32 ± 0.04	0.40 ± 0.16
μ per Cr ^a	3.0 ± 0.2	3.4 ± 0.7

^aAssuming the (π, π, π) type antiferromagnetic structure and the experimental Cr^{2+} form factor.

NEUTRON DIFFRACTION INVESTIGATION OF CHROMIUM ALLOYS

Y. Hamaguchi¹

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Introduction

Chromium metal, which is one of the 3d transition elements, has shown anomalous changes in many physical properties, such as the electrical resistivity, Hall effect, magnetic susceptibility, and specific heat, near 310°K, which are undoubtedly related to the antiferromagnetic transition. Recent neutron diffraction investigations by Shirane and Takei² have indicated that the magnetic structure below the Néel temperature is one in which the magnitudes of the magnetic moments are sinusoidally modulated. Another interesting investigation by Wilkinson *et al.*³ has shown that there is no localized magnetic moment in Cr above the Néel temperature.

Several theories⁴⁻⁶ have been proposed to explain the unusual magnetic properties of chromium. All of them are based on a band theoretical calculation, and the most important feature is the relation between the Fermi level and the Brillouin zone boundaries of band electrons. Thus, it is of great interest to examine how the magnetic properties are changed by changing either the Fermi level or the Brillouin zone boundaries. As shown by the electronic specific heat measurements,⁷ the elements Mn, Fe, and V introduced into Cr should change the Fermi level of electrons, but the Brillouin zone boundaries will be little changed since dilute alloys of such elements with Cr retain the same bcc crystal structure with almost the same lattice spacing. A few years ago, de Vries demonstrated the remarkable change of

transition temperature of Cr with the addition of 1 at. % Ni, Co, Fe, Mn, and V by electrical resistivity measurements. That investigation has now been extended to a wider range of alloying concentrations and to the measurement of other properties. In Cr-Mn alloys,⁸ it has been confirmed by neutron diffraction measurements that the anomalous temperature indicated in the electrical resistivity corresponds to the antiferromagnetic transition. The only way to determine magnetic structures of the sinusoidally modulated or other complex types is by means of a neutron diffraction investigation. Bacon⁹ has shown that a chromium single crystal containing 0.5% Fe and 0.16% Ni as impurities has a Néel temperature of about 26°C. Further, it shows the same satellites as pure chromium but does not show the spin-flip phenomenon down to 90°K; pure chromium shows this spin flip at 120°K. It is therefore of interest to investigate the effect of the alloying element on the magnetic structure of chromium and to compare the results with the theory.

Experimental Results

It is very difficult to obtain single crystals of chromium containing known amounts of alloying elements, but since Wilkinson *et al.* have succeeded in obtaining satellites in the powder diffraction pattern of Cr, this investigation was started with powder samples. The first alloy to be studied was a Cr-2% Mn alloy. The sample was melted in an argon-arc furnace, filed, and annealed at 1000°C in a hydrogen atmosphere for 72 hr. A control sample of the pure chromium which was used as the host material of the alloy was prepared in exactly the same way. This control sample has shown satellites below the Néel temperature and spin-flipping at 120°K.

¹Guest scientist from Japan Atomic Energy Research Institute.

²G. Shirane and W. J. Takei, *J. Phys. Soc. Japan* 17, suppl. B-III, 35 (1962).

³M. K. Wilkinson *et al.*, *Phys. Rev.* 127, 2080 (1962).

⁴W. M. Lomer, *Proc. Phys. Soc. (London)* 80, 489 (1962).

⁵A. W. Overhauser, *Phys. Rev.* 128, 1437 (1962).

⁶M. Tachiki and T. Nagamiya, *Phys. Letters* 3, 214 (1963).

⁷C. H. Cheng, C. T. Wei, and P. A. Beck, *Phys. Rev.* 120, 426 (1960).

⁸N. Kunitomi, Y. Hamaguchi, M. Sakamoto, K. Dai, and S. Komura, *J. Phys. Radium*, to be published.

⁹G. E. Bacon, *Acta Cryst.* 14, 823 (1962).

The diffraction patterns of the Cr-2% Mn alloy at liquid-nitrogen temperature and 123°C are shown in Fig. 1; no satellites were observed. The Néel temperature of this alloy is estimated to be about 250°C by extrapolating data for alloys with higher Mn content. It is not possible from powder diffraction data to distinguish a structure involving a longitudinal modulation of the spins from a superlattice peak due to a classical antiferromagnetic structure. This can only be done with single crystals. The possibility must then be considered that in the present case a spin flip may occur at higher temperatures. Moreover, there will be some

possibility that the induced strain produced by the alloying element will suppress the formation of a modulated spin structure. The measurements will be carried to higher temperatures to test the theory of Tachiki and Nagamiya,⁶ who predicted that 2% Mn should stabilize the classical antiferromagnetic structure. Other alloy systems such as Cr-2% V, Cr-2% Fe, and Cr-1% Mn will be examined also. The theory of Tachiki and Nagamiya suggests that a Cr-2% V alloy should have magnetic satellites if there is no effect of induced strains due to the alloying element.

Fig. 1. Neutron Diffraction Patterns of 2% Mn-Cr Alloy.

THE MAGNETIC PROPERTIES OF INTRA-RARE-EARTH ALLOYS

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J. W. Cable

The investigation of the effects of alloying on the magnetic properties of the heavy rare-earth metals has been extended to the case of binary intra-rare-earth alloys. Selected alloys from five different systems have been examined by neutron diffraction at temperatures from 4.2°K to room temperature to determine the type of magnetic order which they develop. This work is a continuation of the study of rare-earth yttrium and lutetium¹ alloys carried out by the neutron diffraction group in recent months. The oscillatory antiferromagnetic structures found in the pure rare-earth metals² from Tb to Tm led to the development of a large amount of theoretical work on the so-called *s-f* interaction between rare-earth ions via the conduction electrons. It was hoped that the study of rare earths diluted by the magnetically inert Y or Lu would allow some further under-

standing of this interaction. The series of intra-rare-earth alloys were of interest in this regard to try to delineate the effect of the localized magnetic ion in contrast to the case of the magnetically inert ions of Y or Lu.

Nine alloy specimens have been investigated so far, and the most significant results obtained are shown in Table 1. It was found in the Y series that the transition from paramagnetic to oscillatory antiferromagnetic occurred at a temperature T_N which depended only on the average value of the square of the projection of the spin on the total angular momentum. For these heavy rare earths, this value is given by

$$x = c(g - 1)^2 J(J + 1),$$

¹W. C. Koehler *et al.*, *J. Appl. Phys.* 34, 1335 (1963); also, *Phys. Div. Ann. Progr. Rept. Jan. 31, 1963*, ORNL-3425, p. 118.

²W. C. Koehler *et al.*, *J. Appl. Phys.* 34, 1335 (1963); also, J. W. Cable *et al.*, *J. Appl. Phys.* 32, 49S (1961); M. K. Wilkinson *et al.*, *J. Appl. Phys.* 32, 48S (1961); and W. C. Koehler *et al.*, *Phys. Rev.* 126, 1672 (1962).

where *c* is the atomic concentration of the magnetic ion, *g* is the Landé *g* factor, and *J* is the total angular momentum quantum number of the ion. To a very good approximation, the transition temperatures T_N were found to be linear with the two-thirds power of *x* regardless of the type of magnetic

Table 1. Magnetic Characteristics of Some Intra-Rare-Earth Alloys

Alloy	<i>x</i>	T_N (°K)	T_c (°K)	ω_i (deg)	ω'_i (deg)	ω_f (deg)	Remarks
50 Tb-50 Dy	8.79	205 ± 3	165 ± 10	32	28	0	
38.5 Tb-61.5 Dy	8.40	175 ± 3	130 ± 15	<i>a</i>	<i>a</i>	0	
65 Tb-35 Ho	8.40	196 ± 3	131 ± 5	35	23	0	
50 Tb-50 Ho	7.50	178 ± 3	148 ± 5	34	26	0	Another T_c at ~83°K
73.7 Tb-26.3 Er	8.41	190 ± 3	158 ± 5	32	27½	$\left\{ \begin{matrix} 23\frac{1}{2} \\ 0 \end{matrix} \right\}$	Both ferromagnetism and oscillatory component present at 4°K
50 Tb-50 Er	6.52	170 ± 3		42		29	
78 Tb-22 Tm	8.44	205 ± 3	115 ± 10	36	23	0	
44 Tb-56 Tm	5.27	145 ± 3		44			Possible T_c at ~33°K
50 Dy-50 Ho	5.79	157 ± 3		44		29	

^aIntensities too weak in spiral region to measure turn angles.

ion in the alloy. It was natural, therefore, to define a value of x for these intra-rare-earth alloys by

$$x = c_1(g_1 - 1)^2 J_1(J_1 + 1) + c_2(g_2 - 1)^2 J_2(J_2 + 1),$$

and this is the value listed in the table. For these alloys, also, T_N is linear with $x^{2/3}$ and, in fact, falls on the same curve as for the yttrium and lutetium alloys. This provides strong evidence that insofar as the initial ordering is concerned, the nature of the magnetic ions in the lattice is immaterial and it is only the value of the parameter x which is significant.

Further justification of this view is provided by the initial value of the period of the magnetic structure. The long-range oscillatory structures of the heavy rare earths are conveniently characterized by an interlayer turn angle ω which varies as a function of temperature and of the parameter x , approaching a saturation value near 50° at small x . The value ω_i which is found at the Néel temperature, the value ω'_i which is the value of ω at temperatures just above the transition to ferromagnetism, and ω_f which is the value at very low temperatures are listed in the table. To a fair approximation, ω_i is a universal function of the parameter x for both these intra-rare-earth alloys and the rare-earth-yttrium series. Also, the temperature variation of ω decreases with decreasing x in the Y series so that ω_i and ω'_i become nearly the same for sufficiently small x values. These intra-rare-earth alloys were all at relatively large values of x so this tendency is not shown very well by these data.

At temperatures below the Néel temperature, the characteristics of the particular magnetic ions in the alloy become important and the structures which develop do not show any type of systematic behavior except that for those alloys which develop ferromagnetism, such as the Tb-Dy series, the Curie temperatures are roughly linear between the

Curie temperatures of the two pure metals. This is similar to the behavior found for Gd-Dy alloys by Bozorth and Suits.³ These authors investigated the Gd-Dy system extensively and found that the dysprosium-rich alloys showed both a Néel temperature and a Curie temperature and that T_N and T_C were approximately linear with concentration but with different slopes. Furthermore, the two temperatures became equal at about 50 at. % Gd and no antiferromagnetic region existed for alloys with Gd concentrations greater than this value. This concentration corresponds to an x value of 11.4 and lies outside the region of x included in either the present experiments or the former experiments on rare-earth-yttrium alloys. However, extrapolation of the data from these experiments on the intra-rare-earth alloys combined with the rare-earth-yttrium data indicates that the region of antiferromagnetism would indeed disappear at about this x value.

In the pure metals, Tb, Dy, and Ho have their moments predominantly in the base plane while Er and Tm have their moments predominantly along the c axis. It appears from the preliminary results that these two directions are maintained in the alloys, and for alloys such as Tb-Er or Tb-Tm some moments occupy both directions. The data suggest that the ion maintains its preferred moment direction more or less independently of the other ion present. Furthermore, the moments may order at two different Curie points in some cases. The lower ordering temperature is indicated by a change of slope in the intensity vs temperature curves for certain of the samples.

Qualitative analysis of these data has been essentially completed, but quantitative interpretation in terms of ordered moment values and spin directions is still in progress.

³R. M. Bozorth and J. C. Suits, *Ninth Annual Conference on Magnetism and Magnetic Materials*, Atlantic City, November 1963 (to be published).

SOME MAGNETIC STRUCTURE PROPERTIES OF RARE-EARTH ALLOYS

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J. W. Cable

Introduction

At the first Rare Earth Conference a review was presented of the magnetic structures of the heavy rare-earth metals to the extent that they were known at that time.¹ In this paper we shall review briefly the magnetic structural properties, as we know them, of several rare-earth alloy systems. Our earlier report on the pure metals was based on neutron diffraction experiments on single crystals of dysprosium, holmium, and erbium, and on polycrystalline samples of terbium and of thulium. As of this writing, single-crystal specimens of terbium and thulium have been examined and several other single-crystal samples of holmium have been investigated. We shall summarize in the first section of this paper those results of the study of the pure metals which are pertinent to the subject of this investigation.²

Most of the alloy specimens to be considered here are rare-earth-yttrium alloys. The configuration of outer electrons of yttrium is similar to that of the heavy rare-earth metals. Moreover, yttrium crystallizes in the hexagonal close-packed structure, as do the rare earths in question, and its lattice constants are practically indistinguishable from those of gadolinium. For these reasons, yttrium appears to be an ideal, and presumably magnetically inert, diluent for the rare-earth metals. In a few cases, results obtained from alloys of the rare earths among themselves will be described.

Properties of the Pure Metals

Each of the rare-earth metals Tb, Dy, Ho, Er, and Tm undergoes a magnetic ordering transition

to an antiferromagnetic state in which the magnitude of one or more of the components of the magnetic moment varies sinusoidally with displacement along the *c* axis of the crystal. In Tb, Dy, and Ho, the components of the magnetic moment normal to the *c* axis form a helical or spiral magnetic structure; in Er and Tm the components parallel to *c* form an oscillating *z* component type configuration. Generally, the modulation period for a given element varies with temperature, and it is different from element to element. These remarks are summarized in Fig. 1, in which the wave number of the modulation is represented as a function of reduced temperature T/T_N for the five metals; the Néel points are listed at the lower left-hand side of the diagram. The metal gadolinium is not included — it appears not to have an antiferromagnetic transition.

The value for the wave number just below the Néel point we designate as τ_i ; and by τ_f we mean the value of the wave number at very low temperature, or at a temperature just above the Curie point. It may be noted that τ is constant for Tm at a value of 0.286 (corresponding to 3.5 *c* periods, or to an interlayer angle of 51.5°). The initial values for Er and for Ho are close to the same value. For Dy and Tb, τ_i is 0.24 (43° per layer) and 0.114 (20.5° per layer), respectively.

For Tb, the temperature range over which the antiferromagnetic structure exists is quite small. In the absence of an applied magnetic field, there is a transformation at approximately 218°K to a classical ferromagnetic structure in which the moments are in the basal planes. A similar transformation occurs in Dy at about 85°K. In Ho there is a large component of the moment normal to the *c* axis which is ordered in a (modified) helical arrangement. Below 20°K, the overall configuration is conical; that is, there is a small ferromagnetically ordered component parallel to the *c* axis. A similar arrangement is found in Er at low temperatures but in this case the cone is a relatively closed one, the ferromagnetic component being quite large. In Tm there is a component parallel to *c* only, and the magnetic configuration is a ferrimagnetic one which is as close

¹W. C. Koehler *et al.*, "Magnetic Structure Properties of Rare Earth Metals," p. 149 in *Rare Earth Research*, Eugene V. Kleber (ed.), Macmillan, New York, 1961.

²See, for example, W. C. Koehler, H. R. Child, E. O. Wollan, and J. W. Cable, *J. Appl. Phys., Suppl.*, 1963, in press (terbium); M. K. Wilkinson *et al.*, *J. Appl. Phys.* 32, 48S (1961) (dysprosium); W. C. Koehler *et al.*, *J. Phys. Soc. Japan* 17, suppl. B-III, 32 (1962) (holmium); J. W. Cable *et al.*, *J. Appl. Phys.* 32, 49S (1961) (erbium); W. C. Koehler *et al.*, *Phys. Rev.* 126, 1672 (1962) (thulium).

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Fig. 1. Temperature Dependence of Modulation Frequency of Magnetic Structures of Rare-Earth Metals. The modulation frequency in units of b_3 , the reciprocal c spacing, is represented as a function of reduced temperature T/T_N . The Néel points for the five metals are given in the insert.

an approach as possible to an antiphase domain type structure based on a seven-layer repeat distance.

A considerable body of the magnetic properties of the rare-earth metals can be understood if the dominant interaction between rare-earth atom moments is a long-range interaction and if the anisotropy energy is properly taken into account.³ It was to attempt to understand the nature of this interaction that a program for the study of rare-earth alloys was initiated.

Sample Preparation and Procedure

The alloy samples discussed here were all prepared by arc-melting an appropriate mixture of the pure metals in an inert atmosphere. The resulting finger was machined to form a cylinder (for the Dy samples, the melts were cast as buttons which were machined to disks). The solid specimens were examined in the neutron diffractometer at the Oak Ridge Research Reactor in the as-cast condition. Selected samples were reduced to fine filings or turnings in order to eliminate difficulties due to preferred orientation in the samples, which in some cases was severe. Filings were taken and annealed to obtain x-ray diffraction specimens. It was found, in the course

³R. J. Elliott, *Phys. Rev.* **124**, 346 (1961); T. A. Kaplan, *Phys. Rev.* **124**, 329 (1961); H. Miwa and K. Yosida, *Prog. Theoret. Phys. (Kyoto)* **26**, 693 (1961); T. Nagamiya, *J. Appl. Phys.* **33**, 1029S (1962); P. G. de Gennes, *J. Phys. Radium* **23**, 510 (1962); K. Yosida and A. Watabe, *Prog. Theoret. Phys. (Kyoto)* **28**, 361 (1962).

of the investigation, that yttrium forms solid solutions at all concentrations with the rare earths; the lattice parameters of the solid solutions were found to obey Vegard's law approximately.^{4,5}

The weight of each sample was recorded before and after the melting. If no weight loss occurred, the initial weights of the constituents were taken as the analytical data. If weight loss occurred, quantitative spectrographic analyses were made. All alloys containing thulium lost weight on melting due to the low vapor pressure of this metal, and attempts were made to anticipate the loss in preparing the material for melting.

The neutron diffraction patterns, taken with polycrystalline specimens, must be interpreted with some care because of the many overlapping reflections which occur even under the best experimental conditions. However, the regions of the pattern near the origin and near the (102) reflection are generally free of interference, and these regions of the patterns were studied most intensively.

In particular, the modulation period was determined from the position of the satellite of the origin, $000^\pm$, and/or from the separation of the 102^- and 102^+ satellites. The existence of a satellite $000^\pm$ usually implies the existence of a helical spin structure; absence of $000^\pm$ and observation of 102^+ and 102^- implies an oscillating z component type structure.

Néel temperatures were measured from the variation with temperature on warming of the intensity of an appropriate magnetic reflection. The Curie points were nearly always measured from the loss of magnetic intensity in the $(102)^\pm$ satellites to the (102) reflection.

It is to be emphasized that the results obtained here were for specimens in the virgin state. The application of a magnetic field produces extremely complex magnetic structure transformations.

Results and Discussion

The most complete set of data has been obtained from the system terbium-yttrium.⁶ The magnetic structures of these alloys are quite similar to those observed in pure terbium. A helical anti-ferromagnetic structure (perhaps modified) exists for all concentrations studied. In only a few of the more concentrated alloys is a ferromagnetic configuration observed.

Some of the structure properties of the system are shown in Fig. 2. The left-hand ordinate refers to the initial and final value of the interlayer turn angle, designated by open circles and represented as a function of ξ , the concentration of Tb in Y. On the right hand are to be read the Néel and Curie temperatures, designated by the closed circles in the figure. The solid curve drawn through the Néel points is calculated on the

⁶W. C. Koehler, H. R. Child, E. O. Wollan, and J. W. Cable, *J. Appl. Phys., Suppl.*, 1963, in press.

Fig. 2. Magnetic Structure Properties of Terbium-Yttrium Alloys. The initial and final turn angles ω_i and ω_f , and Néel and Curie temperatures T_N and T_C are represented as a function of ξ , the concentration of terbium in yttrium.

⁴Similar results for the alloy systems Tb-Y, Dy-Y, and Ho-Y have been found by S. Weinstein, R. S. Craig, and W. E. Wallace, *J. Appl. Phys., Suppl.*, 1963, in press; S. Weinstein, thesis, University of Pittsburgh, 1962.

⁵For Gd-Y, see W. C. Thoburn, S. Legvold, and F. H. Spedding, *Phys. Rev.* 110, 1298 (1958).

assumption that the Néel temperature is proportional to $\xi^{2/3}$ with the normalization at pure terbium.⁷ It may be seen that the fit for this empirical observation is quite good. The curve illustrating the variation of Curie point with concentration shows that the ferromagnetic transition is suppressed for rather small dilutions; the composition $\text{Tb}_{0.75}\text{Y}_{0.25}$ remains antiferromagnetic to 4.2°K.

The initial and final values of the turn angle approach the same value of about 50° per layer as the concentration ξ becomes small, and the difference between the two becomes difficult to measure at $\xi = 0.5$. The final value ω_f appears to flatten off at $\xi = 0.75$, that is, near the point at which the Curie point is no longer observed. A fairly complete series of alloys Dy-Y also has now been studied in the virgin state. Very low Dy concentrations have not been investigated because of the intensity problems attendant upon samples containing highly absorbing Dy. The results obtained are generally similar to those obtained for the system Tb-Y. The Néel points are again approximately proportional to the $2/3$ power of the concentration and the Curie point is suppressed by as little as 5 at. % yttrium. The initial and final turn angles approach each other, and a value of about 50°, again, for the more dilute alloys.

As early as 1938, Néel⁸ in the molecular field approximation showed that the paramagnetic Curie temperatures, θ_p , of the heavy rare-earth metals are proportional to $S^2(J+1)/J$, where S and J are the spin and total angular momentum quantum numbers. This expression is equivalent to $(g-1)^2 J(J+1)$ for the metals from Gd to Lu, where g is the Landé splitting factor. More recently, de Gennes⁹ calculated the paramagnetic Curie temperatures of the heavy rare-earth metals on the basis of an indirect interaction between ionic spin and conduction electron spin and showed that these spins should vary as $(g-1)^2 J(J+1)$. Experiment appears to confirm this proportionality, although not nearly so well as the early experimental data used by Néel and

de Gennes would indicate. One may further argue that the paramagnetic Curie point of a given magnetic species dissolved in a nonmagnetic matrix should be proportional to the concentration of magnetic ions and to the Curie point of the pure magnetic species.¹⁰ For the rare-earth-yttrium alloys, then, the paramagnetic Curie points may be expected to be proportional to $\xi(g-1)^2 J(J+1)$, where ξ is the concentration of atoms with angular momentum J and splitting factor g .

The existing paramagnetic Curie point data for the pure metals and for the rare-earth-yttrium alloys are summarized in Fig. 3. The abscissa is $x = \xi(g-1)^2 J(J+1)$. It may be noted from the figure that the linear relationship is quite well obeyed up to the value of x corresponding to terbium, after which a definite break appears in the curve. For the data so far available, this

¹⁰S. H. Liu, *Phys. Rev.* 123, 470 (1961).

Fig. 3. The Paramagnetic Curie Points for Rare-Earth-Yttrium Alloys. Paramagnetic Curie point data for the pure rare-earth metals (Ames data) and for rare-earth-yttrium alloys, (a) ref. 5, (b) ref. 4. The data fit on a universal curve with $x = \xi(g-1)^2 J(J+1)$.

⁷The behavior of the Néel temperature with concentration was first noted by S. Weinstein, R. S. Craig, and W. E. Wallace (ref. 4).

⁸L. Néel, *Compt. Rend.* 206, 49 (1938).

⁹P. G. de Gennes, *Compt. Rend.* 247, 1836 (1958).

curve appears to be a universal one; the paramagnetic Curie point apparently depends only on its x value and not upon the particular constituents of the alloy.

It also appears now that the Néel temperatures as well as the paramagnetic Curie temperatures for all the rare-earth-yttrium alloys can be placed on a universal curve. This observation is illustrated by the curves of Fig. 4. The abscissa is, as before, $x = \xi(g-1)^2 J(J+1)$. The Néel points follow very closely a $\frac{2}{3}$ power law. Of interest is the fact that the early Gd-Y data⁵ can be fitted to the same curve when it is recognized that the ordering temperatures of dilute alloys are Néel temperatures and of concentrated alloys are Curie temperatures.

With somewhat less precision it is observed also

that the initial turn angles of the pure metals and of the yttrium alloys follow a universal curve as indicated by the figure. As yet no neutron observations have been made on the Gd-Y system, but one might anticipate from the data already accumulated that alloys of Gd-Y for x values above about 12 would be ferromagnetic in zero field; for those with x less than 12 there would be an antiferromagnetic range, the turn angle for which would follow the dashed line which joins smoothly with the results for the system Tb-Y.

Several rare-earth-rare-earth systems have been studied. The Néel points and initial turn angles for a number of these are plotted in the figure, and, surprisingly, these data also can be fitted to the same curve.

Fig. 4. The Néel Points and Initial Turn Angles for Rare-Earth Alloys. The Néel points and to a lesser extent the ω_i fall on universal curves with $x = \xi(g-1)^2 J(J+1)$. The curve for T_N is very closely a $\frac{2}{3}$ power law curve.

On the one hand, the fact that so wide a variety of alloys may be fitted to these curves suggests that, near to the Néel point, the individuality of the rare-earth constituents is lost and that the Néel point and initial turn angle depend primarily upon the average value of $(g - 1)^2 J(J + 1)$. On the other hand, however, the structures which are adopted by the alloys must be dictated by the relative importance of the several orders of the axial anisotropy energy. Indeed, at low temperatures the magnetic configurations adopted by the rare-earth-rare-earth alloys depend strongly upon the characteristics of the constituents of the alloys. A wide variety of configurations as illustrated by the following examples has been found. In an alloy 0.44 Tb-0.56 Tm, the low-temperature configuration appears to be a conical one in which there is a large ferromagnetic component parallel

to the c axis; in an alloy 0.78 Tb-0.22 Tm, a configuration is found in which there is a small oscillatory component of the moment parallel to c and a large ferromagnetic component normal to c . The alloy 0.50 Dy-0.50 Tb has a very narrow antiferromagnetic region and a relatively high Curie temperature. The alloy 0.50 Ho-0.50 Dy apparently remains helical down to about 12°K.

Systematic studies of various of these systems are in progress in an effort to understand the role of the anisotropy on the various low-temperature transformations. Possible theoretical interpretations of the linearity of θ_p with x , of the apparent variation of T_N with $x^{2/3}$, and of the universal character of the T_N and ω_i curves have been undertaken, and these considerations will be the subject of a separate publication.

CORRELATION OF THE MÖSSBAUER ISOMER SHIFT WITH THE RESIDUAL ELECTRICAL RESISTANCE FOR GOLD ALLOYS

L. D. Roberts

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In the last annual report² an experimental and theoretical study of the correlation between the Mössbauer isomer shift and the residual electrical resistance for gold alloys was reported. This study has been extended by the measurement of the electrical resistance of alloys containing 1 and 2 at. % gold in copper, silver, palladium, platinum, nickel, and iron. The resistance of the pure host metals was also measured, and the measurements were made over the temperature range from 4.2 to 300°K. The residual electrical resistance per atomic percent $\Delta\rho/c$ was calculated from the above measurements for these samples and was found to be in agreement for the 1 and 2% alloys. The results, shown in Fig. 1, are in agreement with earlier measurements where the

latter are available. The measured values for $\Delta\rho/c$ are found to be essentially independent of the temperature — as was expected — for the copper, silver, palladium, and platinum alloys. The large temperature dependence of $\Delta\rho/c$ for the gold-nickel and gold-iron alloys, which must be due to magnetic effects, does not seem to have been observed previously. Recently the $\Delta\rho/c$ measurement for an alloy containing 2 at. % gold in nickel has been extended to a temperature of 1300°K. It was found that $\Delta\rho/c$ rose to a sharp maximum near 2 $\mu\Omega$ cm at the Curie point and then fell abruptly to a roughly constant value of about 0.6 $\mu\Omega$ cm. These observations for temperatures below the Curie point may be discussed qualitatively in terms of an early theory of Mott.³

Returning to the isomer shift, ΔE_I , we have previously given a theoretical estimate of this

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²Phys. Div. Ann. Progr. Rept. Jan. 31, 1963, ORNL-3425, p. 103.

³N. F. Mott, Proc. Roy. Soc. (London) A153, 699 (1935).

Fig. 1. The Residual Electrical Resistance $\Delta\rho/c$ for Gold Alloyed in Copper, Silver, Palladium, Platinum, Nickel, and Iron.

Fig. 2. Comparison of Measured and Calculated Isomer Shifts for Gold Alloyed in Copper, Silver, Palladium, and Platinum.

quantity² where the necessary parameters for the model were obtained from $\Delta\rho/c$ and the s -band filling for the host metal. The results for this calculation are shown in Fig. 2, where the theoretical isomer shift as a function of s -band filling is displayed. There is a proportionality constant in the theory which reflects the charge density at the nucleus in pure gold metal times a function of the change of nuclear size between the ground and excited states. This constant is obtained here by fitting the theoretical isomer shift to its measured value for silver, with the silver s -band filling taken as unity. The theoretical isomer shift may then be given in millimeters per second as a function of s -band filling for the copper, palladium, and platinum alloys. Agreement between theory and

experiment may then be obtained for the palladium and platinum alloys for band fillings of 0.65 for palladium and of 0.38 for platinum. The value of 0.65 is acceptable for palladium, and the lower value of 0.38 for platinum seems reasonable in that the electronic specific heat of platinum is much less than that for palladium. For copper the s -band filling of 1 gives a theoretical isomer shift of 3.7 mm/sec compared to the measured value of 4.4 ± 0.2 mm/sec. The fact that the theoretical estimate of the isomer shift is about 15% low may correspond to the rather large difference of atomic size of copper and gold. These size effects are taken into account in our calculation in terms of the strain field which the impurity introduces into the host metal.

ON THE INTERNAL MAGNETIC FIELD IN NICKEL¹

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The internal magnetic field, H_i , for the Mössbauer nucleus Ni^{61} in metallic nickel has been determined by application of an external magnetic field. Comparing the observed field dependence of the Mössbauer spectra with calculated absorp-

tion curves yields $H_i = -70 \pm 15$ kilogauss, assuming additivity of the fields. This value is in contradiction with the older NMR measurements, but it agrees with the new NMR results published recently. The previously determined ratio of the nuclear magnetic moments, $\mu_e/\mu_g = -0.47 \pm 0.08$, is still valid and may be used with the new value for the ground-state moment, $|\mu_g| = 0.70 \pm 0.04$ nuclear magneton, to obtain the excited-state moment μ_e .

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

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MEASUREMENT OF THE HYPERFINE SPLITTING IN SEVERAL ALLOYS OF IRON-RHODIUM

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As an extension of earlier work⁴ the nuclear Zeeman splitting of Fe^{57} in FeRh has been measured using the Mössbauer effect for three alloys with rhodium compositions near 50, 52, and 53 at. %. It was found by magnetization measurements that the 50 at. % sample is ferromagnetic above 100°K. The temperature dependence of the hyperfine splitting (hfs) of this sample was measured from 100 to 714°K. The Curie temperature was found to be $710 \pm 4^\circ\text{K}$. As shown in Fig. 1, these measurements are well described by a Brillouin function with $s = \frac{3}{2}$ and an $H_{\text{eff}}^F(0) = 285$ kilogauss at 0°K.

The 52 at. % sample displayed a Curie temperature of $654 \pm 5^\circ\text{K}$. It was antiferromagnetic below 330°K and ferromagnetic above this temperature up to the Curie point. The hfs was measured from

4.2 to 670°K. These data are shown in Fig. 2. In the ferromagnetic region a Brillouin function with $s = \frac{3}{2}$ and $H_{\text{eff}}^F(0) = 295$ kilogauss was used to fit the data. The experimentally observed hfs in the antiferromagnetic region fell below this Brillouin function and may be described either by $H_{\text{eff}}^{AF}(T) = H_{\text{eff}}^{AF}(0)(1 - aT^n)$, where $H_{\text{eff}}^{AF}(0) = 276$ kilogauss and $n = 2.5$, or by a Brillouin function with $s = \frac{3}{2}$ and $H_{\text{eff}}^{AF}(0) = 276$ kilogauss and an effective Néel temperature of 610°K (Fig. 2). As indicated above, $B(x - \frac{3}{2})$ gives a good description of the hfs for the 50 at. % alloy. If it is assumed that this function may be used to extrapolate the high-temperature ferromagnetic behavior to 0°K for the 52 at. % alloy, then it may be suggested that the intrinsic effective field per iron atom [i.e., $H_{\text{eff}}(0)$] is slightly lower in the antiferromagnetic than in the ferromagnetic phase.

The measurements on the 53 at. % alloy showed a small amount of nonmagnetic phase. The temperature dependences of the ferromagnetic and antiferromagnetic regions were the same, within experimental error, as for the 52 at. % alloy, with

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⁴F. E. Obenshain et al., *Phys. Div. Ann. Progr. Rept. Jan. 31, 1963, ORNL-3425, p. 99.*

the exception that the transition temperature between these phases had a slightly lower value of 317°K and the Curie temperature was slightly higher ($665 \pm 5^\circ\text{K}$).

Through the application of an external magnetic field of 8 kilogauss, the sign of the magnetic field at the iron nucleus was measured and was found to be negative with respect to the magnetization direction in the ferromagnetic phase for the 50 and the 52 at. % samples.

Fig. 1. Temperature Dependence of the Iron Hyperfine Splitting in an Fe-50 at. % Rh Alloy. The Curie temperature is $710 \pm 4^\circ\text{K}$.

There are a number of factors which enter into the above change of H_{eff} between the ferromagnetic and antiferromagnetic states. One possible contribution to this may be related to a lower $\langle s_z \rangle_{AF}$ for the ground state of an antiferromagnetic sublattice compared to $\langle s_z \rangle_F$ for the ferromagnetic ground state.

Fig. 2. Temperature Dependence of Iron Hyperfine Splitting in an Fe-52 at. % Rh Alloy. The ferromagnetic-to-antiferromagnetic transition occurs at 330°K and the Curie temperature is 654°K .

NUCLEAR ANOMALOUS DISPERSION IN Fe^{57} BY THE METHOD OF TOTAL REFLECTION¹

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E. C. Campbell

The recoil-free coherent resonant scattering of the 14.4-keV Fe^{57} gamma rays has been investigated by employing the techniques of the Mössbauer effect together with those of total reflection. Of particular interest are the observed large interference effects attributed to the coherent superposition of the several resonant nuclear contributions and the nonresonant electronic contribution to the scattering amplitude in the forward direction. Gamma rays from a 300-mc Co^{57} source, diffused into the thin edge of a stainless steel plate, were reflected at small glancing angle θ by an optically flat Fe^{57} mirror through a narrow slit into an NaI scintillation detector. The resonant frequency spectrum of the Fe^{57} nuclei in the mirror was scanned by varying the source velocity, v . Values of the absolute reflectivity $R(\theta, v)$ were obtained by comparison of the direct and reflected measured intensities. In an auxiliary experiment $R(v)$ was measured with an external field applied to the

mirror. The results of these measurements were compared with computer-programmed calculations based on the classical optical theory of total reflection. Appropriately averaged quantum-mechanical expressions were introduced for the coherent resonant nuclear scattering amplitude in the forward direction. Separate computations were made for each polarization state of the incident radiation; these were averaged to give $R(\theta, v)$ appropriate for an unpolarized source and a polarization-insensitive detector. Suitable integrations were performed to take into account the frequency spread and angular width of the incident radiation. For $\theta = 4$ milliradians, $R(v)$, computed with the six resonances of normal ferromagnetic Fe^{57} , agreed in shape and magnitude with the observed reflectivity, when the resonance width was assumed to be four times the natural width. For $\theta = 2$ milliradians, where the gamma-ray penetration depth is small, anomalies in the magnetic and chemical environment of the Fe^{57} nuclei near the mirror surface required the introduction of additional resonances for FeO and for nonmagnetic Fe.

¹Abstract of published paper: *Phys. Rev.* 132, 1625 (1963).

POLARIZATION OF TOTALLY REFLECTED MÖSSBAUER RADIATION

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The preceding abstract — “Nuclear Anomalous Dispersion in Fe^{57} by the Method of Total Reflection,” by S. Bernstein and E. C. Campbell, *Phys. Rev.* 132, 1625 (1963) — describes briefly the results of our study of the intensity of a single-line Fe^{57} gamma-ray source totally reflected from an Fe^{57} metal mirror, as a function of angle

of incidence and frequency of the source. A schematic diagram of the apparatus is shown in Fig. 1. Since this work was completed, we have been looking in further detail into the theoretical aspects of total reflection, especially the polarization of the reflected radiation and the changes in phase on reflection. Some illustrative samples of the results of calculations on these subjects are presented here.

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Fig. 1. Schematic Diagram of Apparatus for Intensity Measurement of Fe^{57} Radiation Reflected from Fe^{57} Mirror.

For the sake of internal completeness, we repeat briefly some of the material discussed in detail in the published paper. The reflectivity of the mirror R is given by

$$R = \left| \frac{1 - \sqrt{1 - z}}{1 + \sqrt{1 - z}} \right|^2, \quad (1)$$

in which the complex number z is given by

$$z = \frac{2\delta + 2i\beta}{\theta^2} = \frac{N\lambda^2}{\pi\theta^2} f(0). \quad (2)$$

The absolute amplitude and phase of the reflected radiation are given by the complex quantity:

$$\sqrt{R} = \frac{1 - \sqrt{1 - z}}{1 + \sqrt{1 - z}}. \quad (3)$$

In (1), (2), and (3), N is the number of scattering centers per unit volume, λ is the wavelength of the radiation, θ is the glancing angle, δ and β are related to the index of refraction by $n = 1 - \delta - i\beta$, and $f(0)$ is the complex coherent scattering amplitude per scattering center in the forward direction. Two coherent contributions to the scattering amplitude are considered: the non-resonant electronic scattering amplitude, f_e ; the resonant nuclear scattering amplitude, f_N . The nuclear amplitude itself consists of coherent contributions from the six possible transitions between the Zeeman levels of the 14.4-keV isomeric level and the ground state of Fe^{57} .

Thirty percent of the intensity of the source is emitted with some energy change and therefore

cannot be resonantly scattered by the Fe^{57} nuclei of the mirror. The total reflectivity, R , is then given by

$$R = 0.30R_e + 0.35(R_1 + R_2), \quad (4)$$

in which R_e is the reflectivity of the energy-changed portion by the electrons of the mirror. R_1 and R_2 are the reflectivities for the two states of polarization of the unchanged-energy portion by the coherent cooperation of the electrons and Fe^{57} nuclei of the mirror.

The coherent superposition of the electronic contribution z_e and the several nuclear contributions z_n to the total resultant z is shown in Figs. 2 and 3 for $\theta = 2 \times 10^{-3}$ radian with no external magnetic field applied to the mirror. (The domain magnetizations were assumed to take random directions in the plane of the mirror.) Figure 2 represents the state of polarization in which the electric vector is perpendicular to the mirror, Fig. 3 the state for the electric vector parallel to the mirror. The parameters used in the calculations of this report are the same as those used in the published paper, except that here the width of the isomeric nuclear energy level was taken to be equal to the natural line width. In Figs. 2 and 3 the electronic contribution to the total $z = z_e + z_n$ is represented by the complex number labeled z_e . To this must be added the complex number representing z_n . It is represented by the severalfold looped curves shown, the number of loops depending upon the number of effective nuclear Zeeman transitions. To each point of the looped curve there corresponds a

Fig. 2. A Point on the Sixfold Looped Curve Represents the Value of the Complex Number $z \propto i(0)/\theta^2$ of Expression (2) for the Polarization State E Perpendicular to the Mirror. To each point of the looped curve corresponds a source velocity. The curves of constant R are contour lines of equal reflectivity. The reflectivity can be obtained as a function of source velocity by graphical interpolation.

frequency of the photon or a (Doppler) velocity of the source. The correspondence is indicated on the loops in terms of source velocity by the numbers shown. The complex number z_e corresponds to the complete absence of nuclear resonances (infinite source velocity, positive or negative). As a point, which starts at z_e , moves clockwise around the several loops in the proper manner indicated by the labeled velocities and returns to z_e , the frequency of the photons goes from energies far below the resonance region to energies far above. For each source velocity, $z = z_e + z_n$ is represented by the appropriate complex number on the locus of the looped curve. For each velocity the absolute amplitude and phase of z can be obtained from the figure. The curves in Figs. 2 and 3 labeled with different values of R are contour lines of constant reflectivity. From these two figures, values of the

Fig. 3. The Coordinates of a Point on the Fourfold Looped Curve Are the Real and Imaginary Parts of the Complex Number $z \propto i(0)/\theta^2$ of Expression (2) for the Polarization State E Parallel to the Mirror. To each point of the looped curve corresponds a source velocity. The curves of constant R are contour lines of equal reflectivity. The reflectivity can be obtained as a function of source velocity by graphical interpolation.

reflectivity can be obtained as a function of source velocity for each of the two states of polarization by graphical interpolation.

If the region of "total reflection" is defined by the requirement that δ be greater than zero, then it is obvious from inspection of the figures that for certain regions of velocity total reflection is involved, whereas for other regions of velocity "ordinary reflection" ($\delta < 0$) is involved.

In Fig. 4 are shown $0.35 R_1$, $0.35 R_2$, and R of expression (4) as a function of source velocity. The velocities at which nuclear resonances occur are indicated by the arrows along the axis of abscissas. From Fig. 4 it can be seen that there is a net polarization of the reflected radiation. The degree of polarization P may be defined by

$$P = \frac{R_{||} - R_{\perp}}{R_{||} + R_{\perp}}, \quad (5)$$

Fig. 4. Reflectivity vs Velocity. $0.35R_1$ and $0.35R_2$ are the velocity-dependent contributions to the total reflectivity R for the two states of polarization [Expression (4)].

in which $R_{||}$ and $R_{\perp}$ are the reflectivities of the two states of polarization including both Mössbauer and non-Mössbauer radiation. The degree of polarization P , in percent, is shown as a function of source velocity in Fig. 5. P varies rapidly and changes sign as the photon energy passes through the nuclear resonance energies. Polarizations as high as 50% are reached for some velocities. The polarization would, of course, be greater if the non-Mössbauer radiation were not present.

Since the value of the resultant z can be seen from Figs. 2 and 3 to differ for the two states of polarization at a given velocity, it follows from expression (3) that the reflected amplitudes will also differ, with respect to both absolute amplitude and phase. The difference $\phi_1 - \phi_2$ in the phases of the reflected radiation for the two states of polarization is shown as a function of velocity in Fig. 6, from which it can be seen that $\phi_1 - \phi_2$ fluctuates markedly in the region of a resonance. For the example shown, the difference in phase can be greater than 100° . These results suggest that if a beam of linearly polarized Mössbauer radiation were incident upon an Fe^{57} mirror, the reflected radiation would be elliptically polarized, and that the shape of the ellipse could be varied by varying the source velocity. Such large changes in polarization do

not take place in the case of reflection of x rays where only the electrons contribute to the scattering. The difference in phase on reflection of the two states of polarization in the case of Mössbauer radiation is due to the fact that the nuclear scattering amplitudes of the two states are different.

Calculations similar to those described here have also been made for the case of an external magnetic field applied to the mirror, and for other glancing angles.

The degree of polarization and the difference in phase on reflection are diminished if the line width of the mirror is taken to be greater than the natural line width.

Fig. 5. Percent Polarization of Reflected Gamma Rays as a Function of Source Velocity.

Fig. 6. Difference in Phase on Reflection of the Two States of Photon Polarization vs Source Velocity.

FRAGMENTATION OF THE EXCITED PARENT IONS, $[\text{CH}_3\text{Kr}^{82}]^+$ AND $[\text{CH}_3\text{O}^{18}]^-$, FOLLOWING THE β^- DECAY OF $\text{CH}_3\text{Br}^{82}$ AND THE β^+ DECAY OF CH_3F^{18} ¹

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The relative abundances of the fragment ions that result, respectively, from the β^- decay of $\text{CH}_3\text{Br}^{82}$ and β^+ decay of CH_3F^{18} have been measured with a specially designed mass spectrometer. Following the β^- decay of $\text{CH}_3\text{Br}^{82}$, only about 0.4% of the parent ion, CH_3Kr^+ , remained intact, as was anticipated from the rather large recoil energy. The most abundant ion observed was CH_3^+ , 89%. A variety of other ions

were also formed and their production is discussed in terms of excitation resulting from a sudden change in nuclear charge. The investigation of the fragment ions formed in the decay of CH_3F^{18} marks the first time a molecule undergoing positron decay has been so studied. The following negative ions were detected: CH_3O^- , O^- , and H^- . A large abundance of positive ions, however, was also observed. The origin of these positive ions is critically discussed, and calculations of the probabilities for electron shakeoff following both positron and negatron decay are given for several atomic systems.

¹Abstract of published paper: *J. Chem. Phys.* **39**, 1748 (1963).

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ATOMIC READJUSTMENT TO INNER-SHELL VACANCIES IN NEON AND ARGON

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The reorganization of the electrons in an atom, following the removal of an inner-shell electron, leaves the atom in some state of ionization. Whenever the primary vacancy is transferred to the outer shell by radiative transitions only, an ion of charge 1 results. For each Auger transition, however, another electron is ejected and the final charge state depends on the number of successive Auger transitions that have taken place in the course of readjustment. Loss of electrons can also result from the sudden change in effective nuclear charge due to the transitory occurrence of one or more vacancies in deep-lying shells. The superimposition of these processes according to their relative probabilities yields the distribution in charge following the de-excitation of the atom initially ionized in an inner shell. In turn, if the location of the initial vacancy is known and one measures the distribution in charge, information can be gained about the various processes in relation to each other, and, in simple cases, upon the processes themselves.

In our experiments we produced vacancies in the *K* shell of neon and in the *K* and *L* shells of argon by photoelectric ejection of the electron. The distribution in charge was measured with a magnetic mass spectrometer. Details of the experimental apparatus and procedure have previously been given.¹ Figure 1 represents the ion source together with the x-ray tube, showing the essential modification of the original instrument.¹ The x-ray beam passes through a beryllium window into the ionization region after being collimated by several apertures that are incorporated into the vacuum system. The entrance and exit holes of the ion source for the x-ray beam are large enough to transmit the x-ray beam without hitting the edges but small enough to mask against spurious electrons which have escaped trapping by the stops in both the collimator and the x-ray trap.

¹A. H. Snell and Frances Pleasonton, *Phys. Rev.* **100**, 1396 (1955).

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Fig. 1. Source Volume for Studying the Charge Distribution of Ions Produced by X Rays.

The ions formed in the region common to the x-ray beam and the acceptance cone of the magnet are extracted by an electric field and accelerated to 5000 v. The energy spread of the ions due to the field gradient across the x-ray beam is approximately 2% and thus within the transmission width of the magnet of 2.8% in energy. After separation by the magnet the ions are accelerated to a final energy of 7500 v times the charge, and impinge on the first dynode of a ten-stage AgMg dynode structure.

The gas pressure in the source volume was usually in the order of 10^{-6} torr, as indicated by the ionization gage. Pressure effects, observable only above 2×10^{-5} torr, were thus insignificant. Pressure and x-ray flux were sufficiently steady for the desired accuracy, so that continual monitoring was not necessary. The x-ray flux was estimated to be in excess of 10^9 photons/sec. Typical counting rates for the ions, integrated over all charges, were in the order of 10 cps; the background amounted to 0.3 cps at most.

The energy of the x rays was chosen to form vacancies preferentially in one principal shell. This required that the major portion of the x-ray spectrum should lie either above the K absorption edge of neon and argon or, as for L ionization of argon, between the K and L absorption edges. Hence, characteristic radiation from suitable targets was used and the long-wavelength tail of the bremsstrahlung was effectively attenuated by absorbers of appropriate thicknesses.

The charge distribution of neon ions was obtained by irradiation of neon with x rays from an aluminum target.² The results are given in column 3 of Table 1, and are compared with earlier data³ and the calculated spectrum. The errors indicate the statistical uncertainty. For charge 1 the error has been increased to account for the estimated contribution from ionization by electrons. The two sets of experimental data compare satisfactorily, although the earlier measurements overemphasize the intensities of the highly charged ions. A discussion of this charge distribution has been given previously.³ In an attempt to determine the magnitude of additional ionization that might be caused by the photoelectron on its passage through the electron cloud, we varied the energy of the photoelectron by using x rays from Al, Ti, W, and Mo anodes. If collisions of the photoelectron with orbital electrons, particularly L electrons, occur with sufficient frequency, say in the order of 10^{-2} , a decrease of the probability of collision with increase of the energy of the photoelectron should be reflected in decreasing abundances of the charge states 3 to 5. The charge spectra obtained, excluding Ne^+ , are listed in Table 2. The observed variation of the relative abundances is essentially within the statistical error. It would seem that ionization by the photoelectron is of very small magnitude; however, final evaluation should await results of experiments using x rays of lower energies, namely, Cu L radiation.

The charge distribution of argon ions as a result of initial L ionization is given in Table 3, column 2. The vacancies in the L shell were produced by x rays from an Al anode. Ar^{2+} and Ar^{3+} are the most abundant charges formed in the rearrangement of the atom. The listed errors indicate the statistical uncertainty and, for charge 1, the estimated uncertainty in the correction for ionization by electrons. For calculating the spectrum, we have assumed an initial vacancy distribution of $0.39L_I$, $0.57L_{II,III}$, and $0.04M$ according to Jönsson's rule⁴ for the absorption jump and Stobbe's law⁵ for the partial absorption of

²We are indebted to J. A. Bearden of Johns Hopkins University for the design and construction of the tube.

³M. O. Krause *et al.*, *Phys. Rev.* **133**, A385 (1964).

⁴A. H. Compton and S. K. Allison, *X-rays in Theory and Experiment*, p. 537 ff., Van Nostrand, New York, 1957.

⁵*Ibid.*, p. 560.

Table 1. Distribution in Charge of Neon Initially Ionized in the K Shell by X Rays

	Experiment I ^a	Experiment II ^b	Calculated ^c
Abundance, %			
Charge 1+	3 ± 1	5.7 ± 0.6	0.6
Charge 2+	66 ± 3	70.1 ± 0.7	84
Charge 3+	24 ± 2	20.7 ± 0.4	15
Charge 4+	6 ± 1	3.2 ± 0.2	1
Charge 5+	0.8 ± 0.3	0.4 ± 0.1	0.04
Average charge	2.35	2.23	2.18

^aAnalysis by time-of-flight mass spectrometer [M. O. Krause *et al.*, *Phys. Rev.* 133, A385 (1964)].^bAnalysis by magnetic mass spectrometer.^cIonization of L electrons by x rays not included.

Table 2. Charge Spectrum of Neon Produced by X Rays of Different Energies

	A	B	C	D
Target	Al	Ti	W	Mo
Energy of x rays, kev				
Maximum	4.5	25	41	50
Line	1.5	4.5	8.5	17.5
Abundance, %				
Charge 2+	74.3 ± 0.7	75.0 ± 1.5	76 ± 1.5	74 ± 3
Charge 3+	22.0 ± 0.4	21.6 ± 0.9	21.2 ± 0.9	21 ± 2
Charge 4+	3.4 ± 0.2	3.2 ± 0.3	2.7 ± 0.4	4 ± 1.5
Charge 5+	0.4 ± 0.1	0.35 ± 0.1		0.4 ± 0.2

Table 3. Distribution in Charge of Argon, Initially Ionized in the L Shell by X Rays^a

	Experimental	Calculated ^b	Calculated ^c
Relative intensity			
Charge 1	5.4 ± 1.8	5.5	5.3
Charge 2	46.9 ± 1.6	56.5	50.8
Charge 3	35.9 ± 1.3	38.0	39.8
Charge 4	9.5 ± 0.8		3.9
Charge 5	1.8 ± 0.4		0.3
Charge 6	0.5 ± 0.3		0.04
Average charge	2.57	2.33	2.43

^aAl target, $h\nu_{\max} = 3$ kev, $K_{\alpha} = 1.5$ kev.^bTransition rates from Rubenstein; initial vacancy distribution $0.39 L_I$, $0.57 L_{II,III}$, $0.04 M$.^cElectron shakeoff included.

x rays in the subshells. For the K_{α} line of Al the $L_I/L_{II,III}$ ratio actually would be 0.45/0.51; but we have used the ratio 0.39/0.57 to account for the greater efficiency of the low-energy region of the bremsstrahlung. The charge spectrum in column 3 of Table 3 is calculated from this ratio and the given contribution of M ionization. According to Rubenstein,⁶ Ar^{2+} results predominantly from an initial $2p$ vacancy, Ar^{3+} results predominantly from an initial $2s$ vacancy. Charge 3 is the maximum charge that is formed from common Auger events alone. The higher charge states are accounted for by shakeoff of additional electrons. The experimental data⁷ on the shakeoff in the beta decay of Ar^{41} were used to determine the probability of shaking off 1, 2, and 3 electrons. They are 9.4%, 0.5%, and 0.1% respectively. In these values a correction factor is included, which

is derived from Slater's rules, to account for the fact that in our case one negative charge is removed from the L shell rather than one positive charge added to the nucleus. The final spectrum is given in the last column of Table 3. Again, as in the case of neon, the observed intensities of the higher charge states are considerably greater than the calculated ones.

In Table 4 the charge spectra are listed for the decay¹ $Ar^{37} \rightarrow Cl^{37}$ and for x-ray irradiation, and these spectra are compared with the corresponding calculated spectra.^{6,8} The spectra resulting from the removal of the inner-shell electrons by electron capture and photoelectric ejection show a close similarity. Differences are due to the different initial vacancy distributions in both modes of excitation (compare columns 6 and 7 of Table 5). The pronounced difference in the abundances of Ar^{2+} shows the Z^4 dependence of the fluorescent

⁶R. A. Rubenstein, thesis, University of Illinois (unpublished), 1955.

⁷T. A. Carlson, *Phys. Rev.* 131, 676 (1963).

⁸R. A. Rubenstein and J. N. Snyder, *Phys. Rev.* 97, 1653 (1955); 99, 189 (1955).

Table 4. Charge Spectra Formed from X Irradiation of Argon and Electron Capture in Ar^{37}

	$Ar^{37} \xrightarrow{EC} Cl^{37}$		X Rays ^a	
	Calculated ^b	Experimental ^c	Experimental	Calculated ^d
Abundance, %				
Charge 1			2.5 ± 0.5	1.7
Charge 2	8.9	7.8 ± 0.1	12.1 ± 0.4	11.4
Charge 3	14.6	14.7 ± 0.4	16.6 ± 0.5	14.0
Charge 4	43.6	41.1 ± 0.5	34.4 ± 0.7	42.9
Charge 5	23.6	25.5 ± 0.4	24.0 ± 0.6	21.2
Charge 6	8.0	9.3 ± 0.2	8.5 ± 0.4	7.6
Charge 7	1.1	1.4 ± 0.1	1.8 ± 0.1	1.5
Charge 8	0.05	0.16 ± 0.05	0.28 ± 0.07	0.15
Average charge	4.1	4.2	4.0	4.0

^aRadiation from Ti target; $h\nu_{max} = 20$ kev, 8-mil Be window, $K_{\alpha} - 4.5$ kev.

^bCalculated with transition rates according to Rubenstein (thesis, University of Illinois, 1955), and electron shakeoff probabilities from the $K-LL$ transition [M. Wolfsberg and L. Perlman, *Phys. Rev.* 99, 1833 (1955)].

^cA. H. Snell and Frances Pleasonton, *J. Phys. Chem.* 62, 1378 (1958). Spectrum shifted by one charge unit.

^dCalculated with transition rates according to Rubenstein and electron shakeoff probabilities obtained from the β^- decay of Ar^{41} [T. A. Carlson, *Phys. Rev.* 131, 676 (1963)].

Table 5. Calculated Charge Spectra of Argon^a

	Initial Vacancy			Initial Vacancy Distribution				
	$L_{II,III}$	L_I	K	0.92 K	0.92 K^b	0.90 K	0.45 L_I	0.39 L_I
				0.08 L_I	0.08 L_I	0.07 L_I 0.02 $L_{II,III}$ 0.01 M	0.51 $L_{II,III}$ 0.04 M	0.57 $L_{II,III}$ 0.04 M
Abundance, %								
Charge 1	2.6	0.1	0.9	0.8	0.8	1.8	5.4	5.5
Charge 2	97.4	2.6	12.3	11.5	8.8	13.2	50.9	56.5
Charge 3		97.3	8.5	15.6	15.9	14.5	43.8	38.0
Charge 4			53	48.8	50.5	47.7		
Charge 5			19.4	17.9	18.4	17.5		
Charge 6			5.7	5.3	5.4	5.1		
Charge 7								
Charge 8								
Average charge	2	3 ^a	3.9	3.9	3.9	3.8	2.4	2.3

^aTransition rates from R. A. Rubenstein's thesis, University of Illinois, 1955.

^bRadiative transition rates for chlorine.

yield on the atomic number, since this charge is formed almost entirely (97%) by the transition $1s \xrightarrow{h\nu} 2p$; $2p-MM$. This, in turn, allows the deduction of the K fluorescent yield from the intensity of Ar^{2+} . The derived value is $\omega_K = 0.14$.

The calculation of the charge spectra followed the same procedure as outlined before. Shakeoff due to the initial vacancy was neglected for $Ar^{37} \rightarrow Cl^{37}$ because the field in which the outer electrons move does not change significantly with electron capture. Instead, the included shakeoff probability of 0.16 (ref. 9) comes from Auger processes of the type $K-LL$. On the other hand, the spectrum of the last column in Table 4 accounts only for shakeoff due to the primary

vacancy; shaking by the creation of further vacancies was not considered.

Table 5 gives the individual charge distributions that arise from vacancies in the $L_{II,III}$, L_I , or K shell and also those charge spectra that arise from vacancy distributions as were used above.

Our measurements, together with the data on electron capture, show that extensive ionization accompanies the electronic readjustment to an inner-shell vacancy. Auger events play a major role in the reorganization. A satisfactory description is obtained by treating the readjustment as a number of subsequent processes proceeding to the outermost shell and the superposition of the shakeoff process. Transition probabilities derived from a pure LS coupling scheme⁶ are in accord with the experimental data on argon. Shakeoff accounts partially for the observed intensities of the highly charged ions.

⁹M. Wolfsberg and M. L. Perlman, *Phys. Rev.* **99**, 1833 (1955).

READJUSTMENT OF THE NEON ATOM IONIZED IN THE K SHELL BY X RAYS^{1,2}

M. O. Krause

M. Vestal³W. H. Johnston³

T. A. Carlson

The distribution of neon ions that result from ionization by x rays has been measured with a coincidence time-of-flight mass spectrometer. Radiation from an aluminum target, filtered through a beryllium foil, was used so that in more than 95%

of the events a *K* electron was removed. The observed charges, including *L* ionization, are distributed as follows: Ne^+ , 3%; Ne^{2+} , 66%; Ne^{3+} , 24%; Ne^{4+} , 6%; Ne^{5+} , 0.8%. On the average, 2.4 electrons are removed per interaction. The charge spectrum has also been computed using calculated *K*-*LL* Auger transition rates and electron shakeoff probabilities as given by the β^- decay of Ne^{23} . The assumptions of the models used, as well as the applicability to the present study, have been examined. Comparison of the calculations with the experimental data indicates the presence of other modes of ionization.

¹Abstract of published paper: *Phys. Rev.* 133, A385 (1964).

²The experimental portion of this study was performed under the auspices of the Wright-Patterson Air Force Base, U.S. Air Force, at Wm. H. Johnston Laboratories, Inc., Baltimore, Md.

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ATOMIC READJUSTMENT FOLLOWING THE FORMATION OF INNER-SHELL VACANCIES¹

T. A. Carlson

M. O. Krause

The processes involved in the atomic readjustment to a vacancy in an inner atomic shell are discussed. This discussion is based on measurements with a mass spectrometer of the relative abundances of the differently charged ions that result from the filling of inner-shell vacancies.

Calculations have been made on multiple ionization following *K* vacancies. These calculations are compared with experimental data on the charge spectra following electron capture of Ar^{37} and x-ray ionization of neon. Fairly good agreement is obtained by treating the atomic readjustment as a series of separate Auger processes and including consideration of shakeoff due to sudden changes in the effective charge. There is, however, also evidence for other contributions to ionization.

¹Abstract of a paper to be published in proceedings of *International Conference on Nuclear Spectroscopy Devoted to the Role of Atomic Electrons in Nuclear Transformations*, Warsaw, Poland, 1963.

IONIZATION OF KRYPTON BY X RAYS

M. O. Krause

T. A. Carlson

The charge distribution of krypton ions as a result of initial inner-shell ionization has been measured with a magnetic mass spectrometer. The primary vacancy was produced by photoelectric ejection of an electron, in one case preferentially from the *K* shell, in another case preferentially from the *L* shell. The charge distribution arising from an initial *K* hole allows comparison with the charge spectrum that results from electron capture.¹ The charge distribution arising from an initial *L* hole is still simple enough to be successfully compared with the calculated spectrum based on the transition rates given by Rubenstein.² The more intense transitions of the type *L*-*XY*, *XY* denoting combinations of *M* and *N* electrons, can then be checked indirectly against the experiment. This is of importance since no experimental values of the *L*-*XY* transition rates exist for krypton or for elements in the medium range of atomic numbers.

The essential parts of the experimental apparatus and procedure have been described in the preceding report. In the first experiment, *K* electrons, and to a lesser extent *L* electrons, were ionized by x rays from an Mo target. In order to minimize radiation of lower energy than the binding energy of the *K* electron in krypton, the x rays were passed through a 0.05-mm-thick Zr filter. This filter also swallowed the Mo *K_β* line and part of the short-wavelength continuum while, at the same time, acting as a window for the Mo *K_α* line of 17.5 keV. It was safe to assume that the major portion of the x radiation lay above the *K* absorption edge of krypton at 14.3 keV. The vacancy distribution between the *K*, *L*, and *M* shells is found to be roughly 0.86, 0.12, 0.02, according to Jönsson's rule.³ In comparison, the distribution for electron capture is about 0.90, 0.09, 0.01. A similar charge distribution following rearrangement of the electrons is, thus, to be expected for

electron capture and x-ray bombardment. The experimental data are listed in columns 3 and 4 of Table 1. The spectra compare satisfactorily; differences can be explained qualitatively on the basis of the slightly different initial vacancy distributions.

In the second experiment, vacancies were formed predominantly in the *L* shell by x rays from a Ti target. The most intense lines of Ti, *K_α* = 4.5 keV and *K_β* = 4.9 keV, were transmitted through the 0.2-mm-thick Be window of the x-ray tube while the long-wavelength part of the bremsstrahlung did not penetrate the window (transmission at 2 keV is 1%). The tube was operated at 10 kV, so that

Table 1. Charge Spectra of Krypton Resulting from Inner-Shell Ionization

	X Rays		Electron Capture <i>K_α</i> ^c
	<i>L_α</i> ^a	<i>K_α</i> ^b	
Abundance, %			
Charge 1	1.5 ± 0.5	1 ± 0.6	
Charge 2	3.1 ± 0.3	2.5 ± 0.4	3.9 ± 0.5
Charge 3	8.5 ± 0.5	6.3 ± 0.5	4.9 ± 0.3
Charge 4	22.0 ± 0.7	16.1 ± 0.7	14.4 ± 0.5
Charge 5	23.8 ± 0.7	19.3 ± 0.7	18.2 ± 0.6
Charge 6	23.1 ± 0.7	17.2 ± 0.8	16.4 ± 0.8
Charge 7	13.5 ± 0.5	15.4 ± 0.8	15.6 ± 0.8
Charge 8	3.9 ± 0.3	11.7 ± 0.7	13.0 ± 0.8
Charge 9	0.52 ± 0.1	7.5 ± 0.5	8.8 ± 0.8
Charge 10	0.11 ± 0.05	2.3 ± 0.5	3.4 ± 0.4
Charge 11		0.9 ± 0.3	0.78 ± 0.06
Charge 12			0.15 ± 0.01
Average charge	5.1	5.9	6.1

^aRadiation from Ti target; $h\nu_{\max} = 10$ keV, 8-mil Be window.

^bRadiation from Mo target; $h\nu_{\max} = 51$ keV, 40-mil Be window; 2-mil Zr + 10-mil Be filter.

^cFrom data on $\text{Kr}^{79} \xrightarrow{\text{EC}} \text{Br}^{79}$ corrected for contributions from β^+ branch and adjusted to charge $n + 1$; A. H. Snell, Frances Pleasonton, and J. L. Need, *Phys. Rev.* 116, 1548 (1959).

¹A. H. Snell, Frances Pleasonton, and J. L. Need, *Phys. Rev.* 116, 1548 (1959).

²R. A. Rubenstein, thesis, University of Illinois (unpublished), 1955.

³A. H. Compton and S. K. Allison, *X-rays in Theory and Experiment*, p. 537 ff., Van Nostrand, New York, 1957.

no x rays were produced which were capable of ionizing a K electron. Under these conditions the entire x-ray spectrum lay between the L and K absorption edges of krypton. In the absence of partial absorption coefficients for the various shells, we relied on the rules by Jönsson³ and Stobbe⁴ to determine the initial vacancy distribution.

A fraction of 0.26 of the x rays is absorbed by $2s$ electrons; 0.60 by $2p$ electrons; 0.10, 0.02, 0.01, and 0.01 by $3s$, $3p$, $3d$, and N shell electrons, respectively. Readjustment of the atom to this vacancy distribution leads to a charge spectrum that peaks at Kr^{5+} and yields an abundance of Kr^{4+} and Kr^{6+} ions. The distribution in charge is given in the second column of Table 1.

In constructing the charge spectrum we used the transition rates of Rubenstein² and shakeoff probabilities⁵ from the β^- decay of Kr^{85} . The following assumptions were made: (1) A $3d$ vacancy is filled by the Auger process $3d-NN$ exclusively. (2) A $3p$ vacancy leads to charge $3+$ in 90% of the cases via the Coster-Kronig transition $3p-3dN$. In silver this process occurs² with a probability of 0.89. (3) The Coster-Kronig transition $L_{II}-L_{III}N$ does not occur. This is probably a safe assumption, since the probability is only 0.06 ± 0.14 in Bi (ref. 6) with 32 N electrons available for the transition to take place. (4) The change in effective nuclear charge by the removal

⁵A. H. Snell and Frances Pleasonton, *Phys. Rev.* 107, 740 (1957).

⁶J. Burde and S. G. Cohen, *Phys. Rev.* 104, 1085 (1956).

⁴*Ibid.*, p. 560.

Table 2. Calculated Charge Spectra of Krypton Arising from Inner-Shell Vacancies

	Initial Vacancies											$L(M)$, X Rays (exptl)
	3d	3p	3s	2p		2s		Weighted Sum ^c		Weighted Sum ^c plus Shakeoff		
				A ^a	B ^b	A ^a	B ^b	A ^a	B ^b	A ^a	B ^b	
Abundance, %												
$q = 1$	0.0	0.0	0.0	0.1	0.1	0.3	0.3	1.2	1.2	1.0	1.0	1.5 ± 0.5
$q = 2$	100	10	14.9	0.7	0.5	0.2	0.2	3.2	3.1	2.7	2.7	3.1 ± 0.3
$q = 3$		90	46.7	0.3	3.7	0.7	0.7	6.9	8.9	6.1	7.6	8.5 ± 0.5
$q = 4$			36.9	69.1	41.2	1.4	1.3	45.4	28.8	38.4	24.7	22.0 ± 0.7
$q = 5$			1.5	12.3	39.3	3	6	8.4	25.5	12.3	24.5	23.8 ± 0.7
$q = 6$				15.7	15.1	65.4	40	26.4	19.5	24.6	20.3	23.1 ± 0.7
$q = 7$				1.7	0.3	13	37	4.4	9.8	7.6	11.8	13.5 ± 0.5
$q = 8$				0.04	0.02	14.3	14	3.7	3.6	5.1	5.5	3.9 ± 0.3
$q = 9$				~ 0.01	~ 0.01	1.5	0.3	0.4	0.1	1.4	1.3	0.5 ± 0.1
$q = 10$						~ 0.04	~ 0.01	0.01	0.01	0.3	0.4	0.11 ± 0.05
$q = 11$										0.1	0.1	
$q = 12$										0.01	0.01	
q	2.0	2.9	3.25	4.47	4.66	6.35	6.52	4.74	4.92	4.98	5.16	5.10
$q_{\max}$	2	3	5	9	9	10	10	10	10			

^aCalculated from Rubenstein's tables.

^bCalculated with experimental transition rates $L_{II,III}-XY$ of ^{208}Tl [J. Burde and S. Cohen, *Phys. Rev.* 104, 1085 (1956)].

^cInitial vacancy distribution: 0.26 $2s$; 0.60 $2p$; 0.10 $3s$; 0.02 $3p$; 0.01 $3d$; 0.01 N .

of an L electron is taken as 1.0 for the N and $3d$ electrons and as 0.85 and 0.35 for the $3s$, $3p$, and remaining L electrons respectively. Initial M vacancies are treated accordingly. (5) The departure of the photoelectron is fast enough to consider the change in effective nuclear charge as "sudden" and, therefore, equivalent to the emission of a β^- particle from the nucleus. The two latter assumptions allow us to use and to adjust the shakeoff probabilities that were measured by Snell and Pleasonton.⁵

Table 2 lists each of the spectra that would result if the initial vacancy occurred in only one of the shells. The weighted spectrum is obtained by combining the five individual spectra according to the actual vacancy distribution. The contribution of shakeoff is then added to give the expected spectrum, column 6. The intensities calculated with Rubenstein transition rates (heading "A") strongly disagree with the measured abundances of charges 4, 5, and 7. The dip in the charge distribution at Kr^{5+} is particularly inconsistent with the experiment. Better agreement of the

spectra cannot be obtained even when modifying our assumptions.

Surprisingly good agreement can be achieved, however, if we use the experimental transition rates $L_{II,III}-XY$ of Burde and Cohen⁶ from Tl and maintain the rates of Rubenstein for the remaining transitions. Since 90% of the initial $2s$ holes will appear as $2p$ holes by $2s-2p3d$, errors in the other transition rates have little weight in the final spectrum. The spectra for an initial $2p$ and $2s$ vacancy, as obtained on this basis, are given in columns 3 and 4 of Table 2 under the heading "B." The good match of the final spectrum (column 6) with the measured spectrum suggests the use of the $L_{II,III}-XY$ transition rates of thallium even for an element of much lower atomic number, such as krypton. In particular, the relative intensity of the Auger process $2p-3d3d$, leading to charge 4, should be 0.3 instead of Rubenstein's² value of 0.68; and the relative intensity of $2p-3p3d$, leading to charge 5, should be 0.4 rather than his value of 0.09.

THE ISOTOPE EFFECT IN THE SPECTRUM OF THORIUM¹

G. W. Charles

In the paper "The Isotope Effect in the Spectrum of Thorium," Vernyi and Egorov² have reported isotope shifts between Th^{229} and Th^{232} for 247 lines of thorium. Included are data for 49 lines listed by the authors as unclassified. Classifications of several of these lines have been previously suggested in ORNL-2319.³ This letter contains some deductions from the data and results of ref. 2 made with the help of the classifications of ORNL-2319 and the analysis of Th I by Zalubas.⁴ Included are the addition of isotope

shifts for 2 levels of Th I and for 20 levels of Th II, the deletion of the results for 2 levels of Th II which are unsupported by data, and the modification of the shifts for 8 levels of Th II to bring them into better agreement with the data. Using the results of ref. 2 as thus extended, one finds that the classifications suggested in ORNL-2319 for 18 Th II lines listed as unclassified in ref. 2 are consistent with the data. All but one of these classifications are also supported by Zeeman-effect data.

Double assignments are given in ORNL-2319 for 13 lines listed in ref. 2. In the case of 11 of these, the choice indicated by the isotope shift data is identical with that indicated by the Zeeman-effect data. In one case no Zeeman-effect data are available. In only one case the two criteria are inconsistent.

¹Abstract of a letter accepted by the *Journal of the Optical Society of America* for publication in February 1964.

²E. A. Vernyi and V. N. Egorov, *Opt. Spectr. (USSR) (English Transl.)* 9, 367 (1960).

³G. W. Charles, *J. Opt. Soc. Am.* 48, 859 (1958).

⁴R. Zalubas, *J. Res. Natl. Bur. Std.* 63A, 275 (1959).

THE USE OF INFRARED LASER RADIATION FOR SPECTRAL SLIT WIDTH STUDIES

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In the interpretation of infrared spectra it is necessary that the relationship be known between the actual characteristics of molecular absorptions and the representations of these absorption bands which are given by infrared spectrophotometers. The spectra are distorted to variable degrees by four factors: the wavelength accuracy and photometric accuracy of the instrument, the finite slit width, and noise. Wavelength accuracy and noise are satisfactory for most applications, while photometric accuracy is presently under study, and standards, now being evaluated, may be generally available in the near future. The effect of finite slit width upon the shape of infrared bands and upon the integrated absorption intensities has alone remained a difficult problem. Studies in high-resolution spectroscopy and in infrared intensities require compensation for the spectral slit width, yet this cannot now be done in satisfactory fashion.

Resolution at the exit slit is described in terms of response to an idealized monochromatic source of energy uniformly illuminating the entrance slit. It is obvious that if monochromatic radiation is actually employed, a frequency scan by the spectrometer will precisely trace the response curve at the exit slit. In order to obtain usable slit functions it is necessary to have a continuously operating monochromatic source, of sufficient and constant intensity, emitting at a number of wavelengths spaced throughout the infrared region. Our studies of the gas laser show that it fulfills these requirements. Laser operation in the infrared has been achieved using various mixtures of the rare gases, and workers at a number of laboratories have now reported over 200 infrared frequencies at wavelengths between 1 and 56 μ . Thus the laser may have the additional advantage of providing convenient frequency calibration.

Studies of laser operation in the infrared show that a properly designed laser will be simple, inexpensive, and reliable, and thus a very practical device for the calibration of infrared spectrometers. This simplicity arises from the generally high gain observed for infrared laser transitions. The visible laser, emitting at 6328 Å with a

helium-neon discharge, may typically exhibit only a 5 to 10% gain per passage of the radiation through 1 m of the discharge. Thus the visible laser must be carefully designed to minimize loss of radiation. Our study of the laser oscillation at 3.507 μ in xenon showed a gain of 2000%, or 20 $\times$, in passage of the radiation through 1 cm of discharge. Though this is the maximum gain observed to date, the gain of a typical infrared transition is so high as to make the construction and operation of a gas laser in the infrared quite simple. It is found that with the extremely high gains in the different rare-gas systems, a number of inert gases may be mixed, and each system will produce laser oscillations independently of the others. In one mixture of rare gases we have observed 12 wavelengths in strong simultaneous oscillation between 1.1 and 3.5 μ , with an unknown number of lines in laser oscillation beyond the transmission region of quartz.

Although much work in the infrared has been done with a 2-m laser, using KBr or CaF₂ windows at the Brewster angle and Au-coated confocal mirrors, more practical lasers have been constructed for spectrometer calibration. A 10½-in. laser is shown in Fig. 1 which is self-contained and portable. This tube is sealed with a getter so as to be independent of a high-vacuum system, and uses two concave quartz lenses as mirrors, gold-plated to about 97% reflectance. The reflectivity is quite arbitrary, and was chosen to facilitate aligning the mirrors visually rather than for achieving maximum output. Since radiation must be observed through the mirrors we are limited to observing lines at 3.5 μ and shorter wavelengths, although laser oscillation will occur within the tube beyond 3.5 μ . It should be noted that the mirrors were aligned in the confocal system, and fastened in alignment to the laser tube using epoxy cement. Alignment techniques are adequate to guarantee laser action. This tube has been operated using radio-frequency excitation, and has also been operated using a Tesla coil such as is normally used for leak hunting in high-vacuum systems. When filled with He, Ne, and Xe, seven frequencies were observed between

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Fig. 1. Infrared Laser for Spectrometer Calibration.

1.15 and 3.5 μ . A spherical mirror such as shown here, together with a flat mirror of infrared-transmitting material (such as Irtan), forms a hemispherical system and allows observation of frequencies beyond 3.5 μ wavelengths.

In the confocal and hemispherical systems the qualities of monochromaticity and parallelism are sacrificed for simplicity of operation. In small laser tubes, the laser modes are each many kilocycles wide because of vibration of the mirrors. Due to the high gain in the infrared, the large number of different modes which oscillate in the confocal system will effectively fill the Doppler width of the transition and broaden the width to several hundreds of megacycles. The output frequency will always have a half-width well below 0.01 wavenumber, which is well beyond the resolving power of all but a very few infrared spectrometers. If some care is taken in isolating axial modes, the half-width can be made less than a thousandth of a wavenumber. Thus, though not truly monochromatic, the radiation may be considered monochromatic for all applications in infrared spectroscopy. The confocal beam will deviate from parallelism since in passing through the mirror it passes through a lens and becomes divergent. In practice, the rear surface of the mirrors may be polished to form a lens which provides the specific divergence needed to match the f number of the spectrometer optics.

Measurements of spectral slit widths have been made on prism spectrometers, and on a commercial grating instrument, the Beckman IR-7. The IR-7

is a double-beam grating spectrophotometer, operated single-beam in these studies. This instrument showed a noise level much higher than normally found, as may be noted in Figs. 2, 3, and 4. Our studies of methods of slit illumination indicate that the response curves we have observed are extremely close to the true slit curves of the instrument under normal operating conditions. Figure 2 shows the instrument response to two infrared frequencies which are separated by 0.89 wavenumber, and are produced in helium-neon. The spectral slit widths measured from these lines are about 0.30 wavenumber, using entrance and exit slits of 45 μ as measured by the slit mechanism. Figure 3 shows the response, at an 80- μ slit, to a line from xenon at 3.5070 μ , the high-amplification line mentioned above. Figure 4 shows the response to this same line using a

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Fig. 3. Spectrophotometer Response (80- μ Slit) to Monochromatic Radiation at 3.5070 μ Wavelength. Effective bandwidth 0.35 cm^{-1} .

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Fig. 4. Spectrophotometer Response (400- μ Slit) to Monochromatic Radiation at 3.5070 μ Wavelength. Effective bandwidth 2.33 cm^{-1} .

400- μ slit. Here the spectral slit width is over 2 wavenumbers, and the approximation to a triangular function is remarkably good. The rounding off at the top of the curve and the small broadening at the base may well have arisen from slight misalignments of the slits or to other imperfections in the optical system. No attempt had been made to perfect the alignment, inasmuch as the slits are curved slightly for the near infrared, and it was not possible to determine the wavelength for which the manufacturer had chosen the curvature. However, since the observed resolving power is close to that calculated for ideal optical elements, it is obvious that the alignment is near perfect. It is of considerable value to determine this close approximation to the triangular slit function. Such a function is easily applied to the determination of intensities, and recently Decius and co-workers¹ have obtained quite consistent results using the triangular approximation and carrying out calculations on a desk computer.

¹J. C. Decius (private communication).

These patterns are quite valuable to the infrared spectroscopist. They provide an objective value for the resolution of an instrument based upon the spectral slit width, or the width of the response pattern at half peak height. It gives a value much more precise than that obtained by the splitting of two overlapping gas-phase absorptions. The response curve, at 30- μ slits, of the Beckman IR-7 grating instrument has actually been observed to have a spectral slit width of 0.26 wavenumber, while values obtained by studies of resolution in the ammonia spectrum indicate a spectral slit

width between 0.3 and 0.4 wavenumber. Using the spectral slit widths as a criterion, one can align an optical system for maximum resolution in a much more efficient manner. Both in spectral slit width values and in symmetry of the response pattern, use of the laser provides an objective criterion for the adjustment of high-resolution infrared spectrometers. In addition, because of the simplicity of laser operation, it has become possible to check as frequently as necessary the characteristics of these instruments, to monitor for changes in their operation.

OPTICAL PHYSICS

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Experimental work¹ on the system krypton and mercury vapor was suspended when attempts to produce laser oscillation on the 5384-A line (mercury $10^3P_1 \rightarrow 7^3S_1$) were unsuccessful and no gain was observed on the several wavelengths of the infrared transitions downward from the 10^3P_1 level. These infrared wavelengths were expected to have amplifications enormously greater than that of the 5384-A transition. It was considered probable that the population of the 10^3P_1 state in mercury was being depleted by transitions upward to the ionization continuum induced by low-energy electrons in the discharge. Since the sensitive test for amplification in this system lay in the attempt to produce laser emission, and since the probable depopulation of the mercury 10^3P_1 state was highly dependent upon the type of excitation used, careful and systematic studies were made of all the parameters of the gas laser. These studies were carried out using the visible and infrared wavelengths of the helium-neon discharge and of other rare-gas mixtures.

In the work on krypton and mercury vapor, radio-frequency excitation of the gas was employed. From experience with the helium-neon system, it was found that the gain of laser transitions was dependent upon the degree of excitation and that at high power levels laser action frequently ceased. With rf excitation there is very little control of the energy in the discharge, due to the impedance changes presented by the discharge as the ionization increases. Although use of a high-power (750-w) oscillator in place of a crystal-controlled power amplifier provided greater control over the coupling of power to the plasma, it still was not possible to maintain discharges at low excitation levels or to obtain truly reproducible data on laser power and gain. For these reasons, dc excitation of the gas was investigated. It was determined that dc was superior in that the energy in the discharge could be varied over a wide range and highly reproducible data obtained. Continued studies of the helium-neon system showed that many laser transitions exhibited widely different variations in power dependence in a manner not fully understood. A certain few previously unreported frequencies were found to have a critical

¹G. W. Charles *et al.*, *Phys. Div. Ann. Progr. Rept.* Jan. 31, 1963, ORNL-3425, p. 128.

dependence on excitation. One of these transitions, at $2.38\ \mu$, has since been shown to be part of a "cascade" system,² while the others have not as yet been identified.

Investigation of gas purity showed this to be a much less-critical factor than had been believed. Laser action at 6328 Å in 600 μ pressure of helium-neon was suppressed only by 10 μ partial pressure of H_2 and by somewhat larger quantities of other contaminants. This proved very favorable for the use of metal electrodes in laser tubes, because long and continued use is required to completely degas metal surfaces exposed to a discharge. Whereas initially the electrodes had been degassed by rf heating and the tubes operated with a metallic getter to remove impurities, present techniques allow degassing in high-current discharges and permit the tube to be permanently sealed off without gettering.

Careful evaluation of the laser optical system led to several improvements in design and construction. Windows, fixed at the Brewster angle, were determined to require primarily nonscattering surfaces, making it possible to construct laser tubes with inexpensive windows instead of optical flats with figure and parallelism of the faces guaranteed. There was found to be a wide tolerance in the angle of the "Brewster angle" window, further simplifying the construction of laser tubes. A remarkably simple visual technique was developed which allows the confocal optics of any laser to be properly aligned within a time of 5 min. Mechanical construction was reduced from a heavy Invar frame to an aluminum base plate with simple adjustable mirror mounts. Figure 1 shows the ultimate in simplicity — laser oscillation at 6328 Å using laboratory ringstands for support and a Tesla coil for excitation.

²J. H. Gerritsen and P. V. Goedertier, *Appl. Phys. Letters* 4, 20 (1964).

The practical result of this experimental work has been the knowledge required to build simply, quickly, inexpensively, and reproducibly, lasers of any desired characteristics for research. Through many improvements, the gain of the 6328-Å transition has been increased from approximately 5%/m in the rf-excited laser to approximately 16%/m in improved laser tubes with dc excitation. These improvements will be employed in a reexamination of the mercury-krypton system and for a study of other gas systems. Construction details for a visible laser designed for undergraduate or graduate projects have been assembled for publication. A portable laser for lecture demonstrations has been designed, constructed, and used extensively for visits to universities in the Southeast under the ORINS lecture program.

Studies of the infrared laser transitions have involved the helium-neon-xenon system. A 2-m dc-excited laser has been employed, using CaF_2 or KBr windows at Brewster's angle and gold-coated confocal mirrors of borosilicate glass. Radiation has been detected in the infrared by reflection from the Brewster windows, but it has been found more advantageous to reflect the radiation from a flat film of plastic, less than 100 Å thick, which is rotated in the beam in a gimbal mounting. While the film absorbs a maximum of only 4% at one frequency in the infrared, the gimbal mount allows reflection out of the cavity of radiation of any desired intensity and degree of polarization. With this system a number of new laser transitions have been observed and identified in the helium-neon and helium-xenon systems. One of these new transitions is the weaker peak shown in Fig. 2 in the section "The Use of Infrared Laser Radiation for Spectral Slit Width Studies," observed only at high resolution because of its proximity to the stronger 3.3913- μ line.

Fig. 1. Simplified Construction of a Helium-Neon Laser Emitting at 6328 Å.

ATOMIC SPECTROSCOPY IN OPTICS AND SPECTROSCOPY, 1959–1962¹

G. W. Charles

Starting with volume 6 (1959), the Russian journal *Optika i Spektroskopiya* became available in cover-to-cover English translation as the journal *Optics and Spectroscopy* under the auspices of the Optical Society of America. From that time until the end of volume 13 (December 1962), 90 papers were published on atomic spectra and closely related subjects in *Optika i Spektroskopiya*.

¹Abstract of a published paper: *J. Opt. Soc. Am.* 53, 1319 (1963).

These papers fall into several main categories, namely, isotope shift and hyperfine structure of spectral lines, measurement and calculation of oscillator strengths, spectra of rare-earth ions in crystals and in solutions, measurement of excitation cross sections of spectral lines, calculation of excitation cross sections of spectral lines, broadening and displacement of spectral lines in plasmas, and quantum mechanical calculations of quantities of significance to spectroscopy. A review is presented of these papers together with 153 references to related literature.

GRAVITATIONAL ACCELERATION OF FREE NEUTRONS^{1,2}

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

D. Paya³
H. Horstmann⁴

The gravitational acceleration of free neutrons from the Oak Ridge Research Reactor has been measured in the evacuated 180-m flight path at ORNL. The transmission edges associated with the (100) and (002) lattice spacings in a polycrystalline beryllium filter have been used to define particular neutron velocities $v = h/2md(ijk)$ in the "slow beam." Boral filters permitted the selection of a "fast beam" which did not fall

appreciably. The differences between the vertical positions of the slit image formed by the "fast beam" and of the two transmission edges (5 and 6 in. lower) has been determined with the aid of least-squares fits to the theoretical curves. An x-ray examination of the beryllium filter established the values for $2d(ijk)$. We find the acceleration of free neutrons due to gravity to be $g = 976 \pm 3 \text{ cm/sec}^2$ (100 planes) and $g = 972 \pm 7 \text{ cm/sec}^2$ (002 planes). These may be compared with the local value, $g = 979.74 \text{ cm/sec}^2$, and McReynolds' early result, $g = 935 \pm 70 \text{ cm/sec}^2$. A recent suggestion of Spitzer that there might be a difference in g for the two vertical neutron spin projections $\pm \frac{1}{2}$ does not appear to be confirmed. No splitting greater than a few percent of g is found.

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

²In addition to this work, data on the neutron spectrum from the reactor has been taken with this instrumental arrangement.

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⁴Visitor from BCMN, Euratom, Geel, Belgium.

BOUNDS ON PLASMA INSTABILITY GROWTH RATES¹

T. K. Fowler

A method is presented for obtaining upper bounds on the growth rate of plasma instabilities predicted by the linearized Vlasov equation. The technique is applicable to spatially nonuniform equilibria not amenable to conventional analysis. As examples, radially confined arc columns and mirror machine configurations are discussed. The

fastest growth in these systems corresponds to that of known electrostatic instabilities in uniform, infinite plasmas. For arbitrary equilibria, it is shown that growth is always slower than some exponential, the plasma frequency being a typical maximum growth constant. Growth is strongly limited for equilibria "near" a stable state. For example, the streaming instability growth rate vanishes at least linearly with the streaming speed.

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

AN IMPROVED ELECTRON MICROSCOPE FOR DETERMINATION OF MOLECULAR STRUCTURE

T. A. Welton

J. Kronsbein¹

Previously reported work^{2,3} on a new method for the correction of electron lenses has led to the conclusion that it is possible to construct an electron microscope capable of locating and identifying atoms in complex molecules of biological interest. As previously pointed out, such an instrument is practically impossible unless the cubic aperture defect can be exactly eliminated, so that a large amount of effort has been devoted in the past year to the problem of showing that such elimination is either possible or impossible. The geometry chosen for study is the so-called annular geometry^{2,3} in which the conventional paraxial assumption is dropped. Thus an annular sheaf of rays, emerging in the form of a hollow cone from an object point on the symmetry axis, is to be accepted by the annular focusing system. The annular sheaf is finally returned to the axis for detection after suitable magnification.

Since the paraxial system suffers from a non-vanishing cubic aperture defect even at unit magnification, and since unit magnification offers considerable computational simplification, we have chosen to study a simple annular system with unit magnification for the initial feasibility determination. For this purpose, a 1604A code has been written for tracing rays through a system which has reflection symmetry around $z = 0$, in addition to the usual rotational symmetry around $r = 0$. Magnetic field singularities can be positioned at $z = \pm z_1$, $\pm z_2$ and $r = r_1$, r_2 . The strengths of these singularities can be independently adjusted, keeping only the reflection symmetry of the field.

A central ray is found which has zero slope at $z = 0$, and z_1 and z_2 are adjusted to make a ray emerging from the assumed axial object, at an angle slightly different from that of the central ray, come to an intermediate annular focus at

$z = 0$ before proceeding on to a second point focus on the axis. Under these conditions, the quadratic aperture defects of the focusing fields for negative and positive z simply cancel to yield a net cubic aperture defect.

An extensive study has been made of the class of configurations in which r_1 and r_2 are both *outside* the ray region, and it has been fairly conclusively shown (by exhaustion) that the cubic aperture defect cannot then be made to vanish. If, on the other hand, r_1 is placed *outside* and r_2 *inside*, simple adjustment of the singularity strengths has in every case studied brought the cubic aperture defect identically to zero.

The fields used were chosen for computational, not constructional, simplicity. They can nevertheless be constructed in principle, since care has been taken to satisfy the free-space Maxwell equations *inside* the *outside* singularities and *outside* the *inside* singularities. An instrument of the desired performance is consequently thought to be feasible in principle, and current efforts are being concentrated on more detailed design problems. A new code, now running successfully, has the desired values of magnification and the various aberration coefficients as input numbers. These values then control a search for the coil locations and currents required to realize the desired value of the parameters. At present, the idealized fields are still in use, but a subroutine to generate the field of a set of real superconducting solenoids is currently in preparation. This program will allow the complete magnetic design of an actual instrument.

In view of the results already obtained, it seems probable that the highly desirable 1-A resolution can be obtained with an electron beam of energy between 200 and 1000 kev. Momentum control appears to be the most difficult problem, but several apparently workable methods have been found for accomplishing this. Studies are in progress on the rate of radiation damage to a sample of biological material, as compared with the rate of data collection possible. Estimates are that base sequence in DNA and RNA and amino acid sequence in proteins can be determined.

¹Summer visitor from the University of Florida, Gainesville.

²T. A. Welton and J. Kronsbein, *Bull. Am. Phys. Soc.* **6**, 29 (1961).

³T. A. Welton and J. Kronsbein, *Phys. Div. Ann. Progr. Rept. Jan. 31, 1963*, ORNL-3425, p. 11.

A very important advantage of the annular geometry, over and above the increased transverse resolution attainable, lies in the longitudinal resolution arising from the finite angle ($\cong 45^\circ$, say)

which the rays make with the symmetry axis. It should thus be possible to achieve 1-A resolution in all directions, thereby enormously simplifying the structure determination problem.

QUANTIZED SPACE-TIME

T. A. Welton

In spite of the divergences which have long plagued the relativistic field theory of the elementary particles, it is currently fashionable to assume that no fundamental limit exists on the precision with which the coordinates of a particle can be defined. On this view, all extensions which are observed for supposedly elementary particles are actually due to the interaction of the particle with the fields representing other elementary particles. A more extreme view refuses to concede the reality of any distinction among elementary and nonelementary particles, at least among those which are strongly coupled. An alternative view, which we believe to possess considerable merit, is that the mathematical machinery of relativistic quantum theory is to be modified to prohibit too precise a definition of the location of a particle. In this way it is hoped that one of the two principal classes of divergences in the theory can be automatically avoided. At the same time, the introduction of a fundamental length into the theory gives considerable hope of simultaneous explanation of a number of previously unrelated observations. These are:

1. the rms charge and magnetic radii of the proton, as well as the magnetic radius of the neutron, all these quantities being essentially the same number $[(0.7-0.8) \times 10^{-13} \text{ cm}]$;
2. the charge and magnetization radii required for the proton and neutron to explain their mass difference as an electromagnetic effect, this radius being similar to that quoted in (1);
3. the charge radius required for the pion to explain the $\pi_+ - \pi_0$ mass difference as an electromagnetic effect;

4. the cutoff radius required in the nonrelativistic theory of the 3-3 resonant state of the pion-nucleon system.

We proceed by a somewhat naïve analogy with elementary quantum mechanics, where introduction of the commutation relation

$$[q, p] = i\hbar \quad (1)$$

has the effect of preventing the definition of an area in the space of p and q to an accuracy beyond that implied by the familiar uncertainty relation

$$\Delta p \Delta q \geq \hbar/2. \quad (2)$$

If space-time were two-dimensional, we could immediately proceed by assuming

$$[x_1, x_2] = ia^2; \quad (3)$$

where we have assumed a formalism in which $x_2 (= ict)$ is treated as a real variable. Such a formalism, when coupled with certain obvious rules as to analytic continuation, is known to yield valid results in conventional calculations, and is extremely convenient for the present purpose. The formalism which is based on (3), in addition to its explicit two-dimensional character, seems to possess the additional disadvantage of implying an anisotropic structure for the (x_1, x_2) space. This latter difficulty is only apparent, as can be seen from the fact that (3) is one of a set of relations with clearly invariant structure. Thus, we assume

$$[x_\mu, x_\nu] = ia^2 \epsilon_{\mu\nu}, \quad (4)$$

where $\epsilon_{\mu\nu}$ is the fundamental pseudo-scalar in two dimensions.

An extensive study of alternative formalisms has shown that gross inconsistencies, both internal and with experiment, must appear if (4) is not supplemented by the further relations

$$[x_\mu, p_\nu] = i\delta_{\mu\nu}, \quad (5)$$

$$[p_\mu, p_\nu] = 0. \quad (6)$$

These are the relations of the conventional theory (we consistently use units with $\hbar = c = 1$) and have the convenient consequences that an essentially conventional momentum-space treatment can be used in actual calculations, with x_μ playing the role of an infinitesimal translation operator in that momentum space.

At this point, it must be emphasized that conventional field theory does not allow independent roles for the coordinates and momenta of individual particles, the coordinates used being only a set of four integration variables. There does not therefore seem to be any simple way to utilize the formalism suggested by (4), (5), and (6) within the general framework of the usual field theory. Fortunately, there is at hand an alternative to the field theory, in which the coordinates and momenta of individual particles play a role essentially analogous to their role as operators in the non-relativistic theory. This relativistic wave mechanics, which leads by simple calculations to physical results identical with those obtained from the covariant field-theoretical methods, has at its base a simple wave equation for each electron (in quantum electrodynamics, that is). Each electron is acted on by a common field, which is random, but unaffected by the electrons. Thus

$$n\psi = \gamma p\psi + e\gamma A\psi, \quad (7)$$

with n to be analytically continued to im , and A specified by

$$A_\mu(x) = \frac{1}{\sqrt{4\pi^3}} \int \frac{dk}{k} \hat{a}_\mu(k) e^{ikx}, \quad (8)$$

$$dk \equiv dk_1 dk_2 dk_3 dk_4,$$

$$k = (k_1^2 + k_2^2 + k_3^2 + k_4^2)^{1/2},$$

$$kx = k_1 x_1 + k_2 x_2 + k_3 x_3 + k_4 x_4.$$

The coefficients $\hat{a}_\mu(k)$ are classical (nonquantized) fixed Fourier amplitudes of definite magnitude but completely uncertain phase. Thus

$$\langle \hat{a}_\mu(k) \rangle = 0, \quad (9)$$

$$\langle \hat{a}_\mu(k) \hat{a}_\nu(k') \rangle = \delta_{\mu\nu} \delta(k + k'), \quad (10)$$

where $\langle \rangle$ signifies a complete average over all these uncertain phases. This formalism provides a complete description of all phenomena of the conventional theory, save those involving vacuum polarization (closed loops). It is important to note that the vacuum polarization problem, which is a crucial difficulty in conventional field theory, is not expected to be cured by the new formalism here introduced.

Calculations using (7), (8), (9), and (10) can be most conveniently performed by use of a separate four-momentum space for each fermion, with e^{ikx} being simply a finite translation operator in momentum space. Thus

$$e^{ikx} \psi(p) \equiv \psi(p - k). \quad (11)$$

An analogous procedure can be attempted for the formalism defined by (4), (5), and (6), with the extension to four dimensions yet to be made. In anticipation, we must find a consistent and plausible way of redefining $A_\mu(x)$, by a relation similar to (8). In the conventional field theory, the Green's function

$$G_{\mu\nu}(x_1 - x_2) = G(x_1 - x_2) \delta_{\mu\nu}$$

$$= \frac{\delta_{\mu\nu}}{4\pi^3} \int \frac{dk}{k^2} e^{ik(x_1 - x_2)} \quad (12)$$

plays a fundamental role. It satisfies Maxwell's equations with a four-dimensional (point-pulse) point source. Thus

$$\frac{\partial^2}{\partial x^2} G(x) = -4\pi \delta(x), \quad (13)$$

and $G(x)$ is related by Fourier transformation to the Fourier coefficient $(4\pi^3 k^2)^{-1}$ which appears in (12).

The Green's function also plays a fundamental role in the reformulation of conventional theory expressed by (7), (8), and (9). Thus, the function $G_{\mu\nu}$ can be written as

$$G_{\mu\nu}(x_1 - x_2) = \langle A_\mu(x_1) A_\nu(x_2) \rangle \quad (14)$$

and enters directly the two-particle wave equation describing the interaction of two fermions. We therefore attempt to generalize the definitions of $A_\mu(x)$, $G(x)$, $\delta(x)$, $\partial^2/\partial x^2$, and $(4\pi^3 k^2)^{-1}$, the so-called photon propagator of the conventional theory.

It is first necessary to generalize the basic commutation relations of the theory to the real four-dimensional case. To do this, we leave (5) and (6) untouched, except that μ and ν now range 1 ... 4. The relation (4) cannot now lead to a covariant formulation (since there is no second-rank, antisymmetric tensor with invariant components in four dimensions). Equation (4) is, however, adequate to suggest the form of the required generalization. We write

$$[x_\mu, x_\nu, x_\lambda, x_\sigma] = 8a^4 \epsilon_{\mu\nu\lambda\sigma}, \quad (15)$$

where the coefficient 8 is chosen for later convenience. The bracket quantity is an obvious generalization of the usual commutator, being just the 4×4 determinant each of whose rows consists of the four enclosed operators. The symbol $\epsilon_{\mu\nu\lambda\sigma}$ is the fundamental pseudo-scalar in four dimensions ($\epsilon_{\mu\nu\lambda\sigma} = \pm 1$, according as $\mu\nu\lambda\sigma$ form an even or odd permutation of 1234, $\epsilon_{\mu\nu\lambda\sigma} = 0$ if $\mu\nu\lambda\sigma$ are not all different). The quantity a is a new natural constant (dimensions of a length), which is here-with introduced by way of the new formalism. The relation (15) has the qualitative consequence of defining a fundamental four-volume which will limit the simultaneous accuracy of definition of x_1 , x_2 , x_3 , and x_4 . Presumably a relation of the general form

$$\Delta x_1 \Delta x_2 \Delta x_3 \Delta x_4 \gtrsim a^4 \quad (16)$$

will now hold, although it has not yet been proved.

Two convenient representations of the x and p can be found. A representation which ignores the

p_μ can be found by writing

$$\begin{aligned} x_1 &= au, \\ x_2 &= ia \frac{\partial}{\partial u}, \\ x_3 &= av, \\ x_4 &= ia \frac{\partial}{\partial v}, \end{aligned} \quad (17)$$

where u and v are two independent, dimensionless variables. In spite of its completely unsymmetric character, the covariant relation (15) is identically satisfied. This has the immediate consequence that any set of four x_μ , related to those of (17) by an orthogonal transformation, will be transformable to the standard form (17) by a unitary transformation on the state vector of the system. Thus the representation (17) has invariant consequences, in spite of its peculiar appearance, the situation being rather analogous to that occurring in the Dirac electron theory, where the constant and arbitrary gamma matrices behave as components of a vector for a similar reason.

Another representation, which displays explicitly the role of x_μ as a displacement operator in momentum space, is given by

$$\begin{aligned} x_1 &= i \frac{\partial}{\partial p_1} + \frac{a^2}{2} p_2, \\ x_2 &= i \frac{\partial}{\partial p_2} - \frac{a^2}{2} p_1, \\ x_3 &= i \frac{\partial}{\partial p_3} + \frac{a^2}{2} p_4, \\ x_4 &= i \frac{\partial}{\partial p_4} - \frac{a^2}{2} p_3. \end{aligned} \quad (18)$$

This also is completely unsymmetric in appearance, but again covariant results will be obtained in computation.

A fundamental operator is the square of the invariant four-distance from the origin to point x , given by

$$r^2 = x_1^2 + x_2^2 + x_3^2 + x_4^2. \quad (19)$$

Although the x_μ cannot be separately diagonalized, we can easily diagonalize r^2 . No loss of generality is incurred by use of the representation (17) to write

$$r^2 \psi_n(u, v) = a^2 \left[u^2 - \frac{\partial^2}{\partial u^2} + v^2 - \frac{\partial^2}{\partial v^2} \right] \psi_n(u, v) \\ = r_n^2 \psi_n(n, v). \quad (20)$$

We thus see that the operator r^2 has the structure of the Hamiltonian operator for the nonrelativistic isotropic harmonic oscillator in two dimensions. The states are properly labeled by two quantum numbers, but it is convenient to suppress the angular momentum, since the eigenvalue of r^2 depends only on the total number of quanta of excitation, not on their distribution between the u and v directions. If we let $n = 0, 1, 2, \dots$, r_n^2 is given by

$$r_n^2 = 2(n+1)a^2. \quad (21)$$

A plausible heuristic device is now used to obtain a reasonable formalism. The Green's function $G(x)$ is a function of $r^2 (= x^2)$ only, in the conventional theory. We postulate that this statement of functional form is to be replaced by the assertion that an operator G is to be found which commutes with the operator r^2 , so that

$$G \psi_n(u, v) = G_n \psi_n(u, v). \quad (22)$$

The source function $\delta(x)$ is to be replaced by another operator, δ , which commutes with r^2 , so that

$$\delta \psi_n(u, v) = \delta_n \psi_n(u, v). \quad (23)$$

We require that the eigenvalues δ_n correspond as closely as possible to a point source, so that we take δ_n to vanish except for $n = 0$. The value of δ_0 will be determined later, by correspondence arguments ($a \rightarrow 0$).

The conventional differential equation (13) is now plausibly replaced by a simple second-order difference equation, relating successive eigenvalues of G . The simplest guess is found by introducing the variable $s = r^2$ in (13), to obtain

$$s \frac{d^2 G}{ds^2} + 2 \frac{dG}{ds} = -\pi \delta, \quad (24)$$

which has the solution

$$G(s) = \frac{1}{\pi s}. \quad (25)$$

We then replace $\left(\frac{d^2 G}{ds^2}\right)_n$, s_n , $\left(\frac{dG}{ds}\right)_n$, and δ_n by

$$\left(\frac{d^2 G}{ds^2}\right)_n = \frac{1}{\Delta^2} (G_{n+1} - 2G_n + G_{n-1}), \quad (26)$$

$$s_n = 2(n+1)a^2, \quad (27)$$

$$\left(\frac{dG}{ds}\right)_n = \frac{1}{2\Delta} (G_{n+1} - G_{n-1}), \quad (28)$$

$$\delta_n = \delta_0 \delta_{0n}, \quad (29)$$

$$\Delta = s_{n+1} - s_n = 2a^2. \quad (30)$$

A simple three-term recursion relation is thus obtained for the G_n , namely,

$$(n+2)G_{n+1} - 2(n+1)G_n + nG_{n-1} \\ = -2\pi a^2 \delta_0 \delta_{0n}, \quad (31)$$

assumed to hold for $n \geq 0$. The solution has an extremely simple form

$$G_n = \frac{2\pi a^2 \delta_0}{n+1}. \quad (32)$$

If we take $\delta_0 = 1/4\pi^2 a^4$, G_n takes the very compelling form

$$G_n = \frac{1}{2\pi a^2(n+1)} = \frac{1}{\pi r_n^2}, \quad (33)$$

which yields a very rapid correspondence with the conventional theory as n becomes larger than unity.

In order to put the new formalism in a form suitable for computation, we find a suitable analogy for the Fourier transformation which yields the photon propagator from the function $G(x)$ in the conventional theory. We rewrite the operator G as

$$G = \frac{1}{4\pi^3} \int \frac{dk}{k^2} F(k^2) e^{ikx} \quad (34)$$

and attempt to determine $F(k^2)$ in such a way that the eigenvalues of G , as defined by (34), will be just the G_n given by (33). It should be noted that the form of the integrand of (34) for small k^2 is dictated by the requirement of correspondence with the conventional theory.

It is first simple to prove that the G given by (34) necessarily commutes with r^2 , so that it becomes extremely plausible that some choice of $F(k^2)$ will actually work. The formalism needed is elementary in character, but too lengthy to be reproduced here, so only the general results will be summarized. Let

$$\langle e^{ikx} \rangle = \frac{1}{2\pi^2} \int d\Omega e^{ikx}, \quad (35)$$

where $d\Omega$ signifies an element of solid angle in the k integration. We consider a special set of eigenfunctions $\psi_n(u, v)$, namely

$$\psi_n(u, v) = H_n(u) e^{-(u^2 + v^2)/2}, \quad (36)$$

where H_n is the usual Hermite polynomial. With some difficulty, it can be shown that

$$\langle e^{ikx} \rangle \psi_n(u, v) = L_n(\eta) e^{-(\eta^2 + \zeta^2)/4} \psi_n(u, v), \quad (37)$$

where $\eta^2 = (k_1^2 + k_2^2)a^2$, $\zeta^2 = (k_3^2 + k_4^2)a^2$, and L_n is the n th Laguerre polynomial. It then turns out that the eigenvalues of (34) will agree with (33) if

$$F(k^2) = e^{-k^2 a^2/4}. \quad (38)$$

An interesting sidelight is that, if we define

$$\delta = \frac{1}{16\pi^4} \int dk F(k^2) e^{ikx}, \quad (39)$$

then

$$\delta \psi_n = \frac{\delta_{0n}}{4\pi^2 a^4} \psi_n, \quad (40)$$

so that an interesting realization of the δ operator has also been obtained, the eigenvalues agreeing with those assumed in obtaining (33). The new formalism is thus seen to be surprisingly consistent.

A number of simple calculations are in process to attempt to decide from available experiments whether a finite value of the constant a will give better agreement than is currently obtainable. Such calculations are now relatively simple, since only modification of the photon propagator in the conventional calculation is required. This is not a completely trivial task, because the standard methods devised by Feynman are inapplicable with the new nonrational integrands, containing $F(k^2)$ as a factor. Present indications are that a value for a of about 0.57×10^{-13} cm will give reasonable agreement with the experiments listed at the beginning. It is important to note that the modified propagator will yield no higher-mass unstable particles, since $F(k^2)$ is free of singularities in the finite plane of k^2 .

SPIN-SPIN INTERACTION AND SCATTERING FROM POLARIZED NUCLEI¹

K. T. R. Davies

G. R. Satchler

The elastic scattering of polarized nucleons from polarized targets is studied, assuming an optical-model potential which includes an interaction of the form $f(r) I \cdot S$. Numerical results,

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

obtained using the distorted-wave Born approximation, are presented for some typical cases, namely, neutrons of 0.3, 2, and 14 Mev and protons of 5 and 14 Mev incident on Mn^{55} and Ho^{165} target nuclei. Comparison with experiment can yield the sign and magnitude of the $I \cdot S$ interaction.

VALIDITY OF THE DWBA FOR INELASTIC SCATTERING FROM NUCLEI¹

F. Perey²

G. R. Satchler

A comparison of the predictions of the DWBA with calculations exactly solving the set of

¹Abstract of published paper: *Phys. Letters* 5, 3 (1963).

²Neutron Physics Division.

coupled equations linking the 0^+ and 2^+ states of even nuclei showed that the DWBA is a very good approximation even for quite strong coupling, providing the optical potentials used are adjusted to reproduce the *observed* elastic scattering.

EXCITATION OF NUCLEAR OCTUPOLES BY PROTON SCATTERING¹

G. R. Satchler

R. H. Bassel²R. M. Drisko³

The available data on the inelastic scattering of medium-energy protons to 3^- levels in even

¹Abstract of published paper: *Phys. Letters* 5, 4 (1963).

²Electronuclear Division.

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nuclei was analyzed in terms of the collective model, using distorted-waves theory. Good agreement was found and all the transitions studied show considerable enhancement.

AMBIGUITIES IN THE OPTICAL POTENTIAL FOR STRONGLY ABSORBED PROJECTILES¹

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G. R. Satchler

R. H. Bassel³

It is shown that the discrete ambiguities which exist for optical-model parameters for 10- to

¹Abstract of published paper: *Phys. Letters* 5, 5 (1963).

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30-Mev deuteron scattering also hold for other strongly absorbed particles and that these ambiguities can be understood in terms of the WKB approximation for the contribution to the reflection coefficients for low partial waves which arises from the nuclear interior.

THEORY OF FINITE-RANGE DISTORTED-WAVES CALCULATIONS^{1,2}

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R. M. Drisko⁴

E. C. Halbert⁵
G. R. Satchler

Most distorted-waves direct-reaction calculations rely upon a "zero-range approximation." In the present article some of the errors caused by this approximation are discussed, and a general method

suitable for numerical computation is described which does not use this approximation. Applications to stripping and knock-on reactions are described in detail.

¹A preliminary account of this work has been given elsewhere.

²Abstract of published paper: *Phys. Rev.* 133, 1B (1964).

³Supported in part by the U.S. National Science Foundation.

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⁵Electronuclear Division.

MULTIPOLE MOMENTS OF A ROUNDED CHARGE DISTRIBUTION¹

L. W. Owen²

G. R. Satchler

The multipole moments of a diffuse-edge charge distribution have been calculated and compared

to those obtained for a uniform, or "square," distribution. It is shown that serious errors may arise if a single "equivalent uniform" radius is used to compute these quantities.

¹Abstract of paper submitted to *Nuclear Physics*.

²Participant in Student Cooperative Program from Virginia Polytechnic Institute.

DISTORTED-WAVES THEORY OF DIRECT NUCLEAR REACTIONS WITH SPIN-ORBIT EFFECTS¹

G. R. Satchler

A general and flexible formulation is given of the distorted-waves theory of direct nuclear reactions which takes account of the effects of including spin-orbit coupling in the distortion and which does not make the zero-range approximation. The evaluation of the transition amplitude is shown to involve two distinct steps: one the

construction of a form factor which characterizes the particular reaction mode and the particular nuclei, and the other the treatment of the dynamics of the distorted-waves, which is similar for all reactions. Expressions are given for various differential cross sections and polarizations. As examples, procedures for treating inelastic scattering and stripping and knock-on reactions are described. The symmetry properties of the reaction amplitudes are also discussed.

¹Abstract of paper submitted to *Nuclear Physics*.

INELASTIC EFFECTS IN STRIPPING AND OTHER DIRECT REACTIONS¹

S. K. Penny²

G. R. Satchler

The distorted-waves theory of direct nuclear reactions, such as deuteron stripping, is generalized to include in the distorted waves the effects of the strong inelastic scattering which

may be present when the nuclei show collective behavior. The possible changes in parity and angular momentum selection rules are discussed in detail. Formulas are given for the general case and also for a simple model in which only one level of the target nucleus (assumed even) can be excited.

¹Abstract of paper submitted to *Nuclear Physics*.

²Neutron Physics Division.

AVERAGE COMPOUND NUCLEUS CROSS SECTIONS IN THE CONTINUUM¹

G. R. Satchler

A simple statistical model for the scattering amplitude was used to emphasize that self-

correlation when entrance and exit channels are identical can lead to significant departure from the Hauser-Feshbach predictions for compound-elastic scattering.

¹Abstract of published paper: *Phys. Letters* 7, 1 (1963).

EXCITED-CORE MODEL OF ODD-A NUCLEI AND THE $\text{Cu}^{63}(p, p')$ REACTIONS¹

F. Perey²R. J. Silva³

G. R. Satchler

The elastic and inelastic scattering of protons from Ni^{62} and Cu^{63} was measured. It is shown

that the inelastic scattering from Cu^{63} can be understood in terms of the simple quadrupole excitation of the Ni^{62} "core."

¹Abstract of published paper: *Phys. Letters* 4, 1 (1963).

²Neutron Physics Division.

³Chemistry Division.

TABLES OF FERMI INTEGRALS AND THE MULTIPOLE MOMENTS OF A ROUNDED CHARGE DISTRIBUTION¹

L. W. Owen²

G. R. Satchler

Tables of numerical values are given for the integrals $\int t^n f(t) dt$, $\int t^n (df/dt) dt$, and $\int t^n (d^2f/dt^2) dt$ over the Fermi function $f(t) =$

¹Abstract of published report: *Fermi Integrals and the Multipole Moments of a Rounded Charge Distribution*, ORNL-3525 (Dec. 27, 1963).

²Participant in Student Cooperative Program from Virginia Polytechnic Institute.

$[1 + \exp(t - k)]^{-1}$. They are presented in a form suitable for use in evaluating the various multipole moments of the rounded charge distributions of nuclei, both explicitly and in terms of the radii of "equivalent" uniform distributions which have the same moments. Analytic expressions for the integrals are discussed.

POLARIZATION IN HIGH-ENERGY INELASTIC SCATTERING¹

R. M. Haybron²A. Werner³H. McManus³R. M. Drisko⁴

G. R. Satchler

The polarization of high-energy protons inelastically scattered from the 2^+ level of C^{12} was

¹Abstract of paper submitted to *Physical Review Letters*.

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calculated in the distorted-wave impulse approximation. The contribution due to spin-orbit coupling effects in the distorted waves was shown to be nonnegligible, effecting a qualitative change in the predicted polarization. It was also shown that the addition to the polarization produced by the spin-orbit force may be treated as a perturbation to that produced by the two-nucleon interaction over a wide range of bombarding energy.

ELASTIC AND INELASTIC SCATTERING OF CARBON FROM CARBON¹

R. H. Bassel²

G. R. Satchler

R. M. Drisko³

The measurements by Wang *et al.* and Garvey *et al.* on the scattering of 127-Mev carbon ions from carbon show, in addition to elastic scattering, strong single excitation of the 4.43-Mev (2^+) state

¹Abstract of published paper: *Proceedings of the Third Conference on Reactions Between Complex Nuclei (Asilomar, Pacific Grove, California, April 14-18, 1963)* (ed. by A. Ghiorso, R. M. Diamond, and H. E. Conzett), pp. 45-49, University of California Press, 1963.

²Electronuclear Division.

³University of Pittsburgh, Pittsburgh, Pa.

in one of the nuclei, the single excitation of the 14-Mev (4^+) state, and the "mutual" excitation of both nuclei to the first excited state. We, assuming the two-body effects to be predominant, have analyzed the data for the single excitations in terms of the collective model (1) in distorted-wave approximation and (2) in strong-coupling approximation where the rotational model is assumed. Good agreement was found between theory and experiment, both in absolute magnitude and in shape of the angular distributions.

PICKUP OF HEAVY CLUSTERS¹

R. M. Drisko² G. R. Satchler
R. H. Bassel³

It has been suggested that the existence of alpha-particle clusters in nuclei might be determined by a study of the (d, Li^6) reaction, or its inverse. Accordingly, Denes and Daehnick have measured angular distributions of Li^6 ions

produced by deuteron bombardment of C^{12} , O^{16} , O^{18} , and F^{19} . These experiments also revealed formation of Li^7 ions with cross sections comparable to those for the production of Li^6 . The angular distributions show forward peaking, suggesting a pickup process. These data were analyzed in distorted-wave approximation; an extreme cluster model was assumed for the heavy cluster and the residual nucleus. Reasonable agreement between experimental and theoretical angular distributions was found. The magnitudes of the calculated cross sections will be discussed.

¹Abstract of published paper: *Proceedings of the Third Conference on Reactions Between Complex Nuclei (Asilomar, Pacific Grove, California, April 14-18, 1963)* (ed. by A. Ghiorso, R. M. Diamond, and H. E. Conzett), pp. 85-89, University of California Press, 1963.

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³Electronuclear Division.

ANALYSIS OF THE SCATTERING OF PROTONS BY Te^{126}

G. R. Satchler Taro Tamura

Elastic and inelastic scattering of protons by Te^{126} was calculated in terms both of DWBA and coupled channel technique, and it was found that

reasonable agreement with experiment can be obtained.

THE SHAPE OF THE SYMMETRY TERM IN THE NUCLEAR OPTICAL POTENTIAL¹

T. Terasawa² G. R. Satchler

It is pointed out that the shape of the symmetry term in the nuclear optical potential need not be

uniform over the nuclear volume. Illustrative calculations are presented which make use of the impulse approximation and different radii for the neutron and proton distributions.

¹Abstract of published paper: *Phys. Letters* 7, 265 (1963).

²Summer Investigator, 1963, from Tokyo University of Education, Japan.

(d, He^3) REACTION ON Ca^{40} AND THE TITANIUM ISOTOPES¹J. L. Yntema²

G. R. Satchler

NUCLEAR REACTIONS. Ca^{40} , $\text{Ti}^{46,47,48,49,50}(d, \text{He}^3)$, enriched targets, $E_d = 21$ Mev; measured $\sigma(\theta)$, He^3 spectrum. K^{39} , $\text{Sc}^{45,46,47,48,49}$, deduced levels, J, π .

The (d, He^3) reaction on Ca^{40} and isotopically enriched targets of Ti^{46} , Ti^{47} , Ti^{48} , Ti^{49} , and Ti^{50} has been investigated. Absolute differential cross sections for a number of transitions were obtained over an angular range from 11 to 33°. The angular distributions are compared with distorted-wave calculations which use the optical-model-potential parameters derived from the elastic scattering of 21-Mev deuterons on the same target materials. The data for the elastic scattering are given together with the optical-model fits. The

$\text{Ca}^{40}(d, \text{He}^3)\text{K}^{39}$ reaction was used to obtain the normalization coefficients necessary to extract spectroscopic factors from the comparison of the measured and calculated differential cross sections. The results show that the excitation energies of the $d_{3/2}$ and $s_{1/2}$ proton hole states are surprisingly low and increase with the number of $f_{7/2}$ neutrons in the nucleus. In the case of Sc^{45} , the $d_{3/2}$ hole state which contains the full $d_{3/2}$ strength is found at an excitation energy of less than 50 keV. The excitation energy of the $d_{3/2}$ hole state increases to 800 keV for Sc^{47} and to about 2.4 MeV in Sc^{49} . The excitation energy of the $s_{1/2}$ hole state increases from 0.92 MeV in Sc^{45} to 2.1 MeV in Sc^{48} .

¹Abstract of paper submitted to the *Physical Review*.

²Argonne National Laboratory, Argonne, Ill.

EXCITATION OF LOW EXCITED STATES IN Cd^{114} BY (p, p') REACTION¹M. Sakai²Y. Nakagima²H. Ejiri²H. Ikegami²K. Yagi²

G. R. Satchler

NUCLEAR REACTIONS. $\text{Cd}^{114}(p, p')$, enriched target, $E_p = 12.16$ Mev; measured $\sigma(\theta)$, p' spectrum. Cd^{114} , deduced levels, J, π .

The excitation of Cd^{114} by 12.16-Mev protons from the INS (Tokyo) cyclotron was studied, and the results analyzed in terms of the collective

model using the DWBA. The first 2^+ , interpreted as a quadrupole vibration, the quintet of levels around 1 MeV, and the 1.95-Mev level were observed. The latter is consistent with an octupole vibration, with a transition strength about 16 times "single particle."

¹Abstract of paper submitted to *Physics Letters*.

²University of Tokyo, Japan.

OPTICAL MODEL PLUS RESONANCE ANALYSIS OF THE ELASTIC SCATTERING OF PROTONS BY C^{12} ¹

Taro Tamura

Tokuo Terasawa²

Analysis of the elastic scattering of protons by C^{12} is made for proton energies ranging from 20 to 30 Mev and is compared with experiment. The basic idea of calculation is that the scattering amplitude is written as a sum of optical and

Breit-Wigner amplitudes, and according to the assumption made about the latter term, it is possible to assign quantum numbers to the resonant states of N^{13} . Figure 1 shows the fit of three differential cross sections as functions of energy, while Fig. 2 shows the fit of the angular distribution at six energies in the above-mentioned energy range. The agreement is rather satisfactory, and the assigned quantum number is also consistent with the knowledge obtained from the photoreactions.

Fig. 1. Differential Cross Sections at Three Angles as Functions of the Proton Energy. Full lines are theoretical.

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

²Tokyo University of Education, Tokyo, Japan.

Fig. 2. Angular Distribution at Several Energies. Full lines are theoretical.

SHELL-MODEL DESCRIPTION OF TRANSITION CHARGE DISTRIBUTION FOR EXCITATION OF VIBRATIONAL STATES IN NUCLEI

D. S. Onley¹

Taro Tamura

Analysis is made of the angular distribution of the inelastic scattering of electrons by Ni^{62} , leaving the latter in the first excited 2^+ state. The transition charge distribution is calculated

by using the random-phase approximation,² and is found to explain the experimental angular distribution³ reasonably well.

¹Summer Research Participant from Duke University.

²Taro Tamura and T. Udagawa, *Progr. Theoret. Phys. (Kyoto)* **26**, 947 (1961).

³H. Crammel *et al.*, *Phys. Rev.* **123**, 923 (1961).

TRUE STRONG COUPLING TREATMENT OF THE STRONGLY COUPLED CHANNEL THEORY OF THE NUCLEAR REACTIONS¹

Taro Tamura

When the target nucleus is very strongly coupled, the strong coupling theory of the scattering becomes a poor approximation if the basic wave function is written as a sum of terms which are written as products of the wave functions of the internal and

the relative motions. To be more precise one has to take into account the freezing of the incident particle to the deformation potential due to the target nucleus. In this article we discuss how this idea is taken into account in the actual machine calculation of such processes, and the implication of such calculation for the scattering of low energy protons by C^{12} is considered.

¹Abstract of published paper: *Phys. Letters* **6**, 111 (1963).

COUPLED CHANNEL CALCULATION OF THE SCATTERING OF 17.5 MeV PROTONS BY Ni^{62}

Taro Tamura

Scattering of 17.5-Mev protons by Ni^{62} is analyzed by using the same code as used in our previous work.¹ Rather good agreement is obtained, as is seen in Fig. 1, for the inelastic scattering for which there exist experimental data.² Same optical model parameters were used as before,¹ but the coupling parameters had to be assumed to be weaker by 10% all the way, compared to the previous work.

¹J. K. Dickens *et al.*, *Phys. Letters* **6**, 53 (1963).

²N. R. Roberson and H. D. Funsten, private communication.

Fig. 1. Inelastic Scattering Cross Sections of 17.5-Mev Protons by Ni^{62} .

HIGHER RANDOM PHASE APPROXIMATION APPLIED TO THE DESCRIPTION OF THE SPHERICAL VIBRATIONAL NUCLEI¹

Taro Tamura

Takeshi Udagawa²

The calculation of the spectra of vibrational nuclei is formulated in the framework of the higher random phase approximation, with the primary

interest in describing the two-phonon states of spherical vibrational nuclei. Most of the numerical calculation has been made for Cu^{114} , where fairly good agreement with experiment was obtained. The implications of the present calculation for other nuclei and possible future improvements are discussed.

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

²Tokyo Institute of Technology, Meguroku, Tokyo, Japan.

ANALYSIS OF THE SCATTERING OF PROTONS BY Ho^{165} IN TERMS OF THE COUPLED CHANNEL CALCULATION

Taro Tamura

A code has been prepared so that the coupled channel calculation can be made for the elastic and inelastic scattering of nucleons by odd- A as well as even- A nuclei. By using this code, analysis of the data¹ of the 17.5-Mev protons by Ho^{165} was made, and rather satisfactory result has been obtained as is seen in Fig. 1.

¹A. Lieber and C. A. Whitten, *Phys. Rev.* **132**, 2582 (1963).

Fig. 1. Comparison of the Differential Cross Sections of the Elastic and Inelastic Scattering of 17.5-Mev Protons by Ho^{165} .

PROTON EXCITATION OF TWO-PHONON LEVELS¹

J. K. Dickens²

F. G. Perey²

R. J. Silva²

Taro Tamura

NUCLEAR REACTIONS. $\text{Ni}^{62,64}(p, p \text{ and } p')$, enriched targets, $E_p = 11$ Mev; measured p, p and $p'(\theta)$. $\text{Ni}^{62,64}$, deduced levels, J, π .

Ni^{62} and Ni^{64} are bombarded by 11-Mev protons of the ORNL tandem Van de Graaff, and the differential cross sections were observed for the elastic and inelastic scattering. We are particularly interested in the excitation of the 0^+ , 2^+ ,

4^+ triad of two-phonon states, as well as that of the 2^+ one-phonon state, and analysis was made by using the coupled-channel code.³ The agreement between theory and experiment is satisfactory, as is seen in Fig. 1. The coupling parameters given in Table 1 are also quite reasonable.

¹Abstract of published paper: *Phys. Letters* **6**, 53 (1963).

²Neutron Physics Division.

³Prepared by Taro Tamura.

Table 1. Parameters of the Analysis

	V_s (MeV)	W_D (MeV)	One-Phonon Level			Two-Phonon Levels		
			Q (MeV)	J^π	β	Q (MeV)	J^π	β
Ni^{62}	50.84	10.21	-1.17	2^+	0.281	-2.05	0^+	0.170
						-2.30	2^+	0.230
						-2.34	4^+	0.281
Ni^{64}	51.23	11.51	-1.34	2^+	0.231	-2.28	0^+	0.170
						-2.62	4^+	0.231
						-2.89	2^+	0.189

Fig. 1. Inelastic Differential Cross Section for the One-Phonon State and the Two-Phonon Triplet (Ni^{62} on the Left and Ni^{64} on the Right). The curves are the results of the coupled channel calculation.

NUCLEAR RADII OF THE ISOTOPES OF TIN

J. A. Harvey

T. Fuketa¹

The neutron transmission data of Fuketa *et al.*² of the highly enriched samples of the tin isotopes have been analyzed to obtain nuclear radii for

¹On leave from Japan Atomic Energy Research Institute, and now at Rensselaer Polytechnic Institute.

²T. Fuketa, F. A. Khan, and J. A. Harvey, *Phys. Div. Ann. Progr. Rept. Jan. 31, 1963, ORNL-3425, p. 36.*

potential scattering. The contributions of nearby resonances to the flat regions between resonances have been computed so that values of the radius can be obtained for several different neutron energy regions from 30 to 2000 ev. The results of the analysis of the 180-m transmission data are given in Table 1. The error on the radius for a single run was determined from the statistical

accuracy of the transmission data and the fluctuation of the measured values of the radius for the different neutron energy regions because of incomplete correction of contributing resonances. Table 1 also gives the average of the individual runs for each enriched sample as well as the nuclear radii computed for the individual isotopes. The errors on the radii of the isotopes include an estimated 2% uncertainty in the thickness of the sample.

Measurements from 0.1 to 200 ev using the 45-m flight path give results in reasonable agreement with the results in Table 1. The 45-m results for the Sn^{112} and Sn^{114} isotopes are somewhat more accurate since the sample thicknesses were 1 and $\frac{3}{4}$ in. respectively; these samples were five times

thicker than those used for the 180-m measurements. The nuclear radii of the Sn^{112} and Sn^{114} isotopes were computed to be (0.61 ± 0.03) and $(0.75 \pm 0.06) \times 10^{-12}$ cm respectively. The Sn^{115} sample was a thin oxide sample and the value obtained for the radius was much too large, possibly due to water in the powder.

The radii for all the tin isotopes are within two standard deviations of a constant value of 0.63×10^{-12} cm. There does not appear to be any detailed structure such as an even- A , odd- A effect or a nuclear shell structure effect. The data are in agreement with the predictions of nuclear optical models.

Table 1. Nuclear Radii of the Isotopes of Tin

Sample	Enrichment (%)	Sample Thickness (atoms of Sn per barn)	Nuclear Radii (cm)				Nuclear Radius of Isotope (cm)
			2000-170 ev	2000-170 ev	200-30 ev	Average	
			$\times 10^{-12}$	$\times 10^{-12}$	$\times 10^{-12}$	$\times 10^{-12}$	$\times 10^{-12}$
Sn^{112}	70.05	0.0178	0.66 ± 0.04	0.68 ± 0.04	0.71 ± 0.04	0.68 ± 0.03	0.70 ± 0.05
Sn^{114}	56.85	0.0135	0.76 ± 0.06		0.78 ± 0.06	0.77 ± 0.04	0.86 ± 0.08
Sn^{116}	95.74	0.0912	0.619 ± 0.010	0.615 ± 0.010	0.613 ± 0.010	0.616 ± 0.006	0.615 ± 0.009
Sn^{117}	89.2	0.0922	0.616 ± 0.020	0.620 ± 0.020	0.621 ± 0.010	0.620 ± 0.008	0.618 ± 0.011
Sn^{118}	97.15	0.0932	0.655 ± 0.020	0.685 ± 0.020	0.624 ± 0.020	0.655 ± 0.020	0.656 ± 0.020
Sn^{119}	89.8	0.0929	0.615 ± 0.010	0.620 ± 0.010	0.619 ± 0.010	0.618 ± 0.006	0.615 ± 0.010
Sn^{120}	97.9	0.0864	0.643 ± 0.010		0.648 ± 0.020	0.645 ± 0.009	0.645 ± 0.011
Sn^{122}	90.8	0.0928	0.603 ± 0.020	0.640 ± 0.020	0.619 ± 0.010	0.620 ± 0.010	0.618 ± 0.012
Sn^{124}	92.8	0.0924	0.652 ± 0.010	0.650 ± 0.010	0.650 ± 0.010	0.651 ± 0.006	0.652 ± 0.010

W

PARAMETERS OF LOW ENERGY RESONANCES IN TUNGSTEN

D. Paya¹K. D. Pearce²

J. A. Harvey

G. G. Slaughter

NUCLEAR REACTIONS. W(n), natural target, $E_n = 1-30$ ev; measured $\sigma(E)$. W^{182,183,186}, deduced resonance parameters.

Neutron transmission measurements have been made upon samples of natural tungsten in order to obtain accurate parameters for the five lowest energy neutron resonances. The parameters of these low energy resonances are of interest in design of nuclear space reactors using tungsten enriched to ~93% in W¹⁸⁴. The absorption of resonance energy neutrons by these five low energy resonances in the isotopes other than W¹⁸⁴ is more than that of W¹⁸⁴ even in a sample enriched to 93% W¹⁸⁴.

The fast chopper time-of-flight neutron spectrometer was utilized to cover the energy region from 1 to 30 ev with an energy resolution of about 1%. The metallic samples ranged in thickness from 0.3 to 120 mils and a liquid sample of Na₂WO₄ dissolved in D₂O had a thickness equivalent to about 0.1 mil of tungsten metal. Using the high intensity spectrometer the individual transmission points can be measured to a statistical accuracy of about 1%.

The transmission data have been analyzed by use of the area and shape analysis programs of Atta and Harvey.³ With the area program, values of the neutron width of each resonance are determined for several assumed values of the total width Γ . The result of a measurement of a resonance with a single sample thickness can be represented by an equation of the form $\Gamma_n \Gamma^m = k$. For thin samples m is ~0 and for thick samples m is ~1. Figure 1 shows the data of the five sample thicknesses for the 18.8 ev resonance. The Doppler width was computed from an effective temperature of 320°K determined from a Debye temperature of the metal of 400°K. Table 1 summarizes the results of the area analysis

program for the 4.16 ev (W¹⁸²), the 7.67 ev (W¹⁸³), the 18.8 ev (W¹⁸⁶), the 21.1 ev (W¹⁸²), and the 27.1 ev (W¹⁸³) resonances. The errors on k arise from the statistical uncertainty of the transmission data; errors arising from the uncertainties in the Doppler broadening, the energy resolution, and sample thicknesses are small. For each resonance a weighted least-squares program has been used to determine the best values for Γ and Γ_n , which are also given in Table 1. The errors are derived from the internal consistency of the measurements for

Fig. 1. Plot of Γ_n vs Γ for five different sample thicknesses for the 18.8-ev Resonance in W¹⁸⁶.

¹Visitor from CENS, Saclay (Seine et Oise), France.

²Summer student trainee, 1963, from St. Edward's University.

³S. E. Atta and J. A. Harvey, *Numerical Analysis of Neutron Resonances*, ORNL-3205 (1961), and *Addendum*; *Phys. Div. Ann. Progr. Rept. Jan. 31, 1963*, ORNL-3425, p. 46.

the different sample thicknesses and the statistical uncertainty of the data. The results are of higher accuracy than earlier results⁴ and, with the exception of the 18.8 ev resonance, are in good agreement with published data.⁴

Parameters for the 4.16, 7.67, 18.8, and 21.1 ev resonances have been determined from the shape

analysis program.³ The results are given in Table 2. The errors on the parameters for the different sample thicknesses are derived from the statistical uncertainty of the data and the uncertainties of the energy resolution and the Doppler broadening. The errors quoted on the best values include estimations of systematic uncertainties. The results of the shape analysis are in good agreement with the results from the area analysis.

⁴Neutron Cross Section Compilation, BNL-325, 2d ed., Suppl. No. 1 (1960).

Table 1. Parameters of Resonances from Area Analysis

Measured E_0 (ev)	Sample Thickness		Exponent, m	k [(mv) ^{1+m}]	Error in k (%)
	Mils	Atoms of W per Barn			
4.16 ev Resonance in W ¹⁸²					
4.17	1	0.172×10^{-3}	-0.05	1.19	1.7
4.14	1	0.172×10^{-3}	-0.10	1.09	4.0
4.17	5	0.791×10^{-3}	0.26	4.25	1.8
4.17	25	0.373×10^{-2}	0.85	44.0	1.3
4.16	87	0.130×10^{-1}	0.99	79.8	1.3
4.21	120	0.189×10^{-1}	1.00	81.6	1.6
Best Values: $E_0 = 4.17 \pm 0.02$ ev $\Gamma = 55 \pm 2$ mv $\Gamma_n = 1.48 \pm 0.03$ mv $\Gamma_\gamma = 54 \pm 2$ mv					
7.67 ev Resonance in W ¹⁸³					
7.70	1	0.172×10^{-3}	-0.09	1.11	10
7.69	5	0.791×10^{-3}	-0.03	1.59	4.7
7.63	5	0.828×10^{-3}	-0.10	1.11	2.2
7.67	25	0.373×10^{-2}	0.23	4.79	1.8
7.68	87	0.130×10^{-2}	0.78	53.6	2.6
7.73	120	0.189×10^{-1}	0.86	73.6	2.4
Best Values: $E_0 = 7.68 \pm 0.03$ ev $\Gamma = 79 \pm 3$ mv $\Gamma_n = 1.74 \pm 0.03$ mv ($g = \frac{3}{4}$) $\Gamma_\gamma = 77 \pm 3$ mv					
18.8 ev Resonance in W ¹⁸⁶					
18.85	Liquid	1.986×10^{-5}	-0.012	297	1.7
18.81	0.3	5.793×10^{-5}	0.21	1103	1.3
18.83	1	1.72×10^{-4}	0.75	25800	5.0
18.83	2	3.23×10^{-4}	0.82	40300	0.9
18.81	5	8.28×10^{-4}	0.96	89000	2.5
Best Values: $E_0 = 18.83 \pm 0.04$ ev $\Gamma = 361 \pm 7$ mv $\Gamma_n = 320 \pm 4$ mv $\Gamma_\gamma = 41 \pm 9$ mv					

Table 1 (continued)

Measured E_0 (ev)	Sample Thickness		Exponent, m	k [(mv) $^{1+m}$]	Error in k (%)
	Mils	Atoms of W per Barn			

21.1 ev Resonance in W ¹⁸²					
21.08	0.3	5.793×10^{-5}	0.0002	41.7	4
21.09	1	1.72×10^{-4}	0.13	71.6	4
21.09	2	3.23×10^{-4}	0.25	125	2.5
21.04	5	8.28×10^{-4}	0.51	424	1

Best Values: $E_0 = 21.08 \pm 0.05$ ev
 $\Gamma = 102 \pm 6$ mv
 $\Gamma_n = 40.1 \pm 1.0$ mv
 $\Gamma_\gamma = 62 \pm 6$ mv

27.1 ev Resonance in W ¹⁸³					
27.07	0.3	0.5793×10^{-4}	-0.104	25.5	8.5
27.07	1	0.172×10^{-3}	-0.08	31	14
27.08	2	0.323×10^{-3}	-0.015	38.4	2.7
27.02	5	0.828×10^{-3}	0.15	93	2.4
27.13	23	0.348×10^{-2}	0.75	1480	1.4

Best Values: $E_0 = 27.08 \pm 0.06$ ev
 $\Gamma = 118 \pm 7$ mv
 $\Gamma_n = 43.3 \pm 1.4$ mv ($g = \frac{3}{4}$)
 $\Gamma_\gamma = 75 \pm 7$ mv

Table 2. Parameters of Resonances from Shape Analysis

E_0 (ev)	Sample Thickness (mils)	Γ (mv)	Γ_n (mv)	E_0 (ev)	Sample Thickness (mils)	Γ (mv)	Γ_n (mv)
4.16 ev Resonance in W ¹⁸²				18.8 ev Resonance in W ¹⁸⁶			
4.168 ± 0.001	1	58 ± 5	1.46 ± 0.03	18.835 ± 0.003	Liquid	385 ± 8	319 ± 3
4.142 ± 0.002	1	60 ± 8	1.63 ± 0.09	18.837 ± 0.002	0.3	368 ± 5	318 ± 3
4.168 ± 0.001	5	58 ± 5	1.48 ± 0.04	18.836 ± 0.006	1	356 ± 30	323 ± 20
Best Values: $E_0 = 4.16 \pm 0.01$ ev $\Gamma = 58 \pm 4$ mv $\Gamma_n = 1.48 \pm 0.03$ mv $\Gamma_\gamma = 57 \pm 4$ mv				18.847 ± 0.002	2	386 ± 15	304 ± 10
Best Values: $E_0 = 18.84 \pm 0.02$ ev $\Gamma = 373 \pm 5$ mv $\Gamma_n = 318 \pm 3$ mv $\Gamma_\gamma = 55 \pm 6$ mv				21.1 ev Resonance in W ¹⁸²			
7.67 ev Resonance in W ¹⁸³				21.08 ± 0.01	0.3	100 ± 10	40 ± 2
7.690 ± 0.004	5	90 ± 20	1.85 ± 0.10	21.10 ± 0.01	1	110 ± 20	39 ± 2
7.631 ± 0.001	5	76 ± 9	1.72 ± 0.05	21.10 ± 0.01	2	114 ± 10	39.0 ± 1.5
7.675 ± 0.001	25	81 ± 13	1.76 ± 0.10	Best Values: $E_0 = 21.09 \pm 0.03$ ev $\Gamma = 108 \pm 8$ mv $\Gamma_n = 39.3 \pm 1.0$ mv $\Gamma_\gamma = 69 \pm 8$ mv			
Best Values: $E_0 = 7.67 \pm 0.02$ ev $\Gamma = 79 \pm 8$ mv $\Gamma_n = 1.75 \pm 0.04$ mv ($g = \frac{3}{4}$) $\Gamma_\gamma = 77 \pm 8$ mv							

NEUTRON TOTAL CROSS-SECTION MEASUREMENTS ON ENRICHED SAMPLES OF THE ZIRCONIUM ISOTOPES¹

R. C. Block

NUCLEAR REACTIONS. $Zr^{90,91,92,94,96}(n)$, enriched targets, $E_n = 0.5\text{--}30$ kev; measured $\sigma(E)$. $Zr^{91,92,93,95,97}$, deduced $\bar{\Gamma}_n^0/\bar{D}$, resonance parameters.

The ORNL fast chopper time-of-flight neutron spectrometer was utilized to make transmission measurements on isotopically enriched samples of Zr^{90} (97.8% enrichment), Zr^{91} (90.9%), Zr^{92} (95.7%), Zr^{94} (96.5%), and Zr^{96} (57.4%). In the energy range from approximately 0.5 to 30 kev, three resonances were assigned to Zr^{90} , four to

Zr^{92} , six to Zr^{94} , and seven to Zr^{96} . Seven resonances were assigned to Zr^{91} up to ~ 3000 ev; above this energy individual resonances in Zr^{91} could not be resolved. By combining the resonance parameter data for all four even-even isotopes, an s-wave strength function of $(0.7 \pm 0.2) \times 10^{-4}$ is computed for zirconium in this energy region. In addition, a p-wave strength function of $(6 \pm 4) \times 10^{-4}$ can be computed for Zr^{91} on the assumption that four extremely weak resonances assigned to Zr^{91} were excited by p-wave neutrons.

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

A METHOD OF CORRECTING FOR "MISSED" RESONANCES IN NEUTRON SPECTROSCOPY¹

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A method is described of obtaining the corrected s-wave strength function and the corrected average spacing of s-wave resonances from the observed resonance parameters from low energy neutron cross-section measurements. The method of

correcting for "missed" resonances is based on the Porter-Thomas distribution of the reduced neutron widths. Several graphical illustrations from the results of an iterative calculation by a digital computer are presented to give a general idea of the nature and numerical significance of the corrections. Finally, a set of master curves is given, from which one can estimate the correction factors using simple algebraic calculations for various experimental conditions.

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GAMMA-RAY SPECTRA FROM NEUTRON CAPTURE IN THE ISOTOPES OF TIN

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NUCLEAR REACTIONS. $\text{Sn}^{116,117,118,119,120,122,124}(n,\gamma)$, enriched targets, $E_n \leq 200$ ev; measured $\sigma(E)$, γ spectrum. $\text{Sn}^{117,118,119,120,121,123,125}$, deduced Γ_γ , resonance parameters.

The gamma-ray spectra from the capture of resonance and thermal energy neutrons in samples enriched in the tin isotopes have been studied using a large sodium iodide crystal. The samples of the seven abundant isotopes, Sn^{116} to Sn^{124} , had isotopic enrichments from 90 to 98%, and each sample weighed about 35 g. Only 1 to 3 g of sample of the isotopes Sn^{112} , Sn^{114} , and Sn^{115} were available, with isotopic enrichments from 30 to 70%. A 5-m flight path was used with the "fast chopper" time-of-flight spectrometer at the Oak Ridge Research Reactor (ORR), which results in a neutron energy resolution of about 15% up to 200 ev. This resolution was sufficient to resolve a number of individual resonances in the enriched samples, but in some cases measurements were made for groups of two or three resonances. Thermal and epithermal neutron capture was studied using cadmium and B^{10} filters in the neutron beam. For these measurements the chopper rotor was held stationary and used as a collimator to allow a neutron beam to impinge on the samples.

The 9-in.-diam by 12-in.-long sodium iodide crystal was shielded with 16 tons of lead and 2 tons of LiH to reduce the background. A 4-in. aperture in the lead shield allowed gamma rays from the sample to strike the crystal. A 3-in.-thick slab of LiH between the sample and lead shield reduced the background from neutrons scattered by the sample. The energy calibration and pulse-height response function for the crystal were measured using radioactive gamma sources, a PoBe source, and thermal neutron capture gamma rays from Pb^{207} , Fe, Y, and N.

The relative intensities of the high energy gamma rays were obtained by fitting response functions to the experimental results and applying corrections

for the absorption of the gamma rays in the fast neutron shielding. An approximate technique (accurate to about a factor of 2) was used to obtain estimates of the absolute intensities [$\nu_\gamma = \text{gamma rays/capture} = \Gamma_\gamma(\text{partial})/\Gamma_\gamma(\text{total})$] of the high energy gamma rays from the area under the pulse-height spectra. Reduced widths for each transition were obtained from the formulas

$$k_{M1} = \frac{\nu_\gamma \Gamma_\gamma}{E_\gamma^3 D}, \quad k_{E1} = \frac{\nu_\gamma \Gamma_\gamma}{E_\gamma^3 A^{2/3} D},$$

where

D = spacing of levels (in Mev) with the same spin and parity as the capturing state,

Γ_γ = total radiation width (in ev),

E_γ = gamma ray energy (in Mev),

A = mass number of compound nucleus.

The observed level spacings, D_{obs} , obtained from transmission measurements of samples of the enriched isotopes by Fuketa *et al.*³ have been used to compute D for the isotopes. D has been assumed to be equal to D_{obs} for the even- A target nuclides, and equal to $2D_{\text{obs}}$ for the odd- A target nuclides. A value of 0.11 ev has been assumed for the total radiation width for all the isotopes. From the summary of Bartholomew⁴ the average values of k_{M1} and k_{E1} in the mass region of the tin isotopes are $\sim 7 \times 10^{-3}$ and the maximum values for k_{M1} and k_{E1} are $\sim 45 \times 10^{-3}$ and $\sim 100 \times 10^{-3}$ respectively. With the above definitions of D , E_γ , and Γ_γ the units of k are $\text{ev} \cdot \text{Mev}^{-4}$ or 10^{-6} Mev^{-3} , and these units are used throughout this paper.

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³T. Fuketa, F. A. Khan, and J. A. Harvey, *Phys. Div. Progr. Rept. Jan. 31, 1963*, ORNL-3425.

⁴G. A. Bartholomew, *Ann. Rev. Nucl. Sci.* 11, 259 (1961).

Thermal Neutron Capture

The intensities and reduced widths of the ground state transitions following thermal capture in each isotope are given in Table 1. (PE is the percentage error in the determination of the relative gamma ray intensities. Systematic errors introduced during the determination of absolute intensities and reduced widths have not been included.) Apart from errors in the assumed parameters (Γ_γ , D , etc.), the systematic errors should not be more than a factor of 2, at least for the strong gamma rays.

Table 1 shows that the ground state transitions are weak for all capturing isotopes and may be zero except for Sn^{117} and possibly Sn^{112} . Observed pulse-height spectra for Sn^{117} capture (thermal and 39-ev neutrons) are shown in Fig. 1. S-wave neutron capture in Sn^{117} and Sn^{119} leads to the formation of either 0^+ or 1^+ capturing states and, hence, the ground state transitions must be $M1$. Likewise s-wave capture in the even isotopes forms $\frac{1}{2}^+$ capturing states. The low lying excited states of the odd- A isotopes so formed have spins $\frac{1}{2}^+$, $\frac{3}{2}^+$, $\frac{1}{2}^-$, and again transitions to these states cannot be electric dipole. The ground state transition for Sn^{117} capture has a reduced gamma-ray strength which is more than 11 times the average value ($\bar{k}_{M1} = 7 \times 10^{-3}$) observed previously

for nuclei in the mass 100 region and approximately 2 times the previous maximum value [$k_{M1}(\text{max}) = 45 \times 10^{-3}$]. Its strength is about equal to half the average $E1$ strengths previously observed.

Epithermal Neutron Capture

Table 1 includes results obtained by using a B^{10} filter difference technique (with a Cd filter permanently in position). These results correspond to capture of neutrons in the energy range between thermal and several kev. It is clear that the ground state transition is very strong in all cases studied. If these strong ground state transitions are to be electric dipole transitions, p -wave capture must make a considerable contribution to the capture of resonance energy neutrons. Otherwise magnetic dipole transitions must be very strong.

Resonance Neutron Capture

Table 2 summarizes the results obtained for thirteen resonances or groups of resonances, and the information concerning ground state transitions is collected in Table 3. Three of the resonances show resonance-potential interference in the total cross-section measurements of Fuketa *et al.*³ and

Table 1. Ground State Transition Intensities from Thermal and Epithermal Neutron Capture in Tin Isotopes

Isotope	Thermal			E_γ (Mev)	Epithermal			
	ν_γ (%)	k_{M1}^a	PE (%)		ν_γ (%)	k_{M1}^a	k_{E1}	PE (%)
		$\times 10^{-3}$				$\times 10^{-3}$	$\times 10^{-3}$	
Sn^{124}	0.6	9	100	5.65	36	540	21	2
Sn^{122}	1.3	18	100	5.81	14	200	8	5
Sn^{120}	0.9	22	100	6.05	23	550	22	5
Sn^{118}	0.6	13	100	6.48	21	450	19	5
Sn^{116}	1.4	26	100	6.86				
Sn^{114}	2.7	40	100	7.78				
Sn^{112}	1.5	130	50	7.96				
Sn^{119}	0.006	0.2	100	9.08	1.5	42	2	10
Sn^{117}	2.8	80	5	9.34	1.5	40	2	5
Sn^{115}	Negligible							

^aThe units of k_{M1} and k_{E1} are 10^{-6} Mev^{-3} .

Table 2. Gamma Ray Intensities from Resonant Neutron Capture in Tin Isotopes

Nuclide	D_{obs} (ev)	$\bar{\Gamma}_n^0$ (mv)	E_n (ev)	Γ_n^0 (mv)	E_γ (Mev)	ν_γ (%)	k_{M1}^a	k_{E1}^a	PE (%)
							$\times 10^{-3}$	$\times 10^{-3}$	
Sn^{124}	400	1.6	62.0	1.40	5.65	50		30	3
					5.46	15		10	6
					4.78	7		7	12
Sn^{122}	400	8.0	107	0.075	5.81	63	870	35	10
					5.63	1	12	0.5	100
					4.90	15	360	15	25
					5.81	19	270	11	20
					5.63				
Sn^{120}	200	1.8	{ 365 427 }	{ 0.11 1.3 }	4.90	11	250	10	30
					6.05	13	190	8	10
					5.64	2.5	76	3	50
Sn^{118}	180	5.8	45.8	0.106	4.98	1.5	65	3	100
					6.48	36	800	33	6
					6.10	4	110	5	30
					5.35	10	410	17	15
					6.48	25	560		25
					6.10	9	240		50
					5.35	≤ 5			
Sn^{116}	180	6.7	111	6.3	6.86	2	43		30
					5.86	2.5	72		50
					6.86	23	410	17	15
					5.86	3	99	4	40
Sn^{119}	30	0.48	{ 115 141 146 }	{ 0.05 0.38 0.05 }	9.08	≤ 1	≤ 30	≤ 1	
					7.90	≤ 3			
					9.08	≤ 1	≤ 30	≤ 1	
					7.90	≤ 3			
Sn^{117}	25	0.95	38.8	0.96	9.34	0.3	8		100
					8.04	9	400		6
					7.44	0.4	20		100
					6.70	3	200		25
					9.34	0.25	7	0.3	100
					8.04	0.5	22	1	100
					7.44	5	180	8	10
					6.70	3	340	15	20
					9.34	5	140	6	25
					8.04	4	180	8	20
					7.44	6	220	9	15
					6.70	4	460	19	15

^aThe units of k_{M1} and k_{E1} are 10^{-6} Mev^{-3} .

these must be *s*-wave resonances. The 359-ev resonance in Sn^{118} has a strong ground state transition but this result is subject to considerable statistical uncertainty. The 111-ev resonance in Sn^{116} has a ground state transition which is within the range of previously observed *M1* strengths, as is also the case for the 39-ev resonance in Sn^{117} . However, the latter has an extremely strong gamma ray to an excited state estimated at 1.30 Mev (see Fig. 1). If this transition is to the 2^+ excited state known at 1.22 Mev,⁵ it is magnetic

dipole or electric quadrupole. Assuming the transition to be *M1*, its strength is 17 times $k_{M1}(\text{max})$.

For the other ten resonances, seven show very strong ground state transitions. The most striking

⁵NAS-NRC publication, Nuclear Data Sheets.

Fig. 1. Observed Pulse-Height Spectra of the Gamma Rays from Sn^{117} from the Capture of Thermal Energy Neutrons and from Neutron Capture in the 39-ev Resonance.

Fig. 2. Observed Pulse-Height Spectra of the Gamma Rays from Neutron Capture in the 62-ev Resonance in Sn^{124} , the 107-ev Resonance in Sn^{122} , and the 46-ev Resonance in Sn^{118} .

Table 3. Ground State Transition Intensities from Neutron Capture in Tin Resonances

Isotope	Neutron Energy (ev)	s-Wave $\Gamma_n^0/\bar{\Gamma}_n^0$ ^a	$k_{M1}/\bar{k}_{M1}$	p-Wave $\Gamma_n^1/\bar{\Gamma}_n^1$ ^b	E_γ (Mev)
Sn ¹²⁴	62	No interference		76	5.65
Sn ¹²²	107	0.009	124	2.4	5.81
	260	0.014	39	1.4	
Sn ¹²⁰	{ 365	0.06		2.1	
	{ 427	0.7	27	20	6.05
Sn ¹¹⁸	46	0.02	114	17	6.48
	{ 308	0.01			
	{ 344	0.02			
	{ 359	3	80	Interference	6.48
Sn ¹¹⁶	111	0.9	6	Interference	6.86
	148	0.04	59	13	6.86
Sn ¹¹⁹	{ 115	0.1			
	{ 141	0.8	≤ 4	58	9.08
	{ 145	0.1			
	223	1.6	≤ 4	77	9.08
Sn ¹¹⁷	39	1.0	1	Interference	
	{ 121	0.8	1	170	9.34
	{ 124	0.4		85	
	{ 196	2.2	20	290	9.34
	{ 201	0.07		9	

^a $\bar{\Gamma}_n^0 = (D_{\text{obs}}) (\bar{\Gamma}_n^0/D)$ for $I = 0$ and $\bar{\Gamma}_n^0 = (2D_{\text{obs}}) (\bar{\Gamma}_n^0/D)$ for $I \neq 0$.

^b $\Gamma_n^1 = 5.38 \times 10^5 \Gamma_n^0/E_0$ (using $R = 0.62 \times 10^{-12}$ cm); $\Gamma_n^1 = S_1 \times D$ assuming $S_1 = 4 \times 10^{-4}$, $D = D_{\text{obs}}$ for $I = 0$, and $D = 2D_{\text{obs}}$ for $I \neq 0$.

results are for the 62-ev resonance in Sn¹²⁴, the 107-ev resonance in Sn¹²², and the 46-ev resonance in Sn¹¹⁸. The spectra for these three resonances are shown in Fig. 2. If these strong gamma rays are to be electric dipole, the resonances must be *p*-wave. The total cross-section measurements of Fuketa *et al.*³ for the 62-ev resonance do not show any interference even though Γ_n is large enough that interference would have been observed if it were an *s*-wave resonance. Thus the 62-ev resonance must be a *p*-wave resonance. The neutron widths of the 107-ev and the 46-ev resonances are not sufficiently large to permit an assignment of the parity of the compound state from the transmission measurements.

Column 3 in Table 3 gives the ratio of the reduced neutron widths for each resonance to the average value expected for *s*-value resonances.³ These values show that the resonances studied are usually smaller than an average *s*-wave resonance. However, column 5 of Table 3 shows that they are usually considerably larger than expected for *p*-wave resonances (based on a *p*-wave strength function, S_1 , of 4×10^{-4} and that $D = D_{\text{obs}}$ for $I = 0$, and $D = 2D_{\text{obs}}$ for $I \neq 0$). If many of the strong gamma rays are explained as due to *p*-wave resonances, it is clear that the tin isotopes must have anomalously strong *p*-wave strength functions.

On the other hand some of the strong gamma rays observed must be magnetic dipole transitions and

it seems likely that there are a number of such cases. Column 4 of Table 3 gives the ratio of the observed reduced widths to $\bar{k}_{M1}$, assuming they are $M1$ gamma rays. The results support the suggestion by Starfelt⁶ and Bergqvist⁷ that enhanced

⁶N. Starfelt, *The Influence of an M1 Giant Resonance on Neutron Capture Gamma-Ray Spectra*, FOA Rapport A 4274-411 (1963).

⁷I. Bergqvist, B. Lundberg, and N. Starfelt, *International Conference on Nuclear Physics with Reactor Neutrons*, Oct. 15-17, 1963, ANL-6797.

$M1$ transitions should occur in this mass region at energies corresponding to the spin-orbit splitting of about 5.5 Mev of the $h_{11/2}$ and $h_{9/2}$ shells. Brink⁸ has estimated that in certain cases such as the tin isotopes, $M1$ transitions can be enhanced by a considerable factor (~ 30) over the Weisskopf estimate of 1.4×10^{-3} for k_{M1} .

⁸D. M. Brink, *International Conference on Nuclear Physics with Reactor Neutrons*, Oct. 15-17, 1963, ANL-6797.

NEUTRON RADIATIVE CAPTURE REACTIONS¹

J. H. Gibbons

Advances made during recent years in the study of radiative capture reactions are reviewed. Im-

¹Abstract of invited paper delivered at International Conference in Fast Neutron Physics, Houston, Tex., February 1963, and published in *Progress in Fast Neutron Physics*, ed. by G. C. Phillips, J. B. Marion, and J. R. Risser, pp. 193-212, University of Chicago Press, 1963.

provements and new techniques in detection devices are discussed with emphasis on the determination of capture cross sections, capture gamma-ray spectra, and applications to astrophysics.

RESONANCE SELF-SHIELDING IN NEUTRON CAPTURE CROSS-SECTION MEASUREMENTS¹

R. L. Macklin

The resonance self-protection correction for neutron capture is developed for a thin circular

disk. Formulas suitable for calculation with an electronic computer or desk calculator are derived.

¹Abstract of paper submitted for publication in *Nuclear Instruments and Methods*.

GAMMA-RAY SPECTRA FROM RESONANT NEUTRON CAPTURE ON F^{19}

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J. H. Gibbons

W. M. Good

I. Bergqvist¹

NUCLEAR REACTIONS. $Fe^{19}(n,\gamma)$, $E_n = 27, 49$ kev; measured γ spectrum. F^{20} , deduced $\Gamma_{\gamma i}$.

Because $F^{19,20}$ occupy a position early in the filling of the s - d shell, they have been the object of extensive study both theoretically and experimentally. Theoretically there should be strong configuration mixing between the s and d orbits, and calculations taking this into account have been moderately successful in predicting level positions and properties.² Alternatively the nuclei in which the s - d shells are filling can be regarded as having deformed cores to which individual nucleons are coupled. Mixing of the resulting bands is required in order to obtain a description of the level structure that agrees with observation.³

Consider the experimental situation as regards adding a neutron to F^{19} . When thermal neutrons are captured the gamma spectrum is dominated by a strong $M1$ transition to ground, while at the same time $E1$ transitions to excited states of parity opposite to ground are suppressed.⁴ In the case of the (d,p) reaction, a weak stripping pattern is observed for the ground state.⁵ Gamma-ray spectra from kev-range neutron resonance capture offer a completely different tool from thermal capture or (d,p) reactions to further study F^{20} in that the spins, parities, and radiative widths are known for the initial states.

We have already reported some results on $F(n,\gamma)$.⁶ Subsequently, (1) further studies of the spectra at the 27 ($J^\pi = 2^-$) and 49 ($J^\pi = 1^-$) kev resonances

have been made with improved intensities and detector response, (2) the radiation widths have been measured, and (3) new data processing facilities have been made available and with them development of more elegant methods to perform the complicated background subtractions that are required.

The gamma-ray spectra due to resonance capture are obtained by means of (1) a 9×12 in. NaI crystal⁷ with appropriate shielding and collimation, (2) pulsed neutron source and time spectrometer, and (3) a 2048-channel analyzer utilized as a 16×128 or 8×256 two-parameter analyzer. The results for the case of $F^{19}(n,\gamma)$ vs E_n are shown in Figs. 1, 2, and 3. The gamma-ray energies and relative intensities are tabulated in Table 1.

From the relative intensities and the total radiation widths⁸ for a given resonance, the partial radiation widths can be obtained from $\Gamma_{\gamma i} = (\text{relative intensity})_i \times \Gamma_{\gamma \text{total}}$. Radiation widths can be written in the form⁹ $\Gamma_{\gamma}(E1) = |M(E1)|^2 E_\gamma^3 A^{2/3}$ and $\Gamma_{\gamma}(M1) = |M(M1)|^2 E_\gamma^3$, where for the light masses both $|M(E1)|^2$ and $|M(M1)|^2 \approx 3.2 \times 10^{-3}$. In terms of this latter quantity, $\Gamma_{\gamma i}(E1) = 3.2 \times 10^{-3} |M'(E1)|^2 E_{\gamma i}^3 A^{2/3}$ and $\Gamma_{\gamma i}(M1) = 3.2 \times 10^{-3} |M'(M1)|^2 E_{\gamma i}^3$, where the $|M'|^2$ are distributed about 1 for transitions to state i .

In Table 2 relative line intensities are listed for the 27- and 49-kev resonances in terms of the

¹Visiting scientist from University of Lund, Sweden.

²J. P. Elliott and B. H. Flowers, *Proc. Roy. Soc. (London)* **A229**, 536 (1955).

³E. B. Paul, *Phil. Mag.* **2**, 311 (1957).

⁴P. J. Champion and G. A. Bartholomew, *Can. J. Phys.* **35**, 1361 (1957).

⁵D. A. Bromley, *Phys. Rev.* **89**, 396 (1953); V. M. Rout, W. M. Jones, and D. G. Waters, *Nucl. Phys.* **45**, 369 (1963).

⁶J. R. Bird, J. H. Gibbons, and W. M. Good, *Phys. Letters* **1**, 262 (1962).

⁷Kindly loaned by ORNL Neutron Physics Division.

⁸Fletcher Gabbard, R. H. Davis, and T. W. Bonner, *Phys. Rev.* **114**, 201 (1959); R. L. Macklin and J. H. Gibbons (private communication).

⁹V. F. Weisskopf, *Phys. Rev.* **83**, 1073 (1951); S. A. Moszkowski, *Beta- and Gamma-Ray Spectroscopy* (K. Siegbahn, ed.), p. 373, North Holland, Amsterdam, and Interscience, New York, 1955; D. H. Wilkinson, *Phil. Mag.* **1**, 127 (1956); D. Kurath, *Phys. Rev.* **130**, 1525 (1963).

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Fig. 1. Yield of Gamma Rays as a Function of Neutron Energy in the $F^{19}(n,\gamma)F^{20}$ Reaction.

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3⁺ 2⁺ ? (1,2)⁺ (2,3)⁺ 3⁺ 2⁺

Fig. 2. Spectrum of Gamma Rays Resulting from Capture of Neutrons at the 27-keV Resonance of F^{19} .

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3⁺ 2⁺ ? (1,2)⁺ (2,3)⁺ 3⁺ 2⁺

Fig. 3. Spectrum of Gamma Rays Resulting from Capture of Neutrons at the 49-keV Resonance of F^{19} .

Table 1. Summary of Relative Intensities of Gamma-Ray Energies Observed in Neutron Capture on F^{19} at Thermal, 27 kev, and 49 kev

E_{γ}	E_{ex}	J^{π}	Thermal		27 kev 2^{-}		49 kev 1^{-}	
			$E_{\gamma \text{ obs}}$	Relative Intensity	$E_{\gamma \text{ obs}}$	Relative Intensity	$E_{\gamma \text{ obs}}$	Relative Intensity
6.60	0	$2,3^{+}$	6.6	25	6.6	1	6.6	<1
5.95	0.65	$1,2,3^{+}$	6.01	13	6.0	7	} 5.9	13
5.77	0.83	$1,2,3^{+}$						
5.61	0.99	$1,2,3^{+}$					5.65	11
5.54	1.06	$0,1^{+}$	5.55	20				
5.29	1.31	$1,2,3^{+}$	5.27	23	5.32	35	5.33	10
4.63	1.97				4.66	46		
4.55	2.05	$1,2,3^{+}$					4.60	36
4.40	2.20	$1,2,3^{+}$			4.43	7	4.40	4
3.73	2.87	$2,3,4^{-}$					} 3.67	10
3.63	2.97	$0,1,2^{-}$			} 3.1	4.5		
3.11	3.49	$0,1^{+}$					} 3.15	15
3.07	3.53	$0,1^{+}$						

observed partial widths and the matrix elements or gamma-ray reduced widths.

Tables 1 and 2 show what appears to be a suppression of $E1$ transitions especially to levels at (or near) ground. The gamma-ray reduced widths are smaller than those observed in nuclei lighter than F^{19} .¹⁰ The obvious question is whether the apparent discrepancy is not just that expected on the basis of a Porter-Thomas distribution. The number of resonances are too few to make a clear-cut experimental test of this point. However, on the basis of such a distribution there is less than one chance in 25 that the ground-state transition should be so weak as it appears in either the 27- or 49-kev resonance and only a few chances in a thousand that it should be simultaneously so small in both.

No attempt has been made to explain the behavior of the observed transition probabilities. The fact that the Porter-Thomas distribution is not obeyed for the transitions at or near ground indicates that the states are simple enough that correlations exist so that the basic assumption of the Porter-Thomas distribution is violated.¹¹ The strength of the magnetic transition to ground at thermal capture may be understandable on the basis of a "magnetic dipole resonance."¹² The weakness of the electric dipole transitions for resonance capture may require specific models for interpretation. The striking character of the behavior of the ground state transition in F^{20} depending upon the parity of the capturing state suggests an investigation of other nuclei in the s - d shells.

¹¹C. E. Porter and R. G. Thomas, *Phys. Rev.* **104**, 483 (1956).

¹²W. C. Barber et al., *Nucl. Phys.* **41**, 461 (1963).

¹⁰D. H. Wilkinson, *Phil. Mag.* **1**, 127 (1956).

Table 2. Summary of Partial Radiation Widths at the 27- and 49-keV Resonances for Neutron Capture on F^{19} Due principally to uncertainty in the total radiation width, the confidence figure is $\pm 50\%$

Capture Gamma Rays		27 keV (2^- , $\Gamma_\gamma = 1.1$ eV)		49 keV (1^- , $\Gamma_\gamma = 1.6$ eV)		
E_γ	E_{ex}	$\Gamma_{\gamma, obs}$	$ M'(E1) ^2{}^a$	$\Gamma_{\gamma, obs}$	$ M'(E1) ^2{}^a$	$ M'(M1) ^2{}^b$
		$\times 10^{-3}$	$\times 10^{-3}$	$\times 10^{-3}$	$\times 10^{-3}$	$\times 10^{-3}$
6.6	0	4	1	16	2	
5.95	0.65	777	14	210	40	
5.77	0.83					
5.61	0.99			175	38	
5.54	1.06					
5.29	1.31	380	100	160	41	
4.63	1.97	500	200			
4.55	2.05			580	240	
4.40	2.20	77	35	64	29	
3.73	2.87			160		970
3.63	2.97	50	40			
3.11	3.49			240	310	
3.07	3.53					

$${}^a B(E1) \equiv |M'(E1)|^2 = \Gamma_{\gamma_i} / 3.5 \times 10^{-3} E^3 A^{2/3}.$$

$${}^b B(M1) \equiv |M'(M1)|^2 = \Gamma_{\gamma_i} / 3.2 \times 10^{-3} E^3.$$

RESONANT NEUTRON CAPTURE GAMMA-RAY SPECTRA FROM NUCLEI IN THE s - d SHELL

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W. M. Good

I. Bergqvist¹

NUCLEAR REACTIONS. Na^{23} , Mg^{24} , Al^{27} , $S^{32}(n, \gamma)$, natural targets, $E_n = 10$ – 110 keV; measured $\sigma(E)$, γ spectrum. Na^{24} , Mg^{25} , Al^{28} , S^{33} , deduced resonant energies.

It has been noted that Al^{28} , like F^{20} , shows a strong $M1$ transition to ground in thermal capture.²

A totally different situation prevails in the case of Mg^{25} , Si^{29} , and S^{33} , each of which is characterized in thermal capture by weak $M1$ transitions to ground, and strong $E1$ transitions to levels well above ground.³

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²B. B. Kinsey and G. A. Bartholomew, *Physica* 18, 1112 (1952).

³G. V. Groshev et al., *Atlas of Gamma-Ray Spectra from Radiative Capture of Thermal Neutrons*, Pergamon Press (1959).

It is tempting to generalize the observations stated above: that *electromagnetic transitions take place "normally" in even-odd (compound) nuclei of the s-d shell, whereas in the odd-odd compound nuclei M1 transitions are strong and E1 transitions are weak, especially for states at and near ground.* There is no obvious reason why these nuclei should behave in this way, but it is an easy matter to check on such a possibility by studying the resonant gamma-ray spectra of other nuclei in the s-d shell.

The neutron time-of-flight spectrometer was used in conjunction with the 9×12 in. NaI spectrometer and the 3-Mv pulsed Van de Graaff to study capture spectra as a function of neutron flight time. The samples were in all cases natural samples, each 1 in. thick and 6 in. in diameter. So far it has been possible to examine resonance capture spectra for target nuclei Na^{23} , Mg^{24} , Al^{27} , Si^{28} , P^{31} , S^{32} , and Cl^{35} in addition to F^{19} , which has already been discussed (see preceding paper). The resulting data are not yet completely processed. Furthermore, it is not yet possible to say much about those new resonances not previously seen in transmission, or in the cases of those resonances for which the resonance parameters have as yet not been determined. However, the nuclides Na^{24} , Mg^{25} , Al^{28} , and S^{33} , obtained by neutron bombardment, have a number of resonances whose parameters are known. In these cases the known spins and parities of the initial states can give unambiguous assignments of observed gamma rays.

Figures 1 through 10 provide a summary of the results for these nuclides. Figures 1-5 show the situation for the odd-odd nuclei Na^{24} and Al^{28} . The thermal capture spectrum for these nuclei shows the strong M1 to levels near ground, "characteristic" of the odd-odd nuclei. Capture at the 3⁺ resonance at 54 kev in Na^{23} shows no appreciable E1 transition to either the 2⁺ or 4⁺ states allowed by the E1 selection rules. The peak near 36 kev has not been observed before. The 35-kev resonance in Al is a well-established positive parity level of $J = 3^+$, and the capture spectrum at this resonance resembles that obtained at thermal (characterized by 3⁺ also). The case of the

88-kev resonance is confused. The resonance reportedly⁴ consists of at least two close lying levels of both parities. That being the case, observance of the "rule" suggested would mean mixing a spectrum containing a relatively strong M1 transition to ground and one having a weak E1 transition to ground. The net effect would be a spectrum of reduced but not a vanishing ground-state transition. The spectrum obtained at the "88-kev" resonance does indeed resemble such a description.

This brings us to the Mg^{25} , S^{33} even-odd compound nuclei. In the case of S^{33} , the 111-kev resonance is $\frac{1}{2}^+$; hence, it should be similar to the thermal spectrum with its strong line several Mev above ground, and indeed it is. The 84-kev p-wave resonance in $\text{Mg}^{24} + n$ represents the case in the even-odd nuclei of a capturing state of opposite parity to ground. Note that in this case the strong "excited" transition at thermal gives way to strong E1 transitions to the states at and near ground. The situation in the case of the 50-kev resonance in $\text{Mg}^{24} + n$, not previously seen in transmission, is interesting. The similarity between the 50- and the 84-kev resonances would mark the 50-kev resonance as having the same parity as the 84-kev resonance, namely, negative. The assignment $\frac{3}{2}^+$ or $\frac{5}{2}^+$ for the 50-kev state comes from observing this same state in (d,p).⁵ The "rule" in this case is therefore not good, or else the parity assignment for this level is wrong. The latter is a distinct possibility since the theoretical stripping pattern is very sensitive to nuclear radius at excitation energies in excess of binding.

The spectra presented here therefore tend to further support the "rule" stated in the beginning. If such a rule does in fact seem to hold, then it could be used to make assignments on the resonance parameters of new resonances.

⁴C. T. Hibdon, *Phys. Rev.* 114, 179 (1959).

⁵R. M. Middleton and S. Hinds, *Nucl. Phys.* 34, 404 (1962).

Fig. 1. Gamma-Ray Yield from Sodium as a Function of Neutron Bombarding Energy.

Fig. 3. Gamma-Ray Yield from Aluminum as a Function of Neutron Bombarding Energy.

Fig. 2. Gamma-Ray Spectrum at the 54-keV 3^- Neutron Resonance of Neutrons on Sodium.

Fig. 4. Gamma-Ray Spectrum at the 35-keV 3^+ Resonance of Neutrons on Aluminum.

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Fig. 5. Gamma-Ray Spectrum at the 88-keV Resonance of Neutrons on Aluminum.

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Fig. 7. Gamma-Ray Spectrum at the 111-keV $\frac{1}{2}^+$ Resonance of Neutrons on Sulfur.

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Fig. 6. Gamma-Ray Yield from Sulfur as a Function of Neutron Bombarding Energy.

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Fig. 8. Gamma-Ray Yield from Magnesium as a Function of Neutron Bombarding Energy.

Fig. 9. Gamma-Ray Spectrum at the 84-keV $\frac{3}{2}^-$ Resonance of Neutrons on Magnesium.

Fig. 10. Gamma-Ray Spectrum at the 50-keV Resonance of Neutrons on Magnesium.

HIGH RESOLUTION NEUTRON TOTAL CROSS SECTIONS

J. A. Biggerstaff J. H. Gibbons W. M. Good
R. L. Macklin P. Pasma¹

NUCLEAR REACTIONS. S³², Fe⁵⁶, Pb^{206,207,208}(n), enriched Fe, Pb targets, E_n = 5-90 keV; measured σ_T(E). S³³, Fe⁵⁷, Pb^{207,208,209}, deduced resonance parameters, I_n.

The measurement of neutron total cross sections by the transmission method is conceptually one of the easiest quantitative measurements in nuclear physics. However, experience has proven that the successful execution of such a measurement is not so simple as one might expect. The principal problems in the keV range, in which our primary interest lies, are neutron source intensity, energy resolution, and an intimate knowledge of backgrounds. During the past year we have made two significant gains:

1. The neutron source strength has been increased with the introduction of klystron bunching of the pulsed proton beam in the accelerator terminal.² This has resulted in greater neutron peak intensities than previously possible.

2. A new technique of background measurement has resulted in both better effective time resolution and more accurate cross section results. Briefly, the neutron detector (B¹⁰-NaI) responds primarily to 478-keV gamma rays from a thin slab

¹Visiting scientist from FOM, Netherlands.

²C. D. Moak *et al.*, *Rev. Sci. Instr.* (to be published).

of $B_4^{10}C$ and also to gamma rays from $I(n,\gamma)$ in a much thicker NaI(Tl) crystal. The fraction of neutron captures in the iodine depends upon neutron transmission through the boron slab, which is energy-dependent. Most of the $I(n,\gamma)$ pulses are eliminated by restricting time analysis to those events producing 478-keV gamma rays [the $B^{10}(n,\alpha\gamma)$ photopeak] but some fall within this window. This effect, which produces a time-dependent background and time-resolution spoiling, has been eliminated by dynamic gating of the detector pulses to time-analyze 478-keV gamma-ray pulses in one section of the analyzer and gamma rays greater than 500 keV [characterizing $I(n,\gamma)$ events] in another section which, when properly normalized, gives a correct description of the background.

In addition to measurements on zirconium isotopes,³ measurements were performed on the nuclides S^{32} , Fe^{56} , Pb^{206} , Pb^{207} , and Pb^{208} . The studies of S^{32} and Fe^{56} were restricted to energy regions where capture cross section⁴ and capture gamma-ray spectra⁵ measurements have indicated that previously unobserved resonances exist. Resonances were located in sulfur (S^{32} at 29.8 keV - Fig. 1) and iron (Fe^{56} at 50.3 keV - Fig. 2), both of which are in good agreement with our capture measurements. The resonance parameters, obtained by area analysis, are given in Table 1. These resonances, which dominate the capture process, illustrate the danger inherent in trying to predict the capture cross section from knowledge of the total cross section.

The nuclear properties of lead are of great interest from the viewpoint of nuclear structure, particularly shell model, studies. The greatest recent interest in neutron reactions in lead comes, however, from those concerned with stellar nucleosynthesis and its time scale for our galaxy. It was primarily for this reason that the total cross sections of lead isotopes were measured. The results are given in Figs. 3, 4, and 5 and summarized in Table 2. Comparison with published

³See "Neutron Total Cross Section and Strength Functions of Zirconium Isotopes," this report, p. 82.

⁴R. L. Macklin, J. H. Gibbons, and T. Inada, *Nucl. Phys.* 43, 353 (1963).

⁵J. R. Bird, J. H. Gibbons, and W. M. Good, private communication of unpublished results.

Fig. 1. Neutron Total Cross Section for Sulfur. The resonance, discovered in capture experiments, is due to p -wave neutrons.

data^{6,7} indicates several areas of disagreement. In the case of $(Pb^{206} + n)$, the earlier work suffered from not having a good sample and also was obtained with poorer energy resolution. In fact, none of the four certain plus three probable additional resonances below 75 keV was reported earlier.⁶

The area of agreement is slightly better for $(Pb^{207} + n)$. There is good agreement on the width and spin (1^-) of the s -wave resonance near 41 keV. Our energy assignments are almost always the average of data obtained from two different flight paths. We do not understand the difference between our values and those given by the Duke group, but assume that the resonance at 16.4 keV is the one they identify as 19.6 keV and 28.6 keV as their value 28.0. The 36.8-keV resonance was previously undetected. We do not observe a resonance reported to be at 50 keV,⁶ and the resonance reported at 72.5 keV⁷ probably in fact belongs to $(Pb^{208} + n)$.

⁶H. W. Newson et al., *Ann. Phys.* 14, 346 (1961).

⁷E. G. Bilpuch et al., *Ann. Phys.* 14, 387 (1961).

We observe resonances (both $l > 0$ and presumed to be $l = 1$) at 70 and 77 kev in ($\text{Pb}^{208} + n$). The latter is in good agreement with studies at Duke both as to width (≈ 1000 ev) and spin ($\frac{1}{2}^-$). The isotopic purity of our sample ($> 99\%$ Pb^{208}) gives the assignment of the 70-kev resonance unambiguously to ($\text{Pb}^{208} + n$), rather than to Pb^{207} as assigned in ref. 7.

The total cross section results given here are now in good agreement with all resonances observed above 15 kev in capture cross section and capture gamma-ray spectra measurements save

one near 20.5 kev in ($\text{Pb}^{206} + n$). The width of this resonance is presumably below our present limit of detection by transmission.

Values for the effective nuclear radius, $R' = (\sigma_{\text{const.}}/4\pi)^{1/2}$, were obtained from these data. The results are $206 = 8.5 \pm 0.2$ fermis, $207 = 9.0 \pm 0.3$ fermis, and $208 = 8.4 \pm 0.3$ fermis. These values are in good agreement with the value 8.7 fermis predicted by the optical model.⁸

⁸F. Perey, private communication.

Table 1. Summary of Resonance Parameters for New Resonances in Sulfur and Iron
Values for the resonance energy as obtained by capture measurements
are given for comparison

Nucleus	$E_0 (\sigma_c)^a$	$E_0 (\text{Spectra})^b$	$E_0 (\sigma_T)$	Γ (ev)	Remarks
S^{32}	30 ± 0.5	30 ± 3	29.8 ± 0.3	50 ± 10 ($J = 1/2$)	Probably $l = 1$
				36 ± 8 ($J = 3/2$)	
Fe^{56}	~ 50	~ 55	50.3	44 ± 8 ($J = 1/2$)	$l = 1$ or 2
				29 ± 6 ($J = 3/2$)	
Fe^{56}	36 ± 1	~ 34	?	< 10	Not observed: Γ given is upper limit.

^aR. L. Macklin, J. H. Gibbons, and T. Inada, *Nucl. Phys.* 43, 353 (1963).

^bJ. R. Bird, J. H. Gibbons, and W. M. Good, private communication of unpublished results.

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Fig. 2. Neutron Transmission Through Fe⁵⁶. The large dip is due to the well-known s-wave level near 28 kev. Neutron capture measurements indicate two additional resonances near 35 and 50 kev. The 50-kev resonance is shown in these results but the 35-kev resonance is too weak to be detected.

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Fig. 3. Total Cross Section for Radiogenic Lead ($\sim 89\% Pb^{206}$). The only resonance shown that is not due to Pb^{206} lies at 41 kev (Pb^{207}). All resonances except the one at 64 kev are assumed to be p -wave.

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Fig. 4. Total Cross Section for Pb^{207} . The large resonance ($E_0 = 40.5$ kev, $J = 1^-$) is clearly due to s-wave neutrons. The remainder of the resonances are due to p-wave neutrons.

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Fig. 5. Total Cross Section for Pb^{208} . Both resonances are assigned to *p*-wave neutrons. No evidence exists for any resonance structure below 70 kev.

Table 2. Summary of Resonance Parameters for Lead Isotopes in the Energy Range 10 to 80 kev

Figures in parentheses correspond to values obtained in only one measurement and are therefore somewhat uncertain

Target Nucleus	E_0 (kev)	Probable I_n	Γ (ev)		
			$J = 1/2$	$J = 3/2$	
206	(12.2)	(1)	<14	<10	
	(16.0)	(1)	<20	<12	
	24.8	1	49 ± 10	34 ± 7	
	35.0	1	58 ± 8	39 ± 6	
	46.0	1	73 ± 9	48 ± 7	
	64.1	0	250 ± 150		
	74	(1)	50 ± 15	33 ± 10	
207			$J = 0$	$J = 1$	$J = 2$
	(12.1)	(1)	25 ± 15	14 ± 8	11 ± 5
	16.4	1	91 ± 20	51 ± 10	36 ± 7
	28.6	1	65 ± 15	30 ± 7	23 ± 6
	36.8	1	70 ± 20	30 ± 8	22 ± 5
	40.7	0		1350 ± 150	
208			$J = 1/2^a$	$J = 3/2$	
	70	1	100 ± 15	68 ± 8	
	77	1	900 ± 100	615 ± 70	

^a $J = 1/2$ preferred.

THE STRENGTH FUNCTIONS OF THE ISOTOPES OF ZIRCONIUM

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H. Kim

NUCLEAR REACTIONS. $Zr^{90,92,94,96}(n)$, enriched targets, $E_n \leq 50$ kev; measured $\sigma_T(E)$. $Zr^{91,93,95,97}$, deduced resonance parameters, strength functions.

The difficulties of agreement between the measured s-wave strength functions and the strength function theory in its original simple form are well known — namely, the inability of the theory to account for the very low value that is observed for masses 80 to 125.

The annual report of 1962 gave the first results of measurements on Zr on both the chopper and the pulsed Van de Graaff at ORNL. Only the observed resonant energies were available from the Van de Graaff measurements; the chopper measurements, which had progressed further,

UNCLASSIFIED
ORNL-DWG 63-5627Fig. 1. Total Cross Section of Zr^{90} . UNCLASSIFIED
ORNL-DWG 63-5628Fig. 2. Total Cross Section of Zr^{92} . Fig. 3. Total Cross Section of Zr^{94} .

UNCLASSIFIED
ORNL-DWG 63-5630 Fig. 4. Total Cross Section of Zr^{96} .

yielded a relatively high value of the s-wave strength function of $0.7 \pm 0.2 \times 10^{-4}$.

The Van de Graaff measurements have been processed since the last annual report. The observed cross sections for the even isotopes are shown in Figs. 1, 2, 3, and 4. The difficulties noted earlier¹ in interpretation are evident in these figures. Since the *p*-wave strength function becomes large in this region of masses, difficulties in separating *s*- and *p*-wave resonances are to be expected. The structure between resonances is mostly reproducible and real (see Fig. 1 which shows an energy region measured at two independent flight paths). It should be recalled that in the Van de Graaff measurements an energy interval is measured ideally over a range of order 40%, the next interval being measured at a 20% longer flight path, etc. Figures 1, 2, 3, and 4 are a composite of five energy intervals, each at a different flight path and under different background conditions. Joining the "pieces" is accomplished by a 1 or 2% shifting along the energy axis.

Table 1 is a summary of the resonances which are judged to be *s*-wave largely by their appearance. As in the measurement made on the ORNL chopper, the strength function is larger than was expected. The average for the four even isotopes is $1.3 \pm 0.4 \times 10^{-4}$, which is still higher than the ORNL chopper values, but the two measurements are on the edge of their combined standard errors.

Table 1. Summary of Resonance Parameters for *s*-Wave Resonances in Zirconium

	E_n	Γ_n (ev)	Γ_n^o (ev)	$\langle \Gamma_n^o \rangle / D$
Zr^{90}	3.8	32.7	0.51	$1.9 \pm 1 \times 10^{-4}$
	6.7	10.2	0.12	
	7.1	10.2	0.12	
	13.4	60.8	0.52	
	17.2	213	1.61	
	19.4			
	34.4			
	39.8	340	1.67	
	41.0	340	1.67	
Zr^{92}	43.0	340	1.67	$0.9 \pm 0.4 \times 10^{-4}$
	2.7	23.5	0.45	
	3.2	2.0	0.035	
	3.3	1.9	0.016	
	3.5	1.9	0.016	
	4.2	3.8	0.059	
	4.75	19.6	0.28	
	5.15	6.0	0.28	
Zr^{94}	6.9	70.6	0.85	$1.5 \pm 0.8 \times 10^{-4}$
	5.7	23.8	0.31	
	6.85	31.5	0.38	
	17.8	59.1	0.44	
Zr^{96}	19.0	264.0	1.90	$0.83 \pm 0.8 \times 10^{-4}$
	3.8	5.69	0.09	
	4.1	12.0	0.19	
	4.6	8.1	0.12	
	5.4	18.9	0.26	
	5.9	13.6	0.18	

¹H. W. Newson *et al.*, *Ann. Phys.* **8**, 211 (1959).

THE INTERACTION OF 350 kev POLARIZED NEUTRONS WITH POLARIZED Ho^{165} NUCLEI¹

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P. D. Miller

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NUCLEAR REACTIONS. $\text{Ho}^{165}(n)$, $E_n = 350$ kev; measured $\sigma_T(\theta, n \text{ polarization})$.

The interaction of polarized and unpolarized 350 kev neutrons with polarized and randomly oriented Ho^{165} nuclei was investigated in order to study the influence due to nuclear deformation and to search for a possible spin-spin interaction. The ORNL 3 Mv pulsed and bunched Van de Graaff was used in conjunction with a time-of-flight spectrometer. The $\text{Li}^7(p,n)$ reaction provided a source of 55% polarized 350 kev neutrons. Using the NBS transportable He^3 refrigerator, a single crystal of Ho^{165} metal was cooled to 0.34°K and a nuclear polarization of 73% was achieved in a magnetic field of 3 kilo-oersteds supplied by a superconducting split solenoid. The total cross section of randomly oriented Ho^{165} was measured between 300 and 400 kev. The differential cross section for unpolarized 350 kev neutrons elas-

tically scattered from randomly oriented Ho^{165} nuclei was measured in a cylindrical geometry, and the results compared with a coupled channel calculation and an optical model calculation, using deformed potentials. To investigate the spin-spin interaction, measurements were made of the transmitted intensities with the target nuclei polarized parallel and antiparallel to the direction of neutron polarization. This change in intensity, $(-0.11 \pm 0.32)\%$, implies a change in cross section of $+30 \pm 85$ mb, where the plus sign corresponds to a larger cross section for the parallel orientation. This result indicates that the strength of the spin-spin term in the optical model potential lies between -50 and $+110$ kev. Since the Ho^{165} nucleus is highly deformed, a transmission measurement was made to determine the change in cross section between a 73%-polarized and a 10%-polarized target. The transmission of the more polarized target decreased by $(1.3 \pm 0.4)\%$, which corresponds to a cross section increase of 350 ± 100 mb. This deformation effect on the cross section is in agreement with the effect from the coupled channel calculation.

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

²On leave of absence from the University of Basel, Switzerland.

³On leave of absence from the Tokyo University of Education.

⁴National Bureau of Standards.

NANOSECOND PULSING FOR VAN DE GRAAFF ACCELERATORS¹

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W. M. Good

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A pulsed ion source capable of delivering 10-ma proton bursts with durations of approximately 1 nsec is described. Critical design constraints are discussed and used to illustrate the general procedure for meeting various experimental require-

ments. The system consists of a duoplasmatron ion source, a lens-chopper combination, and a klystron buncher which uses the entire accelerator as drift path to produce bunched ion bursts at the target. The equipment has been fitted into the terminal of the ORNL 3-Mv Van de Graaff accelerator. Since no accessory bunching magnets are used, ion bursts can be delivered to many different target stations. An external diverter system is used to vary the repetition rate from 10^6 down to 3×10^4 sec⁻¹.

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

²Instrumentation and Controls Division.

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⁴Permanent address: South Africa Atomic Energy Board, Pretoria, South Africa.

SUBNANOSECOND TIMING WITH SEMICONDUCTOR DETECTORS¹

C. W. Williams²

J. A. Biggerstaff

Timing signals capable of better than 1-nsec resolution have been derived from semiconductor

detector systems without degrading their energy resolution performance. The technique employed consists of transformer-coupling a fast amplifier in series with the usual charge-sensitive amplifier used for energy analysis.

¹Abstract of published letter: *Nucl. Instr. Methods* 25, 320 (1964).

²Permanent address: Oak Ridge Technical Enterprises Corp., Oak Ridge, Tenn.

NEUTRON SCATTERING STUDIES¹

H. B. Willard

A review is presented on the development of neutron resonance phenomena in the Mev region.

The neutron, as an important tool for probing the nucleus, is discussed from the characteristic feature that the reactions or scatterings proceed through only a few states of a well-defined compound system.

¹Abstract of invited paper delivered at International Conference in Fast Neutron Physics, Houston, Tex., February 1963, and published in *Progress in Fast Neutron Physics* (ed. by G. C. Phillips, J. B. Marion, and J. R. Risser), pp. 273-88, University of Chicago Press, 1963.

THE INTERACTION OF NEUTRONS WITH Pb^{208}

J. L. Fowler.

NUCLEAR REACTIONS. $\text{Pb}^{208}(n)$, enriched target, $E_n = 0.7-1.9$ Mev; measured $\sigma(E, \theta)$. Pb^{209} , deduced resonance parameters, phase shifts.

The interaction of a nucleon with a closed-shell nucleus not only gives rise to single-particle states for which the nucleon is loosely bound to the relatively stable core, but also gives relatively short-lived compound nuclear states for which the core is in simple states of excitation. For Pb^{208} plus a neutron, for example, the calculated lifetimes of such compound states turn out to be the order of 100 times single-particle lifetimes.¹

Measurements of total² and differential³ cross sections for scattering of neutrons from Pb^{208} disclose a number of such relatively short-lived compound nuclear states.

¹Carl Shakin, *Ann. Phys.* 22, 373 (1963).

²J. L. Fowler and E. C. Campbell, *Phys. Rev.* 127, 2192 (1962).

³J. L. Fowler, *Bull. Am. Phys. Soc.* 8, 82 (1963).

$$\begin{aligned}
 E_n &= 0.821 \pm 0.0020 \text{ Mev} \\
 \delta_{s1/2} &= +75^\circ, \quad \delta_{p1/2} = -31^\circ \\
 \delta_{p3/2} &= -15^\circ, \quad \delta_{d3/2} = 1^\circ \\
 d^{5/2} &\left\{ \begin{array}{l} \Gamma_{1/2} = 0.0054 \text{ Mev} \\ \text{POT.} = -11.5^\circ \\ E_0 = 0.820 \text{ Mev} \end{array} \right.
 \end{aligned}$$

$$\begin{aligned}
 E_n &= 0.800 \pm 0.0036 \\
 \delta_{s1/2} &= +88^\circ, \quad \delta_{p1/2} = +0^\circ \\
 \delta_{p3/2} &= -19^\circ, \quad \delta_{d3/2} = -16^\circ \\
 d^{5/2} &\text{ FROM } 0.821 \text{ Mev} \\
 &\text{RESONANCE}
 \end{aligned}$$

$$\begin{aligned}
 E_n &= 0.769 \pm 0.0025 \\
 \delta_{s1/2} &= +48^\circ, \quad \delta_{p1/2} = -27^\circ \\
 p^{3/2} &\left\{ \begin{array}{l} \Gamma_{1/2} = 0.0020 \text{ Mev} \\ \text{POT.} = -10^\circ \\ E_0 = 0.769 \text{ Mev} \end{array} \right. \\
 \delta_{d3/2} &= +3^\circ, \quad \delta_{d5/2} = -16^\circ
 \end{aligned}$$

$$\begin{aligned}
 E_n &= 0.723 \pm 0.0029 \text{ Mev} \\
 \delta_{s1/2} &= +104^\circ, \quad \delta_{p1/2} = +29^\circ \\
 \delta_{p3/2} &= -15^\circ, \quad \delta_{d3/2} = +5^\circ \\
 d^{5/2} &\left\{ \begin{array}{l} \Gamma_{1/2} = 0.0023 \text{ Mev} \\ \text{POT.} = -9^\circ \\ E_0 = 0.7225 \text{ Mev} \end{array} \right.
 \end{aligned}$$

$$\begin{aligned}
 E_n &= 0.715 \pm 0.0034 \text{ Mev} \\
 \delta_{s1/2} &= +65^\circ, \quad \delta_{p1/2} = +25^\circ \\
 \delta_{p3/2} &= -19^\circ, \quad \delta_{d3/2} = 0^\circ \\
 d^{5/2} &\text{ FROM } 0.723 \text{ Mev} \\
 &\text{RESONANCE}
 \end{aligned}$$

Fig. 1. Least-Squares Partial-Wave Phase-Shift Fit to Differential Cross Sections for Neutron Scattering from Pb^{208} in Energy Region 0.715 to 0.821 Mev.

Figures 1 and 2 give typical differential cross sections of neutron scattering from Pb^{208} , as obtained with apparatus designed to measure the scattering of neutrons from small samples with good energy resolution.³ Collimated $\text{Li}(p,n)$ neutrons, scattered by a cylindrical Pb^{208} sample, were detected with a stilbene crystal. The sample,

which was 99.75% Pb^{208} (ref. 4), and the crystal were mounted in a $1 \times 1 \times 0.6$ m shielded region. Pulses from the crystal arising from gamma rays were suppressed by pulse-shape discrimination.

⁴ Separated by the Isotopes Division.

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Fig. 2. Least-Squares Partial-Wave Phase-Shift Fit to Differential Cross Sections for Neutron Scattering from Pb^{208} in Energy Region 0.855 to 1.111 Mev.

Figures 1 and 2 show the cross sections in the center-of-mass system plotted against the cosine of the center-of-mass angle. These curves have been corrected for the angular resolution of the counting geometry (less than 5%), for the effect of the second group of neutrons from the $\text{Li}(p,n)$ reaction (less than 2%, even for the 1.111-Mev data), and for multiple scattering. This latter correction, which for the curves shown in Figs. 1 and 2 amounted to as much as $\sim 35\%$ (minimum cross section in case of 0.821-Mev resonance, for example), was calculated by use of the procedure described in the literature.⁵ The indicated errors in the cross sections include the standard errors of counting combined statistically with the errors in the multiple-scattering correction, estimated to be one-third of this correction. Arrows indicate the neutron energy of the differential measurements as they are related to published neutron total cross sections.² Resonant energies were relocated prior to each run by a determination of neutron transmission through a 72% Pb^{208} sample. The neutron energy spread (half width at half maximum, as obtained by observing the rise in neutron yield at threshold with a long counter), is noted beside each curve.

The phase shifts and resonant parameters listed beside each set of data yield the solid curves. These result from a least-squares fit to the experimental points. A FORTRAN code, written to compute differential cross sections for neutron scattering from 0-spin nuclei as a function of scattering phase shifts up to $\delta g_{7/2}$ (ref. 6), was incorporated into a search routine to obtain a fit to the data. The resulting combined code, which averages the theoretical curves over the energy spread of experimental measurements, uses matrix operations⁷ to adjust several phase shifts simultaneously in order to arrive at a minimum in the sum of the weighted squares of deviations between experimental points and theoretical values. In practice, one finds it necessary to be very close to the minimum in the square of the deviations in order to have the calculations converge if as

many as four scattering phase shifts are adjusted simultaneously. The procedure adopted, then, is to use the code to vary the phase shifts in pairs until one is reasonably close to a satisfactory fit. After this is done, a final adjustment can often be made by varying all of the phase shifts simultaneously.

The type of analysis illustrated by Figs. 1 and 2 has been extended up to 1.285 Mev. The spin and parity assignments found are listed in Fig. 3

Fig. 3. Total Neutron Cross Section of Pb^{208} and Quantum Parameters of Prominent Resonances.

⁵J. L. Fowler and H. O. Cohn, *Phys. Rev.* **109**, 89 (1958).

⁶J. L. Fowler, John Agnew, and Mary J. Mader, *Bull. Am. Phys. Soc.* **8**, 549 (1963).

⁷M. H. Lietzke, *A Generalized Least-Squares Program for IBM 7090 Computer*, ORNL-3259 (Mar. 21, 1962).

above the prominent resonances. Below these quantum parameters are the reduced widths of the resonances in units of $3\hbar^2/2ma^2$. Reference 2 gives a discussion of how these reduced widths were estimated. It is apparent that for these prominent resonances reduced widths are the

order of 100 times smaller than the single-particle widths in agreement with expectation from theory.¹ The phase-shift analysis is being continued on the additional differential-cross-section measurements which have been obtained up through the 1.761-Mev resonance.

THE SCATTERING OF 3 TO 4 Mev NEUTRONS FROM O¹⁶

J. L. Fowler

C. H. Johnson

NUCLEAR REACTIONS. O¹⁶(n,n), $E_n = 2.25-3.90$ Mev; measured $\sigma(\theta)$. O¹⁷, deduced resonance parameters, phase shifts.

The scattering of neutrons by O¹⁶ is expected to be relatively simple because this is a doubly closed-shell nucleus. Since the target spin is zero, the number of phase shifts required to fit the differential scattering cross section should not be excessive, and the information which they contain should be clear in regard to the sharp compound states of O¹⁷ and also in regard to the short-lived single-particle states of the neutron and the O¹⁶ core.

A measurement of the total neutron cross section is an essential first step. The right-hand side of Fig. 1 shows the total cross section for neutron energies from 0 to 8 Mev as reported by Bockelman *et al.*¹ and Fossan *et al.*² The region below 2.5 Mev, corresponding to 4 to 6.5-Mev excitation in O¹⁷, has already been studied by several groups, and the spins and parities of six of the seven levels in this region have been assigned³ on the basis of the total and the differential scattering cross sections. In addition, the smoothly varying nonresonant phase shifts were determined⁴ from

differential scattering measurements between resonances, and these phase shifts are consistent with a potential that gives the positions of the single-particle states.

Our aim now is to extend the differential scattering measurements and phase-shift analyses at least up to 4-Mev neutrons. Clearly, the total cross section shows a complicated level structure in this region. The very broad peak centered at about 3.6 Mev has a peculiar shape that results from the overlap of more than one resonance. The narrow 3.44- and 3.77-Mev resonances, which ride on top of the broad peak in Fig. 1, were found with 20-keV neutron energy resolution. Two more narrow resonances have been reported^{5,6} with better resolution in the inverse C¹³(α ,n)O¹⁶ reaction at energies corresponding to 3.20- and 3.62-Mev neutrons. Of these four resonances, only the one at 3.77 Mev has sufficient width, 25 keV, to be resolved in the present work. Its peak height corresponds to $J = 5/2$, and its parity is assigned here. The three narrower resonances concern us only in that we have avoided measurements too near them in our effort to study the

¹C. K. Bockelman, *Phys. Rev.* **80**, 1011 (1950); C. K. Bockelman *et al.*, *Phys. Rev.* **84**, 69 (1951).

²D. B. Fossan *et al.*, *Phys. Rev.* **123**, 209 (1961).

³F. Ajzenberg-Selove and T. Lauritsen, *Nucl. Phys.* **11**, 1 (1959).

⁴J. L. Fowler and H. O. Cohn, *Phys. Rev.* **109**, 89 (1958).

⁵M. G. Rusbridge, *Proc. Phys. Soc. (London)* **A69**, 830 (1956).

⁶R. B. Walton, D. J. Clement, and F. Boreli, *Phys. Rev.* **107**, 1065 (1957).

Fig. 1. A Presentation of the Observed Differential Scattering Cross Section and of the Results of the Phase Shift Analysis. The five curves in the center of the figure give the present measurements and some data from ref. 8. The energies for these measurements are indicated by arrows leading to the plot of total cross section at the right. Results of the phase shift analyses are shown at the left.

smoothly varying nature of the phase shifts. One other resonance, which is of interest here, was observed⁵⁻⁷ in the inverse reaction at an energy corresponding to 4.02-Mev neutrons. It is a $J = \frac{1}{2}$, 110-kev-wide level which apparently causes the anomaly near 4 Mev in the total cross section. The neutron width is at least 10 times the alpha-particle width for both the 3.77- and 4.02-Mev resonances.

The five curves in the center of Fig. 1 show the differential cross section vs the cosine of the center-of-mass scattering angle at laboratory neutron energies of 2.25, 3.00, 3.35, 3.77, and 3.90 Mev. The 2.25-Mev measurements were made by J. P. Martin and M. S. Zucker;⁸ data at 3.00 Mev and also the data shown by solid circles at

⁷T. W. Bortner et al., *Phys. Rev.* 102, 1348 (1956).

⁸M. D. Goldberg, V. M. May, and J. R. Stehn (eds.), *Angular Distributions in Neutron-Induced Reactions*, BNL-400, 2d ed., vol. I (October 1962).

3.35 Mev are the work of D. D. Phillips.⁸ Our data duplicate those of Phillips at 3.35 Mev and extend to 3.77 Mev and 3.90 Mev. Neutrons for the present work were produced with about 20-kev energy resolution by the $T(p,n)He^3$ reaction in a gas target. Neutrons were collimated in the forward direction and scattered from a small cylindrical sample which was mounted in the center of a large shielded cavity.⁹ The scattered neutrons were detected by a stilbene crystal with the use of pulse-shape discrimination against gamma rays. The main scattering sample is a BeO cylinder, $\frac{5}{8}$ in. in diameter and $4\frac{1}{2}$ in. long, which has an average transmission of about 80% for the neutrons incident perpendicular to its axis. A matching sample of Be replaced the BeO cylinder during the measurement of background. Data at each angle consisted of a sequence of observations of scattering from the BeO, from the Be, and from the supporting mechanism; and each sequence was preceded and followed by a measurement of the direct flux at 0° . Data were taken in random order for the 12 angles and were repeated until four measurements at each angle were available for averaging to give the final curve. Corrections have been made for finite angular resolution, for the variation in counter efficiency with the energy of the scattered neutrons, and for multiple scattering in the sample. This latter correction was as much as 40% and was made by a procedure described in ref. 4. The indicated errors in the cross section include the standard error of counting statistics combined in quadrature with a multiple-scattering uncertainty which is estimated to be one-third of the correction.

The neutron-energy calibration was checked several times during the experiment by finding the peak of the 3.77-Mev resonance in a simple attenuation measurement with a BeO scatterer. The neutron energy resolution, as determined from the rise in yield near threshold, was about 20 kev for 3 to 4 Mev neutrons.

The absolute values of the cross sections were determined by use of the U^{235} flux measurement, corrected for the dead time of the counter when it is in the direct flux. Integration of these absolute values gave good agreement with the total cross section at 3.35 and 3.77 Mev, but gave a value 20% high at 3.90 Mev. The reason for this discrepancy is not known. All of the curves in

the figure have been normalized so that the integrated cross sections agree with the known total cross sections.

The excellent agreement of our work at 3.35 Mev with that of Phillips indicates that we can use both sets of data in the analysis. A least-squares procedure¹⁰ has been used to fit these angular distributions with a smoothly varying set of phase shifts. At the first two energies, 2.25 and 3.00 Mev, the $s_{1/2}$ phase shift was assigned consistently with the information that is contained in the 2.37-Mev s-wave resonance. At 3.77 Mev, the resonance contribution was required to give a state of $J = \frac{5}{2}$ and width $\Gamma = 25$ kev. The $d_{5/2}$ phase shift at 3.90 Mev was then assigned on the basis of the 3.77-Mev results. The resulting parameters are shown on the left side of Fig. 1.

The data are not yet good enough to give all of the details of the phase shifts; nevertheless, some conclusions are clear. The 3.77-Mev resonance, which could be formed by d - or f -wave neutrons, seems to be formed by d waves. Also the $d_{3/2}$ phase shift goes through resonance near 3.35 Mev and the $p_{3/2}$ phase shift near 3.8 Mev. Both phase shifts vary slowly; hence, they correspond to overlapping $\frac{3}{2}^+$ and $\frac{3}{2}^-$ resonances which contribute to the broad peak. The rise of the $p_{1/2}$ phase shift at 3.90 Mev suggests that the 4.02-Mev, $J = \frac{1}{2}$ level is formed by p waves; however, this statement is speculative. The eventual parity assignment for this level is of particular interest because the parities of the next two levels relative to this one are already known.^{6,11}

These results give good qualitative agreement with an early measurement by Baldinger, Huber, and Proctor¹² on the scattering of neutrons by oxygen in an ion chamber. They found resonances in the $d_{3/2}$ and $p_{3/2}$ phase shifts at 3.33 and 3.80 Mev, respectively, and a rising $p_{1/2}$ phase shift at 4 Mev; however, the energy variations of their phase shifts differ somewhat from ours.

Further measurements with a liquid oxygen scatterer are planned in order to reduce the uncertainties in the positions and widths of the levels.

¹⁰J. L. Fowler, "The Interaction of Neutrons with Pb^{208} ," this report.

¹¹J. P. Schiffer, A. A. Kraus, Jr., and J. R. Risser, *Phys. Rev.* 105, 1811 (1957).

¹²E. Baldinger, P. Huber, and W. G. Proctor, *Helv. Phys. Acta* 25, 142 (1952).

⁹J. L. Fowler, *Bull. Am. Phys. Soc.* 8, 82 (1963).

ELASTIC SCATTERING OF 17- TO 21-Mev NEUTRONS FROM C^{12}

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R. L. Robinson

B. B. Kinsey³

NUCLEAR REACTIONS. $C^{12}(n,n)$, $E_n = 17-21$ Mev; measured $\sigma(\theta)$. C^{13} , deduced level.

Several years ago, Kinsey⁴ reported a resonance in the yield of elastically scattered protons from C^{12} at a proton energy of 22.5 Mev. Dickens, Haner, and Waddell⁵ recently confirmed and studied this resonance more extensively. The resonance corresponds to a 22.7-Mev state (or states) in the compound nucleus N^{13} , which is formed by a proton plus C^{12} . One might expect a similar state to occur in C^{13} , which is formed by a neutron plus C^{12} . If a compound state is present at

22.7 Mev in C^{13} , a resonance should be observed in the yield of neutrons scattered from C^{12} at an energy of 19.3 Mev. A search has been made for such a resonance by investigating the differential elastic cross section as a function of energy at six scattering angles and the total cross section as a function of energy of 17- to 21-Mev neutrons on C^{12} .

The differential elastic cross section was measured with a ring geometry arrangement⁶ as illustrated in Fig. 1. The carbon scatterer was a ring with an inside radius of 3 in. and 1.1 in. $\times$ 1.5 in. cross section. Pulse-shape discrimination was used with the detector to remove the gamma-ray background. Neutrons were produced by bombarding the tritium gas target with deuterons

¹Preliminary experiments and the development of the apparatus for this work began at the University of Texas under the supervision of B. B. Kinsey.

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³Department of Physics, The University of Texas, Austin, Tex.

⁴B. B. Kinsey, *Phys. Rev.* **99**, 332 (1955).

⁵J. K. Dickens, D. A. Haner, and C. N. Waddell, *Phys. Rev.* **132**, 2159 (1963).

⁶M. Walt, p. 1033 in *Fast Neutron Physics, Part II*, ed. by J. B. Marion and J. L. Fowler, Interscience, New York, 1963.

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Fig. 1. Schematic Diagram of the 60° Geometry Used for the Differential Cross-Section Measurement.

obtained from the 5.5-Mv Van de Graaff accelerator.

For the total-cross-section measurements, the shadow cone and carbon annulus shown in Fig. 1 were removed and the detector was placed 36 in. from the tritium target. The cross section was determined from the ratio of neutrons detected with and without a 3-in. length of carbon inserted midway between the target and detector. The results are shown in Fig. 2. They have been corrected for inscattering (the correction was less than 1%). Absolute errors in the total cross section and in the neutron energy are shown by the error bars in Fig. 2. These data show a resonance at 19.6 ± 0.20 Mev with a peak height that is 8% of the nonresonant cross section and with a total width at half maximum of 1.2 Mev.

The differential cross section results are shown in Fig. 3 for center-of-mass scattering angles of 38.8° , 54.7° , 64.1° , 90.8° , 127.5° , and 142.1° . Corrections for multiple scattering, finite sample size, and sample absorption have been applied to the data. Counting statistics for each point are indicated by the error bars in Fig. 2; the absolute error in the cross section is estimated to be about

$\pm 30\%$. At 38.8° , 54.7° , and 64.1° , there is a resonance with a total width at half maximum of approximately 1.2 Mev centered about a laboratory neutron energy of 19.5 ± 0.20 Mev. Its peak height is between 14 and 17% of the value of the nonresonant cross section. Within the 6% statistical error of our measurements, the resonance does not appear at 90.8° . At 127.5° and 142.1° , the cross section decreases monotonically by a factor of 3 between 17.5 and 20.5 Mev.

The variation of the differential cross section curves with energy and angle, as shown in Fig. 2, has a marked semblance with those illustrated by Dickens *et al.*⁵ for elastic scattering of protons from C^{12} . This along with the energy of the resonance indicates that C^{13} does indeed have a state with essentially the same energy as the 22.7-Mev state in N^{13} , and that the characteristics of the two states are similar.

Fig. 2. The Total Cross Section of Neutrons on Carbon.

Fig. 3. The Differential Cross Section for Neutrons Elastically Scattered from C^{12} .

***n-d* SCATTERING: A SEARCH FOR EFFECTS DUE TO THE DINEUTRON**

H. B. Willard

J. K. Bair

C. M. Jones

NUCLEAR REACTIONS. $H^2(n,n)$, enriched target, $E_n = 2.8-3.6$ Mev; measured $\sigma_T(E)$, $\sigma_s(E)$. n^2 , existence.

Attempts¹⁻¹¹ to detect effects due to a bound state of two neutrons, the dineutron, either have yielded negative results, or have been of ambiguous interpretation. A recent¹² calculation predicts a large threshold effect in the $n-d$ scattering cross section on the assumption that the dineutron exists and that one of two possible sets of scattering lengths, $a_2 = 8.3 \pm 0.3$ fermis and $a_4 = 2.6 \pm 0.3$ fermis, is the correct set. This effect would manifest itself either as a cusp in the total cross section or as a rounded step of 15 to 23% variation in the integral scattering cross section in the vicinity of the three-body threshold (neutron bombarding energy of ~ 3.3 Mev in the laboratory system). Its exact location and "width" would depend upon the dineutron binding energy, among other factors, and would be shifted downward from 3.3 Mev by an amount proportional to the binding energy. The energy variation itself should occur within an interval of 100 to 200 kev. Since He^6 is known to undergo beta decay instead of dineutron emission, an upper limit to the binding

energy can be placed from the known mass values.¹³ This limit is 964 ± 18 kev. The effect then may occur between 1.89 and 3.34 Mev neutron bombarding energy. We have searched for such effects in the total and scattering cross sections of neutrons on deuterium in the region an effect is most likely to occur — 2.8 to 3.6 Mev.

Published data¹⁴ on the neutron total cross section of deuterium are spaced about 400 kev apart in this energy region. Accordingly, we have measured this cross section with energy resolution and increments of 20 kev. Neutrons of the appropriate energy were produced by bombarding a $337\text{-}\mu\text{g}/\text{cm}^2$ T-Zr target with protons from the ORNL 5.5-Mv Van de Graaff accelerator. The experimental value of the energy resolution was obtained by observing the 2.076 ± 0.008 Mev resonance¹⁵ in the neutron total cross section of C¹². This resonance has a natural width of 7 kev. From the observed width of 24 kev at 2 Mev, we derived an experimental resolution value of 20 kev at 3 Mev. The calculated energy loss, or target thickness, in the Zr was about 18 kev at this energy. An energy scale was determined to ± 5 kev relative to the $Li^7(p,n) Be^7$ threshold.¹⁶

Transmissions of deuterated polyethylene samples, enriched to 98.3% in deuterium, were compared to graphite samples containing an equivalent amount of carbon. Samples were chosen to give transmission of higher than 60 to 70% and were 1.227 in. in diameter. The neutrons were detected with a stilbene crystal 1 in. in diameter and 1 in. in length located at 0° and 24 in. from the target. Pulse-shape discrimination against gamma rays

¹M. Y. Colby and R. N. Little, *Phys. Rev.* **70**, 437 (1946).

²D. N. Kundu and M. L. Pool, *Phys. Rev.* **73**, 22 (1948).

³N. Feather, *Nature* **162**, 213 (1948).

⁴R. F. Taschek et al., *Phys. Rev.* **79**, 238 (1950).

⁵F. W. Fenning and F. R. Holt, *Nature* **165**, 722 (1950).

⁶K. M. Watson and R. N. Stuart, *Phys. Rev.* **82**, 738 (1951).

⁷A. J. Ferguson and J. H. Montague, *Phys. Rev.* **87**, 215 (1952).

⁸B. L. Cohen and T. H. Handley, *Phys. Rev.* **92**, 101 (1953).

⁹R. Phillips and K. Crowe, *Phys. Rev.* **96**, 484 (1954).

¹⁰V. V. Komarov and A. M. Popova, *Izv. Akad. Nauk SSSR, Ser. Fiz.* **24**, 1153 (1960).

¹¹K. Ilakovac et al., *Phys. Rev.* **124**, 1923 (1961).

¹²R. Alzetta, G. C. Ghirardi, and A. Rimini, *Phys. Rev.* **131**, 740 (1963).

¹³F. Everling et al., *Nucl. Phys.* **15**, 342 (1960).

¹⁴D. J. Hughes and R. B. Schwartz, *Neutron Cross Sections*, BNL-325 (1958).

¹⁵J. E. Wills et al., *Phys. Rev.* **109**, 891 (1958).

¹⁶J. B. Marion, paper presented at Second International Conference on Nuclidic Masses, Vienna, July 15-19, 1963.

was utilized. Measured shadow cone backgrounds were less than 2%. Inscattering corrections of less than 0.5%, employing experimental n - d scattering differential elastic scattering cross sections,¹⁷ were made to the total cross sections. The relative probable error in the total cross section measurements is less than $\pm 2\%$. However, due to some small impurities in the CD_2 samples, the absolute probable error in the data is estimated to be about $\pm 4\%$. The data seem to be systematically lower than the empirical curve of Seagrave and Henkel¹⁸ by about 4%.

The results of our total cross section measurements from 2.8 to 3.6 Mev are shown in Fig. 1. A cusp variation in the total cross section of the type predicted could have been observed easily with the present accuracy and energy resolution. There is no such cusp discernible in the expected energy region.

In order to confirm these results, we performed a similar experiment on the scattering cross section.

¹⁷J. D. Seagrave and L. Cranberg, *Phys. Rev.* 105, 1816 (1957).

¹⁸J. D. Seagrave and R. L. Henkel, *Phys. Rev.* 98, 666 (1955).

For this purpose the same neutron source was employed, but recoil spectra of deuterons from an $800\text{-}\mu\text{g}/\text{cm}^2$ deuterated polyethylene radiator were observed with a surface-barrier detector mounted directly behind. The half angle subtended by the radiator at the neutron source was $\pm 5^\circ$. Backgrounds were measured by removing the radiator. The background spectra were similar to a hydrogen recoil spectrum taken with a CH_2 radiator and indicated a $\sim 100\text{-}\mu\text{g}/\text{cm}^2$ -thick surface layer of hydrogenous material on the silicon detector. The total background was from 20 to 30% of the deuteron recoils. A typical spectrum, after background subtraction, taken at a neutron energy of 2.8 Mev, is shown in Fig. 2. It is well known that the distribution of elastic scattering recoils with pulse height is directly proportional to the angular distribution of neutron scattering in the center-of-mass system.¹⁹ To improve our statistical accuracy, we have integrated the spectra from $\cos \phi = -0.3$ to $\cos \phi = -1.0$. These results from 2.8 to 3.6 Mev are shown in Fig. 3, together with limit curves of $\pm 5\%$, and a dashed theoretical

¹⁹H. H. Barschall and M. H. Kanner, *Phys. Rev.* 58, 590 (1940).

Fig. 1. The Neutron Total Cross Section for Deuterium as a Function of Neutron Energy.

Fig. 2. The Deuteron Recoil Spectrum from 2.8-Mev Neutrons Scattered from Deuterium.

curve calculated for a dineutron binding energy of 50 kev. Again, the predicted step in the elastic scattering cross section is undiscernible in the data. The relative probable error in the data points is estimated to be $\pm 4\%$.

We conclude from these experiments that either (1) the dineutron does *not* exist and the favored scattering lengths $a_2 = 8.3$ fermis and $a_4 = 2.6$ fermis chosen¹² for calculating the threshold effects are valid, or (2) the dineutron may exist

Fig. 3. The *N-D* Elastic Scattering Cross Section Integrated from $\cos \phi = -0.3$ to $\cos \phi = -1.0$ as a Function of Neutron Energy.

and the unfavored scattering lengths $a_2 = 0.7 \pm 0.3$ fermis and $a_4 = 6.4 \pm 0.3$ fermis are correct. Both sets of scattering lengths are consistent with the low-energy *n-d* scattering data, but set 1 seems to hold a slight theoretical preference.^{20,21}

²⁰L. Spruch and L. Rosenberg, *Phys. Rev.* 117, 1095 (1960).

²¹A. N. Metra and V. S. Bhasin, *Phys. Rev.* 131, 1265 (1963).

A SEARCH FOR INTERFERENCE EFFECTS BETWEEN NUCLEAR RESONANCE AND COULOMB EXCITATION IN THE $\text{Na}^{23}(p,p')\gamma$ REACTION¹

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J. K. Bair

R. L. Robinson

H. B. Willard

NUCLEAR REACTIONS. $\text{Na}^{23}(p,p'\gamma)$, $E_p = 828\text{--}1100$ kev; measured $I(0.439\gamma)$.

The narrow, isolated resonance in the $\text{Na}^{23}(p,p')$ reaction at 873 kev, situated upon a continuum due to Coulomb excitation, would appear to be a favorable case for observing interference effects between compound-nucleus inelastic scattering and Coulomb excitation. The yield of 439-kev

gamma radiation emitted from the first excited state of Na^{23} was measured from 828 to 1100 kev incident proton bombarding energy. To within the accuracy of the experimental data, about $\pm 8\%$, the noninterfering compound-nucleus and Coulomb-excitation contributions adequately account for the resonance shape, although the presence of an interference effect cannot be definitely excluded.

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

NEUTRONS FROM THE PROTON BOMBARDMENT OF Li^6 , Li^7 , Be^9 , B^{11} , AND O^{18} ¹

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C. M. Jones

H. B. Willard

NUCLEAR REACTIONS. $\text{Li}^6(p,n)$, enriched target, $E_p = 5\text{--}14$ Mev; measured I_n , Q . Li^7 , Be^9 , $\text{B}^{11}(p,n)$, enriched targets, $E_p = 4\text{--}14$ Mev; measured I_n . $\text{O}^{18}(p,n)$, enriched target, $E_p = 3.5\text{--}10$ Mev; measured I_n . Be^6 , deduced mass. B^9 , C^{12} , deduced levels. F^{19} , deduced resonant peaks.

The total neutron yield from proton bombardment has been measured for Li^6 from threshold to 14 Mev; for Li^7 , Be^9 , and B^{11} from 4 to 14 Mev; and for O^{18} from 3.5 to 10 Mev. The $\text{Li}^6(p,n)\text{Be}^6$ reaction Q measured in this experiment is -5.05 ± 0.05 Mev, giving a Be^6 mass excess of 18.36 ± 0.05 Mev. The neutron yield from Li^7 at higher energies cannot be explained on the basis of the

(p,n) reaction alone and is ascribed in part to multi-particle breakup. An anomaly in the $\text{Be}^9 + p$ neutron-yield curve is ascribed to a threshold for production of neutrons by a state in B^9 at 4.04 Mev. The $\text{B}^{11}(p,n)\text{C}^{12}$ reaction results confirm previous level structure in C^{12} and a new "level" at $E_p = 11.85$ Mev (energy of excitation in C^{12} of 26.81 Mev). The $\text{O}^{18} + p$ neutron yield shows 21 "resonant" peaks (energy of excitation 11.4 to 16.8 Mev).

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

ALPHA-ALPHA CORRELATIONS IN THE REACTION $\text{Li}^7 + d \rightarrow 2\alpha + n$

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C. H. Johnson
H. B. Willard

NUCLEAR REACTIONS. $\text{Li}^7(d, 2\alpha n)$, enriched target, $E_d = 4-7$ Mev; measured $\alpha\alpha(\theta)$.

The reaction $\text{Li}^7 + d \rightarrow 2\alpha + n$ has been studied at deuteron bombarding energies of 4.0 and 7.0 Mev by simultaneously observing at different angles the two emitted alpha particles. Thin LiH-on-C targets were used, and the deuteron beam was provided by the ORNL tandem Van de Graaff accelerator. One detector was fixed at an angle of 45° with respect to the beam and an angle of 80° with respect to the axis of rotation of the second counter. The angle of the second counter with respect to the beam was varied between 30° and 150° .

A fast "crossover pick-off" coincidence system, with a resolving time of 80 nsec, was used to detect coincidences between the two detectors. When a coincidence occurred, the energy in each

detector was digitized and punched on paper tape using elements of the system described by Schmitt.¹ This tape was then sorted on a digital computer to provide a 128×128 -channel, three-dimensional energy vs energy array. A total of 15 such arrays were obtained, with the number of events in each array varying between 0 and 20,000. The analysis of these data is now in a preliminary stage.

In addition, a study has been made of certain aspects of the kinematics of reactions with three emergent particles, and computer programs have been written to calculate kinematical functions of interest.

¹Phys. Div. Ann. Progr. Rept. Jan. 1, 1962, ORNL-3268, p. 55.

LOW-ENERGY (p, n) REACTION ON Mn^{55} ¹

H. J. Kim

NUCLEAR REACTIONS. $\text{Mn}^{55}(p, n)$; measured $\sigma(E_p)$, n spectrum, fluctuations.

Two neutron groups, corresponding to 510 ± 10 kev and 680 ± 10 kev excited states of Fe^{55} , are observed in the neutron time-of-flight spectrum of the reaction $\text{Mn}^{55}(p, n)\text{Fe}^{55}$. The above neutron

groups are observed in addition to the previously observed² neutrons feeding g.s., 410 kev, and 904 kev states of Fe^{55} . Excitation functions of the above neutrons fluctuate with incident energies, and the fluctuation widths are ~ 10 kev.

¹A letter with this title is published in *Phys. Letters* 5, 138 (1963).

²A. J. Elwyn et al., *Phys. Rev.* 112, 1200 (1958).

THE NEUTRON SPECTRA FROM $\text{Li}^7(d,n)\text{Be}^8$ AND $\text{F}^{19}(d,n)\text{Ne}^{20}$ FOR 1.98-Mev DEUTERONS¹

C. H. Johnson

C. C. Trail²

NUCLEAR REACTIONS. $\text{Li}^7(d,n)$, enriched target, $E_d = 1.98$ Mev; measured $\sigma(\theta)$, n spectrum. Be^8 , deduced levels. $\text{F}^{19}(d,n)$, $E_d = 1.98$ Mev; measured $\sigma(E_n)$.

The neutron spectrum from $\text{Li}^7(d,n)\text{Be}^8$ was studied at 120° with respect to the deuteron beam which was incident on a lithium metal target. The average energy of the deuterons in the target was 1.98 Mev. Up to an excitation of 9 Mev in Be^8 , only the ground state and the first excited state are observed. The neutron group to the excited state has a peak corresponding to 3.1 ± 0.1 Mev excitation in Be^8 and a width of 1.75 ± 0.1 Mev in the center-of-mass system; however,

the interpretation of these numbers in terms of the level parameters is obscured by the presence of a continuum from three-body decay. The relative differential cross section for the neutron groups leaving Be^8 in the ground state and in the first excited state was measured from 0° to 135° and normalized to an absolute value at 0° , measured with an LiF target. The cross section for the production of Be^8 in the first excited state has some uncertainty because of the contribution from the competing three-body breakup of the compound system. Cross sections at 0° for $\text{F}^{19}(d,n)\text{Ne}^{20}$ are also given for reactions leaving Ne^{20} in the ground state and first excited state.

¹ Abstract of paper accepted for publication by the *Physical Review*.

² Now at Argonne National Laboratory, Argonne, Ill.

He³-INDUCED CHARGED-PARTICLE REACTIONS

P. D. Miller

M. M. Duncan²W. R. Coker²J. L. Duggan¹V. H. Webb²J. Lin²

NUCLEAR REACTIONS. $\text{Be}^9(\text{He}^3,p)$, $E_{\text{He}^3} = 1-3$ Mev; measured E_p , θ . $\text{C}^{14}(\text{He}^3,\alpha)$, $E_{\text{He}^3} = 6, 8, 10$ Mev; measured α spectrum, θ .

A cooperative program between J. L. Duggan at ORINS, the Physics Department at the University of Georgia, and ORNL has been started for the purpose of investigating reaction mechanisms for He^3 -induced charged-particle reactions.

The $\text{Be}^9(\text{He}^3,p)\text{B}^{11}$ reaction was the first example selected. The ground-state Q value for this reaction is 10.33 Mev, so that many excited states are available in B^{11} , even at modest bombarding energies. Further, the low Coulomb barrier of Be^9 gives rise to usable yields even below 1 Mev. He^3 ions with energies in the 1 to 2 Mev range were obtained from the University of Georgia 2-Mv Van de Graaff accelerator. The experiment was continued at 3 Mev with the ORNL 5.5-Mv

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accelerator. Targets were prepared by evaporating $25\text{-}\mu\text{g}/\text{cm}^2$ elemental beryllium films onto self-supporting C^{12} foils of about the same thickness. Surface-barrier detectors were used to observe the reaction products. These were capable of stopping protons of energies up to 8.2 Mev, in the depletion layer. The various proton groups were identified from their measured energies. Excitation curves were taken at a laboratory angle of 90° for $1.0 \leq E_{\text{He}^3} \leq 2.0$ Mev for the proton groups associated with the second through the ninth excited states of B^{11} . There is a characteristic tendency to level off around 1.9 Mev. Angular distributions were measured for the same proton groups for $10^\circ \leq \theta_L \leq 170^\circ$ at 1.0, 1.5, 2.0, and 3.0 Mev. The angular distributions are quite similar to the $\text{Be}^9(\text{He}^3, n)\text{C}^{11}$ distributions measured by Duggan, Miller, and Gabbard.³ The distributions, as expected from

the earlier work, are complex. Since the spins and parities of the Be^9 ground state and many of the B^{11} excited states are known, an attempt will be made to fit the data with a distorted wave interaction model.

A second series of measurements was begun in December when the tandem accelerator was used to study the $\text{C}^{14}(\text{He}^3, \alpha_0)\text{C}^{13}$ reaction. The targets were polymerized acetylene on 5- $\mu\text{in.}$ nickel backings. Simultaneous spectra were accumulated at four angles for each run. Angular distributions for α_0 were measured at 6, 8, and 10 Mev. The pulse-height spectra are quite complicated at these high bombarding energies, but it should be possible to extract angular distributions for the d_0 group to N^{15} as well as some of the high-energy proton groups to low-lying states in N^{16} from the pulse-height distributions. The data are now being analyzed.

³J. L. Duggan, P. D. Miller, and R. F. Gabbard, *Nucl. Phys.* **46**, 336 (1963).

Reactions

THE $\text{Mg}^{24}(\alpha, \alpha)\text{Mg}^{24}$ AND $\text{Mg}^{24}(\alpha, \alpha')\text{Mg}^{24*}$ (2^+ , 1.37 Mev) REACTIONS

H. J. Kim

C. D. Moak

L. A. Rayburn¹

W. M. Good

NUCLEAR REACTIONS. $\text{Mg}^{24}(\alpha, \alpha \text{ and } \alpha')$, enriched target, $E_\alpha = 18\text{--}21.4$ Mev; measured $\sigma(E, \theta)$.

Angular distributions and absolute differential cross sections have been measured at the tandem accelerator for the elastic and inelastic (from 2^+ , 1.37-Mev state) alpha-particle scattering from a thin ($\sim 200\mu\text{g}/\text{cm}^2$) Mg^{24} target. Measurements were made at 100- and 200-kev intervals for alpha energies from 18 to 21.4 Mev.

Analyses of the above measurements are in progress. The results thus far available show that: (1) the shapes, as well as the magnitudes,

of elastic and inelastic scattering cross sections change very rapidly with energy; (2) despite the rapid change with energy, the elastic differential cross section can be fitted to an optical-model scattering² with reasonable χ^2 if the optical-model parameters are varied to minimize χ^2 ; (3) the relative phase between elastic and inelastic scattering cross sections varies with incident energy, and the relative phase ranges

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²Best χ^2 fittings were done by G. R. Satchler.

from 0 to 180° (see Figs. 1 and 2); (4) the "distributions" of the cross sections have the shapes predicted by the statistical model of compound-nuclear reaction,^{3,4} and (5) it seems feasible to

³T. Ericson, *Phys. Letters* 4, 258 (1963).

⁴R. O. Stephen and D. M. Brink, *The Theory of Fluctuations in Cross Sections of Nuclear Reactions*, Oxford University Press, London, 1963.

separate out compound-nucleus contributions of the differential cross section from direct interactions after having performed a suitable energy average of the measured cross sections, using the method devised by Brink and Satchler⁵ with the statistical model of compound-nuclear reactions.

⁵D. M. Brink and G. R. Satchler, *Phys. Div. Ann. Progr. Rept. Jan. 31, 1963*, ORNL-3425, p. 10.

Fig. 1. Elastic and Inelastic (from 2^+ , 1.37-Mev State) Scattering Cross Section of α -Particles from Mg^{24} . Note that (α, α) and (α, α') oscillations are in phase.

Fig. 2. Elastic and Inelastic Scattering Cross Section of α -Particles from Mg^{24} . (α, α) oscillations are out of phase with (α, α') oscillations.

CROSS SECTIONS FOR (α, n) REACTIONS FOR MEDIUM-WEIGHT NUCLEI¹

P. H. Stelson

F. K. McGowan

NUCLEAR REACTIONS. $\text{Ni}^{58,60,62}$, Co^{59} , $\text{Cu}^{63,65}$, $\text{Zn}^{64,66,68,70}$, Al^{27} , Zr , Nb^{93} , Mo , Pd , $\text{Ag}^{107,109}(\alpha, n)$, enriched targets, $E_\alpha = \text{threshold}-11 \text{ Mev}$; measured $\sigma(E)$.

Thick-target (α, n) neutron yields have been measured from threshold to about 11 Mev alpha-particle energy for 20 targets ranging in A from 27 to 120. The targets of nickel, copper, and zinc were isotopically enriched. The absolute neutron yields, which were measured at approximately 100-kev energy intervals, have an accuracy of $\pm 4\%$. The neutron detector was the 4π , flat-energy-response graphite-sphere detector developed

by Macklin. Cross sections for the (α, n) reactions were obtained to an accuracy of $\pm 15\%$ by differentiation of the smooth thick-target yield curves. For those nuclei in which the (α, n) cross section is thought to account for a significant percentage of the total reaction cross section, the observed cross sections are considerably larger than those predicted by Shapiro for his larger radial parameter of $1.5A^{1/3}$ fermis. Both the shape and absolute values of the observed cross sections agree fairly well with the optical-model analysis of reaction cross sections for alpha particles by Igo.

¹ Abstract of published paper: *Phys. Rev.* 133, B911 (1964).

CROSS SECTIONS FOR THE $\text{Ni}^{58}(\alpha, p)$, $\text{Ni}^{58}(\alpha, \gamma)$, AND $\text{Co}^{59}(\alpha, n)$ REACTIONS¹

F. K. McGowan

P. H. Stelson

W. G. Smith²

NUCLEAR REACTIONS. $\text{Ni}^{58}(\alpha, \gamma)$, enriched target, $E_\alpha = 4.9-6.1 \text{ Mev}$, $\text{Ni}^{58}(\alpha, p)$, $E_\alpha = 4.9-11 \text{ Mev}$; measured $\sigma(E)$. $\text{Co}^{59}(\alpha, n)$, $E_\alpha = 5.8-10 \text{ Mev}$; measured $\sigma(E)$.

Thick-target yields have been measured for the $\text{Ni}^{58}(\alpha, \gamma)$ reaction from 4.9 to 6.1 Mev, the $\text{Ni}^{58}(\alpha, p)$ reaction from 4.9 to 11 Mev, and the $\text{Co}^{59}(\alpha, n)$ reaction from 5.8 to 10 Mev. The reactions were identified by measuring the coincident annihilation radiation from the induced β^+ activities. The absolute thick-target positron yields, which were measured at approximately 100-kev energy inter-

vals, have an accuracy of $\pm 6\%$. The reaction cross sections were obtained to an accuracy of 15 to 20% by the differentiation of the smooth thick-target yield curves. Over the measured energy range, the cross sections increase from 1 to 12 μb for the $\text{Ni}^{58}(\alpha, \gamma)$ reaction, 0.6 μb to 316 mb for the $\text{Ni}^{58}(\alpha, p)$ reaction, and 0.06 to 228 mb for the $\text{Co}^{59}(\alpha, n)$ reaction. The total reaction cross section for Ni^{58} is compared to some values predicted by optical models. The $\text{Co}^{59}(\alpha, n)$ yields are compared to those obtained by measuring the neutrons directly with the graphite-sphere detector.

¹ Abstract of published paper: *Phys. Rev.* 133, B907 (1964).

² Deceased. Work conducted while on assignment to Oak Ridge National Laboratory as a summer research participant from Purdue University.

THE ELASTIC SCATTERING OF ALPHA PARTICLES BY O^{18} ¹

D. Powers²
J. K. Bair

J. L. C. Ford, Jr.
H. B. Willard

NUCLEAR REACTIONS. $O^{18}(\alpha, \alpha)$, enriched target, $E_\alpha = 2.4\text{--}3.5$ Mev; measured $\sigma(E, \theta)$.
 Ne^{22} , deduced levels, J, π .

The differential elastic scattering cross section of alpha particles by O^{18} has been measured for alpha-particle energies between 2.4 and 3.5 Mev and for $\theta_{c.m.} = 90.0, 125.3, 140.7, 152.3$, and 164.4° in order to determine the level parameters of excited states in Ne^{22} . The resonances were analyzed using the single-level and two-level approximation to determine reduced widths and resonance energies of the levels. Scattering

anomalies were observed at bombarding alpha-particle energies of 2.48, 2.56, 2.72, 2.90, 3.17, and 3.33 Mev which correspond to excited states of Ne^{22} with the following energies, angular momenta, and parities: 11.70 Mev, $J^\pi = 2^+$; 11.76 Mev, $J^\pi = 1^-$; 11.89 Mev, $J^\pi = 1^-$; 12.04 Mev, $J^\pi = 0^+$; 12.26 Mev, $J^\pi = 0^+$; 12.39 Mev, $J^\pi = 2^+$. For bombarding alpha-particle energies in the vicinity of 3.5 Mev, it was found necessary to include the effects of two levels above 3.5 Mev to fit the scattering data: 12.57 Mev, $J^\pi = 1^-$ and 12.61 Mev, $J^\pi = 1^-$. None of the levels observed have reduced widths greater than 9% of the Wigner limit.

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

²Summer research participant from Baylor University, Waco, Tex.

THE $O^{18}(\alpha, p)$ REACTION AND THE BETA DECAY OF F^{21} ¹

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

J. K. Bair
H. B. Willard

NUCLEAR REACTIONS. $O^{18}(\alpha, p)$, enriched target, $E_\alpha = 7.76\text{--}9.95$ Mev; measured yield $F^{21} \beta^+$ s.

RADIOACTIVITY. F^{21} , measured $T_{1/2}$.

The $O^{18}(\alpha, p)F^{21}$ reaction has been studied from 7.76 to 9.95 Mev by observing, with approximately 2π geometry, the beta particles following the F^{21}

decay. Prominent peaks in the yield curve occur at incident particle laboratory energies of about 7.86, 8.37, 8.61, 8.72, 8.83, 8.94, 9.16, 9.28, 9.43, and 9.82 Mev. The observed width of the peaks exceeds the experimental resolution of about 15 kev. A half-life of 4.35 ± 0.03 sec was determined for the F^{21} beta decay.

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

ABSENCE OF STATES IN Be^8 AT 7.56, 13.91, AND 18.00 Mev¹

P. D. Miller

J. L. Duggan²M. M. Duncan³

NUCLEAR REACTIONS. $\text{Li}^7(p, \alpha)$, $\text{Li}^7(p, \gamma)$, enriched target, $E_p = 0.6\text{--}1.8$ Mev; measured α spectrum, γ yield. Be^8 , deduced absence of levels.

The $\text{Li}^7(p, \alpha)\alpha$ and $\text{Li}^7(p, \gamma)\text{Be}^8$ reactions have been studied in an effort to confirm recently reported states in Be^8 at energies of 7.56, 13.91, and 18.00 Mev. The alpha particles assigned to the state at 7.56 Mev are shown to be attributable to the $\text{O}^{18}(p, \alpha)\text{N}^{15}$ reaction. The alphas as-

signed to a state at 13.91 Mev are shown to result from the $\text{F}^{19}(p, \alpha_0)\text{O}^{16}$ reaction. The postulation of a state at 18.00 Mev was based upon the presumed resonant formation of Be^{8*} which decayed by first gamma-ray emission to the states at 7.56 and 13.91 Mev, and then alpha-particle breakup of these states. Since both of the alpha-particle groups are assigned to contaminants, this state is also not confirmed. Resonances reported from the $\text{Li}^7(p, \gamma_0)\text{Be}^8$ and $\text{Li}^7(p, \gamma_1)\text{Be}^{8*}$ (2.9 Mev) reactions at 0.72 and 0.87 Mev bombarding energy are also not observed.

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

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FLUCTUATIONS IN THE $\text{C}^{12}(\text{O}^{16}, \alpha)\text{Mg}^{24}$ REACTION¹

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F. E. Durham³

C. D. Moak
Alexander Zucker²

NUCLEAR REACTIONS. $\text{C}^{12}(\text{O}^{16}, \alpha)$, $E_{\text{O}^{16}} = 16.8\text{--}21.6, 30.0\text{--}32.9$ Mev; measured $\sigma(E)$.

Excitation functions at 30 and 150° (lab) were measured for alpha-particle groups from the reaction $\text{C}^{12}(\text{O}^{16}, \alpha)\text{Mg}^{24}$, corresponding to the ground state and first five excited states of Mg^{24} . The O^{16} bombarding energy was varied from 16.8 to 21.6 Mev and from 30.0 to 32.9 Mev. These are equivalent to excitation energies in the Si^{28} compound nucleus of 24.0 to 26.0 and 29.6 to 30.9 Mev. The target thickness ($\sim 10 \mu\text{g}/\text{cm}^2$) determined the energy resolution, which was about 40 keV (c.m.). Strong fluctuations with widths

from 100 to 200 keV were observed in the excitation functions. The autocorrelation function

$$H(\epsilon) = \frac{\langle [\sigma(E + \epsilon) - \langle \sigma \rangle] [\sigma(E) - \langle \sigma \rangle] \rangle}{\langle \sigma \rangle^2}$$

was constructed for various alpha-particle groups, and found to have a maximum at $\epsilon = 0$, with a width of ~ 120 keV. This corresponds to a lifetime of the compound nucleus of 0.5×10^{-20} sec. Similarly defined cross-correlation functions between different states fail to show a maximum at $\epsilon = 0$, indicating that the fluctuations are indeed exit-channel phenomena. The fluctuations in the 29.6 to 30.9 Mev region are equally as strong as those at lower energies. This contrasts with the structure found in light-particle-induced reactions, which becomes less pronounced with increasing excitation energy.

¹Abstract of published paper: *Proceedings of the Third Conference on Reactions Between Complex Nuclei* (Asilomar, Pacific Grove, California, April 14–18, 1963), ed. by A. Ghiorso, R. M. Diamond, and H. E. Conzett, pp. 213–18, University of California Press, Berkeley, 1963.

²Electronuclear Division.

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FLUCTUATIONS IN THE $C^{12}(O^{16}, \alpha)Mg^{24}$ REACTION¹

M. L. Halbert²
F. E. Durham³

C. D. Moak
Alexander Zucker²

NUCLEAR REACTIONS. $C^{12}(O^{16}, \alpha)$, $E_{O^{16}} = 16.8-21.6, 30.0-32.9$ Mev; measured $\sigma(E)$.

Rapid fluctuations were observed in the excitation functions at two angles for $C^{12}(O^{16}, \alpha)Mg^{24}$ reactions involving the low-lying states of Mg^{24} . The energy resolution in the entrance channel was 45 kev. The fluctuations were found at compound nucleus excitation energies of about 25 and

30 Mev. At 30 Mev they were as strong as at 25 Mev. The statistical theory of Ericson was applied and autocorrelation functions were used to determine the width of the fluctuations. The average width, ≈ 116 kev, corresponds to a compound-nucleus lifetime of 0.57×10^{-20} sec. Cross correlations between different transitions are given for the ground-state transition. A comparison is made with $Al^{27}(p, \alpha)Mg^{24}$ results at the same angles and energies in the light of the statistical theory. Other possible interpretations of the experimental data are discussed.

¹Abstract of published paper: *Nucl. Phys.* **47**, 353-66 (1963).

²Electronuclear Division.

³ORINS Research Participant from Tulane University.

COULOMB EXCITATION OF Cu^{63} AND Cu^{65} ¹

R. L. Robinson

F. K. McGowan

P. H. Stelson

NUCLEAR REACTIONS. $Cu^{63,65}(\alpha, \alpha'\gamma)$, enriched targets, $E_{\alpha} = 4-8$ Mev; measured $I_{\gamma}, \gamma\gamma(\theta)$. $Cu^{63,65}$, deduced $B(E2)$, $B(M1)$.

Properties of levels Coulomb-excited in Cu^{63} and Cu^{65} with 4- to 8-Mev alpha particles have been investigated. The $B(E2)$'s for excitation determined from the yields of gamma rays observed in singles and coincidence spectra for the (668 ± 4) -, (961 ± 6) -, and (1323 ± 16) -kev levels in Cu^{63} are, respectively, (1.16 ± 0.12) , (3.49 ± 0.34) , and $(4.0 \pm 0.5) \times 10^{-50} e^2 cm^4$; for the (771 ± 7) -, (1115 ± 11) -, and (1474 ± 19) -kev levels in Cu^{65} , they are (1.02 ± 0.11) , (3.45 ± 0.38) , and $(4.3 \pm$

$0.8) \times 10^{-50} e^2 cm^4$. These results give $B(E2)$'s for decay which are 13 to 16 times the single-particle $B(E2)$. This similarity of $B(E2)$'s was predicted by de Shalit for levels which result from the coupling of the odd particle to the first excited state of the even-even core. From angular correlation studies the 961- and 1115-kev levels have been assigned spin $\frac{5}{2}$ and the 1323-kev level spin $\frac{7}{2}$. Mixing ratios obtained from these measurements along with the $B(E2)$'s establish values of 0.09 and 0.4 $(e\hbar/2Mc)^2$ for the $B(M1)$'s of the 961- and 1115-kev transitions.

¹Abstract of paper submitted to the *Physical Review*.

COULOMB EXCITATION OF VIBRATIONAL TRIPLET STATES AND OCTUPOLE STATES IN THE EVEN CADMIUM NUCLEI

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

NUCLEAR REACTIONS. $\text{Cd}^{110,112,114,116}(\text{O}^{16}, \text{O}^{16'})\gamma$, enriched targets, $E_{\text{O}^{16}} = 42-49$ Mev; measured $\gamma, \gamma\gamma$ spectra. $\text{Cd}^{110,112,114,116}$, deduced levels, $J, \pi, B(E2), B(E3)$.

First-order Coulomb excitation with alpha particles has been used to systematically locate the second $2+$ state in vibrational nuclei and to show that the $2' \rightarrow 2+$ transitions are enhanced.¹ An interesting application of double $E2$ Coulomb excitation is the recent work of Eccleshall *et al.* at Aldermaston.² They have used tandem Van de Graaff-accelerated O^{16} ions to enhance the double $E2$ Coulomb excitation. They were able to locate the $4+$ second phonon state in a number of medium-weight nuclei and thereby considerably increase the available information on vibrational triplets.

The vibrational model predicts that the ratio $B(E2, 4 \rightarrow 2)/B(E2, 2 \rightarrow 0)$ should be 2.0, whereas the asymmetric rotor model predicts that this ratio is approximately 1.37. Since the difference is less than 50%, good experimental results and good theoretical interpretation are required to distinguish between the two predictions. Eccleshall *et al.* obtained values which generally agree with the vibrational value rather than the value predicted by the asymmetric rotor model.

Quite a few $0+$ states in the triplet energy region have now been identified in medium-weight nuclei by experiments not involving Coulomb excitation. Experimental evidence showing that the $E2$ transition between the excited $0+$ state and the first $2+$ state is strongly enhanced would be very strong evidence in favor of a vibrational interpretation of such spectra rather than an asymmetric rotor interpretation, since the latter model cannot produce an excited $0+$ state. However, there is

little known about the lifetimes of excited $0+$ states. A consideration of the ratio of intensities of cascade gamma rays to monopole electrons for the two $0+$ states in Cd^{114} indicates that the 1305-keV state cannot have a very much enhanced $E2$ decay whereas the decay of the 1133-keV state is compatible with an enhanced $E2$ transition. However, this is necessary but not sufficient evidence for establishing that the 1133-keV state is in fact a collective vibrational state.

The Aldermaston group have not been able to find strong evidence for double $E2$ excitation of the $0+$ state because the excitation of $0+$ states is not as strong as that for $4+$ and $2+$ states. In some cases, the $0+$ state is known from other work to be nearly degenerate with either a $2+$ or a $4+$ state.

Oxygen-16 ions with energies of 42 to 49 MeV have been used to Coulomb-excite higher states in the even cadmium isotopes. Typical direct and coincidence gamma-ray spectra are shown for Cd^{114} and Cd^{116} in Figs. 1 through 5. In each case of the direct spectra, there are, in addition to the strong direct $E2$ excitation of the first $2+$ state, weaker peaks which are cascade transitions resulting from excitation of the second $2+$ and $4+$ states. The gamma rays at 1.35 and 1.60 MeV are from the troublesome $\text{C}^{12} + \text{O}^{16}$ nuclear reactions. By making a coincidence measurement on the cascade gamma rays, a considerable increase in sensitivity is achieved. For instance, the peak at 1384 keV in Fig. 2 is interpreted as the cascade transition from a $3-$ state to the first $2+$ state resulting from direct $E3$ excitation of a state at 1945 keV. Figure 3 is an expanded portion of the spectrum shown in Fig. 2. The 805-keV gamma ray is the cascade transition from direct $E2$ excitation of a $2+$ state at 1363

¹P. H. Stelson and F. K. McGowan, *Phys. Rev.* **121**, 209 (1961); F. K. McGowan and P. H. Stelson, *Phys. Rev.* **126**, 257 (1962).

²D. Eccleshall, B. M. Hinds, and M. J. L. Yates, *Nucl. Phys.* **32**, 190 (1962); D. Eccleshall *et al.*, *Nucl. Phys.* **37**, 377 (1962).

UNCLASSIFIED
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Fig. 1. Direct Pulse-Height Spectrum of the Gamma Rays for O^{16} Ions on a Cd^{114} Target.

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Fig. 2. Coincidence Pulse-Height Spectrum of the Gamma Rays for O^{16} Ions on a Cd^{114} Target.

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Fig. 3. Expanded Portion of the Pulse-Height Spectrum Shown in Fig. 2.

Fig. 4. Direct Pulse-Height Spectrum of the Gamma Rays for O^{16} Ions on a Cd^{116} Target.

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Fig. 5. Coincidence Pulse-Height Spectrum of the Gamma Rays for O^{16} Ions on a Cd^{116} Target.

key; the 724-keV gamma ray is the cascade transition from double $E2$ excitation of the $4+$ state at 1282 keV; and the 651-keV gamma ray is the cascade transition from direct $E2$ and double $E2$ excitation of a $2+$ state at 1208 keV. At this bombarding energy somewhat more than half of the observed thick-target yield is attributed to direct $E2$ excitation and the rest is due to double $E2$ excitation. Using the values for $B(E2, 0 \rightarrow 2')$ and $B(E2, 2 \rightarrow 2')$ previously obtained by Stelson and McGowan¹ with alpha particles on Cd^{114} , we find, within an accuracy of $\pm 20\%$, good agreement between predicted and observed intensities. The two modes of excitation are coherent, but a calculation of the interference from semiclassical theory to second order gives only a 4% effect in the thick-target yield.

A careful decomposition of the spectrum near 558 keV leads to the observation of the 575-keV gamma ray which results from double $E2$ excitation of the $0+$ state at 1133 keV in Cd^{114} .

In the case of Cd^{116} the second $2+$ and $4+$ states are degenerate to within 5 keV and the direct $E3$ excitation of a $3-$ state appears at

1900 keV. A relatively weak transition is observed at 865 keV which could be interpreted as a $0+$ state at 1382 keV. A state at this energy has been observed in the (p, p') reaction by Darcey *et al.* at Oxford University.³

By the use of the semiclassical theory to second order, the reduced transition probabilities are extracted from the thick-target yields in a model-independent manner. For this purpose, we have used the valuable numerical calculations by Douglas.⁴ Both the differential and total cross sections have been calculated for double $E2$ excitation of spin states 0, 2, 4 via an initial $0 \rightarrow 2$ transition.

A summary of the reduced transition probabilities is given in Fig. 6. The values obtained for the ratio $B(E2, 4 \rightarrow 2)/B(E2, 2 \rightarrow 0)$ generally agree with the vibrational value rather than the value predicted by the asymmetric rotor model.

³W. Darcey, private communication, 1963.

⁴A. C. Douglas, *Nucl. Phys.* **42**, 428 (1963).

Fig. 6. Level Diagram of the States Observed by Coulomb Excitation and a Summary of the Reduced Transition Probabilities.

The $E2$ transition between the excited 0^+ state and the first 2^+ state in Cd^{114} is strongly enhanced, that is, $B(E2, 0' \rightarrow 2)/B(E2, 2^- \rightarrow 0) = 0.85$. If the spin of the state at 1382 keV in Cd^{116} is 0^+ , the ratio $B(E2, 0' \rightarrow 2)/B(E2, 2^- \rightarrow 0)$ is 0.83 ± 0.17 .

The systematic occurrence of collective octupole states in nuclei is now generally acknowledged. The evidence for collective 3^- states has mostly come from direct-interaction experiments.

States at 2051 ± 16 , 1968 ± 16 , 1945 ± 16 , and 1900 ± 16 keV are excited in Cd^{110} , Cd^{112} , Cd^{114} , and Cd^{116} , respectively. If these states are interpreted to be the result of direct $E2$ Coulomb excitation, the $B(E3, 0 \rightarrow 3)$ are 11.3, 10.6, 9.0, and $7.5 \times 10^{-74} \text{ e}^2\text{cm}^6$ with an accuracy of $\pm 20\%$ provided the branching ratio of cascades to cross-overs from the 3^- state is large compared to unity.

These $B(E3)$ values represent enhancements of 13 to 22 and are 3 to 6 times smaller than the results derived from yield measurements with 14- to 15-Mev alpha particles at Copenhagen.⁵ A calculation by Satchler indicates that the contribution from direct nuclear interaction for 14-Mev alpha particles on Cd^{114} would not explain the large values obtained by the Copenhagen group. The $B(E3)$ values given in Fig. 6 are, however, in good agreement with the value obtained from direct-interaction optical-model analysis of inelastic scattering of 14-Mev neutrons from normal cadmium.⁶

⁵O. Hansen and O. Nathan, *Nucl. Phys.* **42**, 197 (1963).

⁶R. L. Robinson and P. H. Stelson, private communication, 1963.

α **COULOMB EXCITATION OF Br^{81} WITH ALPHA PARTICLES**

R. L. Robinson

F. K. McGowan

P. H. Stelson

NUCLEAR REACTIONS. $\text{Br}^{81}(\alpha, \alpha'\gamma)$, enriched target, $E_\alpha = 2.5\text{--}5.7$ Mev; measured $\gamma, \gamma\gamma$ spectra, $\gamma(\theta)$. Br^{81} , deduced levels, $J, \pi, B(E2)$.

Properties of some low-lying levels in a large number of even-even medium-weight nuclei have been found to be reasonably explained by the simple vibrational model. The addition of one nucleon to an even-even nucleus, however, greatly complicates the low-lying level structure. Although several models have been proposed to account for the properties of levels in even-odd nuclei, none has proven generally successful. To guide the development of these and future models, there is a need for more detailed knowledge of the level properties. Coulomb excitation provides a powerful method of obtaining this type of information. We have thus been engaged in a program of investigating even-odd medium-weight nuclei by means of this technique. Results on our studies of Se^{77} , Br^{79} , Cu^{63} , and Cu^{65} have been previously reported. This paper deals with the Coulomb excitation of Br^{81} .

A thick target of PbBr_2 with the bromine isotopically enriched to 95% Br^{81} was Coulomb-excited with 2.5- to 5.7-Mev alpha particles, which were extracted from the 5.5-Mv Van de Graaff generator. Before the study could be carried out as planned with alpha particles of higher energies, the target was destroyed by the beam even though the precaution was taken of keeping the beam current below $0.02 \mu\text{a}$. However, measurements were made for $E_\alpha = 6.08$ and 7.02 Mev with a PbBr_2 target containing normal bromine.

The gamma rays emitted by the bombarded target were detected with 3×3 in. NaI crystals. Singles spectra were taken for nine different alpha-particle energies, and spectra in coincidence with the strong 276-keV gamma ray were taken for four energies. Representative spectra are illustrated in Figs. 1 and 2.

In the coincidence spectrum in Fig. 2 the peak at 281 keV is broader by 11% than expected for a single gamma ray. It is attributed to a composite peak of the 276-keV gamma ray and a 285-keV

gamma ray. Coincidences between the 285-, 493-, and 558-keV gamma rays, and the 276-keV gamma ray indicate excitation of levels at 561, 769, and 834 keV. A decay scheme incorporating these transitions and levels is shown in Fig. 3. An alternate explanation of the 558-keV gamma ray present in the coincidence spectra is that it results from coincidence of a transition between

Fig. 1. Gamma-Ray Spectrum for 4.973-Mev Alpha Particles on Br^{81} .

Fig. 2. Gamma-Ray Spectrum in Coincidence with the 276-keV Gamma Ray for 5.433-MeV Alpha Particles on Br^{81} .

Fig. 3. Energy-Level Diagram of Br^{81} .

Fig. 4. Relative Yields of the Gamma Rays as a Function of the Alpha-Particle Energy. The solid curves give the energy dependence predicted for the yields of gamma rays from $E2$ Coulomb-excited states with energies ΔE .

the 834- and 559-keV levels (the difference in energy of these two levels is 275 ± 9 keV) and a ground-state transition from the latter level.

Relative yields of the 276-keV gamma ray observed in the singles spectra less the yields of transitions which cascade into the 276-keV level and relative yields of the three coincident gamma rays are shown in Fig. 4. Their dependence on the bombarding energy of the alpha particles agrees with the curves predicted for $E2$ Coulomb excitation of the four excited levels illustrated in Fig. 3. Since the ground-state spin and parity of Br^{81} is $\frac{3}{2}^-$,¹ the spins of the excited states can only be $\frac{1}{2}$, $\frac{3}{2}$, $\frac{5}{2}$, or $\frac{7}{2}$ and their parities are odd.

¹J. E. Mack, *Rev. Mod. Phys.* 22, 64 (1950).

After subtraction of the 527-keV gamma ray due to Coulomb excitation of Br^{79} (the bromine in the enriched target was 5% Br^{79}) and subtraction of the 493- and 558-keV gamma rays found in the coincidence spectra from the singles gamma-ray spectra, there are still two peaks remaining in the singles spectra between 500 and 600 keV. One has an energy of 509 keV. Its yields do not appear indicative of Coulomb excitation, and it is therefore most likely annihilation radiation resulting from production of a positron emitter. However, yields obtained from the other peak, with an energy of 549 keV, are not inconsistent within their large errors with the theoretical curve for $E2$ Coulomb excitation of a level of this energy. This can be seen in Fig. 4. The presence of such a level has already been established through the observed coincidence of the 276- and 285-keV gamma rays. The relative intensities determined for the 285- and 549-keV gamma rays from this level are shown in Fig. 3.

The angular anisotropy of the 276-keV gamma ray was measured for the bombarding alpha-particle energies of 4.472 and 4.973 MeV. A fit of the data to the equation

$$W(\theta) = 1 + a_2 g_2 A_2 P_2(\cos \theta),$$

where a_2 and g_2 are the thick-target particle parameter and correction for the angular resolution of the detector, gives an average value for A_2 of -0.039 ± 0.018 . This indicates the spin of the 276-keV level is $\frac{5}{2}$, and the mixing ratio, $(E2/M1)^{1/2}$, is $+0.09 \pm 0.05$ or -4.9 ± 1.5 . No corrections have been applied for the distortion caused to the angular distribution by the gamma rays which cascade into the 276-keV level. As their intensities are about 2% of the 276-keV gamma-ray intensity for these alpha-particle energies, this correction would be expected to be small.

The reduced transition probabilities for excitation, $B(E2)_{\text{ex}}$, have been determined from the yields of the gamma rays. These are listed in Table 1. The $B(E2)_{\text{ex}}$ of the 276-keV level and mixing ratios of $+0.09$ and -4.9 of the 276-keV gamma ray give a $B(M1)$ for decay of $0.3 (e\hbar/2Mc)^2$ and $9 \times 10^{-5} (e\hbar/2Mc)^2$ respectively. Since the crossover transitions from the 834- and 769-keV states were not observed, we can only put lower limits on the $B(E2)_{\text{ex}}$'s of these levels. Although a 770-keV gamma ray was seen in the singles spectra, its yields increase too rapidly with alpha-particle energy for it to be attributed to Coulomb excitation. If the branching ratios suggested by Sund and Wiedenbeck² for transitions from the 834-keV level are used, the $B(E2)_{\text{ex}}$ of the 834-keV level is $14 \times 10^{-50} \text{ e}^2\text{cm}^4$.

Since both the 834- and 559-keV levels are populated by beta-ray groups with log ft 's of about 6² which originate at the spin $\frac{1}{2}$ nucleus Se^{81} , the spins of the 834- and 559-keV levels are either $\frac{1}{2}$ or $\frac{3}{2}$. The 769-keV level has not been previously reported and therefore probably has spin $\frac{5}{2}$ or $\frac{7}{2}$.

²R. E. Sund and M. L. Wiedenbeck, *Nucl. Phys.* **38**, 478 (1962).

Table 1. The $B(E2)_{\text{ex}}$'s of Levels in Br^{81}

Level (keV)	$B(E2)_{\text{ex}}/e^2\text{cm}^4 \times 10^{50}$
276	6.21 ± 0.55
559	0.99 ± 0.16
769	$>0.64 \pm 0.10$
834	$>5.8 \pm 0.7$

CHARGED-PARTICLE NUCLEAR CROSS-SECTION COMPILATION

F. K. McGowan

H. J. Kim

W. T. Milner

The past year has been devoted primarily to maintaining the literature search up to date, compiling cross-section data in tabular form, reading data from small figures published in the literature with the X-Y reader, and writing input instructions for the digital plotter. About 2000 sets of data have been key punched and processed by computer programs. The program also generates a magnetic tape for the Calcomp 570 digital plotter which plots the data in the desired form for the compilation. About 400 sets of data have

been plotted and input instructions for 800 more sets of data have been written. The compiling of data for the elements manganese through zinc in tabular form is nearly complete. A section of the compilation for these elements is being prepared in the form of a topical report and should be completed this fiscal year (1964). A large amount of the data for the elements lithium through oxygen has been compiled in tabular form.

A number of requests for data from specific nuclear reactions were fulfilled during the year.

GAMMA-GAMMA ANGULAR CORRELATION IN V^{51} ¹

R. L. Robinson

N. R. Johnson²G. D. O'Kelley²

RADIOACTIVITY. Ti^{51} ; measured $I_\gamma, \gamma\gamma(\theta)$. V^{51} , deduced levels, J, δ .

The angular correlation of the 613-319 kev gamma-ray cascade in V^{51} has been measured by using sources of 5.8-min Ti^{51} . After a correction was applied for the finite angular resolution of the detectors, the data were fitted to the function $W(\theta) = 1 + (0.013 \pm 0.030) P_2(\cos \theta) - (0.03 \pm$

$0.05) P_4(\cos \theta)$. If a value of 0.45 is taken for the mixing ratio δ_{319} of the 319-kev transition, the correlation coefficients are compatible with $\delta_{613} = +0.18$ or -0.9 for the spin sequence $\frac{3}{2} \frac{5}{2} \frac{7}{2}$ and with $\delta_{613} = -0.41$ or $+6.3$ for the spin sequence $\frac{5}{2} \frac{5}{2} \frac{7}{2}$. The respective intensities determined for the 613- and 934-kev gamma rays from the second level at 933 kev are $(1.7 \pm 0.2)\%$ and $(5.8 \pm 0.6)\%$ of the 319-kev gamma-ray intensity.

¹Abstract of published paper: *Nucl. Phys.* **47**, 506 (1963).

²Chemistry Division.

CONVERSION ELECTRONS FROM NUCLEAR STATES OF INDIUM EXCITED BY (p,n) REACTIONS

E. C. Campbell

P. F. Fettweis¹

RADIOACTIVITY. In^{114m}, In^{116m} [from $Cd^{114}, Cd^{116}(p,n)$, enriched targets], measured cc.

Conversion electrons associated with the decay of excited states of In^{114} and In^{116} have been

measured with a shaped-field magnetic spectrometer. Thin target foils of cadmium enriched in Cd^{114} and in Cd^{116} at the entrance aperture of the spectrometer were bombarded by 5-Mev protons from the 5.5-Mv Van de Graaff accelerator to

¹Guest Scientist at ORNL during 1963 on assignment from Centre d'Etudes de l'Energie Nucléaire, Mol, Belgium.

Fig. 1. Schematic Diagram of Apparatus for Measurement of Conversion Electrons and Gamma Rays from Nuclear States Excited by Proton Beam.

produce excited states by the reactions $\text{Cd}^{114}(p,n)\text{In}^{114}$ and $\text{Cd}^{116}(p,n)\text{In}^{116}$, respectively. A schematic diagram of the apparatus is shown in Fig. 1. Square-wave modulation of the proton beam and synchronous gating of the electron and gamma-ray scintillation detectors served to distinguish between prompt and delayed effects and to permit measurement of the half-life by variation of the modulation frequency.

Figure 2 shows the conversion-electron spectrum arising from the decay of the 40-msec state in In^{114} . The 312 ± 2 keV transition is characterized as $E3$ from measurements of the K conversion coefficient (0.10 ± 0.02) and the $K/(L+M)$ ratio (3.05 ± 0.50). Similarly, the second excited state of In^{116} of half-life 2.5 sec gives rise to a 165-keV transition with a $K/(L+M)$ ratio of 1.6 ± 0.2 . The conversion-electron spectrum associated with this transition is shown in Fig. 3. In addition, conversion electrons corresponding to "prompt" transitions of 182 and 282 keV from excited states in In^{116} were observed. The $K/(L+M)$ ratios measured for these transitions are 9 ± 3 and 5.6 ± 0.6 , respectively, leading to an $E1$ or $M1$ assignment. These transitions may

Fig. 2. Conversion Electron Spectrum of In^{114m} (40 msec).

be identified with those of 188 keV and 280 keV observed² in the neutron capture gamma-ray spectrum of In^{115} .

A summary of the comparison between the experimental and theoretical conversion coefficients and conversion coefficient ratios is shown in Tables 1 and 2.

²J. E. Draper, C. A. Fenstermacher, and H. L. Shultz, *Phys. Rev.* 111, 906 (1958).

Fig. 3. Conversion Electron Spectrum of In^{116m} (2.5 sec).Table 1. Comparison of Experimental and Theoretical^a Conversion Coefficients

Nucleus	Transition Energy (kev)	Half-Life (sec)	$\alpha_K(\text{exp})$	$\alpha_K(\text{theoretical})$							
				E1	E2	E3	E4	M1	M2	M3	M4
In^{114m}	312	0.040	0.1 ± 0.02	6.6×10^{-3}	2.55×10^{-2}	9.0×10^{-2}	3×10^{-1}	2.0×10^{-2}	8.6×10^{-2}	3.3×10^{-1}	1.22
In^{116m}	165	2.5	1.15 ± 0.09^b	3.8×10^{-2}	2.15×10^{-1}	1.1	4.7	1.15×10^{-1}	7.7×10^{-1}	4.2	1.85×10

^aM. E. Rose, *Internal Conversion Coefficients*, North Holland, Amsterdam, 1958.^bP. H. Heckmann *et al.*, *Z. Phys.* 163, 451 (1951).Table 2. Comparison of Experimental and Theoretical^a Conversion Coefficient Ratios

Nucleus	Transition Energy (kev)	Half-Life (sec)	$K/LM(\text{exp})$	$K/LM(\text{theoretical})$							
				E1	E2	E3	E4	M1	M2	M3	M4
In^{114m}	312	0.040	3.05 ± 0.5	6.1	4.8	3	1.8	5.9	5.0	4.0	3.1
In^{116}	282	"Prompt"	5.6 ± 0.6	6.1	4.6	2.8	1.6	5.8	4.8	3.8	2.9
In^{116}	182	"Prompt"	9 ± 3	6.1	3.8	1.8	0.7	5.8	4.4	3.0	1.8
In^{116m}	165	2.5	1.6 ± 0.2	6	3.5	1.5	0.6	5.8	4.3	2.7	1.4

^aM. E. Rose, *Internal Conversion Coefficients*, North Holland, Amsterdam, 1958.

PRECISION MEASUREMENT OF THE RECOIL ENERGY SPECTRUM FROM THE DECAY OF He^6 ¹

C. H. Johnson

Frances Pleasonton

T. A. Carlson

RADIOACTIVITY. He^6 , measured He^6 recoil spectrum; deduced $E_{\beta}(\text{max})$, $e\nu(\theta)$.

The energy spectrum of recoil ions from the β^- decay of He^6 was observed repeatedly under a variety of operating conditions with a spectrometer which uses a tandem arrangement of magnetic and electrostatic analysis. Analyzed ions were detected with an electron multiplier. A composite spectrum is formed from the several observations, random errors are assigned on the basis of the observed fluctuations, and four parameters are adjusted to give the best fit of theory to experiment. These parameters are the maximum β^- energy W_0 , an electron-neutrino correlation coefficient α , a normalization constant, and a de-

tensor parameter. The analysis gives $\alpha = -0.3343 \pm 0.0030$, where the uncertainty represents a careful evaluation of both random and systematic effects. The conclusion is reached, with "68% posterior probability," that the limit to the tensor interaction is

$$(|C_T|^2 + |C_{T'}|^2)/(|C_A|^2 + |C_{A'}|^2) \leq 0.4\%.$$

If one assumes that there is no tensor interaction but that higher-order terms may be present, then one can conclude from a plane-wave ($Z = 0$) approximation for the He^6 decay that $b = -(0.5 \pm 1.3)(2M)^{-1}$, where b is a second-order term defined in Gell-Mann's paper on weak magnetism, and M is the ratio of nucleon to electron mass.

¹Abstract of published paper: *Phys. Rev.* **132**, 1149 (1963).

A SYSTEM FOR CONTINUOUS GENERATION AND FAST TRANSFER OF RADIOACTIVE GASES¹

Frances Pleasonton

C. H. Johnson

The system was developed to provide a stable and strong source of He^6 for the ORNL recoil spectrometer. A continuous flow of water vapor

swept the He^6 through about 80 ft of piping from the generator to the laboratory in 3 to 4 sec; the gas was then purified and delivered to the spectrometer in an additional 1 to 1.5 sec. Modifications in design for other experiments and for use in leak detecting are discussed.

¹Abstract of published paper: *Rev. Sci. Instr.* **35**, 97 (1964).

EXPERIMENTS WITH VERY HEAVY IONS¹

C. D. Moak

A method for producing small but usable numbers of very heavy ions in a tandem Van de

Graaff accelerator, having energies up to 120 Mev, will be described in detail. Experiments with these ions have included studies of the responses of various types of silicon detectors and studies of the stopping powers of several elements for heavy ions.

¹Abstract of invited paper presented at Third International Accelerator Conference, Boston, Mass., Nov. 11-13, 1963. Proceedings of conference will be published in *Nuclear Instruments and Methods*.

SOME STOPPING POWERS FOR IODINE IONS¹

C. D. Moak

M. D. Brown²

The multicomponent heavy-ion beam from the Oak Ridge tandem accelerator has been used to

measure the atomic stopping cross sections of Au, Ni, Al, and C for I¹²⁷ ions in the energy range from approximately 25 to 115 Mev.

¹Abstract of published paper: *Phys. Rev. Letters* 11, 6 (1963).

²Graduate student, University of Tennessee, Knoxville.

HEAVY-ION ENERGY ACCUMULATION IN THE TANDEM VAN DE GRAAFF ACCELERATOR¹

C. D. Moak

H. W. Schmitt

J. H. Neller²

F. J. Walter³

G. F. Wells⁴

A new energy-accumulation method has been found for accelerating very small but usable beams of artificial fission fragments such as bromine and iodine ions to energies three times

higher than those previously available from tandem Van de Graaff accelerators. Energies up to 120 Mev now available cover completely the energy range found for the fission particles from uranium. The ions have been used to study the behavior of silicon solid-state fission-particle detectors of many types. For the first time direct calibration methods are available to aid in experimental studies of the fission process. Further work will be directed toward an experimental study of the stopping power of various elements for heavy ions.

¹Abstract of published paper: *Rev. Sci. Instr.* 34, 8 (1963).

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FISSION

R. W. Lamphere

NUCLEAR FISSION. Th^{231,233}, U^{235,237,239}, measured fission-product θ .

NUCLEAR REACTIONS. Th²³⁰(n, θ), E_n = threshold–3 Mev; measured $\sigma(E)$.

Fragment angular anisotropies for fast-neutron-induced fission have been measured for Th²³⁰, Th²³², U²³⁴, U²³⁶, and U²³⁸. These measurements have been carried out near threshold for the purpose of recognizing the first few distinct K bands of channels which contribute to fission.

The fission cross section of Th²³⁰ has been measured from threshold to 3 Mev. Unfortunately, premature failure of the 5-Mv Van de Graaff precluded obtaining certain key measurements during the last run. Consequently, final analyses of the

thorium isotopes will have to await further time on the generator.

Uranium-236 is a particularly interesting isotope. Foils of higher purity have been requested in order to pursue fragment angular anisotropies to higher accuracies at energies in the region of the fission threshold.

Foils of Pu²⁴⁰ are being prepared by the ORNL Target Center and will be used to study the fission mechanism near threshold by means of angular distribution measurements on the fragments from neutron-induced fission.

INTERPRETATION OF THE FRAGMENT MASS DISTRIBUTION FOR U²³⁵ THERMAL-NEUTRON-INDUCED FISSION WITH LONG-RANGE ALPHA EMISSION¹

H. W. Schmitt

N. Feather²

An analysis of the fragment mass distribution for the thermal-neutron-induced ternary fission of U²³⁵ is given. Quantitative comparison of the mass distribution data for binary and ternary fission is consistent with the influence of the

closed-shell configurations in fission, although it is shown that these mass distributions of themselves are not sufficient to determine unambiguously the origin of the alpha particle. Results of this analysis are discussed in relation to some recently proposed models of ternary fission. It is shown that the results of measurements of the number of neutrons emitted in binary fission as a function of fragment mass are consistent with the cluster-model interpretation.

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

²Department of Natural Philosophy, University of Edinburgh, Scotland.

FRAGMENT MASS DISTRIBUTIONS FOR THERMAL-NEUTRON-INDUCED FISSION OF Pu^{239} AND Pu^{241} ¹

F. J. Walter²

H. W. Schmitt

J. H. Neiler³

NUCLEAR FISSION. $\text{Pu}^{240,242}$, measured fission-product mass distribution.

The fragment mass distributions for thermal-neutron-induced fission of Pu^{239} and Pu^{241} have been determined from correlated energy measurements of fragment pairs. These mass distribu-

tions are compared with each other and with the post-neutron-emission mass yield for Pu^{239} obtained from radiochemical and mass spectrometric measurements. It is shown that these comparisons are consistent with the sawtooth character of the function $\nu(M)$ as well as with the cluster model of fission in which the stability of the closed-shell structures fundamentally influences the fragment mass and energy distribution of low excitation energy.

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

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FISSION OF ORIENTED NUCLEI

J. W. T. Dabbs

F. J. Walter

G. W. Parker¹

The appearance of significant changes (with neutron energy) in the anisotropy of fission fragments from aligned U^{235} nuclei² has prompted several avenues of effort.

Comparison with Other Measurements

A multilevel fit to the fission cross-section data of U^{235} has been made in the region below 2 ev, using parameters recently obtained by Kirpichnikov *et al.*³ for the 0.28- and 1.14-ev levels, and estimates of the parameters for two assumed bound levels. The bound level nearest

$E = 0$ was assumed to have the same spin J as the 0.28-ev resonance, while the other bound resonance and the level at 1.14 ev were assumed to have spin $J' = J \pm 1$. These relative spin assignments are in accord with those observed in our earlier work.²

The purpose of this multilevel fit was to obtain estimates of $\sigma(J, E)$ and $\sigma(J', E)$ so that the fraction

$$F(E) = \sigma(J', E) / [\sigma(J', E) + \sigma(J, E)] \quad (1)$$

could be compared to our earlier fission anisotropy results and to the recent radiochemical data of Faler and Tromp on peak-to-valley ratios in U^{235} as a function of energy.⁴ In making such comparisons, the tacit expectation is entertained that the variations observed are related, probably proportionally, to the variations in $F(E)$.

¹Reactor Chemistry Division.

²J. W. T. Dabbs, F. J. Walter, and G. W. Parker, *Phys. Div. Ann. Progr. Rept. Jan. 31, 1963*, ORNL-3425, p. 82.

³I. V. Kirpichnikov, K. G. Ignatyev, and S. I. Sukhoruchkin (to be published). A preprint of this work was kindly supplied by M. S. Moore.

⁴K. T. Faler and R. L. Tromp, *Phys. Rev.* **131**, 1746 (1963).

Figure 1 shows the radiochemically determined peak-to-valley ratio

$$R(E) = A_{asy}/A_{sym}, \quad (2)$$

where A_{asy} is the activity associated with a "peak" product nuclide (usually Mo^{99}) and A_{sym} the activity associated with a low-mass-yield ("valley") nuclide (such as Ag^{111} or Cd^{115m}). $R(E)$ is normalized to 1 at the thermal neutron energy value. The total fission cross section, multiplied by E , is also shown in Fig. 1.

Fig. 1. Upper Curve: U^{235} Total Fission Cross Section; Lower Curve: Peak-to-Valley Ratio vs Energy.

Fig. 2. Curve: Relative Contribution of Total Angular Momentum J' to $\sigma_f(\text{U}^{235})$; Points: Measured Fragment Anisotropy from Oriented U^{235} (Arbitrary Scale). The point marked X is not corrected for "off Bragg" neutrons.

Figure 2 is a plot of $F(E)$ vs E as obtained from the multilevel fit to the fission cross section mentioned above. The same general behavior is evident as in the $R(E)$ plot, but there clearly are differences in the shapes of the two curves, especially in the region near 0.05 to 0.2 ev. This suggests that the peak-to-valley ratio does not depend linearly on the relative contributions of states with total angular momentum J and J' to the total fission cross section. Also shown in Fig. 2 are the previously reported values² of $A(E)$ in the angular distributions

$$W(\theta) = 1 + \frac{A_2(E)}{T} P_2(\cos \theta) \quad (3)$$

of fission fragments from U^{235} in $\text{UO}_2\text{Rb}(\text{NO}_3)_3$. The point at the 1.14-ev resonance has been corrected for a measured amount of "off-Bragg reflection" background which has been assumed to be isotropic in approximate agreement with the "off-Bragg" background at 8.8 ev. The uncorrected point is marked X. The scale for the $A_2(E)$ values has been chosen to give an approximate fit to the $F(E)$ curve. There appears to be a reasonable consistency with the expectation of a linear dependence on $F(E)$, although such a relation is not proved. Such a dependence would suggest that particular projection quantum numbers K (or sets of K 's) are associated with each of the J values.² This point is one of the most interesting which can be resolved by more detailed and accurate measurements on the aligned-fission anisotropies. A linear dependence of this type would also suggest that in regions where σ_f is due primarily to states of total angular momentum J' (the value associated with the 0.3 ev resonance), an anisotropy constant A_2 near zero would be expected.

Recalculation of Alignment Parameter P

Recently, Salusti has published⁵ a new "variational boundary condition" calculation of the relative amplitudes (at the nuclear surface) of the various partial waves which are involved in the alpha decay of U^{233} . This calculation gave amplitudes and phases in the spheroidal coordinate system associated with the nuclear surface. Upon request, Salusti has kindly made

⁵E. Salusti, *Nuovo Cimento* 30, 171 (1963).

available to us the corresponding amplitudes at infinity in spherical coordinates. These are given (in arbitrary units) in the first row of Table 1. The subscripts 0–3 refer respectively to s and d waves in the ground-state transition and to d and g waves in the first-excited-state transition ($E_\alpha = E_0 - 42$ kev). The relative phases are given by the signs of the terms. Under the very reasonable assumption that no other waves are of importance in determining the angular distribution, it is possible to calculate, by comparison with the observed alpha-particle anisotropy, the magnitude of the quadrupole coupling constant P . Using the relative amplitudes and phases given by Salusti, we calculate an angular distribution

$$W(\theta) = 1 - 2.896 \left(\frac{Phc}{kT} \right) P_2(\cos \theta). \quad (4)$$

The observed angular distribution was

$$W(\theta) = 1 - 0.064 P_2(\cos \theta). \quad (5)$$

Therefore a coupling constant $Phc/k = 0.0221^\circ\text{K}$ is obtained for U^{233} in $\text{UO}_2\text{Rb}(\text{NO}_3)_3$. This may be compared with the value obtained by Chasman and Rasmussen⁶ using the amplitudes and phases of the second line of Table 1. They obtained $Phc/k = 0.0277^\circ\text{K}$.

Since the alignment parameter is given by

$$P = \frac{3eQ}{4I(2I-1)} \left\langle \frac{\partial^2 V}{\partial z^2} \right\rangle, \quad (6)$$

where Q is the nuclear quadrupole moment and V is the crystalline electrostatic potential, the corresponding coupling constant for U^{235} may be obtained, using the known spins and the quadrupole moment ratio Q_{233}/Q_{235} . The best value of this ratio now available is that of Dorain, Hutchison, and Wong,⁷ which is 0.855 ± 0.15 . This leads to a coupling constant for U^{235} of $Phc/k = 0.0123^\circ\text{K}$ (Salusti) or 0.0154°K (Chasman and Rasmussen). These values ($P = 0.00856 \text{ cm}^{-1}$ and $P = 0.0107 \text{ cm}^{-1}$) are both markedly lower than the estimate⁸ ($P = 0.015 \text{ cm}^{-1}$) pre-

Table 1. Partial Wave Amplitudes in U^{233} Alpha Decay

Reference	f_0	f_1	f_2	f_3
<i>a</i>	+2.025	+2.074	+1.379	+0.361
<i>b</i>	1.000	+0.577	1.000	0

^aE. Salusti, *Nuovo Cimento* **30**, 171 (1963); personal communication.

^bR. Chasman and J. O. Rasmussen, *Phys. Rev.* **115**, 1257 (1959).

viously used, and suggest that the largest observed fission anisotropy ($A = +0.056$) is closer to the maximum possible values than previously thought. This calculation emphasizes the importance of an independent measurement of P .

Modifications of Cryostat and Associated Equipment

A complete redesign and rebuilding of the equipment reported last year² is now essentially finished. The general aims of this effort were (1) to increase counting rates by a factor of ~ 10 ; (2) to make lower temperatures (factor of 1.5) available; (3) to obtain a degree of reliability consistent with the new need, especially in the counting and control equipment; (4) to reduce the downtime associated with sample changes and other internal cryostat changes to a few days; and (5) to permit the use of computer techniques for data reduction and analysis.

The sample space has been modified to allow use of three single crystals of ~ 2 cc each in place of one crystal; this change, together with a change to four 7-cm^2 Si solid-state detectors in place of a single detector, gives the increased counting rate. The aim to make lower temperatures available has been implemented by redesigning the expansion section of the He^3 refrigerator to incorporate a "brush" of 3000 forty-gage, 1-in. long oxide-coated copper wires as a heat exchanger between the cold He^3 vapor at 0.3°K and the sample space (127 cm^2 surface area). Previously, the lowest available temperature was 0.45°K . Since the effects being observed depend linearly on $1/T$, this means a further reduction in counting times by a factor $(T_1/T_2)^2$. The geometrical alterations required have also removed the need to rotate the cold sample; instead the

⁶R. Chasman and J. O. Rasmussen, *Phys. Rev.* **115**, 1257 (1959).

⁷P. B. Dorain, C. A. Hutchison, and E. Wong, *Phys. Rev.* **105**, 1307 (1957); C. A. Hutchison, private communication.

⁸J. W. T. Dabbs, F. J. Walter, and G. W. Parker, *Phys. Div. Ann. Progr. Rept. Jan. 31, 1963*, ORNL-3425, p. 83, Table 1.

four detectors (at 77°K) are rotated from outside the Dewar; this will facilitate future angular distribution measurements. The new arrangement also will not cause sample heating (upon rotation) as before; this means that if long nuclear-spin-lattice relaxation times are encountered at the lower temperatures, their effects can be (1) studied and (2) avoided.

In connection with the changes in the sample and detector configuration, it has been necessary to develop a new fission fragment window arrangement; the new window is a cylinder 1.375 in. in diameter by 1 in. high and is made (as before) of 0.25-mg/cm² nickel foil. This window surrounds the sample crystals and permits the passage of the incoming neutron beam as well as the fission fragments and alpha particles emitted by these target crystals while containing, inside the cold sample container, He³ heat exchange gas at a pressure of a few microns. Extreme precautions are necessary to prevent excessive pressure differences across the window; these consist of carefully prearranged pumping lines, valves, and apertures. The basic approach is to make the *length* of the two connecting tubes inversely proportional to the volumes being evacuated. In the present case the ratio of lengths is ~800, and the "short" line is obtained by using a number of parallel holes through a $\frac{1}{8}$ -in. plate. The pump-down portion of the cycle appears to be quite predictable; however, during the first moments of letup, turbulent flow or other disturbances cause rather surprising dependences on the rate of letup, and resort was made to a trial and error approach. It is now possible to evacuate and refill the (40 liter) cryostat in less than 20 min with pres-

sure differences always within the range $0 \leq d \leq 0.05$ mm Hg. Previously, a range of 1 mm Hg was considered satisfactory for the smaller (2 cm diam) nickel window.

The reliability of the experimental equipment has been greatly improved. The cryostat has been disassembled and completely rebuilt with detailed design changes which have been dictated by experience in many of the piping and vacuum joints and connections. Helium leak detector tests were made at each stage of the reassembly. As many piping and electrical connections as possible were made demountable. This new feature permits complete removal of the inner portion of the cryostat (He³ refrigerator, He⁴ bath, and sample chamber) in less than 1 hr (after overnight warmup). This portion of the cryostat is shown in Fig. 3. Other improvements in this apparatus include more efficient use of the liquid He⁴ heat transfer "brush" mentioned above, and the addition of two electrically indicating gas thermometers, using strain-gage transducers.

The glow-tube scalers and stacked-discriminator pulse-height analyzer² have been replaced with a Nuclear Data ND-120 512-channel analyzer. Punched paper tape output, with parity indication, is also available. A transistorized cycle control logic unit (Q-2709) was designed in collaboration with J. W. Woody, Jr., and J. M. Madison of the Instrumentation and Controls Division, and has been completed and tested there. A block diagram showing the logic elements in the usual ORNL notation is shown in Fig. 4. This controller programs a complete experiment or repeated experiments, including sample or detector alternations, routing to various sections of the analyzer

Fig. 3. He³ Refrigerator, Inner Assembly. Operating Temperatures are 77°K, 2.2°K, and 0.3°K in the three main sections. The sample container and window are at the bottom end.

SWITCHES SHOWN
WITHIN PRESET
TEMPERATURE RANGE

memory, automatic readout, timing of runs, paper tape punch control, etc. With relatively minor analyzer modifications, it may be used for external control of any multichannel analyzer. Art work for duplicating the printed circuit boards, etc., will be made available from the Instrumentation and Controls Division.

Data reduction and analysis by means of the CDC-1604 computer at ORNL have been made possible in two steps. (1) M. J. Mader of the Mathematics Division has completed a program (designated TAND-195-1) which will be used routinely on the CDC-160A computer to reduce the paper tape output of the ND-120 analyzer to IBM card form. In addition, this program lists the input and corrects several types of possible errors, and lists parity and other errors in the input paper tape. Finally a semilog plot of the input data is plotted on the 160-A printer itself. Thus, errors, such as dropped channels, or undesired test pulse generator peaks, may easily be found and corrected on the IBM cards. (2) A second program, written in the ALGOL language, is then used to compute the coefficients A_2 in the angular distributions

$$S(\theta) = 1 + A_2 P_2(\cos \theta), \quad (7)$$

which obtain for both alpha particles and fission fragments from the oriented nuclei. This is done as a function of the lower integration limit of the pulse-height spectrum. This program, designated FAR-3, extrapolates the fission pulse-height distribution under the alpha-particle distribution, subtracts and time-normalizes the alpha data, and averages data from two sets of detectors. A tape is also prepared for the Calcomp plotter. Both programs have been "debugged." These programs can also be used, without change, for other experiments on fission of oriented nuclei now being planned.

A "cold filter" assembly for use in the direct beam has been fabricated and will permit Be-, Bi-, and Pb filtered neutrons to be used in this work. Interchangeable polycrystalline rods of these materials may be inserted in a vacuum-jacketed, liquid-nitrogen-cooled chamber. The liquid-nitrogen consumption is only 25 liters/day. This unit has already been used in a correlated fragment energy experiment.

Improved methods and equipment for growing single crystals of $\text{UO}_2\text{Rb}(\text{NO}_3)_3$ from a hot nitric acid solution have been introduced. A group of crystals is shown in Fig. 5.

Fig. 5. $\text{UO}_2\text{Rb}(\text{NO}_3)_3$ Crystals. The scale is in inches.

INSTRUMENTATION FOR FISSION FRAGMENT ENERGY CORRELATION EXPERIMENTS¹

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Experiments have been performed at the Oak Ridge National Laboratory in which the kinetic energies of correlated fragment pairs from thermal- and resonance-neutron-induced fission have been measured. In addition, a three-parameter ternary fission experiment has been performed in which the energies of correlated fragments were measured in coincidence with the energy of a third

emitted particle, usually a long-range alpha particle. The detectors were large-area silicon surface-barrier detectors. The instrumentation associated with these experiments is discussed in detail. The complete system is described, with attention given to the problems of background reduction (fast-coincidence requirements), stability, linearity, and resolution. Particular attention is given to the reduction of spectrum distortion by pile-up pulses, for example, alpha-on-fission pile-up within the amplifier resolving time. Methods and limitations of pile-up detection are discussed. A new method for inspection and removal of pile-up pulses, which may be useful in a wide variety of applications, is presented.

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A SEARCH FOR Λ -NUCLEON RESONANCE

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Recent experiments at ORNL² on Σ^- interactions with helium strongly suggest the existence of a resonance in the Λ -nucleon system. A search was made for such a resonance in other reactions. The requirements for possibly observing a resonance in the Λ -nucleon system are that both a Λ and a nucleon be present in the initial or final state of an interaction, and that the event products can be identified and measured, so as to permit kinematic analysis. The obvious experiment of Λ -nucleon scattering is very difficult with only meager statistics being available from Λ -scattering observations in hydrogen and propane.³ In K^- interactions with helium, which is the film we analyzed, a Λ and nucleon are present in the final states: $\Lambda + p + p + n + \pi^-$ and

$\Lambda + p + d + \pi^-$. The film was scanned for K^- interactions that yielded a Λ , a negative pion, and two heavily ionizing tracks for which momentum information could be obtained. These events were analyzed on the basis of three assumptions: (1) both heavy tracks are protons, (2) the first heavy track is a deuteron and the other a proton, and (3) the second track is the deuteron and the first is a proton. On the basis of a χ^2 goodness-of-fit criterion, 86 events fit assumption 1, and 55 fit assumption 2 or 3. Events that were acceptable on the basis of the χ^2 fit into groups 1 and 2 or 3 were accepted twice. The best-fit kinematic momentum and space position values were used to calculate the effective mass of the Λ -nucleon system assuming that the Λ and one nucleon were emitted as one unit. The effective (or "missing") mass distribution for the Λ -p system, assuming a deuteron in the final state, is shown in Fig. 1. Figure 2 shows the Λ -p and Λ -n missing mass distributions for the $p + p + n + \Lambda + \pi^-$ final state; here two Λ -p values are calculated for each event, one of

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²H. O. Cohn and W. M. Bugg, *Bull. Am. Phys. Soc.* 9, 23 (1964).

³G. Alexander *et al.*, *Phys. Rev. Letters* 7, 348 (1961); also F. Oppenheimer *et al.*, *Bull. Am. Phys. Soc.* 8, 348 (1963).

which certainly cannot represent a Λ - p resonance. Difference in appearance of the Λ - n and Λ - p curves in Fig. 2 can partially be explained by the bias in selection of events. Requirement that two stubs be measurable rejects low-momentum protons and biases in favor of lower-momentum neutrons. Since the Q value is a measure of the combined kinetic energy for the Λ and nucleon, high Q values are favored for the Λ - p case. Since the isotopic spin of the Λ is 0 and for the nucleon $\frac{1}{2}$, the Λ -nucleon system must have isotopic spin $\frac{1}{2}$ so that two states with components $\frac{1}{2}$ and $-\frac{1}{2}$ corresponding to Λ - p and Λ - n would be expected. Certainly no pronounced peaks are found in the distribution that might be interpreted as resonances. This does not, however, mean that there is no such resonance, only that the four- and five-body final state is too complicated to show up a nucleon- Λ resonance in a convincing manner. Due to kinematic limits, phase-space distribution is peaked just where one might expect the nucleon- Λ resonance to show up. The search failed to show a Λ -nucleon resonance which, however, does not disprove its possible existence.

Fig. 1. Effective Mass Distribution for the Λ - p System from $K^- + \text{He} \rightarrow \Lambda + p + d + \pi^-$.

Fig. 2. Effective Mass Distribution for Λ - p and Λ - n Systems from $K^- + \text{He} \rightarrow \Lambda + p + p + n + \pi^-$.

He

PARITY IN Σ^- INTERACTION WITH HELIUM

H. O. Cohn W. M. Bugg¹
R. D. McCulloch²

Nonconservation of parity in a reaction that yields a Λ in the final state has been searched for by looking for an asymmetry in the angular distribution of the Λ decay products. The angular distribution in the center of mass is given by $I(\theta) \sim 1 + \alpha \bar{P} \cos \theta$, where α is the asymmetry parameter and $\bar{P}$ is a measure of the polarization of the Λ . The asymmetry parameter α is a measure of the analyzing power of the Λ decay and is known to be nonzero. Thus $\alpha \bar{P}$ gives a direct measurement of the polarization of the Λ in the production process, and a nonvanishing value of $\alpha \bar{P}$ would constitute evidence for parity nonconservation in the production process. Evidence of parity nonconservation in the $\Sigma - \Lambda$ conversion process has been looked for with Λ 's produced by

K^- interaction with helium.³ A large fraction of these Λ 's are produced through the $\Sigma - \Lambda$ conversion process; however, a considerable fraction are directly produced. Sigma minus interactions in helium afford a direct means of looking at the $\Sigma - \Lambda$ conversion process. In the present experiment all Λ 's are products of the $\Sigma^- + \text{He}$ interaction. Slow Σ^- 's were produced in the Northwestern University helium bubble chamber by K^- mesons. To date 112 Σ^- interactions with measurable Λ 's have been analyzed. The angular distribution in center of mass for the Λ -decay pion is shown in Fig. 1. A best fit to the function $1 + \alpha \bar{P} \cos \theta$ yields $\alpha \bar{P} = 0.06 \pm 0.16$. Thus no evidence for parity nonconservation in this process is observed, in agreement with previous results.

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³Helium Bubble Chamber Collaboration Group, *Proceedings of the 1960 Annual International Conference on High Energy Physics at Rochester*, p. 423, 1960.

Fig. 1. Angular Distribution of Λ Decay Pion in Center of Mass.

WAVE FUNCTIONS FOR MUON CAPTURE IN THE HYDROGEN MU-MOLECULAR ION

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The coupling strengths for the weak interactions responsible for muon capture are less well known at present than those for the other weak interactions among the nonstrange elementary particles. In order to obtain high enough counting rates for the reaction $p + \mu^- \rightarrow n + \nu_\mu$, a high density of protons must be used. In the past two years data have been reported on muon capture in ultrapure liquid hydrogen. Nearly all the captures are from the ortho state of the molecular ion $p - \mu - p$. The most recent measurement at Columbia¹ gives a capture rate of $464 \pm 42 \text{ sec}^{-1}$. The best theoretical estimate for this experiment is 562 sec^{-1} . This involves the assumption that the induced pseudoscalar coupling constant is 8 times the axial vector, that the ratio of axial vector to (polar) vector is the same as in beta decay (-1.21), and that the vector interaction enters through a conserved current and has a momentum transfer dependence equal to that of the electromagnetic form factor of the nucleon. In addition there is an uncertainty in the probability of finding the muon at either proton in the $p - \mu - p$ molecule. This uncertainty in the best available wave function, that of Cohen, Judd, and Riddell,² is usually cited as about 10%. It is clearly desirable to reduce this uncertainty,

hopefully to about 1%, in order to draw conclusions regarding the nature of the mu capture interaction.

A calculation of the muonic wave function in $p - \mu - p$ is in progress. It aims to give an improvement over that of Cohen *et al.* in two ways. First, the muonic wave functions for fixed nuclei are taken to be the exact solutions of the two-center one-electron Coulomb field problem rather than the Guillemin-Zener variational solution. Secondly, the nonadiabaticity correction (i.e., the correction to the Born-Oppenheimer approximation) is to be evaluated to the extent required to achieve the desired accuracy in the overall wave function.

Codes have been written to compute the separation constants and expansion coefficients for the adiabatic wave functions. These have given values in agreement with the literature for the hydrogen molecular ion, and in addition can provide additional significant figures if desired.

Analytic expressions for the coupling terms which produce the nonadiabaticity corrections have been worked out. Codes to evaluate the coupling terms are being written, and quantitative results concerning the rate of convergence of the expansion procedure are expected to be available in the near future. As a by-product, the method can also be applied to the ordinary hydrogen molecular ion, for which the nonadiabaticity corrections are very much smaller because of the small electron mass.

¹J. E. Rothberg *et al.*, *Phys. Rev.* **132**, 2664 (1963).

²Stanley Cohen *et al.*, *Phys. Rev.* **119**, 384 (1960).

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PAPERS PRESENTED AT SCIENTIFIC AND TECHNICAL MEETINGS

Meeting papers for January 1963 are listed in ORNL-3425, *Physics Division Annual Progress Report for Period Ending January 31, 1963*.

Academic Year Institute (sponsored by the National Science Foundation and Arizona State University), Phoenix, Arizona, February 20, 1963

S. Bernstein, "The Mössbauer Effect."

International Conference in Fast Neutron Physics, Houston, Texas, February 26-28, 1963

J. H. Gibbons (invited paper), "Neutron Radiative Capture Reactions."

H. B. Willard (invited paper), "Neutron Scattering Studies."

American Physical Society Meeting, Houston, Texas, February 28-March 2, 1963

D. Powers, J. K. Bair, H. B. Willard, J. L. C. Ford, and T. M. Hayes, "The Elastic Scattering of Alpha Particles by O^{18} ."

American Physical Society Meeting, St. Louis, Missouri, March 25-28, 1963

J. W. Cable (invited paper), "Magnetic Properties of Some Transition-Metal Alloys."

Southeastern Section Meeting, American Physical Society, Knoxville, Tennessee, April 4-6, 1963

- R. L. Becker, "Singularities of the Brueckner Reaction Matrix."
- R. L. Becker, L. D. Roberts, and J. O. Thomson, "Calculation of Au^{197} Mössbauer Isomer Shifts from Residual Electrical Resistivities."
- J. A. Biggerstaff, J. R. Bird, J. H. Gibbons, and W. M. Good, "Resonant Neutron Capture Gamma-Ray Spectra in Ti and V."
- J. W. Cable (invited paper), "Magnetic Moment Distribution in Palladium-Transition Metal Alloys."
- E. C. Campbell and S. Bernstein, "Amplitudes for Mössbauer-Bragg Resonant Gamma Scattering."
- H. R. Child, W. C. Koehler, E. O. Wollan, and J. W. Cable, "Magnetic Properties of Dy-Y Alloys."
- H. O. Cohn, W. M. Bugg, and R. D. McCulloch, "Evidence for Parity Conservation in Σ^- Interactions."
- J. W. T. Dabbs, F. J. Walter, and G. W. Parker, "Resonance Neutron Fission Cryostat for Aligned U^{235} Nuclei."
- D. W. Forester, F. E. Obenshain, L. D. Roberts, and J. O. Thomson, "A Study of the Temperature Dependence of the Sublattice Magnetization of Antiferromagnetic $\alpha\text{-Fe}_2\text{O}_3$."
- J. L. Fowler, John Agnew, and Mary J. Mader, "Resonant Parameter Assignments for Resonances in Pb^{208} Neutron Scattering."
- J. A. Harvey, G. G. Slaughter, J. R. Bird, and G. T. Chapman, "Neutron Capture Gamma Rays from Isotopes of Tin."
- C. H. Johnson (invited paper), "Precision Recoil Experiments in Nuclear Beta Decay."
- H. J. Kim, J. A. Biggerstaff, and W. M. Good, "Total Neutron Cross Sections in Isotopes of Zr, Fe, Cr, and Ca."
- M. O. Krause and T. A. Carlson, "The Charge Spectrum of Neon Resulting from Inner Shell Ionization by X-Rays."
- R. W. Lamphere, "Fission Fragment Angular Anisotropies near Threshold."
- F. K. McGowan, R. L. Robinson, P. H. Stelson, and J. L. C. Ford, Jr., "Coulomb Excitation of the Isotopes of Osmium."
- H. C. Meyer, W. T. Pinkston, and G. R. Satchler, "Collective Effects in Stripping Reactions on Light Nuclei."
- F. E. Obenshain, L. D. Roberts, and D. W. Forester, "Measurement of the Hyperfine Splitting in FeRh Using the Mössbauer Effect."
- R. L. Robinson, F. K. McGowan, and P. H. Stelson, "Coulomb Excitation of Cu^{63} and Cu^{65} ."
- H. W. Schmitt (invited paper), "Kinetics of Fission from Multiparameter Correlation Measurements."
- K. L. Vander Sluis (invited paper), "Demonstration of Visible Coherent Light from a Laser."
- T. A. Welton, "Random Motion of Elementary Particles Produced by Interaction with Bose Fields."

Annual Sherwood Theoretical Meeting, Berkeley, California, April 8-9, 1963

- T. K. Fowler, "A Unified View of Streaming Instabilities."

Third Conference on Reactions Between Complex Nuclei, Asilomar, Pacific Grove, California, April 15-17, 1963

- R. H. Bassel, G. R. Satchler, and R. M. Drisko, "Elastic and Inelastic Scattering of Carbon from Carbon."
- R. M. Drisko, G. R. Satchler, and R. H. Bassel, "Pickup of Heavy Clusters."
- M. I. Halbert, F. E. Durham, C. D. Moak, and A. Zucker, "Fluctuations in the Reaction $\text{C}^{12}(\text{O}^{16}, \alpha)\text{Mg}^{24}$."

Nuclear Physics Section of Bavarian Physical Society, Erlangen, Germany, April 20-24, 1963

- J. K. Bienlein and Frances Pleasonton, "Das Spektrum der inneren Bremsstrahlung von He^6 " ("The Internal Bremsstrahlung Spectrum of He^6 ").

Third Rare Earth Conference, Clearwater, Florida, April 21–24, 1963

W. C. Koehler, E. O. Wollan, H. R. Child, and J. W. Cable, "Some Magnetic Structure Properties of Rare Earth Alloys."

American Physical Society Meeting, Washington, D.C., April 22–25, 1963

J. A. Biggerstaff, J. R. Bird, J. H. Gibbons, and W. M. Good, "Resonant Neutron Capture Spectra in $\text{Fe}^{54,56}$ and $\text{Ca}^{40,42,44}$."

W. M. Bugg and H. O. Cohn, " Σ^- Interaction with Helium."

T. A. Carlson, "Electron Shake-Off Following the β^- Decay of Ar^{41} ."

J. L. C. Ford, Jr., J. K. Bair, C. M. Jones, and H. B. Willard, "The $\text{O}^{18}(\alpha, p)\text{F}^{21}$ Reaction and the Beta Decay of F^{21} ."

T. K. Fowler, "Bounds on Plasma Instability Growth Rates."

J. H. Gibbons (invited paper), "Neutron Capture and Stellar Nucleosynthesis."

M. V. Harlow, Jr., R. L. Robinson, and B. B. Kinsey, "Elastic Scattering of 17- to 21-Mev Neutrons from C^{12} ."

C. H. Johnson, Frances Pleasonton, and T. A. Carlson, "An Experimental Limit to Tensor Interaction in the Beta Decay of He^6 ."

P. D. Miller, G. C. Morrison, Noel Gale, and Geoffrey Dearnaley, "Alpha Particles from the Bombardment of B^{10} and B^{11} by Li^6 and Li^7 ."

T. Tamura and T. Udagawa, "Quasi-Particle Description of Higher Excited States of Vibrational Even Nuclei."

F. J. Walter, J. H. Neiler, and H. W. Schmitt, "Fragment Mass Distribution for Thermal and Resonance Neutron Induced Fission of Pu^{239} ."

Conference on Instrument Techniques in Nuclear Pulse Analysis, Monterey, California, April 29–May 3, 1963

C. W. Williams and M. V. Harlow, "Pulse Shape Discrimination."

Symposium on Molecular Structure and Spectroscopy, Columbus, Ohio, June 10–14, 1963

H. W. Morgan, P. A. Staats, P. M. Griffin, K. L. Vander Sluis, and G. K. Werner, "The Use of Infrared Laser Radiation for Spectral Slit Width Studies."

American Physical Society Meeting, Buffalo, New York, June 24–26, 1963

T. K. Fowler (invited paper), "Stability Criteria in a Plasma."

Fontenay Study Group on Mirror Configurations, Paris, France, July 15–19, 1963

T. K. Fowler, "Growth Rates of Electrostatic Instabilities in Mirror Configurations."

Seventh European Congress on Molecular Spectroscopy, Budapest, Hungary, July 22–27, 1963

H. W. Morgan, P. A. Staats, P. M. Griffin, K. L. Vander Sluis, and G. K. Werner (invited introductory lecture), "The Use of Infrared Laser Radiation for Spectral Slit Width Studies."

Fourteenth Annual Infrared Spectroscopy Institute, Nashville, Tennessee, August 10–18, 1963

P. A. Staats and H. W. Morgan, "Experimental Infrared Spectroscopy."

Gordon Research Conference on the Chemistry and Physics of Solids – Magnetism, Meriden, New Hampshire, August 12–16, 1963

W. C. Koehler (invited paper), "Spin Configurations in Rare Earth Metals and Alloys."

American Physical Society Meeting, Edmonton, Alberta, Canada, August 28–30, 1963

C. D. Moak (invited paper), "Accelerator Techniques for Nanosecond Pulsing."

International Colloquium on Neutron Diffusion and Diffraction, Grenoble, France, September 3-5, 1963

J. W. Cable, E. O. Wollan, and W. C. Koehler, "The Crystal Structure of Nickel Hydride."

G. P. Felcher and W. C. Koehler, "Magnetic Structure of Rare Earth Iridium Compounds RIr_2 ."

Low Energy Nuclear Physics Conference, Manchester, England, September 4-6, 1963

H. W. Schmitt, F. J. Walter, and J. H. Neiler, "Fission Fragment Mass Distributions from Energy Correlation Experiments."

Third International Conference on the Mössbauer Effect, Ithaca, New York, September 4-7, 1963

S. Bernstein and E. C. Campbell, "Total Reflection of Gamma Rays by Fe^{57} in the Region of Nuclear Anomalous Dispersion."

D. W. Forester, B. K. Moore, L. D. Roberts, and J. O. Thomson, "A Transducer Giving Equal Times at Each Velocity."

F. E. Obenshain, L. D. Roberts, D. W. Forester, and J. O. Thomson, "Measurement of the Hyperfine Splitting in Several Alloys of FeRh ."

F. E. Obenshain and H. H. F. Wegener, "Direct Measurement of the Internal Field in Nickel."

L. D. Roberts, R. L. Becker, F. E. Obenshain, and J. O. Thomson, "A Correlation of Isomer Shifts of Gold in Several Dilute Gold Alloys with the Alloy Residual Electrical Resistivities."

European-American Nuclear Data Committee Symposium on Absolute Determination of Neutron Flux in the Energy Range 1-100 kev, St. John's College, Oxford, England, September 10-13, 1963

R. L. Macklin (invited paper), "The MnSO_4 Bath and Graphite Pile."

H. W. Schmitt, "Remarks on Heavy Element Neutron Capture Cross Sections Determined by the Sphere-Transmission Method."

Conference on Electronic Structure of Alloys, Sheffield, England, September 23-25, 1963

J. W. Cable, E. O. Wollan, W. C. Koehler, and H. R. Child, "Alignment of Rare Earth Moments in Dilute Pd-Fe Alloys."

International Conference on Nuclear Spectroscopy (devoted to the Role of Atomic Electrons in Nuclear Transformations), Warsaw, Poland, September 24-28, 1963

J. K. Bienlein and Frances Pleasonton, "Internal Bremsstrahlung in the β -Decay of He^6 ."

T. A. Carlson and M. O. Krause, "Atomic Readjustment Following the Formation of Inner Shell Vacancies."

Conference on Compound Nuclear States (Topical Conference sponsored by the American Physical Society and the Oak Ridge National Laboratory), Gatlinburg, Tennessee, October 10-12, 1963

I. L. Bergqvist, J. A. Biggerstaff, J. H. Gibbons, and W. M. Good, "Gamma Rays from Neutron Resonance Capture in $2s-1d$ Shell Nuclei."

J. A. Biggerstaff, W. M. Good, and H. J. Kim, "The Strength Function and Level Spacing of the Even Zirconium Isotopes."

J. L. C. Ford, Jr., J. K. Bair, R. L. Robinson, and H. B. Willard, "Interference Between Compound Nucleus Inelastic Scattering and Coulomb Excitation in the $\text{Na}^{23}(p,p')$ Reaction."

J. L. Fowler, "The Interaction of Neutrons with Pb^{208} ."

T. Fuketa, F. A. Khan, and J. A. Harvey, "S-Wave Neutron Strength Functions and Level Spacings of the Ten Isotopes of Tin."

W. M. Good, H. J. Kim, C. D. Moak, and L. A. Rayburn, "The Cross Sections and Angular Distributions in the Reactions $\text{Mg}^{24}(\alpha, \alpha_0)$, $\text{Mg}^{24}(\alpha, \alpha_1)$."

M. L. Halbert, F. E. Durham, C. D. Moak, and A. Zucker, "Fluctuations in the Reaction $\text{C}^{12}(\text{O}^{16}, \alpha)\text{Mg}^{24}$."

International Conference on Nuclear Physics with Reactor Neutrons, Argonne, Illinois, October 15-17, 1963

J. A. Harvey, G. G. Slaughter, J. R. Bird, and G. T. Chapman, "Gamma Ray Spectra from Resonance Neutron Capture in the Tin Isotopes."

D. Paya, J. W. T. Dabbs, J. A. Harvey, and H. Horstmann, "Acceleration of Free Neutrons Under Gravity."

F. J. Walter, H. W. Schmitt, and J. H. Neiler, "Correlated Fragment Energy Measurements for Low Energy Neutron Induced Fission."

C. W. Williams, F. J. Walter, and J. H. Neiler, "Instrumentation for Fission Fragment Energy Correlation Experiments with Pile-Up Reduction Capabilities."

American Physical Society Meeting, Chicago, Illinois, October 18-19, 1963

R. C. Block and M. C. Moxon, "Neutron Total Cross Section and Radiative Capture Measurements on Pb and Radiogenic Pb."

J. W. T. Dabbs, J. A. Harvey, and D. Paya, "Gravitational Acceleration of Free Neutrons."

H. J. Kim, "A Possible Evidence of Electric Polarizability of Deuteron in Coulomb Field."

Eastern Theoretical Physics Conference, Chapel Hill, North Carolina, October 25-26, 1963

T. A. Welton, "Successive Finite Approximations for the Fermion Propagator."

Sixth Industrial Lubrication Conference, Knoxville, Tennessee, October 28-29, 1963

P. A. Staats, "Infrared Spectroscopy as a Diagnostic Tool for the Lubrication Engineer."

Southeastern Section Meeting, American Physical Society, Lexington, Kentucky, November 7-9, 1963

J. A. Biggerstaff (invited paper), "Nanosecond Time Measurements."

E. C. Campbell and P. F. Fettweis, "Conversion Electrons from the 40 Millisecond Isomeric State in In^{114} ."

T. A. Carlson (invited paper), "Atomic Readjustment to Inner Shell Vacancies."

W. R. Coker, M. M. Duncan, J. L. Duggan, F. H. Webb, and P. D. Miller, "The $\text{Be}^9(\text{He}^3, p)\text{B}^{11}$ reaction."

H. Horstmann, J. W. T. Dabbs, J. A. Harvey, and D. Paya, "Analysis of Gravitational Acceleration Measurements for Free Neutrons."

C. H. Johnson and J. L. Fowler, "Differential Elastic Scattering of Neutrons from O^{16} ."

W. C. Koehler (invited paper), "Recent Developments in Rare Earth Magnetism."

R. L. Robinson (invited paper), "Excitation of Collective States by Inelastic Scattering of 14 Mev Neutrons."

T. A. Welton and J. Kronsbein, "Determination of Structure of Non-Crystallizable Molecules by a New Type of Electron Lens."

Symposium on the Utilization of Research Reactors, Atlanta, Georgia, November 7-9, 1963

J. A. Harvey (invited paper), "Use of Research Reactor for Nuclear Physics."

Third International Accelerator Conference, Boston, Massachusetts, November 11-13, 1963

C. D. Moak (invited paper), "Experiments with Very Heavy Ions."

Ninth Annual Conference on Magnetism and Magnetic Materials, Atlantic City, New Jersey, November 12-15, 1963

R. M. Moon, J. W. Cable, and W. C. Koehler, "The Magnetic Structure of Neodymium."

Seventy-third Meeting, Tennessee Academy of Science, Chattanooga, Tennessee, November 29-30, 1963

P. M. Griffin (invited paper), "Lecture Demonstrations with He-Ne Laser."

Mary J. Mader, J. F. Agnew, and J. L. Fowler, "Phase Shift Analysis of Differential Scattering of Neutrons from 0 Spin Nuclei."

G. K. Werner (invited paper), "Design and Construction of a Home-Made Laser."

ANNOUNCEMENTS

The Physics Division welcomes the return, in January 1964, of the Nuclear Data Project to ORNL and to the Division. Members of the group moving to Oak Ridge are Katherine Way (Director), Agda Artna, W. B. Ewbank, H. Ogata, M. J. Martin, N. B. Gove, and A. Sen Gupta. The Nuclear Data Project has had a long and distinguished history as one of the country's most successful nuclear data information centers. Pioneering efforts in data collection were begun at ORNL in 1946; in 1949 the Project joined the National Bureau of Standards in Washington, and since 1953 it has worked as an operating unit within the National Academy of Sciences—National Research Council in Washington. The physicist members of the team make a systematic collection and analysis of nuclear data, and publish them in tabulated summary form for easy reference by research scientists. These publications have included *Nuclear Level Schemes*, *Nuclear Data Sheets*, *Nuclear Theory Index Cards*, *Nuclear Theory Reference Books*, *Nuclear Data Tables*, and *A Directory to Nuclear Data Tabulations*.

In addition to Ph.D. candidates engaged in thesis research, one Oak Ridge postdoctoral fellow, co-op students, and consultants under subcontract listed later in this report, assignees to the various other research groups within the Division during the past year were as follows: C. F. Coleman¹ of the Atomic Energy Research Establishment in Harwell, England (High Voltage Group); P. M. Griffin² (Optical Physics Group); Y. Hamaguchi¹ of the Japan Atomic Energy Research Institute in Tokai, Japan (Neutron Diffraction Group); M. O. Krause¹ (Charge Spectrometry Group); J. B. McGroarty¹ (Theoretical Physics Group); R. M. Moon, Jr. (Neutron Diffraction Group); D. Paya^{1,3} of the Commissariat de l'Energie Atomique in Paris, France (Low Energy Neutron Time-of-Flight Spectroscopy Group); and G. K. Werner² (Optical Physics Group).

H. Maier-Leibnitz,¹ Director of the Laboratorium für Technische Physik der Technischen Hochschule in Munich, Germany, has for the past several months been assigned to the Director's Division of ORNL; he has collaborated closely with staff members of the Physics Division, particularly with the Physics of Fission Group.

Loanees to the Division during this period have included: R. B. Dove,¹ R. S. Kaeser,¹ and H. Marshak¹ of the National Bureau of Standards (High Voltage Group); G. E. Sonja Fetsch¹ and Martha W. Jordan,¹ graduate students from Hollins College (Spectroscopy Research Group); and R. M. Haybron, professor of physics from Michigan State University (Theoretical Physics Group).

The following individuals completed assignments or terminated employment during this report period: I. L. Bergqvist¹ of the University of Lund in Lund, Sweden, and of the Research Institute of National Defense in Stockholm, Sweden (High Voltage Group); W. H. du Preez¹ of the South African Atomic Energy Board in Pretoria, South Africa (High Voltage Group); P. F. M. Fettweis¹ of the Centre d'Etude de l'Energie Nucléaire in Mol, Belgium (Mössbauer Program); H. Horstmann¹ of EURATOM in Geel, Belgium (Low Energy Neutron Time-of-Flight Spectroscopy Group); P. J. Pasma¹ of the State University of Groningen in Groningen, Netherlands (High Voltage Group); and F. J. Walter (Low Temperature Group).

¹Temporary assignment.

²Transferred from Thermonuclear Division to Physics Division.

³Exchange visitor. G. de Saussure of the Neutron Physics Division was the ORNL exchange visitor to the Paris laboratory.

H. B. Willard, formerly co-director of the High Voltage Laboratory, was recently appointed Associate Director of the Physics Division. He will share the duties and responsibilities of this position with E. O. Wollan, who has been Associate Director of the Division for the past 15 years. H. B. Willard has also been made responsible for various educational-connected activities which are mentioned in later sections of this report.

P. H. Stelson was appointed Director of the High Voltage Laboratory of the Physics Division.

R. C. Block (Low Energy Neutron Time-of-Flight Spectroscopy Group), J. H. Gibbons (High Voltage Group), and P. H. Stelson (High Voltage Group) resumed their duties at ORNL during this period upon completion of one-year assignments, respectively, at the Atomic Energy Research Establishment in Harwell, England, the Oak Ridge Institute of Nuclear Studies, and Rice University.

During the past year, three information centers were designated within the Division. These and the persons in charge are as follows: Charged Particle Information Center (F. K. McGowan), Nuclear Data Information Center (Katherine Way), and Neutron Cross Section Collection Information Center (J. A. Harvey).

ADVISORY COMMITTEE

Several advisory committees are attached to various divisions of the Oak Ridge National Laboratory for the purpose of offering advice on the cogency and effectiveness of the many scientific programs under way.

At the time of the Annual Information Meeting of the Physics Division and the Electronuclear Division (June 18–21, 1963), the research programs in these divisions were reviewed by a joint Advisory Committee whose members are listed below:

Dr. A. M. Clogston	Bell Telephone Laboratories Murray Hill, New Jersey
Prof. B. L. Cohen	University of Pittsburgh Pittsburgh, Pennsylvania
Prof. Martin Deutsch	Massachusetts Institute of Technology Cambridge, Massachusetts
Prof. D. L. Judd	Lawrence Radiation Laboratory University of California Berkeley, California
Prof. L. J. Rainwater	Columbia University New York, New York
Prof. J. A. Wheeler	Princeton University Princeton, New Jersey

AMERICAN PHYSICAL SOCIETY

SOUTHEASTERN SECTION MEETINGS

Two meetings of the Southeastern Section of the American Physical Society were held in 1963, the first at the University of Tennessee in Knoxville, April 4–6, and the second at the University of Kentucky in Lexington, November 7–9. Physics Division staff members took an active part in planning, conducting, and participating in these meetings. Hereafter, the Southeastern Section will meet annually in the fall of the year.

For both meetings, L. D. Roberts of the Physics Division (as the elected Vice-Chairman of the Southeastern Section of the American Physical Society) was Chairman of the Program Committee; this 15-member Committee included two other members of the Physics Division – J. L. Fowler and F. E. Obenshain.

At the Knoxville meeting it was announced that L. D. Roberts had been elected Chairman of the Section for 1963–64.

Also at the Knoxville meeting, J. L. Fowler conducted an informal placement service which has now become a regular part of the Southeastern Section meetings.

TOPICAL CONFERENCE

A Topical Conference on Compound Nuclear States, cosponsored by the American Physical Society and the Oak Ridge National Laboratory, was held in Gatlinburg, Tennessee, October 10–12, 1963. Various aspects of compound nuclear states were reviewed in 30-min talks by 10 invited experts, and 71 contributed talks were presented,¹ 7 of the latter by Physics Division staff members.

J. L. Fowler, Director of the Physics Division, was Chairman of the Program Committee responsible for organizing and conducting the Conference; the six-member Program Committee also included three other members of the Physics Division – G. R. Satchler, T. A. Welton, and H. B. Willard.

Two hundred sixty-one scientists from universities and installations in Belgium, Brazil, Canada, France, Finland, Germany, and the United States were among the participants in the three-day meeting.

¹Invited papers to be published in the October 1964 issue of *Reviews of Modern Physics*; abstracts of contributed papers to be published in the *Bulletin of the American Physical Society* (Tucson meeting, February 1964).

MISCELLANEOUS ACTIVITIES OF DIVISIONAL PERSONNEL

Physics staff members are frequently appointed to, or requested to assume, certain professional duties, incident to their primary responsibilities at ORNL, in connection with scientific journals, societies, committees, and institutes. Among these activities during the past year are the following:

J. L. Fowler	Member of Brookhaven National Laboratory Physics Visiting Committee Member of Carnegie Institute of Technology Physics Visiting Committee Member of American Physical Society Committee on the Character of Topical Conferences Advisory Consultant to Nuclear Data Project ¹
N. B. Gove	Secretary of the National Academy of Sciences—National Research Council Subcommittee on Nuclear Constants
J. A. Harvey	Reviewer for <i>Computing Reviews</i> Reviewer for <i>Physical Review</i> Reviewer for <i>Nuclear Science and Engineering</i> Reviewer of "Proposals in Neutron Physics Research" for the National Science Foundation Assistant in preparation of new edition of BNL-325, <i>Neutron Cross Section Compilation</i>
C. H. Johnson	ORNL Radiation Control Officer (Physics Division) ORNL Safety Officer (Physics Division)
W. C. Koehler	Member of Advisory Committee for the "Conference on Magnetism and Magnetic Materials" Member of ORNL High Flux Isotope Reactor Review Committee
R. L. Macklin	Member of Oak Ridge Gaseous Diffusion Plant Nuclear Safety Committee Member of the Membership Committee for the Research Society of America — Oak Ridge Branch
F. K. McGowan	Reviewer for Nuclear Data Project ¹ (<i>Nuclear Data Sheets</i>)
P. D. Miller	Reviewer for <i>Computing Reviews</i> Representative from the Physics Division for ORNL Computer Advisory Committee
C. D. Moak	Reviewer for <i>Reviews of Scientific Instruments</i>
H. W. Morgan	Faculty member of Fisk Infrared Spectroscopy Institute Member of National Institute of Health Advisory Committee on Computers in Research

¹Affiliated with the National Academy of Sciences—National Research Council in Washington, D.C., until January 1964, at which time the Nuclear Data Project will become a part of the Physics Division of the Oak Ridge National Laboratory.

L. D. Roberts	Chairman of the Southeastern Section of the Americal Physical Society Chairman of the Fritz London Award Committee Member of the Organizing Committee for "Ninth International Conference on Low Temperature Physics"
G. R. Satchler	Member of the Organizing Committee for "Gordon Research Conference on Nuclear Reaction Mechanisms"
P. A. Staats	Faculty member of Fisk Infrared Spectroscopy Institute
P. H. Stelson	Member of the National Academy of Sciences—National Research Council Subcommittee on Nuclear Structure Reviewer for Nuclear Data Project ¹ (<i>Nuclear Data Sheets</i>)
K. L. Vander Sluis	Member of the National Academy of Sciences—National Research Council Committee on Line Spectra of the Elements
Katherine Way	Chairman of the National Academy of Sciences—National Research Council Subcommittee on the Techniques of Distribution of Scientific Information Member of American Institute of Physics Advisory Committee on Man-power
T. A. Welton	Reviewer for <i>Journal of Applied Physics</i>
H. B. Willard	Member of the Atomic Energy Commission Nuclear Cross Section Advisory Group

ACTIVITIES RELATED TO EDUCATIONAL INSTITUTIONS

Research Participants

The Research Participation Program of the Oak Ridge Institute of Nuclear Studies¹ enables selected university faculty members to participate in research, primarily during the summer months, at several major installations of the U.S. Atomic Energy Commission. The Oak Ridge National Laboratory provides most of these appointments; some projects are conducted at the University of Tennessee Agricultural Research Laboratory and at the Oak Ridge Institute of Nuclear Studies. In addition, appointments are now possible at the Puerto Rico Nuclear Center and at the Savannah River Laboratory. Of obvious mutual benefit both to the participant and to the laboratory where he carries out his work, this arrangement between the Oak Ridge Institute of Nuclear Studies and laboratories in Oak Ridge has, over the past 15 years, also been extremely important to the progress of nuclear energy research and development, not only in the South, but in the entire nation.

¹Under contract with the USAEC.

In the summer of 1963, 59 Research Participants, representing 46 colleges and universities in 26 states, received appointments. The following 6 investigators were engaged in research with various groups within the Physics Division of the Oak Ridge National Laboratory: R. T. Folk (Assistant Professor, Lehigh University), Theoretical Physics Group; W. E. Hunt (Assistant Professor, David Lipscomb College), Charge Spectrometry Group; A. Mukerji² (Visiting Fellow, University of Alabama), Low Temperature Group; D. S. Onley³ (Assistant Professor, Duke University), Theoretical Physics Group; L. A. Rayburn (Professor, University of Georgia), High Voltage Group; and R. G. Steinhardt, Jr.⁴ (Professor, Hollins College), Spectroscopy Research Group.

Summer Visitors

Summer visitors with the Division in 1963 included: W. M. Bugg (Assistant Professor, University of Tennessee), High Energy Physics Group; V. M. deLany (graduate student, University of California, Berkeley), Theoretical Physics Group; D. W. Forester (graduate student, University of Tennessee), Low Temperature Group; R. M. Haybron (Professor, Michigan State University), Theoretical Physics Group; J. Kronsbein (Professor, University of Florida), Theoretical Physics Group; J. T. Rapaport (Research Physicist, University of Chile, Santiago), High Voltage Group; T. Terasawa (Assistant Professor, Tokyo University of Education), Theoretical Physics Group; and J. B. Thomas (graduate student, Stanford University), Theoretical Physics Group.

Summer Student Trainee Program

The Summer Student Trainee Program is administered by the Oak Ridge Institute of Nuclear Studies in cooperation with the Oak Ridge National Laboratory under the sponsorship of the U.S. Atomic Energy Commission. The program offers temporary summer appointments, on a competitive basis, to a limited number of students who have completed their junior year of college and who are majoring in the sciences. Primarily for students (citizens of the United States) from small colleges in the southern region, this arrangement affords students the opportunity of working in a full-time research laboratory during the summer months and serves to encourage them to carry on graduate work after they have attained the bachelor degree in science.

In 1963, the fifth year of the Student Trainee Program, students with the Division under the auspices of this program were: J. W. Frickey (Nebraska Wesleyan University), High Energy Physics Group; J. G. Lipham (Oglethorpe University), High Voltage Group; D. H. Lovegrove (Berea College), Theoretical Physics Group; B. K. Moore (Phillips University), Low Temperature Group; K. D. Pearce (St. Edward's University), Low Energy Neutron Time-of-Flight Spectroscopy Group; and G. Rebecca Zepeda (Our Lady of the Lake College), Theoretical Physics Group.

²On leave from Tata Institute of Fundamental Research, Bombay, India.

³Oak Ridge Institute of Nuclear Studies Research Participant on loan to the Physics Division of Oak Ridge National Laboratory.

⁴On leave to Stanford University, Stanford, Calif., during the academic year 1963-64.

Cooperative Education Program for Undergraduate Students

Promising students in science and engineering, who have completed at least two quarters of undergraduate study, are selected to participate in the Cooperative Education Program of the Oak Ridge National Laboratory. These students alternate between equal periods of time spent in school attendance and of work at the Laboratory. The Co-op Program, now in its 12th year at ORNL, has proved highly successful both as a means for promoting the professional development of students and for providing valuable technical assistants for scientific research in the Laboratory.

Nine Co-op students were with the Physics Division during the past year and were assigned to the High Voltage Group, the Theoretical Physics Group, and the High Energy Physics Group. These students included: J. F. Agnew,⁵ M. B. Johnson, and L. W. Owen⁵ of the Virginia Polytechnic Institute in Blacksburg, Va.; D. J. Burkholz and S. L. Kramer of the Drexel Institute of Technology in Philadelphia, Pa.; R. G. Beidel, D. N. Mashburn, and R. J. Metzger of the University of Tennessee in Knoxville; and D. T. Olson of the University of Louisville, Ky.

COOPERATIVE PROGRAM IN GRADUATE EDUCATION BETWEEN ORNL AND THE UNIVERSITY OF TENNESSEE SUPPORTED BY THE FORD FOUNDATION

Over the last several years ORNL has explored actively with the University of Tennessee various schemes for a more intimate involvement between basic research at the Laboratory and graduate science education at the University. These studies led to a joint proposal, submitted to the Ford Foundation early in 1963, which culminated in an appropriation of about \$750,000 to be awarded to the University over a ten-year period. This unique cooperative arrangement promises to create a graduate school of science and engineering of the highest caliber at a time when the manpower shortage in these fields is considered critical.

Under terms of the Ford Foundation grant, the University of Tennessee was able to appoint recently a number of qualified ORNL staff members as part-time faculty members in the Departments of Chemistry, Mathematics, Physics, and Chemical and Metallurgical Engineering. Similar appointments have been made in the Departments of Nuclear Engineering and Engineering Mechanics under University support.

These joint appointments, under AEC approval, allow the participants to be released from their Laboratory duties in order to spend up to 20% of their time at the University teaching courses, supervising theses, consulting with students and other professors, and participating in seminars, staff meetings, and examinations. At present about 20 such positions have been filled with the expectation that the number will increase to 30 or 40. Three of the five appointments in the University's Department of Physics were made to members of the ORNL Physics Division. L. D. Roberts, T. A. Welton, and H. B. Willard were appointed Professors of Physics as of October 1, 1963.

⁵Completed Co-op assignment during this period.

Students in the program may elect to do their thesis research either at the University or at the Laboratory. In the latter case AEC-sponsored Oak Ridge Graduate Fellowships are available to support the student during this phase of his graduate career. These fellowships were recently broadened to include one year of on-campus study prior to the commencement of thesis research. It should be emphasized that Oak Ridge Graduate Fellowships are open to all qualified U.S. citizens enrolled in graduate schools throughout the country. It is expected that these bright young students performing their research at the Laboratory will provide a flow of ideas and be a source of stimulation that will greatly benefit the Laboratory.

Oak Ridge Graduate Fellowship Program

The expanded graduate program of ORNL has resulted in 36 new applications for doctoral fellowships during the 1963 calendar year. Of these, 26 were recommended for Oak Ridge Graduate Fellowships by the ORNL Graduate Fellow Selection Panel chaired by H. B. Willard and with T. A. Welton as a panel member for physics and mathematics. Thus, the current number of Oak Ridge Graduate Fellows at ORNL has increased to 32, or about three times the average number during the past 14 years. This is interpreted not as a large fluctuation in the average, but rather as an encouraging sign for the future of this program.

The distribution in fields of current doctoral fellows is rather interesting: there are 18 in physics (6 are carrying out their research in the Physics Division),¹ 5 in biology, zoology, forestry, and ecology, 4 in chemistry, 3 in mathematics, 1 in chemical engineering, and 1 in nuclear engineering. Thirteen of the fellows are from the University of Tennessee, 3 from the University of Texas, 2 from Vanderbilt, 2 from Texas A and M, and 1 each from Catholic University, Duke University, Georgia Institute of Technology, Louisiana State University, Princeton University, and the Universities of Delaware, Louisville, Massachusetts, Minnesota, Mississippi, Missouri, and South Carolina.

J. H. Gibbons collaborated in the program by temporarily serving as Head of the University Participation Section of the University Relations Division of ORINS until October 1963.

Oak Ridge Postdoctoral Fellowship Program

During the past year a new AEC Postdoctoral Fellowship Program, administered by ORINS in cooperation with ORNL, was inaugurated. These fellowships provide a means of promoting the progress of science and engineering in subjects related to AEC-approved programs by making available to scientists of unusual ability and promise an opportunity for advanced training in basic research at the Laboratory. Initial appointments are for a one-year period and are renewable for a maximum of one additional year. Applicants for this program are screened by the ORNL Graduate Fellow Selection Panel.

¹Listed in section titled "Ph.D. Thesis Research" (p. 34).

Four of the six applicants during 1963 were approved for fellowships. Those selected represent the fields of physics (2), chemistry (1), and biology (ecology) (1). Their doctoral degrees were awarded from Yale University, the Massachusetts Institute of Technology, the University of Virginia, and Northwestern University. F. P. Gibson (Ph.D. in physics, 1963, from MIT), one of the Oak Ridge Postdoctoral Fellows, is presently carrying out his research with the Theoretical Physics Division.

Ph.D. Thesis Research

During the past year, 22 Physics Division staff members served in an advisory or supervisory capacity for thesis research conducted by 19 Ph.D. candidates, as listed below:

Ph.D. Candidate	Staff Member(s)	Field of Research
Raymond Carpenter University of Tennessee	H. W. Morgan and P. A. Staats	High Resolution Infrared Spectroscopy of Tritiated Molecules
H. R. Child University of Tennessee	E. O. Wollan and W. C. Koehler	Magnetic Properties of Rare Earth Alloys
D. W. Forester ^{2,3} University of Tennessee	L. D. Roberts and F. E. Obenshain	Use of the Mössbauer Effect in the Study of Ferromagnetism and Anti- ferromagnetism at Low Temperatures
M. V. Harlow ³ University of Texas	R. L. Robinson and J. L. Fowler	The Yield of Elastically Scattered 17- to 21-Mev Neutrons from C ¹²
R. W. Hockenbury Rensselaer Polytechnic Institute	R. C. Block	Neutron Capture Measurements
R. L. Kernell ⁴ University of Tennessee (on leave from College of William and Mary)	R. L. Macklin and J. H. Gibbons	Neutron Capture Cross Sections in the Kilovolt Range
W. E. Kiker ³ University of Tennessee	H. W. Schmitt	The Physics of Fission
R. W. Lamphere ⁵ University of Tennessee	J. L. Fowler and W. M. Good	The Angular Distribution of Fission Fragments from the Fast-Neutron Induced Fission of U ²³⁴
A. D. MacKellar ³ Texas A and M	R. L. Becker and T. A. Welton	Brueckner Theory for Finite Nuclei
J. H. Marable University of Tennessee	T. A. Welton	Nuclear Three-Body Problem
W. T. Milner University of Tennessee	F. K. McGowan	Coulomb Excitation with Heavy Ions

²Formerly National Science Foundation Cooperative Fellowship.

³Presently Oak Ridge Graduate Fellowship.

⁴Presently National Science Foundation Faculty Predoctoral Fellowship.

⁵Doctorate received in 1963.

R. B. Muir ³ University of Tennessee	H. O. Cohn	Systematics of 450 Mev/c K^- Interactions with Helium
W. F. Mruk ⁵ University of Tennessee	H. W. Schmitt and L. D. Roberts	Double Time-of-Flight Analysis of Fission Fragments
C. W. Nestor, Jr. Vanderbilt University	G. R. Satchler	Theory of Nuclear Structure
T. C. Oakberg University of Cincinnati	P. M. Griffin	Experimental Determination of Atomic Transition Probabilities
S. K. Penny University of Tennessee	G. R. Satchler	Theory of Nuclear Reactions
Gordon Soper ³ University of Tennessee	T. K. Fowler	Studies of Ion Cyclotron Resonance Instability
F. J. Walter University of Tennessee	J. W. T. Dabbs and H. W. Schmitt	The Kinetics of Thermal and Resonance Neutron-Induced Fission
M. L. West II ³ University of Texas	H. B. Willard and C. H. Johnson	(n,p) Differential Scattering Cross Section

Oak Ridge Resident Graduate Program of the University of Tennessee

At present there are approximately 250 students enrolled in the Oak Ridge Resident Graduate Program of the University of Tennessee; 25 are candidates for the Ph.D. degree in physics. About one-half of the 59 Ph.D.'s granted in physics, since the Graduate Program of the University began operation in 1947, have been conferred on students enrolled in the Oak Ridge Resident Graduate Program.

During the past year three members of the Physics Division have been affiliated with this program: E. C. Campbell as Acting Director, and R. L. Becker, E. C. Campbell, and W. C. Koehler as lecturers in physics.

Consultants Under Subcontract

Staff members of universities, both in the United States and in Europe, who have served as consultants to the Division during the past year are listed below. Numerous other consultants have presented seminar talks and have worked in collaboration with the various Physics groups during this period.

L. C. Biedenharn, Jr. Duke University	Theoretical Physics Group
W. M. Bugg University of Tennessee	High Energy Physics Group
G. T. Condo University of Tennessee	High Energy Physics Group
J. B. French University of Rochester	Theoretical Physics Group

J. H. Goldstein Emory University	Spectroscopy Research Group
W. H. Holladay Vanderbilt University	Theoretical Physics Group
J. M. Jauch University of Geneva Geneva, Switzerland	Theoretical Physics Group
T. Lauritsen California Institute of Technology	High Voltage Group
R. W. Lide University of Tennessee	Physics of Fission Group
J. B. Marion University of Maryland	Low Energy Neutron Time-of-Flight Spectroscopy Group
S. A. Moszkowski University of California at Los Angeles	Theoretical Physics Group
A. H. Nielsen University of Tennessee	Spectroscopy Research Group
H. W. Newson Duke University	High Voltage Group
W. T. Pinkston Vanderbilt University	Theoretical Physics Group
W. Thiele Max-Planck Institut für Chemie Mainz, Germany	Nuclear Data Group
J. O. Thomson University of Tennessee	Low Temperature Group
H. H. F. Wegener University of Erlangen Erlangen, Germany	Mössbauer Program
K. Wildermuth Florida State University	Physics of Fission Group
J. H. Wise Washington and Lee University	Spectroscopy Research Group

Two graduate students are under subcontract with the Division as part-time consultants:

J. Ginocchio University of Rochester	Theoretical Physics Group
C. S. Han University of Maryland	Nuclear Data Group

Traveling Lecture Program

The Traveling Lecture Program is conducted in cooperation with the Oak Ridge Institute of Nuclear Studies as a part of the AEC's program of disseminating scientific and technical information to universities, particularly those in the South. Laboratory personnel present in their lectures unclassified information to university undergraduate and graduate students and to faculty members. The lectures serve to stimulate interest in research in the university departments and also assist the teaching staff in expanding the scope of instruction offered under the regular curricula. Through such personal contacts, ORNL staff members are also able to observe departmental activities at the universities. During the current academic year (1963-64), 12 members of the Division have to date accepted invitations to present 41 lectures under this program; a complete listing of these will appear in the next annual report. Listed below are nine members of the Physics Division who participated in the Traveling Lecture Program during the academic year 1962-63, presenting a total of 25 lectures at 21 different colleges and universities:

R. L. Becker	Georgia Institute of Technology, December 5, 1962 University of Alabama, December 6, 1962 University of Kentucky, March 22, 1963 Louisiana State University, May 2, 1963 Rice University, May 3, 1963 "Pair Correlation Effects in Nuclei"
J. W. Cable	University of Oklahoma, October 16, 1962 University of Texas, October 18, 1962 "Recent Applications of Neutron Diffraction to Solid State Physics Problems"
T. K. Fowler	Tuskegee Institute, March 7, 1963 Auburn University, March 8, 1963 "Some Problems and Methods in Plasma Physics"
J. A. Harvey	State University of New York, March 28, 1963 "Neutron Capture Gamma Ray Experiments with Resonance Energy Neutrons"
W. C. Koehler	Virginia Polytechnic Institute, February 26, 1963 Louisiana State University, May 15, 1963 Rice University, May 16, 1963 "Recent Applications of Neutron Diffraction to Solid State Physics Problems"
H. W. Schmitt	Florida State University, March 28, 1963 "Kinetics of Fission: Fragment Energy Correlation Measurements"

P. A. Staats	Glenville State College, October 9, 1962
	Bethany College, October 10, 1962
	"An Introduction to Infrared Spectroscopy"
	West Liberty State College, October 10, 1962
	University of Arkansas, March 29, 1963
K. L. Vander Sluis	"Techniques of Experimental Infrared Spectroscopy"
	Texas Woman's University, March 28, 1963
	Brescia College, April 16, 1963
	"A Contestant for the 'Most Useful Radioisotope' Crown"
	Sam Houston State Teachers College, April 24, 1963
H. B. Willard	University of Oklahoma, April 25, 1963
	"The Role of the Zeeman Effect in Atomic Spectroscopy"
	University of Georgia, November 20, 1962
	Texas A and M College, January 9, 1963
	"Polarization of Beta Rays"
	University of Texas, January 10, 1963
	"Resonances in Nuclear Reactions"

ORINS-ORNL Summer Institute

The third Summer Institute for Small College Physics Teachers, conducted by the Oak Ridge Institute of Nuclear Studies in cooperation with the Oak Ridge National Laboratory, was held June 17 through August 9, 1963. As in past years this Institute, sponsored by the U.S. Atomic Energy Commission, was designed primarily to give participants an opportunity to review modern physics, acquire an understanding of current developments, become familiar with new equipment, and gain greater insight into the development of college courses in the fields of their interests.

Attendance at this Summer Institute was restricted to 20 college physics teachers from as many colleges. The scheduled program was geared to adhere to normal academic work loads; the major portion of the formally scheduled time was used for classroom lectures, laboratory assignments, and visits to Oak Ridge laboratories. Additional unscheduled time was provided for group discussions, library work, individual study, and attendance at lectures and discussions given by distinguished visiting scientists.

Included among the lecturers during the eight-week Institute were four Physics Division staff members. Fifteen lectures were presented by J. L. Fowler on "Nuclear Physics"; R. L. Becker presented five lectures on "Elementary Particle Physics"; and T. A. Welton and W. C. Koehler lectured, respectively, on "Lasers" and "Neutron Diffraction."

Demonstrations and tours conducted by members of the Division were as follows:

E. C. Campbell	Mössbauer Experiment at ORNL
H. B. Willard	Tour of High Voltage Laboratory
J. A. Harvey	Neutron Chopper at ORNL

Participation in International School and Winter Institute

R. L. Becker (Theoretical Physics Group) participated in the International School of Physics "Ettore Majorana" which was held in Eryx, Sicily, May 26 through June 8, 1963. The subject of this school dealt with "Present Problems in Strong, Electromagnetic, and Weak Interactions" and sponsorship was by CERN – European Organization for Nuclear Research, the Italian Ministry of Public Education, and the Italian Physical Society. The school, devoted to those physicists interested in acquiring a deeper theoretical understanding of strong, electromagnetic, and weak interactions, was composed of 10 invited scientists actively working in high-energy physics and 40 students selected from applicants according to their scientific qualifications.

T. A. Carlson⁶ (Charge Spectrometry Group) attended the Winter Institute in Quantum Chemistry, Solid State Physics, and Quantum Biology which was held at the University of Florida in Gainesville, December 2 through 28, 1963. Director and main lecturer of the Institute was Professor P. O. Löwdin of the University of Florida and the University of Uppsala, Uppsala, Sweden. A preparatory course was conducted the first week, with the next three weeks devoted to the main course which was designed as an advanced institute for theoretical chemists and physicists, and for experimentalists having good backgrounds in these and neighboring fields.

University Seminars

In addition to lectures presented under the Traveling Lecture Program and to talks given at scientific meetings and conferences, Divisional staff members receive numerous requests from universities for seminar talks. During this report period, 16 such invitations were accepted from 15 different universities:

S. Bernstein	Arizona State University, February 21, 1963
	University of Southern California, February 25, 1963
	"Total Reflection of Nuclear Resonance Radiation"
	University of Illinois, September 23, 1963
	"The Mössbauer Effect"
J. L. Fowler	Marshall University, August 5, 1963
	"Neutron Physics"
T. K. Fowler	University of Wisconsin, October 21–25, 1963
	"Plasma Stability Theories"
P. M. Griffin	University of Cincinnati, December 9, 1963
	"An Introduction to the Optical Maser with Demonstrations"
C. H. Johnson	University of Tennessee, May 7, 1963
	"Precision Experiments in Nuclear Beta Decay"
W. C. Koehler	Iowa State University, May 2, 1963
	"Spin Configurations in Rare Earth Metals and Alloys"

⁶On loan from ORNL Chemistry Division.

H. Maier-Leibnitz ⁷	University of Tennessee, November 19, 1963 "Neutron Optics"
H. W. Morgan	University of North Carolina, December 27, 1963 "Demonstration of Optical Phenomena with a Visible Laser"
G. R. Satchler	University of Rochester, March 15, 1963 "Recent Developments in Theory of Direct Nuclear Reactions"
H. W. Schmitt	University of California Radiation Laboratory, Berkeley, April 11, 1963 "Fission Correlation Experiments"
	Duke University, December 17, 1963 "Kinetics of Fission and Fission Correlation Experiments"
Taro Tamura ⁷	Carnegie Institute of Technology, June 6, 1963 Columbia University, June 13, 1963 University of Pennsylvania, June 14, 1963 "Vibrational Motion of the Nuclei"

⁷Temporary assignment.

ORNL PHYSICS SEMINARS

Divisional seminars are normally held at the Laboratory each Friday afternoon; for topics of especial timeliness or interest additional talks are frequently scheduled. H. O. Cohn has been seminar chairman since July 1962. Lectures presented during calendar year 1963 are listed below:

January 4	T. K. Fowler, ORNL "Current Status of Thermonuclear Research"
January 11	F. B. Malik, ¹ Princeton University "Program for Relativistic Hartree Wave Function"
January 11	Taro Tamura, ORNL "Vibrational Motions in Even-Even Nuclei"
January 18	H. W. Schmitt, ORNL "Kinetics of Fission: Fragment Energy Correlation Measurements"
February 1	R. K. H. Wagner, ORNL "Nuclear Physics Research at the University of Basel"
February 8	R. H. Dalitz, University of Chicago "Recent Progress in the Physics of Hypernuclei"
February 15	H. W. Bertini, ORNL "Intranuclear Cascade Calculations for Incident Particles Between 50 and 400 Mev"
February 19	M. Borghini, Centre d'Etudes Nucléaires, Saclay, France "Experimental Scattering of Polarized Protons of 20 Mev by a Target of Polarized Protons"

¹Presented as part of a Special Theoretical Physics Seminar Series arranged by R. L. Becker.

- February 27 C. J. Gallagher, Jr., Columbia University
"Two Quasi-Particle Excitations in Deformed Even-Mass Nuclei"
- March 1 Sami Cuperman, ORNL
"On Impurity Radiation Losses from a Hot Spherical Plasma"
- March 8 P. F. M. Fettweis, Centre d'Etude de l'Energie Nucléaire, Mol, Belgium
"Study of Some Short Lived Isomeric States at CEN, Mol, Belgium"
- March 15 R. Berman, Oxford University, Oxford, England
"Some Recent Experiments in Heat Conduction"
- March 22 P. J. Pasma, Foundation for Fundamental Research on Matter, Groningen, Netherlands
"Nuclear Physics Research at Groningen"
- March 25 P. Huber, Physikalisches Institut der Universität, Basel, Switzerland
"The Basel Source of Polarized Deuterons"
- March 29 Toyojiro Fuketa, Japan Atomic Energy Research Institute, Tokai, Japan
"Level Spacings and s-Wave Neutron Strength Functions of the Isotopes of Tin"
- April 15 Brebis Bleaney, Clarendon Laboratory, Oxford, England
"Nuclear Moments of the Lanthanons"
- April 16 Brebis Bleaney, Clarendon Laboratory, Oxford, England
"Crystal Field Effects in Pr, Ce, Nd Metals"
- April 17 Brebis Bleaney, Clarendon Laboratory, Oxford, England
"Crystal Field Effects in LnNi_2 , LnNi_5 Compounds"
- May 3 M. O. Krause, ORNL
"The Readjustment of Atoms Ionized in an Inner Shell"
- May 10 T. Nagamiya, University of California, Berkeley
"Magnetic Configuration and Electronic Structure"
- May 17 Cloyd Beasley, ORNL
"Recent Theoretical Work on Pion and Nucleon Electromagnetic Structure"
- May 24 R. B. Setlow, ORNL
"DNA: Its Structure, Function, and Inactivation"
- May 31 Enrique Silberman, University of Buenos Aires, Buenos Aires, Argentina
"Physics Research and Training in Argentina"
- June 5 D. D. Clayton, California Institute of Technology
"The New Significance of Neutron-Capture Cross Section"
- June 7 D. D. Clayton, California Institute of Technology
"Neutron Capture Clocks and Galactic History"
- June 14 I. G. Schroder, Brookhaven National Laboratory
"Thermal Neutron Fission of U^{235} with Emission of Long Range Alpha Particles"
- June 28 W. D. Ehmann, University of Kentucky
"Determination of Meteoritic Elemental Abundances by Activation Analysis"
- July 12 K. K. Seth, Northwestern University
"P-D Scattering and Polarization Measurements Using Gas Mixtures"
- July 16 through August 21 V. M. deLany,¹ University of California, Berkeley (12 lectures presented)
"Complex Variables in Elementary Particle Physics"
- July 19 R. M. Moon, ORNL
"Coherent Scattering of Polarized Neutrons from Hexagonal Cobalt"

- July 26 R. T. Folk, Lehigh University
"Many-Body Theory Applied to Few-Nucleon Problems"
- August 1 J. Rapaport, Institute of Science, University of Chile, Santiago, Chile
"Studies of Nuclear Energy Levels of Ca^{45} , Sc^{46} , and Ti^{47} from (d,p) Reactions"
- August 7 and Eugene Guth,¹ ORNL
August 14 "Report on the International Conference on Nuclear Structure (Stanford)"
- August 9 R. P. Levey, Y-12, ORNL
"High Pressure Tooling Design for Isostatic Pressing"
- August 14 E. R. Rae, Atomic Energy Research Establishment, Harwell, England
"Neutron Capture Cross Section Measurements with the Harwell Electron Linac"
- August 16 Ambuj Mukerji, University of Alabama
"Decay of Ru^{103} "
- August 23 R. G. Steinhardt, Jr., Hollins College
"Infrared Absorption Spectroscopy of Simple Non-Polar Liquids"
- August 30 D. S. Onley, Duke University
"High Energy Electron Inelastic Scattering from Nuclei"
- September 4 R. T. Folk,¹ Lehigh University
"Few-Body Problem"
- September 6 I. L. Bergqvist, University of Lund, Lund, Sweden
"Neutron Capture Gamma-Ray Spectra and Evidence for an $M1$ Giant Resonance"
- September 11 J. Olsen, Eidg. Technische Hochschule, Zurich, Switzerland
"Effect of Pressure on Superconductivity and Electron Scattering"
- September 13 Eugene Eichler, ORNL
"Study of Delayed Neutron Emission Following the Decay of N^{17} "
- September 20 F. B. Malik, Princeton University
"Independent Bare Model for Finite Nucleus"
- September 27 C. W. Williams, ORNL
"Recent Developments in Instrumentation for Nuclear Spectroscopy"
- October 4 J. C. Wheatley, University of Illinois
"Low Temperature Properties of He^3 "
- October 8 Ingmar Bergstrom, Nobel Institute of Physics, Stockholm, Sweden
"Recent Measurements of Auger Spectra in the Decay of Radioactive Xe, Kr, and Ar"
- October 11 B. R. Cooper, Harvard University
"The Study of Spin Waves in Spiral Spin Structure by Magnetic Resonance"
- October 25 G. J. Perlow, Argonne National Laboratory
"Mössbauer Effect on Xenon Compounds"
- October 29 W. R. Gibbs and J. Griffin, Los Alamos Scientific Laboratory
"Evidence for Nuclear Pairing Effects at the Fission Barrier"
- November 1 H. Nifenecker, Centre d'Etudes Nucleaires, Saclay, France
"Fission Cross Section of U^{233} and Related Distributions"
- November 1 John Perring, Argonne National Laboratory
"Analysis of Nucleon-Nucleon Scattering"
- November 5 Lyle Borst, University of Buffalo
"Lambda Point in He^4 "

- November 15 T. A. Carlson and H. W. Morgan, ORNL
"Life and Science Behind the Iron Curtain: Reports of Meetings in Warsaw and Budapest"
- November 18 Rene Pauthenet, Laboratoire d'Electrostatique et de Physique du Métal, Grenoble, France
"Ferromagnetism in Ordered Fe-Ni Alloys"
- November 22 R. D. Lowde, Atomic Energy Research Establishment, Harwell, England
"Some Current Work on Magnetism at Harwell"
- December 6 R. M. Haybron, Michigan State University
"Inelastic Scattering of High Energy Nucleons"
- December 9 J. F. Vervier, Centre d'Etudes de L'Energie Nucléaire, Mol, Belgium
"Effective Neutron-Proton Nuclei for A Between 50 and 58"
- December 13 George Condo, University of Tennessee
"The Atomic Cascade of K^- Mesons in AgBr"
- December 20 T. A. Welton, ORNL
"Molecular Structure Determination by Electron Microscopy"

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