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MASTER

Argonne National Laboratory

PHYSICS DIVISION

SUMMARY REPORT

March 1961

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ARGONNE NATIONAL LABORATORY
9700 South Cass Avenue
Argonne, Illinois

PHYSICS DIVISION
SUMMARY REPORT

March 1961

Morton Hamermesh, Division Director

Preceding Summary Reports:

ANL-6235 - November 1960
ANL-6262 - December 1960
ANL-6288 - January, February 1961

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FOREWORD

The Summary Report of the Physics Division of the Argonne National Laboratory is issued monthly for the information of the members of the Division and a limited number of other persons interested in the progress of the work. Each active project reports about once in 3 months, on the average. Those not reported in a particular issue are listed separately in the Table of Contents with a reference to the last issue in which each appeared.

This is merely an informal progress report. The results and data therefore must be understood to be preliminary and tentative.

The issuance of these reports is not intended to constitute publication in any sense of the word. Final results either will be submitted for publication in regular professional journals or, in special cases, will be presented in ANL Topical Reports.

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I. EXPERIMENTAL NUCLEAR PHYSICS

I-9-3 Lifetimes of Energy Levels Excited by Slow-Neutron Capture (Formerly "Excited Levels of Mn⁵⁶") (51210-01)

S. J. du Toit* and L. M. Bollinger
Reported by S. J. du Toit

Our knowledge of the lifetimes of low-lying excited states in nuclei is still rather incomplete.¹ Data on this are, however, of importance because the theoretical estimates of these lifetimes depend on specific nuclear models. Absorption of a slow neutron by a nucleus usually results in the prompt emission of a cascade of γ rays which appreciably populates low-lying states of both parities and various spins. The observation of the low-energy part of a capture- γ -ray spectrum will thus often reveal transitions inaccessible by β decay because of spin considerations. In addition, many of the isotopes that can be formed by neutron capture, especially odd-odd nuclei, cannot be reached by β decay.

If one goes through the literature he finds, however, only one reported experiment on the lifetimes of excited states fed by neutron capture. This experiment was performed at Argonne by D'Angelo.² In view of the importance of this field we decided to continue D'Angelo's work, using essentially the same equipment.

* South African Atomic Energy Board, Pretoria, Union of South Africa.

¹ D. H. Wilkinson in Nuclear Spectroscopy, edited by Fay Ajzenberg-Selove (Academic Press, New York and London, 1960), Part B, p. 852.

² N. D'Angelo, Phys. Rev. 117, 510 (1960).

The functioning of the equipment was checked by repeating D'Angelo's measurements of the half-lives of the first two excited levels of Mn^{56} . Half-lives of 11.4^{+2}_{-3} nsec and 5.1 ± 0.5 nsec were found for the first and second excited states of Mn^{56} , respectively, in agreement with the values found by D'Angelo. A subsequent determination of the half-life of the first excited state at 32 keV in Al^{28} gave a value of 2.3 ± 0.2 nsec. This was in excellent agreement with the value of 2.1 ± 0.3 nsec found by Severiens and Hanna,³ who used a completely different technique, and it served as an additional check on the reliability of the method.

In the decay of Rh^{104} the first excited state was found to have a half-life of 2.6 ± 0.2 nsec, and the state associated with the 96-keV transition a half-life of ≤ 0.6 nsec. Both the first and second excited states in Cu^{64} showed half-lives ≤ 0.3 nsec. The energies of the low-lying states in Cu^{64} and Cu^{66} were determined with improved accuracy.

Fig. 1. Decay of 137-keV transitions in I^{128} .

The study of the γ spectrum of I^{128} produced a number of interesting results. Prominent lines were found at 30 ± 1 , 88 ± 2 , and 137 ± 2 keV, and evidence was found for further lines at 182 ± 5 , 220 ± 5 , 240 ± 5 , 300 ± 10 , and 430 ± 10 keV. Previously only transitions of 135 ± 3 and 158 ± 4 keV had been established.⁴ By obtaining the spectra from capture in various neutron resonances, it was shown that

³ J. C. Severiens and S. S. Hanna, Phys. Rev. 104, 1612 (1956).

⁴ L. F. Kalinkin, A. S. Melioranskii, and I. V. Estulin, J. Exptl. Theoret. Phys. (USSR) 36, 1613 (1959) [translation: Soviet Physics JETP 9, 1146 (1959)].

these lines originate from transitions in I^{128} . The 30-kev line was shown to be due also to a transition in I^{128} , and not to consist exclusively of conversion x rays.

The 30-kev transition has a half-life of 8.8 ± 1.0 nsec, and the 88-kev transition a half-life ≤ 0.7 nsec. With the window of the analyzer set at 137 kev, the decay was found to be complex, with a "prompt" component and a component with a half-life of 8.0 ± 0.6 nsec. The decay curve is shown in Fig. 1 which also shows a "prompt" resolution curve taken with γ rays from cadmium, for comparison. In spite of the similarity of the half-lives found for the 30-kev and 137-kev transitions, it was possible to show that these transitions are not connected, and that I^{128} has excited states at 30 kev and 137 kev decaying directly to the ground state.

I-11-27 Installation and Operation of the Van de Graaff Generator
(51210-01)

Jack R. Wallace

This report covers the operation of the Van de Graaff generator in the Physics Division for the period from October 1 to December 31, 1960 inclusive.

The generator was used to accelerate protons, deuterons, and alphas. Its voltage varied from 1.6 to 4.0 Mv. The beam currents measured at the target varied from 0.1 to $40 \mu a$.

The following list shows the type of experiments performed with the generator and the number of hours per experiment.

1. Total cross section and capture cross section of B^{10} , B^{11}	Huddleston, Mooring	87.9 hr
2. Fission cross section of U^{235}	Stupegia	43.6
3. Polarized protons from Ti^{48} (d,p)	Smither, Weinman	385.8
4. Neutron polarization	Elwyn, Lane, Langsdorf	189.1
5. Mossbauer effect in Fe^{57} by Coulomb excitation	Holland, Lynch	144.4
Total		<hr/> 850.8
Startup and daily maintenance		43.5
Machine repairs and experimental setups		<hr/> 293.7

Total time available (62 days $\times$ 16 hr/day + 24.5 days $\times$ 8 hr/day) 1188.0 hr

Mr. Harold Yarger, Student Aide (Co-op) from Antioch College, completed a study on possible ways to improve the output of our rf ion source in our Van de Graaff accelerator. The most promising way appears to be to follow the suggestion of Oak Ridge National Laboratory. This is the addition of an externally-adjusted electromagnet placed around the ion-source bottle to produce a magnetic field parallel to the length of this bottle. This improves the ionization of the gas in the ion source and thereby increases the beam output for a given probe and focus voltage. Plans are now underway to try the magnet on the ion source of the accelerator.

For some time now the glass shop of D203 under the direction of Mr. Julius Ostapowicz has been making the ion-source bottles for us. Their fine work and many helpful suggestions have improved the reliability and extended the useful life of these ion bottles. Mr. Sigmund Omiecinski of the glass shop has suggested a further improvement in our cleaning procedure that we feel will give us better reproducibility from one ion source to another.

I-19-5 Nuclear Resonance Absorption of Gamma Rays (51210-01)

S. S. Hanna, J. Heberle, C. S. Littlejohn, L. Meyer-Schützmeister, G. J. Perlow, R. S. Preston, and D. H. Vincent
Reported by S. S. Hanna

A. THE INTERNAL MAGNETIC FIELD AT THE NUCLEUS IN FERROMAGNETIC IRON

In the experiments described in ANL-6130, it was shown that in ferromagnetic iron the effective magnetic field at the iron nucleus is strongly correlated with the magnetization. The sense of the correlation, however, was not determined, i. e., it was not known whether the effective field was parallel or antiparallel to the magnetization. The sense of the correlation was established by observing the change in the hyperfine splitting of the nuclear energy levels of Fe^{57} on application of an external field of 17 to 20 koe.

For the effective field at the nucleus we write

$$\vec{H}_n = H_{n0} \vec{M}_0 + \vec{H}_{\text{ext}} ,$$

where $\vec{M}_0$ is a unit vector along the direction of magnetization in a ferromagnetic domain, and H_{n0} is the magnitude of the effective field in the absence of the external field $\vec{H}_{\text{ext}}$. The latter quantity includes the demagnetizing field, which is negligible for the planar samples used. Since $H_{\text{ext}}/H_{n0} \ll 1$ in the present experiment, it is assumed in the above equation that H_{n0} is not appreciably influenced by H_{ext} . The quantity of interest is the sign of H_{n0} . Since $\vec{M}_0$ and $\vec{H}_{\text{ext}}$ are parallel under saturation conditions, the sign can be determined by observing whether the hyperfine splitting increases or decreases on application of a field. With a field of 17.6 koe a shift of $\pm 2.65\%$ is expected in the lines of the hyperfine spectrum of iron.

Fig. 2. Outermost line in hyperfine spectrum of Fe^{57} observed with $H_{\text{ext}} = 0$ and $H_{\text{ext}} = 17.6$ koe, where H_{ext} is the external field applied to the source of resonance radiation. The ordinate is in units of 10^3 counts.

Fermi contact interaction. The polarization of inner shells of electrons results in negative contributions to the field. In view of the experimental result, these negative terms must completely dominate the other contributions. Several attempts have been made recently² to calculate these

The result

obtained for the last line of the spectrum is shown in Fig. 2. On application of the field to the source, a shift to lower energy is unmistakable. The correlation is therefore negative. The magnitude of the observed shift is $(2.7 \pm 0.4)\%$, which is compatible with the linear relation $H_n = H_{n0} - H_{\text{ext}}$.

The effective field

at the iron nucleus has now been determined both in sign and magnitude. The existence of such a large negative magnetic field (-333 koe) was unexpected. Marshall¹ has discussed a number of sources of the effective nuclear field. The main effect of the unpaired 3d electrons is to polarize the various s electrons, which then contribute to the field via the

¹ W. Marshall, Phys. Rev. 110, 1280 (1958).

² D. A. Goodings and V. Heine, Phys. Rev. Letters 5, 370 (1960); A. J. Freeman and R. E. Watson, Phys. Rev. Letters 5, 498 (1960).

negative terms quantitatively, but without complete success.

When the source and the absorber of resonance radiation are maintained at different temperatures, two separate and interesting phenomena may be observed.

The first effect is seen in Fig. 3. With the source at 80°K and the absorber at 410°K , the central line in absorption is shifted toward negative velocities. An identical shift is observed in all the other lines in the hyperfine spectrum (Fig. 4).

Fig. 3. Central resonance line obtained with source at 80°K and absorber at 410°K . The line broadening and structure are due to the change in hyperfine splitting with temperature. The shift of the line is due to the temperature shift in the Mössbauer effect.

Fig. 4. Outermost line in hyperfine spectrum of Fe^{57} with source at 80°K and absorber at 460°K . The line obtained at negative velocities (right) is plotted separately from the line at positive velocities (left).

Fig. 5. Temperature shift in Fe^{57} . The shift observed in the absorption spectrum is plotted as a function of the temperature of the absorber. The solid line is the theoretically expected curve for a Debye temperature of 420°K . The dashed curve was computed from the total specific heat of iron.

This temperature shift may be explained in two equivalent ways. (1) During the recoilless emission (or absorption) of a gamma ray, the linear velocity of the emitting nucleus averages to zero so that there is no first-order Doppler broadening of the line. On the other hand, the square of velocity does not average to zero and hence there is a second-order Doppler shift in frequency. Since v^2 is a function of temperature, this leads directly to the temperature shift.³ (2) With the other point of view, one notes that the mass of the emitting nucleus changes on emission of the gamma quantum and so also does the vibrational frequency of the lattice. This change in the vibrational energy of the crystal is temperature dependent so that again one may derive the temperature shift in the resonant lines.⁴ The temperature shift in iron has been measured from 77 to 1200°K with the result shown in Fig. 5. The solid line is

³ R. V. Pound and G. A. Rebka, Jr., Phys. Rev. Letters 4, 274 (1960).

⁴ B. D. Josephson, Phys. Rev. Letters 4, 341 (1960).

a theoretical curve based on a Debye temperature of 420° .

The second effect of temperature is observed in ferromagnetic substances and can be attributed to the temperature dependence of the effective field at the nucleus. A decrease in temperature produces an increase in the magnitude of the effective field. This can be seen in Fig. 6, which shows the change in the position of the last line of the hyperfine spectrum when the temperature is changed from about 300°K to 80°K . The change in the value of the effective field also accounts for the broadening and structure observed in the central line in Fig. 3. The change in the internal field as a function of temperature is shown in Fig. 7. The measurements are compared with the saturation magnetization curve obtained by Potter.

The experiments described in this section and in ANL-6130 show that the internal field at the nucleus in a ferromagnet is correlated with the magnetization both in magnitude and direction. Hence we can write

$$\vec{H}_n = a \vec{M}.$$

The constant a is negative (Fig. 2) and is nearly independent of tempera-

Fig. 6. Outermost line in hyperfine spectrum of Fe^{57} observed with source and absorber at $T = 80^\circ\text{K}$ and then at $T = 300^\circ\text{K}$. The shift in the line is due to change in the hyperfine splitting.

Fig. 7. Temperature variation of the internal magnetic field at the nucleus in iron. The field is normalized to the field at 0°K , and the temperature to the Curie temperature ($T_c = 1040^\circ\text{K}$). The solid curve is the result obtained by Potter for the saturation magnetization in iron.

ture (Fig. 7). Experiments are now under way to explore the small temperature dependence that is evident in Fig. 7.

Above the Curie point, the internal field vanishes as indicated by the points plotted on the $H_n = 0$ axis in Fig. 7. The vanishing of the field in the absorber produces a spectrum of the hyperfine lines emitted by the cold source as seen in Fig. 8. The six lines in Fig. 8 comprise the basic hyperfine pattern of Fe^{57} .

B. RESONANT ABSORPTION AND NUCLEAR ZEEMAN EFFECT IN Sn^{119}

The energy-level diagram for Sn^{119} is shown in Fig.

9. The Mössbauer absorption and scattering by the 24-kev level has been

Fig. 8. Hyperfine spectra of Fe^{57} obtained with a cold source and an absorber above the Curie point. The six lines are the basic hyperfine pattern for Fe^{57} .

Fig. 9. Energy-level diagram of Sn^{119} .

studied in some detail by several investigators.⁵⁻⁷ With nonferromagnetic sources and absorbers, no magnetic splitting of the nuclear levels had been

⁵ R. Barloutaud, E. Cotton, J. L. Picou, and J. Quidort, *Compt. rend.* 250, 319 (1960); C. Tzara and R. Barloutaud, *Phys. Rev. Letters* 4, 405 (1960); R. Barloutaud, J. L. Picou, and C. Tzara, *Compt. rend.* 250, 2705 (1960).

⁶ A. J. F. Boyle, D. St. P. Bunbury, C. Edwards, and H. E. Hall, *Proc. Phys. Soc. (London)* 76, 165 (1960); L. Grodzins, report at Mössbauer Conference, University of Illinois (unpublished).

⁷ N. N. Delyagin, V. S. Shpinel', V. A. Bryukhanov, and B. Zvenglinskii, *J. Exptl. Theoret. Phys. (U.S.S.R.)* 39, 220-222 (1960).

Fig. 10. Resonant absorption spectra of the 24-keV radiation from $\text{Sn}^{119\text{m}}$. Top: pure tin absorber in the form of a 2-mil metal foil of natural tin. Bottom: annealed Mn_3Sn absorber 67 mg/cm^2 thick.

reported. This section describes a series of measurements on ferromagnetic alloys of tin in which the nuclear Zeeman effect in Sn^{119} was observed. The source of radiation was metallic tin containing $\text{Sn}^{119\text{m}}$. At the top of Fig. 10 is shown the absorption spectrum obtained with a pure tin absorber. Only a single resonant line, symmetric about zero velocity, is observed.

The first alloy studied was Mn_3Sn which was known to be ferromagnetic with a transition temperature of about 150°C .⁸ The velocity spectrum obtained with an annealed Mn_3Sn absorber is shown at the bottom of Fig. 10.

The single line observed with pure tin has been split magnetically into two prominent lines. The asymmetrical location of these lines (at about $+1.5$ and -3.0 mm/sec) is due to the difference in composition between the source and the absorber. The spins and parities of the ground state and first excited level of Sn^{119} are $\frac{1}{2}^+$ and $\frac{3}{2}^+$, respectively, so that for M1 radiation the basic hyperfine pattern con-

⁸ F. Heusler, Z. angew. Chem. **17**, 260 (1905); H. H. Potter, Phil. Mag. **12**, 261 (1931). This alloy has been generally called Mn_4Sn in the literature, and was thus labeled in our first report: Phys. Rev. **120**, 2211 (1960). We now identify it as Mn_3Sn , which has a close-packed hexagonal structure of the Ni_3Sn type (DO_{19}). Actually, single-phase samples appear to have a composition between Mn_3Sn and Mn_4Sn . We are greatly indebted to M. V. Nevitt for this information.

sists of six lines, as in the case of Fe^{57} . (See Fig. 8). Since the radiation emitted by the non-magnetic source is unsplit (mono-energetic), the structure observed with Mn_3Sn should contain these six lines. Therefore, each of the two lines in the Mn_3Sn spectrum is an unresolved triplet, so that the splitting in the excited state of Sn^{119} is smaller than in the ground state. With this interpretation, the splitting observed in the Mn_3Sn spectrum is approximately equal to the ground-state splitting. Since the magnetic moment of the ground state is -1.041 nuclear magnetons,⁹ the measured splitting gives a value of roughly 40 000 oersteds for the internal field at the tin nucleus in Mn_3Sn .

In the hope of obtaining an internal field large enough to resolve the splitting of the excited state, the alloy Mn_2Sn was investigated. This alloy was reputed to show enhanced magnetic properties below 0°C .⁸ The spectrum observed at low temperature is shown at the bottom of Fig. 11. The lines at about

Fig. 11. Resonant absorption in Mn_2Sn , with a metallic Sn^{119} source at 77°K , at absorber temperatures below and above the Curie point. At 370°K the absorber thickness is 54 mg/cm^2 ; at 80°K it is 91 mg/cm^2 .

⁹ W. G. Proctor, Phys. Rev. 79, 35 (1950).

+1.5 and -3.0 mm/sec are attributed to the presence of Mn_3Sn in the sample. The intensity of these lines was found to vary in different batches of alloy, while the other structure in the spectrum retained its main features. Although this latter structure (which is attributed to Mn_2Sn) is incompletely resolved, one can easily distinguish the six lines of the Zeeman spectrum.

The spectrum at the top of Fig. 11 was obtained at a temperature above the Curie point. It shows that the splitting practically disappears at this temperature and strengthens the assumption that the

Fig. 12. Resonant absorption in Mn_2Sn , with a metallic Sn^{119} source at 77°K , at two absorber temperatures above the Curie point. The velocity scale is expanded over that in Fig. 11. Absorber thickness is 54 mg/cm^2 .

structure is primarily magnetic. Actually there is possibly a residual doublet splitting above the Curie point, as shown in greater detail in Fig. 12. This splitting would correspond to a quadrupole interaction of about 27 Mc/sec or 10^{-7} ev .

The energy level diagram shown in Fig. 13 is based on the above interpretation of the spectrum from Mn_2Sn . The splitting in the ground state is $2\mu_g H_n = (16.0 \pm 1.0)\text{ mm/sec}$ in velocity units. The magnetic moments in the ground state and first excited state are designated by μ_g and μ_{ex} , respectively, and the internal field at the nucleus by H_n . With $\mu_g = -1.041$ nuclear

Fig. 13. Energy-level diagram of Sn^{119} in a magnetic field. The magnetic dipole transitions are shown.

magnetons, one obtains $H_n = (192 \pm 12) \times 10^3$ oersteds. In the excited state the splitting is (4.0 ± 0.2) mm/sec. Hence $\mu_{\text{ex}} = (0.78 \pm 0.08)$ nuclear magnetons. Since μ_g is negative, μ_{ex} is positive. The value of $+0.78$ nm is in good agreement with the prediction of the shell model. A pure $d_{3/2}$ level would give a value of $+1.15$ nm (Schmidt limit). Empirically, $d_{3/2}$ levels have values of the magnetic moment which cluster around $+0.8$ nm.

The spectrum at the bottom of Fig. 14 was obtained with the same sample of Mn_2Sn but it was placed in an external field of about 600 oersteds. This was done in order to magnetize the sample so as to align the internal fields at the nuclei. In an aligned field, the relative intensities of the Zeeman lines change from 3:2:1 to 3:4:1. The effect in

Fig. 14. Resonant absorption of the 24-keV radiation from $\text{Sn}^{119\text{m}}$ in the range of 5-18 mm/sec. Top: Mn_2Sn absorber, unmagnetized. Bottom: same absorber, magnetized.

Fig. 15. Resonant absorption in Mn_3Sn , with a metallic Sn^{119} source at 77°K , for various absorber temperatures above and below the Curie point. Absorber thickness is 39 mg/cm^2 .

Fig. 14 is not very pronounced but the enhancement in the central line seems well established.

In Fig. 15 are shown measurements on Mn_3Sn at several temperatures from room temperature to above the Curie point at about 150°C . At these relatively high temperatures the absorption is very small and high precision has not been achieved in the data. The temperature variation of the internal field, as obtained from these and similar measurements, is displayed in Fig. 16. The data are normalized to the point obtained at the temperature of liquid nitrogen (Fig. 10). The solid curve

in the figure is a theoretical Weiss curve which is in rather good qualitative agreement with the experimental points. The value of the field at 0°K is estimated to be roughly 45 koe.

To obtain the sign of the internal field in these alloys, the magnetic splittings in the absorption spectra were observed in an external field of 17 koe, as was done for iron (Sec. A). In the case of Mn_3Sn the measurements could be carried out with the absorber at room temperature, at which tempera-

Fig. 16. Temperature variation of the internal field at the tin nucleus in Mn_3Sn . A Curie temperature T_c of 423°K has been assumed. Data taken from Fig. 15.

Fig. 17. Resonant absorption in Mn_3Sn at room temperature ($\approx 300^\circ\text{K}$) without an external magnetic field (above) and with an applied field of 17.5 koe (below). The splitting is decreased by application of the field. Absorber thickness is 42 mg/cm^2 . Source temperature is 77°K .

Fig. 18. Resonant absorption in Mn_2Sn at approximately 250°K without an external magnetic field (above) and with an applied field of 17.5 koe (below). The splitting is increased by application of the field. Absorber thickness is 45 mg/cm^2 . Source temperature is 77°K .

ture the internal field at the tin nucleus has a value of about 40 koe. Relative to this field, the applied external field of about 17 koe should produce an easily detectable shift. The observations are shown in Fig. 17. On application of the external field the doublet separation is seen to decrease. Hence the internal field at the nucleus in Mn_3Sn is negative. The amount of the shift is compatible with the linear relation

$$H_n = H_{n0} - H_{\text{ext}},$$

where H_n and H_{n0} are the hyperfine fields with and without the external field H_{ext} .

In the case of Mn_2Sn it was necessary to cool the absorber below the Curie point (-11°C).¹⁰ To produce a convenient internal field of about 40 koe the absorber was maintained at a temperature of about -23°C . The measurements are shown in Fig. 18. In this case

¹⁰

C. Guillaud, Thesis, Strasbourg (1943), quoted in R. M. Bozorth, *Ferromagnetism* (D. Van Nostrand Company, Inc., Princeton, New Jersey) p. 340; R. Ochsenfeld, *Z. Metallkunde* **49**, 472, (1958).

the doublet separation is seen to increase on application of the field. Hence the hyperfine field at the tin nucleus in Mn_2Sn is positive. The amount of shift is compatible with the relation

$$H_n = H_{n0} + H_{\text{ext}}.$$

Thus, a possible demagnetizing effect of the applied field in the sample is not noticeable in the above measurements.

Since the hyperfine field is large and negative (≈ -300 koe) in the pure ferromagnetic transition elements, it is of considerable interest to find such a large positive field (+200 koe) at the tin site in the case of Mn_2Sn . Moreover, this field is very sensitive to the Mn:Sn ratio, since it changes sign in going to Mn_3Sn . It is significant, perhaps, that the saturation magnetization is some four times as great in Mn_2Sn as in Mn_3Sn .⁸ If the polarization of conduction electrons (produced by the adjacent magnetic electrons) increases with saturation magnetization, then the polarization and so also the field at the nucleus might be expected to be greater numerically in Mn_2Sn than in Mn_3Sn . The simplest explanation of the large positive field in Mn_2Sn is that the hyperfine field produced by polarization of conduction electrons is a positive field.

As for the pure transition elements, it is necessary to postulate, in addition, the presence of a negative field, presumably associated with polarization of the core electrons of tin. In Mn_3Sn this field predominates. That this field is smaller, if different at all, in Mn_2Sn is consistent with the fact that the Weiss field is smaller, since the Curie temperature is lower and the magnetization larger, in Mn_2Sn than in Mn_4Sn .

These effects observed in the manganese-tin alloys are somewhat analogous to those obtained by Boyle et al.¹¹ in dilute solutions of tin in the ferromagnetic transition elements. It is gratifying that essentially the same

¹¹ A. J. F. Boyle, D. St. P. Bunbury, and C. Edwards, Phys. Rev. Letters 5, 553 (1960).

mechanisms¹¹ can be invoked to give a qualitative explanation of the observations on all these tin alloys.

I-22-15

Scattering of Charged Particles

(51210-01)

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Reported by B. Zeidman

INTRODUCTION

The neutron configurations of the iron and nickel isotopes are of interest because these configurations arise predominantly from the filling of the 1f and 2p neutron shells. There is considerable evidence to indicate that there is competition between the $2p_{3/2}$, $2p_{1/2}$, and $1f_{5/2}$ orbitals. The (d,t) pickup reaction provides a convenient and direct way of studying the neutron configurations of the target nuclei. There are several theoretical treatments of nuclei in this region, based upon pairing forces. The work being reported is a continuation of the experiments and analysis previously published¹ and involves the use of the earlier data, as well as the earlier equipment and techniques.

RESULTS

Energy spectra were obtained at 3° intervals between 12° and 30° for all targets. In the previous study of (d,t) reactions in this region of the periodic table, it was seen that the desired information could be obtained within this angular range. This results from the fact that the various l values are clearly differentiated at the energy used for the Q values studied. The

¹

B. Zeidman, J. L. Yntema, and B. J. Raz, Phys. Rev. 120, 1723 (1960); B. J. Raz, B. Zeidman, and J. L. Yntema, Phys. Rev. 120, 1730 (1960).

spectra at 21° (lab) for the iron isotopes are shown in Fig. 19 while the spectra for the nickel isotopes are shown in Fig. 20. Angular distributions have been obtained for the unresolved groups in the various spectra except when the level spacing permitted reliable separation of the contributions from the individual states. The angular distributions of tritons leading to the ground state and the 2.5-Mev group in the reaction $\text{Ni}^{60}(\text{d},\text{t})\text{Ni}^{59}$ are shown

Fig. 19. Triton spectra from $\text{Fe}^{54}(\text{d},\text{t})\text{Fe}^{53}$ and $\text{Fe}^{58}(\text{d},\text{t})\text{Fe}^{57}$ at 21° (lab). The abscissae are the excitation energies of the residual nuclei.

Fig. 20. Triton spectra from (d,t) reactions on Ni^{58} , Ni^{60} , and Ni^{61} . The abscissae are the excitation energies of the residual nuclei.

Fig. 21. Angular distributions from the $\text{Ni}^{60}(\text{d},\text{t})\text{Ni}^{59}$ reaction. These distributions are representative of the two types of angular distributions observed.

in Fig. 21. In this region of the periodic table, the observed angular distributions correspond to pickup of 2p and 1f neutrons. Figure 21

illustrates the two types of angular distributions observed:

- (a) distributions fitted by $\ell = 1$ Butler curves (p-neutron pickup) as in the $\text{Ni}^{60}(\text{d},\text{t})\text{Ni}^{59}$ ground-state reaction, and (b) distributions fitted by $\ell = 3$ Butler curves (f-neutron pickup) as in the $\text{Ni}^{60}(\text{d},\text{t})\text{Ni}^{59}$ reaction leading to the 2.5-Mev group. All the angular distributions observed in the present ex-

periment correspond to pickup with $\ell = 1$, $\ell = 3$, or mixtures of both. It should be noted that weak $\ell = 1$ admixtures are observable in the presence of $\ell = 3$ contributions, but $\ell = 3$ admixtures are easily obscured or completely hidden by slightly stronger $\ell = 1$ contributions.

The spectrum from $\text{Fe}^{54}(\text{d},\text{t})\text{Fe}^{53}$, shown in Fig. 19, indicates the presence of only one prominent group which occurs in the vicinity of the ground state of Fe^{53} . The angular distribution of this group corresponds to pickup with $\ell = 3$.

The Fe^{58} target consisted of 53% Fe^{58} and 46% Fe^{56} with small amounts of the other iron isotopes. In order to obtain the spectra from the $\text{Fe}^{58}(\text{d},\text{t})\text{Fe}^{57}$ reaction, the contribution from Fe^{56} was subtracted from the data obtained with the Fe^{58} target. The effect of the subtraction is to introduce possible errors in intensity and peak position which are greater than those for the other targets. After sub-

traction, spectra such as that shown in Fig. 19 are obtained. Peaks are observed corresponding to excitations of approximately 0, 1.3, and 2.2 Mev and a very wide group at about 4.7 Mev. The angular distributions of the 0 and 1.3 Mev groups correspond to $\ell = 1$ transitions, but the possibility of $\ell = 3$ admixtures cannot be excluded. The 2.2-Mev group has an $\ell = 3$ angular distribution.

The spectra at 21° for the nickel isotopes is shown in Fig. 20. It is seen that the spectra of Ni^{58} and Ni^{60} are similar. Although there are several low-lying peaks in the Ni^{61} spectra, there are a number of groups whose Q values range between roughly 5 and 7.5 Mev, the region of large cross sections for Ni^{58} and Ni^{60} . Little is known about the levels of Ni^{57} . In this experiment, groups have been observed at excitation energies of 0, 0.85, 1.15, 2.5, and 3.2 Mev in Ni^{57} . The angular distribution of the ground-state group corresponds to $\ell = 1$, which is consistent with the presumed spin of $\frac{3-}{2}$ for the Ni^{57} ground state. The angular distribution of the 0.85-Mev group is a mixture of $\ell = 1$ and $\ell = 3$, which indicates that this group arises from contributions from at least two levels. At 2.5 Mev is a strong $\ell = 3$ group with some $\ell = 1$ admixture.

It is clear from changes in peak shape with variation of angle that several groups in the $\text{Ni}^{60}(\text{d}, \text{t})\text{Ni}^{59}$ reaction are composed of contributions from more than one level. From the known levels² of Ni^{59} it is seen that the ground state is resolved and its angular distribution corresponds to a strong $\ell = 1$ transition, in agreement with a $\frac{3-}{2}$ spin and parity for this state. The group at 0.4 Mev results from contributions from the 0.34- and 0.47-Mev levels. The angular distribution of this group involves a combination of $\ell = 1$ and $\ell = 3$ contributions, but the resolution of the detection

²

Nuclear Data Sheets, National Academy of Sciences, National Research Council, 1960 (U. S. Government Printing Office, Washington, D.C.). This continuing compilation of data contains all pertinent references.

system was not sufficient to determine precisely which of the two levels gave rise to a particular l value. The level at 0.87 Mev is weak, but evident. The 1.8-Mev group appears to be split, with peaks at about 1.7 and 1.9 Mev. Peaks are observed at 2.5 Mev and 2.9 Mev. The 2.5-Mev group exhibits a strong $l = 3$ character with no apparent $l = 1$ admixture.

The spin and parity of Ni^{61} is known to be $\frac{3}{2}^-$, which is anomalous for a nucleus of even proton number and 33 neutrons. The orbital from which the neutron is picked up is therefore restricted to the $2p_{3/2}$ shell when the reaction proceeds to the ground state of Ni^{60} and a strong $l = 1$ transition is observed. Although, on the basis of angular momentum, both $l = 1$ and $l = 3$ transitions are allowed in the reaction leading to the 1.33-Mev 2^+ state of Ni^{60} , the angular distribution indicates only the presence of $l = 1$. The groups at 2.2 and 3.3 Mev appear to be pure $l = 1$ transitions, while the groups at 2.5 and 5.9 Mev excitation are pure $l = 3$ transitions.

ANALYSIS

The Butler form for the differential cross section for neutron pickup³ via a (d,t) reaction may be expressed as $d\sigma/d\omega = \Lambda C G_l^2 \theta^2$, where Λ is a constant involving the overlap of the deuteron and triton wave functions, C is a constant which (for a given reaction) is determined by the kinematics of the reaction, G_l^2 is the term containing all of the angular dependence, and θ^2 is the reduced width for the transition. The desired information is contained in θ^2 . Both C and G_l^2 are explicitly given by the theory. The value of Λ may be obtained from comparison of (d,p), (p,d), and (d,t) reactions between the same pairs of levels. In view of the scarcity of reliable measurements of this type in this region of the periodic table, there is considerable uncertainty as to the correct value of Λ to be used. As a result, the data have been summarized in Table I in terms of both $\Lambda \theta^2$, and θ^2 , where θ^2 has been obtained by use of a value of 200 for Λ . The

³ S. T. Butler, Nuclear Stripping Reactions (John Wiley and Sons, Inc., New York, 1957).

TABLE I. Reduced widths for strong groups. The groups are listed according to excitation in the final nucleus. The symbols designate reduced widths for $l = 1$ and $l = 3$, respectively.

Target	Level	$\Lambda \theta^2 (1)$	$\Lambda \theta^2 (3)$	$100 \theta^2 (1)$	$100 \theta^2 (3)$
Fe ⁵⁴	0		2.97		1.49
Fe ⁵⁸	0	9.02	< 2	4.5	< 1
	1.3	2.81	< 0.5	1.4	< 0.25
	2.2		3.96		1.98
	≈ 4.7	?	≈ 3 ?	?	≈ 1.5 ?
Ni ⁵⁸	0	4.3		2.15	
	0.85	0.3	0.45	0.15	0.23
	1.15	0.4		0.2	
	2.5	0.1	1.1	0.05	0.55
Ni ⁶⁰	0	7.0		3.5	
	0.34 + 0.47	0.7	1.2	0.35	0.6
	0.87	0.6		0.3	
	1.31	0.4		0.2	
	1.8	0.2	0.4	0.1	0.2
	2.5		1.1		0.55
	2.9	0.2		0.1	
Ni ⁶¹	0	2.46		1.23	
	1.33	3.17		1.59	
	2.2	0.55		0.28	
	2.5		1.65		0.83
	3.3	6.9		3.45	
	3.9	1.35	0.2	0.63	0.1
	4.5	0.6	0.15	0.3	0.08
	5.9		0.9		0.45

accuracy of $\Lambda \theta^2$ is also determined by the value of $d\sigma/d\omega$ at the primary peak of the angular distribution. For $l = 1$ transitions, this has been obtained from an extrapolation to the peak value which has been previously described, and

is believed reliable to within 20%. For $\ell = 3$ transitions, the angular range covered in the experiment encompasses the primary peak of the angular distribution so that the corresponding $d\sigma/d\omega$ used in calculation is reliable to within 10%. As previously remarked, $\ell = 3$ reduced widths may be regarded as minimum values for the transitions.

The reduced width $\theta^2(\ell)$ may be broken up into two terms, $S(\ell)$ and $\theta_0^2(\ell)$. The term $\theta_0^2(\ell)$ is the single-particle reduced width and in this formalism is determined empirically from experiments involving pure single-particle transitions such as $O^{16}(d,p)$ or $Ca^{40}(d,p)$ or by the use of sum rules. The other term $S(\ell)$ is called the spectroscopic factor and is a function of the nuclear wave functions alone. It measures the amount of overlap between the initial wave function and the final wave function with the picked-up neutron considered in the appropriate manner. The evaluation of S depends on the particular nuclear model used. A more interesting quantity is the sum over S for all levels of a given j or a given ℓ . This may be written in two forms, depending on whether a neutron is added or subtracted from the nucleus. Subtracting a neutron, as in (d,t) reactions, one obtains

$$\sum \theta^2(\ell, j) = NW(\ell, j) \theta_0^2(\ell, j) .$$

Adding a neutron, as in (d,p) reactions, leads to

$$\sum \left(\frac{2j_0 + 1}{2J + 1} \right) \theta^2(\ell, j) = [(2j + 1) - NW(\ell, j)] \theta_0^2(\ell, j) ,$$

where $W(\ell, j)$ is the probability of finding a neutron with that value of ℓ and j in the nucleus and N is the number of neutrons in the nucleus. In simple terms, the sum of the (d,t) reduced widths is proportional to the number of identical particles of a given ℓ and j in the nucleus, while the (d,p) cross section is proportional to the number of holes of a given ℓ and j in the nucleus.

DISCUSSION

One aspect of the (d,t) reactions on nuclei with 28 neutrons (V^{51} , Cr^{52} , and Fe^{54}) is the absence of any observable $l = 1$ transitions. This shows there is no effective mixing of the $1f_{7/2}$ level and the 2p orbitals, so that the 28 shell for neutrons is a good closed shell in terms of the purity of ground-state wave functions.

In addition, the value of $\theta_0^2(2p)$ is of importance. Values for $\theta_0^2(2p)$ have been obtained from (d,p) reactions⁴ on the Ca isotopes and V^{51} . We have also measured the reduced widths for the ground-state groups in the (d,p) reactions on Mn^{55} , Fe^{54} , Fe^{56} , Ni^{58} , and Ni^{60} , at a deuteron energy of about 14.5 Mev. These reduced widths are approximately 50% larger than those previously obtained for $\theta_0^2(2p)$.

In view of evidence supporting two values for $\theta_0^2(2p)$, these data have been analyzed for both values of $\theta_0^2(2p)$. The sum rules have been used to deduce the values of $W(1, j)$ since it is not possible to distinguish j values in most of the reactions. The locations of $1f_{7/2}$ contributions have been determined and are not included in the analysis. Since it is possible to miss some $l = 3$ contributions, the $\sum_j W(1, j)$ have been subtracted from unity to provide values for $W(3, 5/2)$. This eliminates questions concerning $\theta_0^2(1f)$ in this region and also allows Λ to depend on l , for which there now appears to be some evidence. The results of the analysis are presented in Table II. In Table III, the results of pairing-force calculation for the nickel isotopes are given. The exact calculations⁵ have been performed for a $2p_{3/2} - 2p_{1/2}$ splitting of 500 kev, while the approximate calculation⁶ has been performed for a 2-Mev splitting. The results of the two calculations

⁴ M. H. Macfarlane and J. B. French, Revs. Modern Phys. 32, 567 (1960).

⁵ A. M. Kerman, R. D. Lawson, and M. H. Macfarlane (private communication).

⁶ L. Kislinger and R. Sorenson (to be published).

TABLE II. Probabilities for finding neutrons in orbitals of given l and j . The column headings indicate the values of $\theta_0^2(2p)$ used in the analysis.

Nucleus	$\theta_0^2(2p) \approx 2.2 \times 10^{-2}$		$\theta_0^2(2p) \approx 3.3 \times 10^{-2}$	
	$\sum_j W(i, j)$	$W(3, \frac{5}{2})$	$\sum_j W(1, j)$	$W(3, \frac{5}{2})$
Mn ⁵⁵	1.06	-0.06	0.76	0.24
Fe ⁵⁶	0.66	0.34	0.47	0.53
Fe ⁵⁷	0.45	0.55	0.32	0.68
Fe ⁵⁸	0.67	0.33	0.46	0.54
Ni ⁵⁸	0.58	0.42	0.41	0.59
Ni ⁶⁰	0.52	0.48	0.37	0.63
Ni ⁶¹	0.69	0.31	0.49	0.51

TABLE III. Theoretical values for $W(l, j)$ obtained from calculations of pairing force. ΔP indicates the value of the $2p_{3/2} - 2p_{1/2}$ splitting used in the calculations.

Nucleus	$\sum_j W(1, j)$	$W(3, 5/2)$	$W(1, 3/2)$	$W(1, 1/2)$	ΔP
Ni ^{58a}	0.81	0.19	0.70	0.11	≈ 0.500
Ni ^{58b}	0.70	0.30	0.66	0.04	≈ 2.0
Ni ^{60b}	0.63	0.36	0.57	0.06	≈ 2.0
Ni ^{61b}	0.57	0.40	0.51	0.06	≈ 2.0

^a Reference 5.

^b Reference 6.

are in excellent agreement with each other, when the same splitting is used. There is no significant difference in the results as the splitting varies between 2 Mev and 500 kev. It is seen that there is fairly good agreement between the experiment and the theories, particularly for the analysis of the data when the smaller value of $\theta_0^2(2p)$ is used.

I-34-1

Decay of ${}_{68}\text{Er}^{172}$

(51210-01)

S. B. Burson and R. G. Helmer

INTRODUCTION

The radioactive nuclide Er^{172} , which decays by beta emission to Tm^{172} , has been reported by Nethaway et al.¹ They report a half-life of 49.8 ± 1.0 hr for the erbium activity. No measurements of the radiations associated with this activity have been reported.

The nuclide Er^{172} was produced by the successive capture of two neutrons in the stable isotope Er^{170} .

The source material was erbium oxide enriched to 87% in Er^{170} . Most of the activations were carried out in the Materials Testing Reactor, Arco, Idaho in a flux of approximately 2×10^{14} neutrons $\text{cm}^{-2} \text{sec}^{-1}$. Preliminary investigations were made with samples irradiated in the Argonne CP-5 reactor in a flux of about 3×10^{13} . In addition to the activities shown in (1), these samples contained observable amounts of the radionuclides Sc^{46} (85 days), Ho^{166} (1 day), Er^{169} (9 days), Tm^{170} (125 days), Yb^{169} (32 days), and Yb^{175} (4 days).

After activation, these samples were chemically separated

¹D. R. Nethaway, M. C. Michel, and W. E. Nervik, Phys. Rev. 103, 147 (1956).

with an ion-exchange column. This process provided positive identification of the elements involved as well as a means of producing chemically pure erbium samples. The separated samples contained the radionuclides Er^{169} (9 day), Er^{172} , and some Tm^{172} which had grown back in during and after the separation. The only gamma ray associated with Er^{169} is an 8-kev transition that did not interfere with these studies. The radiations associated with Tm^{172} have been discussed in detail in a previous report by the authors.²

The apparatus used in this study consists of a set of 180° magnetic internal-conversion-electron spectrographs, a 180° magnetic beta-ray spectrometer, and a 256-channel scintillation coincidence spectrometer. The scintillation spectrometer was used for both gamma-gamma and beta-gamma coincidence measurements.

Fig. 22. Gamma-ray spectrum of Er^{172} . The dashed lines represent the contribution of the thulium daughter.

EXPERIMENTAL RESULTS

The scintillation spectrum of a chemically separated sample is shown in Fig. 22. The decomposition of the spectrum into individual components is shown. The amount of Tm^{172} present is indicated by the intensities of the 181- and 79-keV photopeaks which are associated with the thulium. The spectral shapes for single gamma rays are interpolated from those of Cs^{137} (662 keV), Au^{198} (412 keV), Ce^{141} (142 keV), and Eu^{152} (122 keV). The shape of the thulium K x-ray peak was derived from the ytterbium K x-ray peak from a $\text{Tm}^{170, 171}$ source. The gamma-ray energies and relative intensities calculated from this spectrum are listed in Table IV.

TABLE IV. Gamma-ray energies and relative intensities calculated from the scintillation spectrum.

Gamma -ray energy (keV)	Relative intensity
610 ± 8	42
450 ± 10	2.7 ± 1.5
408 ± 4	44 ± 5
200 ± 6	0.8 ± 0.4
160 ± 4	1.0 ± 0.5
125 ± 3	3.1 ± 1.0
K x ray	69 ± 15

The singles spectrum in Fig. 22 was measured in the geometric arrangement shown, in which the collimator defines a solid angle of approximately 0.3% of 4π . This small solid angle, together with the absorbers used, reduces the summing of any coincident radiations to a negligible amount. In order to investigate any strong coincidence relationships, singles spectra were taken with solid angles nominally equal to 2π (with one crystal) and 4π (with two crystals). (When two crystals are used, the gains

of the photomultipliers are matched and the output pulses are added electronically before being amplified.) These spectra contained peaks at 460 and 510 kev, which are interpreted as the result of a summing of coincident radiations of $408 + 50$ and $408 + 50 + 50$ kev. Therefore it is concluded that there are two 50-kev radiations in coincidence with each other as well as with the 408-kev transition. This conclusion is supported by the results of triple-gamma-coincidence measurements. Each of these 50-kev radiations may result either from a 50-kev transition or from K conversion of a transition whose energy is >59.4 kev.

The end-point energies of the beta-ray components in coincidence with the dominant gamma-ray transitions were measured by the standard aluminum absorption method. These data indicate that the 610- and 408-kev gamma rays are in coincidence with beta branches of (310 ± 30) and (370 ± 30) kev, respectively. The difference in the energies of these two beta-ray components is estimated to be 60 ± 20 kev.

No gamma rays were found to be in coincidence with the 610-kev transition.

A series of coincidence spectra were measured in order to determine the radiations in cascade with the 408- and 450-kev transitions. Analysis of these spectra indicates that the 408-kev transition is in coincidence with radiations of 200 ± 6 , 160 ± 15 , and 125 ± 4 kev, in addition to the K x ray. The 450-kev gamma ray is in coincidence only with a 160 ± 4 kev transition and the K x ray. This analysis also indicates that the numbers of 160-kev gamma rays in coincidence with the 408- and 450-kev gamma rays are about equal.

In addition to the experiments described above, a thorough search was made for any coincidences between the 125-, 160-, and 200-kev gamma rays. None were found.

Attempts were made to observe the internal-conversion-electron and beta-ray spectra. The results were limited by the presence of an intense beta-ray spectrum from the decay of Er^{169} . However, the Er^{172}

beta-ray spectrum did provide some evidence for an additional branch of about 900 kev.

DECAY SCHEME

The proposed decay scheme is shown in Fig. 23. The relative photon intensities are shown in parentheses. The lack of conversion-electron data prevents calculation of the transition intensities. It should be acknowledged that there may be other decay schemes that are consistent, within the experimental uncertainties, with these data.

The absence of any gamma rays in coincidence with the 610-kev transition indicates that this transition goes to the ground state and that there is an excited state at 610 kev. From the observation of coincidences between this gamma ray and a beta-ray branch of approximately 310 kev, it follows that the total decay energy is about 900 kev.

The observation of coincidences between the 408- and 200-kev gamma rays suggest that this cascade is parallel to the 610-kev transition. The intermediate level is then placed at 408 kev as a result of the relative intensities and the beta-gamma coincidence data. The two transitions which produce the intense

50-kev radiations are concluded to

be in cascade and to populate the 408-kev level. The 125-kev gamma ray is then interpreted as the cross-over transition. The energy of each of the two transitions producing 50-kev radiations must be above about 47 kev. If it is accepted that the sum of the two transitions is 125 kev, an upper

Fig. 23. Proposed decay scheme of Er^{172} . The relative photon intensities (in percent of decays) are shown in parentheses. All energies are in kev.

limit of about 78 kev may be placed on the energy of each of these transitions. Thus the intermediate level is placed at 470 ± 15 kev.

The coincident gamma rays of 450 and 160 kev also sum to 610 kev. The sequence of the transitions is not unambiguous.

There is no experimental evidence for beta-ray transitions to the 408-, 450-, and 470-kev levels. For the beta-ray branches to the 530- and 610-kev levels, the log ft values can be computed by use of the relative intensities of the 408- and 610-kev transitions. These log ft values indicate that both beta-ray branches have allowed character.

Since Er^{172} is an even-even nucleus, the spin and parity of its ground state are summed to be 0^+ .

Since the beta transitions to the 610- and 530-kev levels are allowed, the spin of each of these levels is either 0 or 1 with positive parity. There is no experimental information on which to base a choice between these values.

From the study of the decay of Tm^{172} , the spin and parity of its ground state were concluded² to be 2^- .

I-40-3 Decay of Pm^{149} (50 hr) (51210-01)

S. B. Burson and L. C. Schmid

This project has been completed and the results have been published in a report entitled " Pm^{149} (50 hr)," L. C. Schmid and S. B. Burson, Phys. Rev. 120, 158-161 (October 1, 1960).

I-98-27

Neutron Total Cross Sections in the Kev Region (51210-01)

Carl T. Hibdon

FLUORINE

1. General Features of the Resonances

The study of the nuclear energy levels of F^{20} by the $F^{19}(n,n)$ process, reported previously,¹ is still in progress. No further measurements have been made but a number of the levels have been analyzed. This report is concerned with the resonances at neutron energies from about 1 to 150 kev. The general features of the neutron cross-section data up to 150 kev are displayed in a logarithmic plot in Fig. 24, in which data

Fig. 24. Neutron total cross section of fluorine from about 1 to 150 kev. Open circles show data obtained by flat detection; solid circles data by self-detection. (A) The curve shown by a broken line was obtained by a multiple-level plot of s-wave levels and includes the potential scattering $\sigma_P = 1.80$ barns. (B) The curve shown by a solid line is drawn through the points obtained by flat detection.

¹ C. T. Hibdon, Physics Division Summary Report ANL-6146 (April-May 1960), p. 7; ANL-6235 (November 1960), p. 33.

obtained by self-detection are shown by solid circles and data obtained by flat detection are shown by open circles. Variations in the cross section show a number of resonances corresponding to nuclear levels of F^{20} . The small peaks Nos. 1, 3, 4, 5, and 7 were not observed previously because measurements were not made at sufficiently closely spaced intervals with small enough neutron energy spreads. It was feared that the small peak No. 1 was due to impurities in the LiF transmission samples or that erroneous measurements had occurred. Therefore it was restudied. Then the measurements were repeated again with Teflon samples of known high purity. Later, it was learned that Gibbons, Macklin, Miller, and Neiler² at Oak Ridge had also observed this peak by neutron-absorption measurements. From a comparison with peak No. 2, the width of which is 0.35 kev, the width of No. 1 is expected to be of the order of 10 ev. Therefore, these small peaks are insufficiently resolved to be analyzed.

Some years ago it was thought that the levels shown by peaks Nos. 2 and 6 were p-wave levels and mutually interfered but no satisfactory multiple-level fit was obtained for them. The present data still indicate that these two peaks are attributable to p-wave levels because no pronounced minima occur on their low-energy sides to identify them as s-wave levels and their widths appear to be too large for d-wave levels. However, the present data show the asymmetry of each peak to be just the reverse of what it should be for mutual interference. This lack of interference implies that they have different values of J as is suggested also by their peak heights.

In agreement with unpublished data obtained several years ago, the present data show a cluster of levels in the region near 100 kev and also small peaks in the wings of the cluster.

² J. H. Gibbons, R. L. Macklin, P. D. Miller, and J. H. Neiler (private communication).

2. Cross Section below 15 kev

In the region below 15 kev, the cross section is nearly flat and averages about 3.4 barns. To account for this, one has two choices:

- (1) Let the potential scattering σ_p have the highly unlikely value of 3.4 barns. In the first place, this is a surprisingly large value for a light element and appears to be too large for the low cross section around 60 to 65 kev. Further, it appears to be inconsistent with data obtained at high energies by other experimenters.³ (2) Take a value less than 3.4 barns. This appears to be in better agreement with the data in the region of the resonances. If so, a contribution from bound levels must be included, at least in the region up to about 40 to 50 kev. In the present work, the value of σ_p given by $\sigma_p = \sum_{\ell} (2\ell + 1) 4\pi\chi^2 \sin^2 \delta_{\ell}$ was assumed. For $R = 0.14 A^{1/3} \times 10^{-12}$ cm, this amounts to about 1.80 barns. The contribution from bound levels can be inferred only from the present data because the parameters of the bound levels are unknown. Several possibilities were explored: (1) The use of p-wave bound levels shows little promise of producing a relatively flat cross section of the amount needed over so large an energy interval because the penetrability factor P_1 is so small throughout the region up to 15 kev. (2) A single s-wave level would not appear to maintain a flat cross section over the energy range up to 15 kev unless it were quite wide and relatively far removed from the unbound region. (3) A combination of two bound s-wave levels can produce a relatively flat cross section over the region needed but three levels tend to maintain a relatively flat cross section farther

³

Neutron Cross Sections, 2nd ed., compiled by D. J. Hughes and R. B. Schwartz, Brookhaven National Laboratory Report BNL-325; and Suppl. No. 1 (1960) compiled by D. J. Hughes, B. A. Magurno, and M. K. Brussel (Superintendent of Documents, U. S. Government Printing Office, Washington, D. C., 1958).

out in the unbound region. The curve shown by a broken line in part A of Fig. 24 includes the potential scattering and the multiple-level contribution of three assumed bound s-wave levels and peak No. 11. The parameters of No. 11 are given in Table V. The three bound levels were assumed to be at -80, -60, and -30 kev with reduced widths of 11.0, 11.0, and 9.0 kev, respectively. This curve provides the background upon which the p-wave unbound levels sit in the region up to 150 kev and by use of it the levels can be analyzed. However, the contributions from the three bound levels may be equivalent to the effects of many bound levels at other energies so the data give no unambiguous indication about the bound levels.

TABLE V. Summary of the levels of F^{20} derived from neutron reactions with F^{19} . The parameters J , Γ , and ℓ were determined by multiple-level analyses of the resonances. Probable values of the parameters for resonances Nos. 14 through 18 are given in parentheses.

No.	E_r (kev)	J	Γ_n (kev)	ℓ
1	15.25			
2	27.35	2	0.35	1
3	32.0			
4	34.5			
5	38.0			
6	49.7	1	2.0	1
7	71.0			
8	87.8	0	4.0	1
9	96.0	1	5.5	1
10	100.0	2	1.2	1
11	102.4	1	3.0	0
12	113.2	0	1.2	1
13	121.7	0	1.0	1
14	134.0	(0)	(1.8)	(1)
15	138.0	(0)	(1.7)	(1)
16	143.1	(0)	(1.4)	(1)
17	148.0	(0)	(1.7)	(1)
18	152.5	(0)	(1.6)	(1)

3. Analyses of the Resonance Levels

The method of analysis is the same as was used before.⁴ It consists in using a set of provisional parameters for the levels to obtain single- and multiple-level plots for all pertinent levels in a region. These parameters are revised until a best fit to the data is obtained. It was found that mutual interference is strong and distorts the shapes of the wings of the present levels from the shapes of truly isolated levels. Because of this interference and the overlapping of wings of levels, it became necessary to make plots for all of the levels and to analyze them simultaneously.

A. The 27-keV Resonance

The data in the immediate region of this resonance are shown in a semilogarithmic plot in Fig. 25. In the region of the peak, measurements were made by use of a lithium target slightly less than 0.70 keV thick (measured by the rise-curve method⁴) and a transmission

Fig. 25. Semilogarithmic plot of the neutron total cross section of fluorine in the region of the 27-keV resonance No. 2. Points shown by open circles were obtained by flat detection. Solid circles show points obtained by self-detection. The curve shown by a solid line was obtained for a width $\Gamma_n = 0.35$ keV and is a multiple-level plot for peaks Nos. 2, 11, and an assumed bound level at a neutron energy of -4.0 keV. The curve shown by a broken line is a single-level plot for peak No. 2, obtained with the same parameters used for the multiple-level plot. Both curves include the multiple-level plot of the s-wave levels discussed in the text, the potential scattering $\sigma_p = 1.80$ barns, and also a small multiple-level contribution from peaks Nos. 6 and 9.

⁴ C. T. Hibdon, Phys. Rev. 114, 179 (1959); 118, 514 (1960); Phys. Rev. (May 15, 1961).

sample of LiF 50 mils thick. The correction for Li was based on measurements on a sample of Li metal at each energy setting. For the self-detection measurements, a 125-mil Teflon scattering sample was used and for flat detection a 6-in. graphite scattering sample. Neutrons emitted at an angle of 120° with respect to the direction of the proton beam were used for this 27-kev resonance and all measurements up to 150 kev. The entrance slit of the collimator to the neutron counter was $\frac{1}{8}$ in. wide and 13 in. from the neutron source. By flat detection a peak cross section of 63.0 barns was obtained and by self-detection 89.0 barns. The difference between these observed peak heights indicates that the width of this level is less than the neutron energy spread. Consequently, the peak is not resolved to its true peak height. The self-detection data show a peak height somewhat above and the flat-detection data somewhat below the corresponding single-level height for $J = 1$. One then expects that the correct value of J is 2. Some thought has been given to the problem of correlating the two types of data and the neutron energy spread in an analytical method for determining the correct value of J for narrow levels. This method is quite involved and when completed will be treated separately. In its approximate form, valid only at the peak of a level, it predicts a value of $J = 2$ for the 27-kev resonance. This peak is then taken to be a p-wave level with $J = 2$. Its width of 0.35 kev was determined by comparing many plots with the data. Because of its asymmetrical shape, a multiple-level plot with a bound level seemed to provide better agreement with the shape of the wings of this level than did a single-level plot. The curve shown by a solid line in Fig. 25 provided the best fit obtained and includes the following contributions: (1) a p-wave multiple-level plot of the two peaks Nos. 2 and 10 (Fig. 24) together with an assumed p-wave bound level at -4.0 kev ($J = 2$) with a reduced width of $\gamma_1^2 = 87.5$ kev, (2) a continuation of the curve shown in part A of Fig. 24, and (3) a small contribution from the multiple-level plot for peaks Nos. 6 and 9. The curve shown by a broken line in Fig. 25 is a single-level plot

for No. 2 and was obtained by use of the same parameters that were used for the multiple-level plot. These two plots show that the asymmetry of this level is attributable in part to its natural single-level shape but to a greater degree to mutual interference with some bound level. Contributions from bound levels undoubtedly extend into this region and some part of these contributions is due to p-wave levels. The contribution coherent with the 27-kev resonance was localized to a single level at -4 kev, but this may be a fictitious level equivalent to small contributions from a number of as yet unresolved bound levels.

During the measurements around the peak of the 27-kev resonance, it was found that a 300-mil Teflon scattering sample yielded about 65% of the counting rate obtained by the 6-in. graphite scattering sample and that the yield for the 125-mil Teflon scattering sample was about 45%. This indicates that the level scatters strongly. Moreover, the $F^{19}(n,\gamma)F^{20}$ measurements performed by Gabbard, Davis, and Bonner⁵ at the Rice Institute yielded a peak cross section of about 300 mb after correction for resolution. This, when compared with the total height of the level, indicates a neutron scattering of more than 99.5%. Hence Γ_n is nearly identical with Γ .

The width of 0.35 kev corresponds to reduced widths of $\gamma_1^2 = 78.5$ and $\gamma_2^2 = 40\ 450$ kev for p- and d-wave neutron interactions, respectively, compared with the Wigner limit of $\hbar^2/(\mu R^2) = 2.77$ Mev.⁶ The largest possible value of the potential scattering is $\sigma_p = 3.40$ barns, the cross section below 15 kev. The corresponding nuclear radius, which may be regarded as an upper limit, is 37% larger than the one used. For this larger radius, the reduced widths amount to $\gamma_1^2 = 32.0$ and $\gamma_2^2 = 8210$ kev, respectively, for p- and d-wave neutron interactions, compared with a Wigner limit of 1.48 Mev. Thus, for either value of the nuclear radius,

⁵ F. Gabbard, R. H. Davis, and T. W. Bonner, Phys. Rev. 114, 201 (1959).

⁶ C. E. Porter and R. G. Thomas, Phys. Rev. 104, 483 (1956), footnote No. 9.

the reduced width for a d-wave neutron interaction exceeds the Wigner limit by a large factor. If this limit is meaningful, the 27-keV resonance is a p-wave level. The preceding discussion illustrates the method of analyses in detail. A briefer discussion will be given for the remainder of the levels.

B. The 49.7-keV Resonance

The data in the region of this resonance, peak No. 6, are shown on an expanded scale in Fig. 26. Peak heights measured by flat- and self-detection differ little and come close to the possible single-level height for $J = 1$ with $\ell = 1$. The shape of the resonance is generally that of a p-wave level but is noticeably asymmetrical with the high cross section on its low-energy side. Its apparent width of about 2.0 keV appears

Fig. 26. Neutron total cross section of fluorine in the region of the 49.7-keV resonance No. 6. Self-detection data are shown by solid circles; flat-detection data by open circles. The curve shown by a solid line, obtained with a width of 2.0 keV, is a multiple-level plot for peaks Nos. 6 and 9. The curve shown by a broken line is a single-level plot obtained with the parameters used for the multiple-level plot. Each curve includes the multiple-level contribution from the s-wave levels discussed in the text and the potential scattering $\sigma_p = 1.80$ barns.

to be too large for a d-wave level. Hence this resonance is attributed to a p-wave level with $J = 1$. Its asymmetrical shape indicates mutual interference with some level at a higher energy. The first level that can interfere coherently is peak No. 9, which is quite wide and hence undoubtedly a p-wave level. These two levels, peaks Nos. 6 and 9 in Fig. 24, are therefore analyzed together. The curve shown in Fig. 26 by a solid line is a multiple-level plot for Nos. 6 and 9, obtained with the parameters listed in Table V. The curve shown by a broken line in Fig. 26 is a single-level plot obtained with the same parameters

used in the multiple-level plot. It might appear at first sight that a shift of the single-level plot to a lower energy might fit the data. Around say 52.0 kev, the shift to coincide with the data would be about 0.25 kev. The peak would then fall on the low side of the data by a sizeable amount. Moreover, the single-level plot would still fall considerably below the data in the low-energy wing of the resonance.

C. The Resonances Near 100 kev

The level structure seen near 100 kev in Fig. 24 is shown more clearly on an expanded scale in Fig. 27. The general features of the data enable one to conclude that (1) peak No. 9 is a p-wave level with $J = 1$, (2) peak No. 10 is a narrow p- or d-wave level with $J = 2$, and (3) peak No. 11 is an s-wave level with $J = 1$. The remainder of the peaks are reserved for a later part of this report. A knowledge of the correct value of J for peak No. 10 is

Fig. 27. Neutron total cross section of fluorine in the region of the cluster of levels near a neutron energy of 100 kev. Self-detection data are shown by solid circles; flat-detection data by open circles. Curve A was obtained as described in the text. The width used for peak No. 10 is 1.2 kev. Curve B is a multiple-level plot of s-wave levels described in the text. A width of 3.0 kev was used for resonance No. 11. Both curves A and B include the potential scattering $\sigma_p = 1.80$ barns. By subtracting curve A and the resonance part of curve B (i.e., the part due to peak No. 10 but not the potential scattering) from the data, one obtains curve C shown in Fig. 28.

very useful. Correction for the lack of resolution, by the method mentioned in Sec. 3A, indicates that $J = 2$. In applying this method, corrections were estimated for the wings of Nos. 9 and 11. Peak No. 9 is obviously due to a wide level without the minimum on the low-energy side or the following rapid rise to the peak, so it is not an s-wave peak. Peak No. 11 exhibits a high cross section in its high-energy wing characteristic of an s-wave level. Peaks Nos. 9 and 10 contribute sizeable amounts to this wing but the cross section is too high for a level of the apparent width of No. 11 unless it is taken to be an s-wave level. Moreover, the peak of the fairly wide peak No. 8 is depressed below its possible height for $J = 0$ and the low-energy wing of No. 9 appears to be unduly distorted. For these reasons, peak No. 11 is taken to be an s-wave level.

There appears to be no way to untangle this 100-keV cluster of levels except by trial and error. The widths that provide the best fit to the data are

Fig. 28. Analyses of the 96-keV p-wave level and the smaller peaks in its wings. Curve C, shown by a solid line, was obtained by the subtractions in Fig. 27 to remove the wings of peak No. 10, the wings of the s-wave levels, and the potential scattering. Curve D, a multiple-level plot for resonances Nos. 6 and 9, was obtained with a width of 5.50 keV for No. 9. Curve E is a single-level plot for No. 9, obtained by use of the same parameters that were used in the multiple-level plot. By subtracting curve D from curve C, one obtains the points shown in inserts A and B. The curve shown by a broken line in each of these two inserts is a multiple-level plot for peaks Nos. 8, 12, and 13. The potential scattering is not included in any curve.

tabulated in Table V. To avoid confusion, only two theoretical plots are shown in Fig. 27. Curve A is a part of the p-wave multiple-level plot for peaks Nos. 2 and 10 and a level at -4 kev discussed in connection with the 27-kev resonance. Curve B is a continuation of the plot for the s-wave levels mentioned previously. Both curves include the potential scattering σ_p . Then by subtracting curve A and the resonance part of curve B (i.e., the part due to peak No. 10 but not the potential scattering) from the data in Fig. 27, one obtains curve C in Fig. 28. In Fig. 28, curve D is a p-wave multiple-level plot for peaks Nos. 6 and 9. Curve E is a single-level plot for No. 9, obtained by use of the same parameters that were used to obtain the multiple-level plot. By subtracting curve D from curve C one obtains the points shown in inserts A and B. The curve shown by a broken line in these two inserts is a multiple-level plot for peaks Nos. 8, 12, and 13, obtained by use of the parameters listed in Table V. No better fit to Nos. 12 and 13 seems feasible because their wings are not sufficiently defined.

The width given for peak No. 12 corresponds to reduced widths of $\gamma_1^2 = 33.5$ and $\gamma_2^2 = 4070$ kev, respectively, for p- and d-wave neutron interactions, compared with the single-particle reduced width⁷ of 2.77 Mev for the nuclear radius used. An increase of 37% in the nuclear radius (mentioned in Sec. 3A) leads to reduced widths of $\gamma_1^2 = 13.8$ and $\gamma_2^2 = 860$ kev, compared with the single-particle reduced width of 1.48 Mev. For peak No. 13, the width given corresponds to reduced widths of $\gamma_1^2 = 25.2$ and $\gamma_2^2 = 2810$ kev. The 37% increase in the nuclear radius would lead to reduced widths of $\gamma_1^2 = 10.4$ and $\gamma_2^2 = 600$ kev. The neutron width of peak No. 10 is comparable with the ones used for peaks Nos. 12 and 13.

⁷ A. M. Lane, R. G. Thomas, and E. P. Wigner, Phys. Rev. 98, 693 (1955); T. Teichmann and E. P. Wigner, Phys. Rev. 87, 123 (1952); A. Bohr and B. Mottelson, Kgl. Danske Videnskab. Selskab., Mat.-fys. Medd. 27, 16 (1953).

Moreover, the widths of peaks Nos. 14 through 18, Fig. 24, appear to differ little from the widths of Nos. 12 and 13. Thus, for either value of the nuclear radius, the sum of the reduced widths for all of these narrow levels with $\ell = 2$ exceeds the single-particle width⁷ by a large factor. These peaks are therefore taken to be p-wave levels. Peaks Nos. 14 through 18 are to be studied further in order to obtain better values for the parameters.

Some time ago Lane⁸ measured angular distributions of neutrons scattered in this 100-kev cluster of resonances. Although his neutron energy spread was too large to resolve the individual resonances, his measurements indicated a large interference between s- and p-wave resonances where the p-wave resonances are expected to show a preference for low J values. The present results are in agreement in that several p-wave levels having low J values were found in the cluster along with an s-wave level.

The parameters of the levels obtained in these analyses are collected in Table V. Probable parameters for peaks Nos. 14 through 18 are also given.

4. Strength Functions

The strength functions were evaluated for the levels that were analyzed. These are defined as $\langle \gamma_\ell^2 \rangle_{\text{av}} / \bar{D}_\ell$, the ratio of average reduced neutron width to the average level spacing, where $\gamma_\ell^2 = \Gamma_n / (2P_\ell)$ and $\bar{D}_\ell$ are averaged for a given value of ℓ . (Here, of course, Γ_n is the neutron width that gives the best fit and P_ℓ is the penetrability factor.) By averaging over both possible spins for s-wave levels, a strength function of 0.02 was

⁸ R. O. Lane (private communication).

obtained for the one unbound s-wave level. Averaging over all three possible values of J for p-wave levels resulted in a strength function of 1.80. For the 37% increase in the nuclear radius mentioned in Sec. 3A, the value of the p-wave strength function is reduced to 0.85. Either value seems to be anomalously large. For the nuclear radius used, the sum of the reduced widths for all of the p-wave levels in this region is 35% of the single-particle reduced width⁷ or about 27% for the largest possible value of the nuclear radius. This indicates that F^{20} is located near the peak of the p-wave maximum for the reduced widths.

The large value of the p-wave strength function appears to be due to an anomalously large value of $\langle \gamma_1^2 \rangle_{av}$ rather than to an anomalously small value of $\bar{D}_1$. Since a p neutron can have two states,⁷ the $P_{1/2}$ and $P_{3/2}$ states, the giant maximum for p neutrons will be double and F^{20} may well lie on one of the peaks. An evaluation of the p-wave strength function over a larger energy interval may yield a smaller value.

A paper covering this material in more detail is in preparation.

I-107-2 Standard Boron Solutions for Neutron Absorption (51210-01)

Sol Wexler

This project has been completed and the results have been published in a report entitled "Standard Boron Solutions for Neutron Absorption Measurements," S. Wexler, Nuclear Sci. and Eng. 8, 270-273 (September 1960).

I-129-2 The Helicity of the Neutrino Emitted in the Electron-
Capture Decay of Beryllium-7 (51210-01)

T. B. Novey, P. Rice-Evans, and V. L. Telegdi*
Reported by P. Rice-Evans

This project has been discontinued because the empirically determined counting rate for the nuclear-resonance fluorescence scattering turned out to be much too low to make the helicity experiment feasible.

* University of Chicago.

I-144-13 Investigation of Scintillators (51300-01)

L. J. Basile, W. L. Buck, and A. Weinreb*

ABSORPTION SPECTRUM OF POLYSTYRENE IN THE VACUUM ULTRAVIOLET

W. L. Buck and A. Weinreb

In an earlier report¹ an account was given of a preliminary determination of the absorption spectrum of a thin film of pure polystyrene in the region of wavelengths from 1000 Å to 2500 Å. Knowledge of this spectrum is required for subsequent investigations concerning the efficiency of plastic scintillators under high-energy excitation and the processes of energy transfer in such scintillators, inasmuch as these phenomena are related to electronic excitation and ionization in the polymer molecules. As pointed out in the earlier report, the spectrum shown therein was subject to the following

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¹ Physics Division Summary Report ANL-6235 (November 1960), pp. 56-60.

sources of error and uncertainty.

(a) The background of polychromatic stray light issuing from the monochromator results in erroneously low measured values of absorbance, particularly at wavelengths at which the sample absorbance is high and the intensity of monochromatic light available from the monochromator is low. Although some corrections were made for this background in the earlier work, the adequacy thereof was open to question.

(b) The sample may fluoresce, and a portion of this fluorescent light may be "seen" by the detector. This too leads to erroneously low measured values of absorbance, particularly at wavelengths at which the sample absorbs strongly. In the earlier work the sample was located quite near to the detecting photomultiplier, and it was estimated that errors as large as 6% resulted from this effect.

(c) Subsequent observations suggested that during the course of the original measurements there was probably a certain amount of masking of the light beam by the metal frame which supported the film. This would lead to erroneously high measured values of absorbance, particularly at wavelengths at which the actual absorbance of the sample is low.

(d) Attempts to measure the thickness of the polystyrene film by two different methods yielded widely different results. This discrepancy could not be resolved, since one of the methods employed led to destruction of the film. For this reason it was not possible to express the results of our measurements in the form of absorption coefficients (absorbance per unit thickness) for this film.

Subsequent modifications in the apparatus and in the techniques of using it, together with an improved method of measuring film thickness, have made it possible to make more accurate measurements of the absorption coefficient of another thin film of pure polystyrene over the wavelength region from 1100 Å to 2300 Å. A discussion of this more recent work follows.

The Polystyrene Film; Preparation and Determination of Thickness

The film used in this work was prepared in the following manner. Approximately 0.2 g of polystyrene, prepared by anaerobic thermal polymerization of purified styrene for 10 days at 140°C, was dissolved in 5 ml of benzene. A portion of this solution was diluted by a factor of 100 by adding the appropriate amount of cyclohexane. Next 2 ml of this diluted solution were poured onto the fresh, clean surface of distilled water contained in a crystallizing dish 14.5 cm in diameter. The dish was then loosely covered, and the solvent was allowed to evaporate completely from the layer of polystyrene solution.

If the solution had completely covered the water surface and this condition had persisted during evaporation of the solvent, polystyrene films made in this way should have had a uniform thickness of about 1400 Å. It was observed, however, that the layer of solution tended to contract away from the sides of the dish as evaporation proceeded. The resulting films failed to cover the entire water surface and usually showed markedly nonuniform thickness (evidenced by regions of varying color and appearance). It was found empirically that addition of 1 or 2 drops of ethyl acetate to the layer of polystyrene solution helped to reduce these undesirable effects.

In spite of the over-all nonuniformity of the resulting films, it was occasionally possible to select small areas suitable for measurements of thickness and absorbance. The selected area of the film was lifted from the water surface on a small aluminum frame containing a rectangular aperture 1.25 cm by 0.65 cm. This frame was of proper size to fit into a Beckman cell holder and was used as a permanent mounting for the film.

For the purpose of determining the thickness of such a mounted film, a Beckman DK-2 spectrophotometer was used to measure the

transmission of the film throughout the region from 3400 Å to 7000 Å. In this region of wavelengths the absorbance of polystyrene is negligible and its refractive index is known.² Owing, however, to the wavelength-dependent interference of light waves reflected from the two surfaces of such a thin film, the measured transmission spectrum shows one or more maxima and minima. By noting the wavelengths at which these occur, it is possible to calculate the thickness of the film. This procedure is a modification of a technique described in the literature.^{3,4}

The particular polystyrene film selected for absorption measurements was found in this way to have a thickness of 530 ± 30 Å. The uncertainty in this value arises partly from the rather broad maxima and minima of transmission obtained with such a thin film and partly from indications of some slight nonuniformity in the thickness. This film showed no discernible interference colors when viewed by reflected or transmitted white light.

Measurement of Absorbance; Photometric Errors

For these measurements, the Jarrell-Ash 50-cm Seya-Namioka vacuum monochromator was equipped with a new grating which was found to give an unusually low intensity of stray light. A useful rule adopted by some users of this type of monochromator for specifying the amount of stray light is as follows. With the Tanaka light source supplied with the monochromator operated with hydrogen at a pressure of about 2 mm Hg, and with a photomultiplier coated with sodium salicylate used as the detector, determine the measured intensities of light issuing from the

²

It is assumed that the refractive index of the thin film is the same, at any wavelength, as that of the bulk material.

³

M. F. Bechtold, J. Opt. Soc. Am. 37, 873-878 (1947).

⁴

C. D. Miller, J. Polymer Sci. 24, 311-314 (1957).

monochromator when it is set for 700 Å and for 1750 Å. The ratio of these measured intensities, expressed as a percentage, is taken as a measure of the intensity of stray light. By this formula, our monochromator gave only 1.1% stray light after installation of the new grating. This is only a tenth of the intensity of stray light obtained with the original grating used for the earlier measurements.

By placing appropriate filters between the monochromator and detector to absorb the strong monochromatic light issuing from the monochromator while transmitting part of the stray light, it was possible to determine that the intensity of stray light is a minimum when the monochromator is set for a wavelength of about 700 Å and that this intensity increases as the monochromator setting is either increased or decreased. The intensity of stray light obtained at a setting of 2000 Å was found to be about twice as great as that obtained at a setting of 700 Å.

Partly for the purpose of reducing the effects of fluorescence of the sample, a new sample compartment was provided in which the polystyrene film is separated from the photomultiplier by a distance of about 14 cm. At this distance the solid angle subtended by the sensitive area of the detector is so small that only a very small fraction of any fluorescence from the film should reach the detector. In this sample compartment the film is precisely positioned in a manner which precludes any possibility of masking of the light beam by the frame supporting the film. As additional insurance against errors arising from this effect, the reference measurements of the unattenuated light beam were made through an identical empty frame placed in the same position.

To determine the residual contribution of sample fluorescence to the measured intensities of light transmitted by the polystyrene film, a thin cleaved section of KBr crystal was placed adjacent to the film, between it and the photomultiplier. This crystal was known to be practically opaque at wavelengths below 1900 Å but is transparent to poly-

styrene fluorescence. Also, this KBr crystal had been found to give no detectable fluorescence when it was placed in this position (with the film removed) and irradiated by the unattenuated light beam from the monochromator at wavelengths below 1900 Å.

With both KBr crystal and polystyrene film in the light path, as described above, only the expected weak background of stray light transmitted by the film and crystal was detected as the monochromator was scanned from 1900 Å down to 700 Å, except for the observation of a few small peaks in the vicinity of 1600 Å which corresponded in wavelength and relative intensity to the very intense lines known to be emitted from the hydrogen lamp in this wavelength region. The intensity of the strongest of these peaks was only about three times the intensity of stray light transmitted by the polystyrene film. Since in this region of wavelengths very intense monochromatic light is obtained from the monochromator and the absorbance of the film happens to be relatively weak, it is possible to say that fluorescence of the polystyrene film affects the measured values of absorbance by not more than 1%, and then only at a few discrete wavelengths. For this reason, no corrections for the effects of fluorescence of the sample have been made in the results reported here.

Discussion of Results

Figure 29 shows the manner in which the absorption coefficient α of the polystyrene film was found to vary with wavelength in the region from 1100 Å to 2300 Å. The absorption coefficient here means the apparent absorbance per unit thickness, specifically,

$$\alpha(\lambda) = \frac{1}{s} \log_{10} \left(\frac{I_0}{I} \right),$$

Fig. 29. Absorption spectrum of a film of pure polystyrene in the vacuum ultraviolet region. The film thickness was 530 ± 30 Å.

where s is the thickness of the film (cm), I_0 is the intensity of monochromatic light of wavelength λ incident upon the film, and I is the intensity of light of this same wavelength transmitted by the film. It should be realized that the values of α depend not only upon internal absorption of light within the film but also upon partial reflection of the light at the surfaces of the film. The magnitude of the latter effect at any particular wavelength is determined primarily by the refractive index of the film. Although this index is unknown (to us) in the region of wavelengths under study, we hope to be able to determine the actual coefficient of internal absorption by comparing measurements made on polystyrene films of different thicknesses.

For the work reported herein, the width of the entrance and exit slits on the monochromator was set so as to give an effective spectral bandwidth of ≈ 1 A. The limits of error shown for the data in Fig. 29 are based primarily upon the uncertainty ($\pm 6\%$) in our determination of the thickness of the polystyrene film.

The absorption spectrum shown in Fig. 29 exhibits the same general features as were described in the earlier report, namely a "knee" in the region of 2150 A, a strong peak at about 1940 A, and a valley at about 1550 A followed by a steep increase toward shorter wavelengths. The peak-to-valley ratio is, however, nearly 60% greater in the spectrum reported here. This is attributed to the reduction or elimination of certain distorting factors in the measurements, as discussed above.

II. MASS SPECTROSCOPY

II-40-8

Fragmentation of Organic Molecules

(51300-01)

H. E. Stanton and J. E. Monahan

Reported by H. E. Stanton

Recently the measurements of the "temperatures" of ionic precursors in the fragmentation of organic molecules¹ has undergone further theoretical study and experimental development.

The model constructed earlier comprised a molecule containing a large number of atoms, excited by electron impact. The energy imparted by the collision was thought to appear as vibrational energy in the molecule, which then emitted the fragment under study, as a sort of evaporation. The distribution in kinetic energy of the fragment would presumably be a measure of this energy in the precursor.

In deriving the theoretical expression, it was assumed that this distribution in ion kinetic energy was Maxwellian and was, therefore, characterized by a "temperature." If one takes account of slit widths in the analyzer, the shape of the measured peak if the underlying assumptions were approximately realized would be given by

$$F(E) = \frac{2}{\sqrt{\pi}} A \int_{E-B}^{E+B} \left(\frac{x}{kT} \right)^{\frac{1}{2}} \exp \left(\frac{-x}{kT} \right) dx, \quad (1)$$

where B is a parameter representing the loss of energy selectivity as a result of nonvanishing slit widths, E_0 locates the theoretical point of zero energy

¹ Physics Division Summary Report ANL-5955 (December 1958-January 1959), p. 36.

Fig. 30. Two distribution curves for (a) mass 20 (doubly charged argon) and (b) mass 14 from ethylene together with the points calculated by Eq. (1). The parameters determined by the calculated curves are: for (a), $A = 326$ counts/sec, $E_0 = -0.0680$ eV, $B = 0.0779$ eV, and $kT = 0.0677$, and for (b), $A = 140.1$ counts/sec, $E_0 = -0.0743$, $B = 0.0902$ eV, and $kT = 0.1553$. The calculated errors in both cases are less than 2%.

of the true Maxwellian in the measured distribution, A is the amplitude factor, and T is the so-called "temperature" which is sought.

Expression (1)

was coded for the IBM-704, and a typical fit for an experimental curve is shown in Fig. 30. The fit is seen to be quite satisfactory, and it was discovered soon that, with persistence in the application of the program, guessing input parameters, etc., almost all of the experimental curves could be satisfactorily accommodated by this method.

It also became evident that "temperatures" for parent ions, ions from the rare gases, etc. which by hypothesis should have temperatures approaching 0.025 eV ($\approx 300^\circ\text{K}$), the temperature of the ion box, had calculated values several times this amount. The selectivity parameter B also was frequently less than the value indicated by the constants of the mass spectrometer.

Attempts were made to modify the ion source and electron gun to improve the quality of the experimental curves. Rare gas temperatures (kT values) of from 0.04–0.07 eV represent about the best values so far attained.

While these values represent a limit to the accuracy of the method, it is possible to gain some insight into the fragmentation of large molecules by using the rare gas ions as a standard of comparison. An example is shown in Fig. 31 in which the calculated "temperatures" of the precursors for the ion fragments are shown as functions of the mass number of the fragments for ethylene. Singly charged, doubly charged, and triply charged argon, and singly charged water are also shown for comparison.

Fig. 31. The "temperatures" obtained by a best fit to the distribution curves plotted as a function of the fragment's mass number for ethylene and the standard peaks from argon and water.

All of the latter peaks, as well as the parent peak of the ethylene (mass 28^+) should show the same temperature; the variations indicate the magnitude of the errors. The average "ambient" kT value for each of these thermal peaks is shown in the figure, the largest deviation being for triply charged argon (mass $13\frac{1}{3}$) which showed an unusually low value (but still $\approx 300^\circ\text{C}$). A thermocouple attached to the ion-box structure indicates a temperature of about $40^\circ - 50^\circ\text{C}$ when the spectrometer is in operation and at approximate equilibrium.

The selectivity parameter B , which should be a constant for all peaks if the same source conditions prevail, is approximately so, except for the fragments of masses 12^+ and 13^+ .

Fig. 32. The values of the calculated parameters A , B , and kT as a function of the energy of the ionizing electrons. This figure indicates that the spectrometer is operating consistently and that the "temperature" of the reaction is independent of the electron energy.

In Fig. 32 the variations of the three parameters in the distribution (A , B , and kT) are shown for the parent peak as a function of the energy of the bombarding electrons. The over-all resolution was much poorer during these determinations than it was for Fig. 31, but, as one would expect, the temperature kT and selectivity parameter B remained quite constant for all electron energies. Hence, although "temperatures" are too high for ions formed "at rest," the model and theory show some plausibility.

It is suspected that perturbations under study at present may account for the results. The ions are formed in a volume traversed by the electrons in one direction, and in a static electric field at right angles to them. This field is necessary to remove the ions for analysis. If the equipotential surfaces were all parallel to each other and to the direction of the electrons, and if the ribbon of electrons were very thin, the theory would need no important further modifications. However, such a thin ribbon of electrons has not been obtained and curved field lines have so far been necessary to focus the emerging ion beam to give usable intensities.

Deviations from the ideal arrangement cause the ions formed at different points in space to start at different potentials. The differences in potential at the points of formation appear in the final analysis as a distribution in energy, indistinguishable from the true ionic kinetic energy. Maladjustment has been quite troublesome, producing

excessively broad or double-humped distributions. The net effect has been a confusion between the selectivity B and the "temperature."

In order to make a partial correction for this, a standard (argon) was introduced for purposes of comparison. Parent peaks, as shown in Figs. 31 and 33, tend to confirm this interpretation. The theoretical implications of this formation in depth are under study with the idea of revising the computer program. Also, a new ion source being designed will hopefully reduce the effects further.

If the above interpretation is assumed, Fig. 31 seems to give evidence that the more complicated the reaction necessary to produce the fragment, the "hotter" the precursor in ethylene. In Fig. 33 the same results are shown for the fragmentation of acetylene. Unfortunately, in the latter case the peak at mass 12 was so weak that it could not be detected. Mass 14 in ethylene and mass 13 in acetylene represent the rupture of multiple carbon-carbon bonds and this, on the basis of the temperature of the triply ionized argon, requires a high degree of molecular agitation. It is curious that the extra "thermal energy" required in the ethylene is almost twice that required in the acetylene. If one is inclined to discount the anomalously low values of temperature for mass $13\frac{1}{3}$ as a standard, this difference in behavior becomes much greater.

In ethylene, the peaks of lower mass number seem to partake of the energy necessary for rupturing the double carbon bond, as

Fig. 33. The variation of the "temperatures" of the various fragments from acetylene under electron impact. In contrast to those shown for ethylene (Fig. 31), variation of these "temperatures" is small.

if this bond rupture were a necessary prerequisite.

On the other hand, fragments derived from the parent molecule by the shedding of one or more hydrogens do not exhibit a spectacular increase in apparent temperature for either ethylene or acetylene. For ethylene, a slight increase in temperature seems to be necessary to eject a second hydrogen (presumably from the other end of the molecule) after the first hydrogen has been lost or to eject a H_2 molecule from the parent. The removal of the third and fourth hydrogens (again, presumably from opposite ends of the radical) requires still more internal energy but, with this amount of energy available, either one or both remaining hydrogens may be expelled (but not necessarily with equal probability).

In acetylene, all of the peaks in the high-mass group appeared to have the same temperature as the standard argon peaks. The energy selectivity was much poorer (by a factor of 2) than for ethylene and the derived temperatures were subject to errors large enough to obscure variations.

Taubert² has discussed the increase in kinetic energy in fragments from the saturated hydrocarbons as one or more hydrogens are lost and finds a variation similar to the one described above for the unsaturated ones. Such relationships have also been seen in MA-17, but not carefully studied to date.

There is one very important discrepancy between the two investigations. Taubert finds fragment energies ranging up to more than a volt, whereas the theory outlined above was developed to try to measure kinetic energies of only a few tenths of a volt. This difference of almost an order of magnitude in the size of the effects remains to be explained. The

²

R. Taubert, in Advances in Mass Spectrometry, edited by J. D. Waldron (Pergamon Press, London and New York, 1959), p. 489.

calibration of MA-17 does not appear to be off by nearly that amount, since the high-energy peak in the kinetic energy distribution of methyl ions, previously reported, checks with values given in the literature, the known distribution of O^+ from CO seems to agree with the experimental results, and the design constants and other checks indicate that it is correct.

Taubert also mentioned informally a mechanism to explain the increasing kinetic energies of fragments with progressively fewer attached hydrogens. He offered the hypothesis that, in the saturated hydrocarbons, each hydrogen ejected is released with a fixed amount of kinetic energy in the center-of-mass system. That is, he postulated a reaction of the type

We are in the process of introducing this modification into the "temperature" theory described above.

One postulates a fragment or molecule of mass M and energy E_M which ejects a fragment with mass m , a fixed portion Q of the energy of reaction appearing as kinetic energy of the fragment, and asks for the energy distribution of such fragments in the laboratory frame if all angles of ejection in the center-of-mass frame are equally probable. Let E_f be this fragment energy, $f(E_f) dE_f$ the probability that there is a fragment with this energy in the interval dE_f , and $E_0 = \frac{m}{M} E_M$ that fraction of the precursor's kinetic energy attributable to the fragment.

One may then show that this distribution is a constant over a certain range of energies, i.e.,

$$f(E_f) = \begin{cases} \frac{1}{4\sqrt{E_0 Q}} & \text{for } (\sqrt{E_0} - \sqrt{Q})^2 \leq E_f \leq (\sqrt{E_0} + \sqrt{Q})^2. \\ 0 & \text{for } E_f < (\sqrt{E_0} - \sqrt{Q})^2 \text{ or } E_f > (\sqrt{E_0} + \sqrt{Q})^2. \end{cases} \quad (3)$$

Now let $P(E_f) dE_f$ be the number of fragments of energy E_f in the interval dE_f arising from $n(E_0)$ precursors with energy E_0 in the energy interval dE_0 . Then it follows from Eq. (3) that

$$P(E_f) dE_f = dE_f \int \frac{(\sqrt{E_f} + \sqrt{Q})^2}{(\sqrt{E_f} - \sqrt{Q})^2} \frac{n(E_0)}{4\sqrt{E_0}Q} dE_0. \quad (4)$$

If $n(E_0)$ is a Maxwell-Boltzman distribution, it follows that

$$\begin{aligned} P(E_f) &= \frac{A}{2\sqrt{\pi k T Q}} \int \frac{(\sqrt{E_f} + \sqrt{Q})^2}{(\sqrt{E_f} - \sqrt{Q})^2} \exp\left(\frac{-x}{k T}\right) dx \\ &= \frac{A}{\sqrt{\pi}} \sqrt{\frac{k T}{Q}} \exp\left[\frac{-(E_f + Q)}{k T}\right] \sinh \frac{2\sqrt{E_f Q}}{k T}. \end{aligned} \quad (5)$$

This approaches the original Maxwellian distribution when Q approaches zero. In order to determine the values of Q and $k T$ from an experimental distribution, it will be necessary to fold Eq. (5) as before because of the effects of slit widths, etc.

In Fig. 34, plots of distributions given by Eq. (5) for four values of $Q/k T$ are shown, the curve for $Q = 0$ being the Maxwell-Boltzmann distribution.

Whether the mass spectrometer will be able to distinguish unambiguously between these two types of distributions remains to be seen, but effort is being devoted to this end.

Fig. 34. Theoretical distributions derived from Taubert's hypothesis for four different values of the quantity Q in units of kT . The curve for $Q = 0$ gives the Maxwell-Boltzmann distribution which was assumed for the precursor.

V. THEORETICAL PHYSICS, GENERAL

V-6-1 Electron Excitation of Collective Nuclear Transitions (51210-01)

L. J. Tassie and A. S. Reiner*

For large enough momentum transfer, the cross sections for both elastic and inelastic electron scattering will depend upon the form of the nuclear charge distribution. It is known from the Stanford experiments on the elastic scattering of high-energy electrons that the nucleus has an inhomogeneous charge distribution with a surface of finite thickness. Usually, in the collective model of the nucleus, the nuclear charge distribution is taken to be uniform with the nucleus having a sharp surface.

However, to treat inelastic electron scattering, it is necessary to extend the usual collective model to an inhomogeneous charge distribution. For instance, when considering a deformed nucleus which is homogeneous with a sharp surface, it is only necessary to specify the deformation at the surface of the nucleus. For an inhomogeneous charge distribution, or an inhomogeneous distribution of mass density, we must also specify how the deformation varies with radius throughout the nucleus. One simple way of doing this is to assume that the deformed nucleus is obtained by deforming an originally spherically symmetrical nucleus, and that as the deformation takes place the flow of the nuclear fluid is incompressible and irrotational. This is not necessarily a very good prescription. Although we have some reason to expect the nucleus to be very incompressible in the middle, there is no reason to expect the nucleus to be incompressible

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in the outer surface region where the charge density and mass density are very low.

On the other hand, it is a fairly simple prescription, and if we calculate the electron scattering by use of this assumption of incompressibility, then the incompressibility or compressibility of the nucleus can be investigated experimentally by inelastic electron scattering.

The inelastic scattering of electrons with excitation of collective nuclear transitions has previously been considered¹ by use of this incompressible prescription, but the nuclear matrix elements were calculated only to the first order in the nuclear deformation. In the present calculation, we work to second order in the deformation. Electric-monopole excitation is then included. This should be important in testing for nuclear compressibility.

The electron scattering has been calculated by use of the Born approximation, and the nuclear charge distribution was described by a folded charge distribution of the type used by Helm,² namely,

$$\rho(r) = \int \rho_1(r') \rho_2(|\vec{r}' - \vec{r}|) d^3r',$$

where $\rho_1(r)$ is a uniform distribution of radius R and $\rho_2(r)$ is a Gaussian function. It should be noted that when this charge distribution is inserted into the prescription of an incompressible and irrotational deformation, the transition charge density obtained differs from the transition charge density used by Helm² and by Crannell et al.³

¹ L. J. Tassie, Australian J. Phys. 9, 407 (1956); 11, 481 (1958); Nuovo cimento 18, 525 (1960).

² R. H. Helm, Phys. Rev. 104, 1466 (1956).

³ H. Crannell, R. Helm, H. Kendall, J. Oeser, and M. Yearian (preprint).

Fig. 35. Electron scattering by Sm^{152} . The square of the form factor for (a) elastic scattering, (b) E2 inelastic scattering with excitation of the first excited state (2^+), (c) E0 inelastic scattering with excitation of the 0^+ β vibration state, (d) E2 inelastic scattering with excitation of the 2^+ β vibration state. The quantity $\hbar q$ is the momentum transfer in the scattering event, and R is the radius of the uniform distribution $\rho_1(r)$.

Calculations have been made for ${}_{62}\text{Sm}^{152}$.

Samarium has a rotational band 0^+ , 2^+ , 4^+ on the ground state, and another rotational band 0^+ , 2^+ starting at the first β vibration state. There is also a 1^- level at 963 kev, and above that are γ vibration states. The excitation of the first two 2^+ states and of the 0^+ state has been considered.

The results of the calculation are shown in Fig. 35 as the ratio to point-charge scattering. This is also the square of the form factor. The results are shown for the excitation of the first 2^+ state and of the β vibration states (the 0^+ and the 2^+ state). Also shown for comparison is the Born approximation for the elastic scattering. The cross section for the electric-monopole excitation of the 0^+ state is about

one tenth of the cross section for electric quadrupole excitation of the 2^+ β vibration state, and the two angular distributions are quite different. The maxima of one is more or less in line with the minima of the other.

The cross sections for excitation of the β vibration states are much smaller than for the excitation of the first 2^+ rotational

state. The variation with momentum transfer is almost the same for the excitation of the second 2^+ state as for excitation of the first 2^+ state. The cross section for the 0^+ state is only about a hundredth of the cross section for the first 2^+ state.

The energy levels of a deformed nucleus lie rather close together, when compared with the sort of resolution one can expect in an experiment on the scattering of 200-Mev electrons. However, it should usually be possible to resolve the β band from the ground-state rotational band, and some information could be obtained in this manner.

The experimental situation is better for the vibrational levels of a spherically symmetrical nucleus.³ We have yet to calculate the excitation of the 2-phonon levels (the 0^+ , 2^+ , and 4^+ levels) of a spherically symmetrical nucleus.

V-8-6 Fractional Parentage Coefficients in Intermediate Coupling
(51210-01)

Dieter Kurath

In an earlier report (ANL-6111, February, 1960) the basic idea and the method of extracting coefficients of fractional parentage (CFP) was presented. In the course of time many cases have been carried out, and the results have been compiled for the large number of cases in the $1p$ shell where the generator method provides a simplification over standard procedures. A description of the method together with the compilation are contained in a topical report entitled "Fractional Parentage Coefficients in Intermediate Coupling," Dieter Kurath, Argonne National Laboratory Report ANL-6312 (March 1961).

V-10-1

Rotational Model for Fe⁵⁷

(51210-01)

R. D. Lawson and M. H. Macfarlane^{*}

INTRODUCTION

Recent experimental studies have determined many of the properties of low-lying levels in Fe⁵⁷ with considerable accuracy but interpretation of these data has been mainly qualitative. A shell-model calculation would at the very least demand explicit consideration of three neutrons and two proton holes. Similar calculational difficulties encountered in the (ds) shell have been avoided by the use of rotational models.¹⁻⁴ The qualitative success of such calculations prompted us to examine a single-particle rotational model of Fe⁵⁷.

In this model, a single nucleon moves in the deformed field of an axially symmetric rotor. The parameters of this model are the quantities characterizing the potential well and the moment of inertia of the rotor. We have used a potential of the type discussed by Nilsson⁵—a deformed harmonic oscillator with spin-orbit coupling. The energy levels

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¹ E. B. Paul, Phil. Mag. 15, 311 (1957).

² G. Rakavy, Nuclear Phys. 4, 375 (1957).

³ A. E. Litherland, H. McManus, E. B. Paul, D. A. Bromley, and H. E. Gove, Can. J. Phys. 36, 378 (1958).

⁴ E. B. Paul and J. H. Montague, Nuclear Phys. 8, 61 (1958).

⁵ S. G. Nilsson, Mat. Fys. Medd. Dan. Vid. Selsk. 29, No. 16, (1955).

of this Hamiltonian are shown in Fig. 36. In earlier studies of the rotational properties of light nuclei, the positions of the unperturbed bands were freely chosen to give optimum agreement with experiment. In our calculation, we fix the parameters of the well and the rotor, and thereby determine the Hamiltonian of the model completely. All subsequent comparisons with experiment are made in terms of the eigenvalues and eigenfunctions of this Hamiltonian. The effects of band

mixing introduced by the term $(\hbar^2/2\mathcal{J})\vec{I} \cdot \vec{J}$ in the Hamiltonian are, of course, very important since $\hbar^2/2\mathcal{J}$ is now more than ten times as great as in the rare-earth region.

In a single-particle rotational model, all nucleons but the last are placed in pairs in the lowest available Nilsson orbits. The possibility of promoting such pairs to unfilled levels is neglected, which is sensible only when there is a sizable energy separation between the last core orbit and the first odd-particle orbit. In other words, it is not meaningful to apply a single-particle rotational model close to a crossing in the Nilsson level diagram. In the case of Fe^{57} , it will be seen from Fig. 36 that for $-2 < \eta < 4$ no such crossings occur. Thus we may reasonably hope that our single-particle calculation will provide a good first approximation to a many-particle calculation with residual forces.

Difficulties with crossings in the Nilsson level diagram may already have been encountered in the (ds) shell. It is believed that

Fig. 36. Energy levels in the (1f, 2p) shell as a function of the deformation η . This diagram is part of Fig. 5 in reference 5.

beyond Si^{28} we are dealing with negative deformations.⁶ In Si^{29} we then have a large energy separation between the last core orbit (Nilsson level No. 7) and the first single-particle orbits (Nos. 8 and 9). Accordingly one would expect, and indeed finds,⁷ that the positive-parity levels in Si^{29} are well described by the model under consideration. On the other hand, in S^{33} the last core orbit can be either No. 8 or 9, which lie very close in energy and actually intersect for deformations in the region of interest. The expectations of the above "crossing" arguments are again borne out in practice;⁸ the single-particle rotational model cannot give adequate agreement with experiment for S^{33} .

The Hamiltonian of our model is⁹

$$H = \frac{\hbar^2}{2\mathcal{J}} [(I_{\mu} - j_{\mu})^2 - (I_z - j_z)^2] + H_{\text{intrinsic}}$$

$$= \frac{\hbar^2}{2\mathcal{J}} [I^2 + j^2 - 2I_z^2] + \frac{\hbar^2}{2\mathcal{J}} (I_+ j_- + I_- j_+) + H_{\text{intrinsic}},$$

where $\mathcal{J}$ is the moment of inertia of the rotor, $I_{\mu} - j_{\mu}$ is the angular momentum of the core, and $H_{\text{intrinsic}}$ is the Nilsson Hamiltonian. We diagonalized H for Nilsson's choice of single-particle parameters and several values of η . Two values of $\hbar^2/2\mathcal{J}$ were used: 0.14 Mev (1/6 the excitation energy

⁶ Proceedings of the International Conference on Nuclear Structure (University of Toronto Press, 1960), p. 441.

⁷ M. H. Macfarlane and J. B. French, Revs. Modern Phys. 32, 567 (1960). See in particular pp. 665-666.

⁸ R. Bhatt (to be published).

⁹ A. K. Kerman, Mat. Fys. Medd. Dan. Vid. Selsk. 30, No. 15, (1956).

of the first excited state in Fe^{56}) and 0.11 Mev. The fact that this rather sizable variation in $\hbar^2/2\mathcal{I}$ makes little difference to the predictions of the model indicates that the precise value chosen for the moment of inertia is not of critical importance to the calculation. The resulting spectra are shown in Fig. 37. The eigenfunctions that diagonalize the Hamiltonian were then used to calculate¹⁰ various moments and transition rates. The results are summarized in Tables VI and VII.

COMPARISON WITH EXPERIMENT

(a) Spectrum

In Fe^{57} there are five known levels below 1 Mev.¹¹

The spins of the three lowest are well established, whereas that of the 365-kev state is fixed by stripping data¹² as either $\frac{3}{2}^-$ or $\frac{1}{2}^-$. Nothing is

Fig. 37. Spectrum of Fe^{57} . The first three columns show the spectra obtained for positive deformation ($\eta = 1, 2$, and 3) and $\hbar^2/2\mathcal{I} = 0.14$ Mev. The next three columns are the resulting spectra when $\eta = 2, 3$, and 4 with $\hbar^2/2\mathcal{I} = 0.11$ Mev. Column 7 shows the experimental results.

¹⁰ A. K. Kerman, Chap. X of Nuclear Reactions, edited by P. M. Endt and M. Demeur (North-Holland Publishing Co., Amsterdam, 1959), Vol. I.

¹¹ Nuclear Data Sheets, National Academy of Sciences, National Research Council, 1960 (U. S. Government Printing Office, Washington, D. C.).

¹² A. W. Dalton, G. Parry, H. D. Scott, and S. Swierszczewski (to be published). We wish to thank Dr. Parry for sending us his results prior to publication.

TABLE VI. Static multipole moments and stripping widths of some of the low-lying states in Fe^{57} for various values of the deformation and moment of inertia of the rotor. In calculating matrix elements of the magnetic dipole operators, a value of $Z/A = 0.464$ was taken for g_R . The quantity listed in column 4 is a measure of the strength of the proton groups relative to the third excited state $\left(\frac{3}{2}^-\right)^*$ and to the ground state doublet in $\text{Fe}^{58}(d,p)\text{Fe}^{57}$. $\mathcal{S}_{1/2}$ is the spectroscopic factor for the ground state.

η		Magnetic moment of the ground state in n.m.	Magnetic moment of the first excited state in n.m.	Quadrupole moment of the first excited state in barns	$\frac{4\mathcal{S}_{3/2}^*}{2\mathcal{S}_{1/2} + 4\mathcal{S}_{3/2}}$	$\mathcal{S}_{1/2}$
Experiment		+0.0903 ^a	-0.153 ^b	negative ^c	$\approx 0.6^d$	$\approx 0.25^e$
$\frac{\hbar^2}{2\mathcal{I}} = 0.14$ Mev	1	+0.39	-0.42	+0.04	0.51	0.012
	2	+0.58	+0.77	+0.05	450.	0.002
	3	+0.70	+0.06	-0.02	3.32	0.002
$\frac{\hbar^2}{2\mathcal{I}} = 0.11$ Mev	2	+0.59	+0.75	+0.05	120	0.005
	3	+0.71	+0.02	-0.04	3.08	0
	4	+0.78	-0.53	-0.12	1.08	0.007

(a) G. W. Ludwig and H. H. Woodbury, Phys. Rev. 117, 1286 (1960).

(b) S. S. Hanna, J. Heberle, C. Littlejohn, G. J. Perlow, R. S. Preston, and D. H. Vincent, Phys. Rev. Letters 4, 177 (1960).

(c) Reference 14.

(d) Reference 12.

(e) Reference 20.

TABLE VII. Reduced transition probabilities for low-lying states in Fe^{57} .

η		$10^{48} \text{ B(E2; } \frac{5-}{2} \rightarrow \frac{1-}{2})$ ($\text{e}^2 \text{ cm}^4$)	$10^{48} \text{ B(E2; } \frac{5-}{2} \rightarrow \frac{3-}{2})$ ($\text{e}^2 \text{ cm}^4$)	$10^{30} \text{ B(M1; } \frac{5-}{2} \rightarrow \frac{3-}{2})$ ($\text{e}^2 \text{ cm}^2$)	$10^{30} \text{ B(M1; } \frac{3-}{2} \rightarrow \frac{1-}{2})$ ($\text{e}^2 \text{ cm}^2$)
Experiment		0.014 ^a	0.0074 ^b	0.23 ^a	1.4 ^c
Weisskopf estimate		0.0013		200	
$\frac{\hbar^2}{2g} = 0.14 \text{ Mev}$	1	0.0005	0.0003	0.0044	5.6
	2	0.0020	0.0028	1.23	7.3
	3	0.0047	0.0057	1.17	19.9
$\frac{\hbar^2}{2g} = 0.11 \text{ Mev}$	2	0.0023	0.0026	1.41	9.0
	3	0.0054	0.0052	1.22	24.1
	4	0.010	0.0074	0.83	47.8

^a A. T. G. Ferguson, M. A. Grace, and J. O. Newton, Nuclear Phys. 17, 9 (1960).

^b G. R. Bishop, M. A. Grace, C. E. Johnson, A. C. Knipper, H. R. Lemmer, J. Perez y Jorba, and R. G. Scurlock, Phil. Mag. 46, 951 (1955).

^c H. R. Lemmer, O. J. A. Segalert, and M. A. Grace, Proc. Phys. Soc. (London) A68, 701 (1955).

known about the spin or parity of the state at 705 kev. From Fig. 37 it is evident that the calculated and observed spectra are in moderate agreement for either value of the moment-of-inertia parameter and $\eta \approx 3-4$. A spin of $\frac{3^-}{2}$ rather than $\frac{1^-}{2}$ is predicted for the third excited state.

The 705-kev level is not observed either by stripping $^{12}_{12}$ from $^{56}_{56}\text{Fe}$ or pickup $^{13}_{13}$ from $^{58}_{58}\text{Fe}$. These characteristics are consistent with its identification as the $\frac{7^-}{2}$ state predicted by our model at about 1 Mev. On the other hand, we may, in fact, be dealing with a complicated excitation of the core.

Our calculated energy levels tend to be more widely spread than is found experimentally. This is reasonable, since one of the effects of the neglected core excitations would be to compress the lower part of the predicted spectra. In view of the additional error involved in simulating the nuclear potential by a harmonic oscillator, we conclude that agreement between the theoretical and experimental energy levels is adequate.

(b) E2 Transition Rates and Quadrupole Moments

Since $^{57}_{57}\text{Fe}$ is an odd-neutron nucleus, the static quadrupole moments and E2 matrix elements are proportional to the quadrupole moment Q_0 of the core. On the assumption that

$$Q_0 = \frac{4}{5} Z e R_0^2 \delta (1 + 0.17 \delta + \dots)$$

with R_0 , the radius of the charge distribution, taken to be $1.2 A^{1/3} \times 10^{-13}$ cm, it is seen from Table VII that rather good agreement is obtained for the values of $B(E2)$. The negative sign for the quadrupole moment of the first excited state (Table VI) comes about from the fact that this $\frac{3^-}{2}$ level arises predominantly from a $K = \frac{1^-}{2}$ band. This agrees with the sign of the quadrupole

¹³ B. Zeidman (private communication).

moment as deduced by Bersohn.¹⁴

(c) M1 Transition Rates and Magnetic Moments

The calculated magnetic moment of the first excited $\frac{3}{2}^-$ state is a sensitive function of the deformation, passing through the experimental value for η between 1 and 2 and again between 3 and 4. As we have seen, the larger value of deformation gives reasonable agreement with experiment both for the spectrum and for the electric-quadrupole properties of Fe^{57} .

The matrix element of the M1 transition between the second ($\frac{5}{2}^-$) and first ($\frac{3}{2}^-$) excited states of Fe^{57} is overestimated by a factor of two (for $\eta \approx 4$). In rotational-model calculations in the (ds) shell, Paul has obtained about the same quality of agreement between theory and experiment for M1 transitions in F^{19} (see Table I of reference 1), while Paul and Montague find larger discrepancies for M1 transitions in Na^{23} (see Table I of reference 4). In analyzing M1 data in the rare-earth region, the standard procedure has been to treat the intrinsic matrix elements of the magnetic-dipole operator as empirical parameters. The values of these parameters required to fit the M1 transition rates frequently differ markedly from calculated values obtained from Nilsson's wave functions. It is, therefore, rather hard to compare our results with those obtained for M1 transitions in the rare-earth nuclei. Kerman, in his semiempirical analysis¹⁰ of band mixing in W^{183} (a nucleus similar to Fe^{57} in that it has an odd neutron, a ground-state spin of $\frac{1}{2}^-$, and an equilibrium deformation $\delta \approx 0.2$), obtains agreement to within 50% for nine M1 matrix elements (see Table IV of reference 10), which is rather better than we have done. We conclude that the agreement between theory and experiment for the 122-keV M1 transition in Fe^{57} is marginal.

¹⁴

R. Bersohn, Phys. Rev. Letters 4, 609 (1960).

On the other hand, the calculated values of the ground-state magnetic moment and the M1 transition rate between the first excited state and ground state are quite clearly in disagreement with experiment. The discrepancy in the ground-state magnetic moment is very similar to that found¹⁵ in W¹⁸³ and Os¹⁸⁷. In each case we are dealing with a $\frac{1}{2}^-$ odd-neutron nucleus with a magnetic moment close to 0.1 nuclear magnetons. For such nuclei both the rotational model¹⁶ and the shell model¹⁷ (even with configuration mixing) predict magnetic moments very close to the Schmidt value (0.638 nm). This disagreement indicates serious deficiencies in either the magnetic-moment operator or the ground-state nuclear wave function, or both. The fact that agreement with experiment for the 14-keV M1 matrix element is considerably worse than for the 122-keV matrix element suggests that the main trouble lies in the ground-state nuclear wave function.

(d) Stripping and Pickup

The reaction $\text{Fe}^{56}(\text{d}, \text{p})\text{Fe}^{57}$ has recently been studied.¹²

Strong $l = 1$ transitions are observed to the unresolved ground-state doublet and to the third excited state at 365 keV; the excited state at 136 keV has $l = 3$.

In comparing these experimental data with the predictions of our model, the relevant quantities are the reduced widths θ^2 . Since the spin of the target nucleus is zero, θ^2 for the r th level of spin I in Fe^{57} is given by¹⁸

$$\theta^2(I, r) = \mathcal{S}(I, r) \theta_0^2(l)$$

$$\mathcal{S}(I, r) = \frac{2}{(2I + 1)} \left\{ \sum_{K, S} A_{KS}^{\text{Ir}} c_{KS}^I \right\}^2, \quad (5)$$

¹⁵ B. R. Mottelson and S. G. Nilsson, Mat. Fys. Skr. Dan. Vid. Selsk. 1, No. 8 (1959), Table 7b.

¹⁶ See Eq. (26) of reference 5.

¹⁷ H. Noya, A. Arima, and H. Horie, Progr. Theoret. Phys. (Japan), Supplement 8, 33 (1958).

¹⁸ Reference 7, particularly Eq. (III. 203) and p. 611.

where $\theta_0^2(l)$ is the appropriate single-particle reduced width and c_{KS}^I is the amplitude of angular momentum I in χ_{KS} .

We do not give quantitative estimates of the relative strength of $l = 1$ and $l = 3$ transitions because too little is known about the single-particle reduced widths. However, the large calculated spectroscopic factor S of the $\frac{5}{2}^-$ state (> 0.5 for all cases considered) is consistent with the fact that a strong $l = 3$ transition is observed.

In comparing the reduced widths of the two $l = 1$ transitions, only the spectroscopic factors S need be considered since the single-particle reduced width cancels. From Table VI, we see that the calculated value of $[4S_{3/2}^*/(2S_{1/2} + 4S_{3/2})]$ for $\eta \approx 4$ is close to 1, in fair agreement with the observed value of 0.6.

The calculated contribution of the ground state to the combined $l = 1$ reduced width of the ground-state doublet is negligible, amounting to less than 1% of the single-particle reduced width. This is in direct contradiction to the fact that an $l = 1$ transition to the Fe^{58} ground state is seen quite clearly¹⁹ in $Fe^{57}(d,t)Fe^{58}$. The strength of the transition in question indicates, very roughly, that the reduced width is about a quarter of the single-particle value. This discrepancy in the reduced width of the ground-state, involving a factor of between 20 and 30, is further clear indication that the ground-state wave function of our model is seriously defective.

Discussion

Within an oscillator shell, the Nilsson potential is characterized by three parameters. For the (1f, 2p) shell we may take these to be the deformation δ and the single-particle level separations in the limit of zero deformation, namely,

¹⁹

B. Zeidman, J. L. Yntema, and B. J. Raz, Phys. Rev. (to be published).

$$E(2p_{1/2}) - E(2p_{3/2}) = \Delta(p)$$

and

$$E(1f_{5/2}) - E(2p_{3/2}) = \Delta(fp) .$$

So far we have followed Nilsson's original calculation, taking $\Delta(p) = 1.6$ Mev and $\Delta(fp) = 0.8$ Mev. To test the sensitivity of the model to changes in the parameters characterizing the single-particle potential, we repeated the calculation using $\Delta(p) = 1.5$ Mev, $\Delta(fp) = 0.5$ Mev, and $\hbar^2/2\mathcal{J} = 0.14$. The spectra for $\eta = 2$ and $\eta = 3$ were not significantly altered from those shown in Fig. 37. Furthermore, the overlap between corresponding eigenvalues (same value of η) from the two sets of single-particle parameters was in each case greater than 99%. We conclude that the predictions of the model are insensitive to reasonable changes in the single-particle parameters, always remaining within the harmonic-oscillator approximation.

It does not seem possible to obtain agreement with experiment for a single-particle model with negative deformation. For $\eta = -2$, a $\frac{5}{2}$ ground state is obtained, the next level lying at about 500 kev excitation. At $\eta = -4$ (see Fig. 36) we encounter a crossing in the Nilsson diagram involving orbit_s Nos. 15 and 16 so that, as discussed earlier, an extreme single-particle model cannot be used. Finally, for $\eta = -6$, we obtain a $\frac{3}{2}$ ground state with the lowest $\frac{5}{2}$ state lying about 500 kev too high. Further, the second $\frac{3}{2}$ state is predicted to show no stripping from Fe^{56} , in disagreement with experiment.

Vervier and Bartholomew²⁰ have discussed the levels of

²⁰

J. F. Vervier and G. A. Bartholomew, quoted on p. 650 of reference 7.

Fe^{57} in a qualitative fashion on the basis of a rotational model. Assigning $K = \frac{3}{2}$ to the first excited state, they are led by the negative sign of the observed quadrupole moment to select an oblate deformation, $\eta \approx -3$. As mentioned above, orbits Nos. 15 and 16 are then close to an intersection. Although Vervier and Bartholomew consider the promotion of pairs of particles among these levels (and level No. 17 which is close by), they neglect any residual pairing forces. In addition the effects of band mixing, which we have seen to be quite large, are not considered. Since the negative sign of the measured quadrupole moment can be obtained for positive deformation, the above argument for negative deformation is not conclusive.

In principle, the equilibrium deformation of a nucleus can be determined by minimizing the total energy as a function of deformation. Calculations in the (ds) shell⁶ predict a sharp change from prolate to oblate deformations around $A = 26$; such a change seems to be observed, but at $A = 28 - 29$. Thus we expect a change of sign in the deformation around the middle of the (fp) shell, probably somewhere between Fe and Ni. However, calculations of the type under consideration are not sufficiently reliable to locate it exactly.

The present model might also be expected to be applicable to Ni^{59} , which has the same (odd) number of neutrons as Fe^{57} . However, the ground-state spin of Ni^{59} is $\frac{3}{2}$, which we cannot obtain on the single-particle rotational model without proceeding to rather large negative deformations ($|\eta| \geq 6$). Since a change of sign of η between Fe^{57} and Ni^{59} would not be unexpected, it is possible that a reasonable description of Ni^{59} could be obtained at $\eta \approx -4$ with a three-body rotational model including residual two-body interactions.

We therefore conclude that a moderately accurate description of many of the known properties of levels below 1 Mev in Fe^{57} is obtained for prolate shapes corresponding to values of δ between 0.15 and 0.2. Serious

discrepancies are, however, encountered for quantities which depend on the intrinsic wave function of the $\frac{1}{2}^-$ ground state.

The predictions of the model are remarkably insensitive to reasonable variations in the moment of inertia of the rotor and in the parameters (other than the deformation) characterizing the deformed (harmonic-oscillator) potential. This significant fact is obscured if, instead of using the full rotational Hamiltonian, the relative positions of the pure bands are arbitrarily adjusted to fit the observed spectrum.

Since agreement with experiment for Fe^{57} is not fully satisfactory and, moreover, cannot be significantly improved by reasonable adjustments of the parameters of the model, the single-particle rotational picture must be refined. We might consider a many-particle rotational model, including residual two-body forces between the nucleons outside the core. Such a calculation would be similar in spirit and in degree of complication to conventional shell-model studies. Alternatively, we might carry the single-particle approach one step further, replacing the axially symmetric rotor by something better able to describe the Fe^{56} core. One such model is that of a neutron in the field of an asymmetric rotor.

V-11-2

Some Aspects of p-Shell Hypernuclei

(51210-01)

R. D. Lawson and Manuel Rotenberg (U. of Chicago)
Reported by R. D. Lawson

This project has been completed and the results have been published in a report entitled "Branching Ratios for the Decay of p-Shell Hypernuclei," R. D. Lawson and Manuel Rotenberg, *Nuovo cimento* 17, 449-461 (August 16, 1960).

V-24-2 Imaginary Part of the Delbrück Scattering Amplitude
(51210-01)

W. Zernik

This project has been completed and the results have been published in a report entitled "Imaginary Part of the Delbrück Scattering Amplitude," W. Zernik, Phys. Rev. 120, 549-551 (October 15, 1960).

VI. MISCELLANEOUS

VI-2-1

Mathematical Logic

(51210-01)

William C. Davidon

As the scope of physics enlarges to include phenomena far removed from direct experience, it becomes increasingly necessary that our concepts and the assumed relationships among them be subject to continual critical examination. Only in this way can we strengthen them (so that they have a wider domain of validity) or, when necessary, replace them by others.

This represents one important application of logical methods to the development of physical theories. Another immediate one is the systematization of numerical, algebraic, functional, and logical (or inferential) analysis so that at least some problems in these areas can be solved by computers. Computers have already been used for solving physical problems by non-numerical means, such as in evaluating Feynman integrals (analytically) and for certain matrix reductions.

A series of seminars on mathematical logic, currently being conducted at Argonne, reviews methods that have been coded for computers to solve certain algebraic and logical problems. Some of the general principles relevant to this work have been developed, and possible new approaches have been considered briefly.

Brief lecture notes are available from the author.

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PARAMETERS AND GAMMA-RAY SPECTRA OF NEUTRON RESONANCES IN THE ISOTOPES OF MERCURY

R. T. Carpenter and L. M. Bollinger.....(Project I-3,7)
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ACHIEVEMENT OF EXTREMELY HOMOGENEOUS MAGNETIC FIELDS

L. S. Goodman.....(Project I-80)
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DECAY OF ${}_{68}\text{Er}^{161}$ (3.1 hr)

H. A. Grench and S.B. Burson.....(Project I-30)
Phys. Rev. 121, 831-840 (February 1, 1961).

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M. N. Hack and M. Hamermesh..... (Project I-19)
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Clarendon Laboratory, Oxford University.)

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David C. Hess and Royal R. Marshall.....(Project II-18)
Geochim. Cosmochim. Acta 20, 284-299 (November 1960).

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Phys. Rev. 121, 1464-1471 (March 1, 1961).

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ZEROTH LAW OF THERMODYNAMICS

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ABSTRACTS

(α, He^3) REACTION ON Fe^{56} , Ni^{58} , Ni^{60} , AND Zn^{64}

T. H. Braid, J. L. Yntema, B. Zeidman, and H. Broek (Project I-22)
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CROSS SECTIONS FOR THE (p,n) REACTION AT 9.85 MEV

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THE ARGONNE 60-IN. SCATTERING CHAMBER

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CO-OP STUDENT REPORTS

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S. Barkan.....(Project I-43)
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BRANCHING RATIO OF α AND β EMISSION FROM Bi^{212} (ThC)

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NUCLEAR SPIN AND MAGNETIC MOMENT OF 2.6-HR Mn^{56}

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ENERGY DISTRIBUTION AND FRAGMENTATION PROCESSES RESULTING FROM ELECTRON IMPACT ON PROPANE AND nBUTANE

William A. Chupka and Manfred Kaminsky
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LEVEL SCHEME OF Au^{198} DETERMINED BY ANALYSIS OF HIGH-PRECISION CAPTURE-GAMMA-RAY MEASUREMENTS

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PRECISION MEASUREMENT OF GAMMA RAYS FROM DECAY IN Au^{198} AND Au^{199}

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"FOOLPROOF" MERCURY CUTOFF TO WITHSTAND ATMOSPHERIC PRESSURES

David C. Hess.....(Project II-18)
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THE DESIGN OF BUNCHING MAGNETS

R. E. Holland

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DESIGN AND CONSTRUCTION OF A SYSTEM OF PULSED MAGNETS

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MEASUREMENT OF THE ENERGY OF THE GAMMA RADIATION FROM NEUTRON CAPTURE BY HYDROGEN

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Nuclear Phys. in April 1961 issue.

THE QUANTUM MECHANICAL EFFECTS OF MAGNETIC FIELDS CONFINED TO INACCESSIBLE REGIONS

Murray Peshkin, Igal Talmi, and L. J. Tassie

Ann. Phys.

MAGNETIC MOMENTS OF THE Λ AND Σ HYPERONS

Katsumi Tanaka.....(Project V-45)

Phys. Rev. in April 15, 1961 issue.

PERSONNEL CHANGES IN THE ANL PHYSICS DIVISION
NEW MEMBERS OF THE DIVISION

Staff Member

Mr. Allen P. Magruder.

B.S.,

University of Chicago, 1959. He joined the Physics Division on March 13, 1961 to work as a mathematical analyst of the data from the bent-crystal gamma-ray spectrometer.

Student Aide (Co-op)

Mr. Robert Obenchain, Northwestern University. Working with R. O. Lane on the differential cross sections for neutron scattering and on neutron polarization. Came to ANL on March 27, 1961.