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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 individual 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-7-5

I. EXPERIMENTAL NUCLEAR PHYSICSI-7-5 Gamma-Ray Spectra from Capture in Neutron Resonances (5220)L. M. Bollinger, and R. E. Cote¹

Reported by L. M. Bollinger

DETERMINATION OF SPINS OF RESONANCES FROM TWO-
STEP GAMMA-RAY CASCADES

Recently it has become increasingly popular to use the high-energy portion of the γ -ray spectrum from resonant capture of neutrons to try to determine the spin of resonances.¹ This approach has been most widely used for even-proton odd-neutron target nuclides of spin $I = 1/2$ and negative parity, for which case the compound nucleus is formed in either 1^- or 0^- states by capture of s-wave neutrons. For this special case the observation of a transition directly to the 0^+ ground state is conclusive evidence that the total angular momentum J of the initial state is 1, since a transition from 0 to 0 is not possible. However, failure to observe a ground-state transition does not necessarily imply that $J = 0$; the transition may merely be too weak to be observable, a not improbable circumstance because of the large fluctuations in partial radiation widths.² Similar applications may be made of the high-energy capture gamma rays for other classes of target nuclides of odd parity, but in each case there is an ambiguity in the interpretation when no transition is observable. In general, the high-energy gamma rays from capture in nuclides of positive parity are not useful for spin assignments because, although

¹ H. H. Landon and E. R. Rae, Phys. Rev. 107, 1333 (1957).

² L. M. Bollinger, R. E. Cote', and T. J. Kennett, Phys. Rev. Letters 3, 376 (1959).

they may allow an assignment in principle, they will generally be too weak to be observable. Thus the application of single high-energy capture gamma rays for the determination of spins is seen to be useful only for some resonances of several classes of nuclides of negative parity.

$$\left\{ \begin{array}{l} \text{RELATIVE} \\ \text{INTENSITY} \end{array} \right\} = \int \left(\frac{\Gamma_{ab}}{\Gamma_a} \right) \rho_b \left(\frac{\Gamma_{bc}}{\Gamma_b} \right) dE$$

$$= \frac{1}{\Gamma_a} \int \Gamma_{ab} \left[\rho_b \frac{\Gamma_{bc}}{\Gamma_b} \right] dE$$

$$\Gamma_{ab} \sim D_a f(E) \sim (2J+1)^{-1} f(E)$$

Fig. 1. Two-step gamma-ray cascades.

In an effort to devise a more widely applicable method for spin assignments than is the observation of single gamma rays, we have investigated the characteristics of gamma-ray cascades which proceed from the initial compound state to some final state in exactly two steps. Consider first the special case of an even-odd target nuclide of spin 1/2 and positive parity. Then, as in Fig. 1, a two-step cascade to the 0^+ ground state

from either the 0^+ or 1^+ initial state is expected to proceed largely by way of two E1 transitions. The intensity for such a two-step transition is proportional to the quantity

$$P = \int \left(\frac{\Gamma_{ab}}{\Gamma_a} \right) \rho_b \left(\frac{\Gamma_{bc}}{\Gamma_b} \right) dE$$

$$= \frac{1}{\Gamma_a} \int \Gamma_{ab} \left[\rho_b \frac{\Gamma_{bc}}{\Gamma_b} \right] dE, \quad (1)$$

where Γ_{ab} and Γ_{bc} are the partial radiation widths for the transitions from the states a to b and b to c, Γ_a and Γ_b are the total radiation widths of states a and b, and ρ_b is the nuclear level density at the intermediate state of energy E. In the second writing of Eq. (1) we see that the transition intensity depends on the total angular momentum J_a of the initial state only

through Γ_{ab} , since Γ_a has been shown experimentally to be independent of J_a and the factors in the bracket are identical for both values of J_a . Thus, since $\Gamma_{ab} \propto \rho_a^{-1} \propto (2J_a + 1)^{-1}$, the relative intensity for a two-step transition to the ground state is three times as strong for the 0^+ as for the 1^+ initial state. Moreover, the intensity would be expected to be approximately constant for all resonances of a given J , since many different two-step cascades contribute to the intensity.

Arguments similar to the above can be made for two-step transitions to an excited state in other classes of nuclides of positive parity. The results of these simple considerations for even-odd nuclides are summarized in Table I. There we see that cascades to the ground state or the 2^+ excited state are sufficiently dependent on J_a to offer hope that there will be a measurable difference between the intensities for the two possible values ($J_a = I \pm \frac{1}{2}$) for all values of I .

TABLE I. Calculated intensities of 2-step cascades from initial states of positive parity in even-even nuclides. The quantity listed in columns 2 and 3 is the intensity of transitions from states with $J = I - \frac{1}{2}$ relative to the intensity for states with $J = I + \frac{1}{2}$. It is assumed that only E1 transitions contribute to the intensity and that $\rho_b \Gamma_{bc}$ is independent of J_b .

Target spin	Final state	
	0^+	2^+
1/2	3	3/2
3/2	2	10/9
5/2	∞	21/10
7/2		18/7
9/2		∞

³ J. M. Blatt and V. F. Weisskopf, Theoretical Nuclear Physics (John Wiley and Sons, New York, 1952), Chap. XII.

Our initial effort to obtain experimental confirmation of the ideas outlined above has been to study states formed by capture in resonances of Cd^{113} and Cd^{111} , both of which have $I = \frac{1}{2}$. The two-step transitions were observed by recording the distribution of the sum of pulse heights when coincidence counts were detected in two 4×4 in. NaI(Tl) scintillators. The solid angle subtended by the detectors was small enough to insure that only 2-step cascades would be detected with a significant degree of probability. The sum spectrum resulting from capture of thermal neutrons in Cd^{113} is shown in Fig. 2, where it is seen that the line resulting from two-step transitions to the ground state is partially resolved. The results of measurements of this kind for five resonances of Cd^{113} are given in Table II. The expected 3 to 1 ratio in the intensity for ground-state transitions from the known 0^+ and 1^+ states is experimentally confirmed. Moreover, the intensities for three of the states of unknown spin are the same (within errors) as that for the resonance at thermal energy, a fact which indicates that $J = 1$ for all of them and tends to confirm the expectation that the fluctuations in intensities are small for resonances of a given J .

In the assignment of spins for the resonances of Cd^{113} , we make use of the known spin of the resonance at thermal energy. For Cd^{111} there is no resonance of known spin. Therefore one must make use of the fact that the shape of the sum spectrum depends on J .

Fig. 2. Sum spectra for the 0.2-ev resonance of Cd^{113} and the 28-ev resonance of Cd^{111} . The absolute value of the ordinate applies only to the latter spectrum.

TABLE II. Experimental values of the relative intensities of 2-step cascades. Column 4 gives the intensity of 2-step cascades to the ground state. Column 5 gives the intensity of counts for which the energy dissipated in the crystal is roughly that of a transition to the first excited state. Thus it includes the one-quantum escape peak of transitions to the ground state.

Target nuclide	Resonance energy (ev)	Known J-values	Relative intensity		
			0^+	2^+	J-value assignment
	0.2	1	100	100	1
Cd^{113} ($\frac{1}{2}^+$)	18		83 ± 19	103 ± 12	1
	64		119 ± 28	97 ± 14	1
	108		85 ± 18	101 ± 11	1
	193	0	272 ± 35	145 ± 15	0
Cd^{111} ($\frac{1}{2}^+$)	28		100	100	1
	99		88 ± 18	91 ± 12	1
	138		118 ± 43	72 ± 19	1
	164		58 ± 24	90 ± 16	1
Hg^{199} ($\frac{1}{2}^-$)	-2	0	100	100	0
	34	1	71 ± 6	77 ± 3	1
	130	(0,1)	111 ± 15	100 ± 8	0
	173	1	62 ± 10	54 ± 4	1

A comparison of the spectrum for the 28-ev resonance of Cd^{111} with the 0.2-ev resonance of Cd^{113} indicates that the spin is the same for the two, namely $J = 1$. The results for other resonances of Cd^{111} are given in Table II. Again the data tend to confirm the expectation that the fluctuations in relative intensity should be small for resonances of a given J.

Measurements are now in progress to extend the sum-coincidence measurements to even-odd nuclides for which $I \neq \frac{1}{2}$.

When the consideration of two-step gamma-ray cascades is enlarged to include initial states of negative parity, an element of uncertainty is introduced. It seems probable that the dominant mode of transition to the ground state would be an E1 followed by an M1 transition. However, a cascade comprising an E1 followed by an E2 transition cannot be excluded. Thus we proceeded to measure the sum spectra of Hg^{199} ($I = \frac{1}{2}$) without being sure what ratio of intensities to expect for the two spin states. The results obtained are given in Table II. It is seen that the sum transition to the ground state is weaker for the known states of $J = 1$ (34 and 175 ev) than for the state having $J = 0$ (-2 ev). However, the difference is not as great as for initial states of positive parity. As a result, further information about fluctuations of intensities of 2-step cascades is required before one can make spin assignments with absolute certainty when the initial state has negative parity. Nevertheless, the data seem to indicate strongly that $J = 0$ for the 130-ev resonance, a level about which there has been some controversy.

In summary, the 2-step cascade method appears to be capable of being a powerful tool for the assignment of spins to resonances of even-odd target nuclides of positive parity; for certain values of I it can also be useful for even-odd nuclides of negative parity. The method tends to be less applicable to odd-odd compound nuclides because of the small spacing of their low-energy states.

I-98-25

I-9-2

Excited Levels of Mn⁵⁶

(5220)

N. D'Angelo

The work on this project has been completed and the results have been published in a paper entitled "Excited Levels of Mn⁵⁶", N. D'Angelo, Phys. Rev. 117, 510-513 (January 15, 1960).

I-98-25

Neutron Total Cross Sections in the Kev Region

(5220)

Carl T. Hibdon

1. CROSS-SECTION MEASUREMENTS

For some time the virtual nuclear energy levels of Na²⁴ have been under investigation by the Na²³ (n,n) process.¹ Because of the profusion of levels observed, the work has been divided into parts. Part I is concerned with the 86 resonance levels up to 350 kev. These levels have been analyzed and the paper has been accepted for publication² and is scheduled to appear in the April 15, 1960 issue of the Physical Review. Part II is concerned with the 71 levels in the region from 350 to 630 kev. These levels have been analyzed and a paper covering this material has been completed and will soon be ready to submit for publication. Part III will cover the region from 630 to 860 kev. The data have been obtained in this region. Each level therein has been studied both by flat detection and by self-detection in order to obtain better values of the parameters of the many levels. The method, techniques,

¹ C. T. Hibdon, Physics Division Summary Report, ANL-5978 (February-April 1959), p. 14; ANL-6038 (July-August 1959), p. 3; ANL-6052 (September 1959), p. 34; ANL-6072 (October-November 1959), p. 16.

² C. T. Hibdon, Phys. Rev. 118, (April 15, 1960).

and samples used in these measurements are the same as previously used except that these measurements were made by use of neutrons emitted at an angle of 0° with respect to the direction of the proton beam. The data have not been analyzed.

An investigation of the nuclear energy levels of F^{20} by the $F^{19}(n,n)$ process has been started. A rather thorough study from about 1 to 280 kev was made by flat detection measurements. Some levels were also studied by self-detection. The samples used are LiF crystals, ranging in thickness from 50 mils to one inch. The crystals were grown from natural LiF by the Harshaw Chemical Company of Cleveland, Ohio. At the same time, it was necessary to make measurements on natural lithium. Metal samples ranging in thickness from 0.20 to 3.00 inches were used. These samples were canned in aluminum cans of 2-in. i.d. having 1-mil stainless steel end windows. The canning was performed in a manner similar to that described for the sodium samples.² None of the levels studied in these measurements have been analyzed.

The remainder of this report is concerned with the levels of Na^{24} from 350 to 630 kev. First, a brief summary of the general results obtained from the analyses is given with a tabulation of the parameters of the levels. From these parameters one obtains the strength functions and the distribution of the angular momenta, neutron widths, and level spacings.

2. EXPERIMENTAL RESULTS FOR Na^{24}

The neutron cross-section data from 350 to 630 kev show 71 peaks, comprising a relatively small number of large peaks and many small ones. These levels have been analyzed by the method described previously.^{1,2} The analyses show a few s-wave levels, a small number of p-wave levels, and a large number of d- and f-wave levels. Table III shows a summary of the parameters of the 71 levels in this region. The parameters are those that

TABLE III. Summary of the levels of Na^{24} (from 350 to 630 kev) derived from neutron reactions with Na^{23} . The parameters J , Γ_n , and l are probable values obtained as a best fit to the data.

No.	E_r (kev)	J	l	Γ_n (kev)
68	352.6	1	1	1.6
69	355.9	1	1	1.5
70	359.7	2	2	0.9
71	362.0	2	2	1.0
72	363.8	2	2	0.8
73	368.0	1	1	1.6
74	372.2	2	1	0.9
75	375.0	2	1	1.5
76	378.9	2	1	1.6
77	382.7	3	3 (2)	0.9
78	384.7	2	1	1.5
79	388.8	3	3 (2)	1.4
80	391.2	3	3 (2)	0.7
81	393.6	3	3 (2)	0.8
82	397.9	4	2	1.3
83	400.5	4	2	1.4
84	403.0	4	2 (3)	1.1
85	405.8	2	0	3.0
86	411.2	2	2	1.5
87	414.6	3	3 (2)	0.9
88	417.0	2	3 (2)	1.2
89	419.1	3	3 (2)	0.9
90	421.6	2	0	1.9
91	426.5	1	3 (2)	0.9
92	428.4	2	3	0.6
93	430.4	2	3	0.7
94	432.2	2	3	0.9

TABLE III (continued)

No.	E_r (kev)	J	l	Γ_n (kev)
95	436.5	3	3	0.7
96	439.0	3	3 (2)	1.1
97	443.0	3	2 (3)	1.3
98	446.2	4	3 (2)	1.2
99	449.6	4	2 (3)	1.9
100	451.2	2	0	3.7
101	456.6	2	3 (2)	0.8
102	459.7	2	3 (2)	0.6
103	463.2	2	2 (3)	1.1
104	465.7	2	0	0.70
105	471.5	2	3 (2)	0.70
106	476.5	2	2	1.3
107	481.3	2	3 (2)	0.75
108	487.2	2	3	1.1
109	493.9	2	3	0.75
110	511.0	2	3	1.0
111	530.3	3	3	0.75
112	532.7	3	3	1.0
113	535.4	3	3	1.1
114	538.8	2	0	4.5
115	545.0	2	3	0.6
116	549.9	2	2	1.4
117	552.8	2	2	1.4
118	557.0	3	3 (2)	0.8
119	561.2	3	2 (3)	1.3
120	564.8	3	2 (3)	1.3
121	568.3	3	3 (2)	0.6
122	570.4	3	3 (2)	0.9
123	575.3	3	2	1.5
124	578.7	2	2	2.0

TABLE III (continued)

No.	E_r (kev)	J	ℓ	Γ_n (kev)
125	582.9	3	2 (3)	1.6
126	586.6	3	2 (3)	1.6
126A	590.0	1	2	1.6
127	592.8	4	3	1.2
128	595.3	4	3	1.3
129	601.0	4	2	3.5
130	605.0	3	3	1.7
131	608.3	4	3	1.0
132	611.3	3	3	1.7
133	615.2	4	3	1.1
134	618.8	3	3	1.7
135	621.0	4	3	0.8
136	623.0	4	3	0.8
137	626.2	3	2	2.7

TABLE IV. The number of levels and their distribution among the various values of the angular momentum J. The relative numbers are the ratios of the densities of levels to the density for J = 1. All resonance levels of Na²⁴ up to 630 kev are included.

J	0	1	2	3	4
Number of levels	27	47	45	26	12
Relative numbers	0.57	1	0.96	0.55	0.26

Fig. 3. Number of levels of Na^{24} with energies $\leq E_n$ as a function of the neutron energy E_n .

appear to give a best fit to the data. Table IV shows the number of levels assigned to each value of J and their distribution among the various values of J for all of the 157 resonance levels of Na^{24} up to 630 keV.

Figure 3 shows the distribution of the levels, in which the number of levels $\leq E_n$ is plotted as a function of the neutron energy E_n for all levels up to 630 keV. This distribution exhibits the following characteristics:

1) There is no downward curvature to indicate a general missing of

levels in the high-energy region. 2) The observed levels are spaced somewhat at random—not at equal intervals. 3) The plot does, however, show a general trend toward a linear distribution, the fluctuations about this line, presumably, resulting in part from irregularities introduced by missing some levels too narrow to be resolved. In addition, the element of randomness in level spacings expected from any appropriate model of the nucleus would introduce further irregularities into the distribution. One, then, should expect the plot to show some deviations from a linear distribution.

3. DISTRIBUTION OF THE ANGULAR MOMENTA AMONG THE NUCLEAR LEVELS

For the single-particle model, Bloch gives for the density of levels as a function of the total angular momentum J the expression³

³ C. Bloch, Phys. Rev. 93, 1094 (1954).

$$\rho(U, J) = \rho(U) \{ \exp[-J^2/2\sigma^2] - \exp[-(J+1)^2/2\sigma^2] \}, \quad (1)$$

where $\rho(U, J)$ is the density of all levels for the energy region in question

Fig. 4. Distribution of the angular momenta among the resonance levels of Na^{24} . Experimentally determined points are shown by solid circles. The experimental points for Al^{28} are shown by open circles. The curves are plots of Eq. (1) for values of $\sigma = 1.58$, 1.73, and 1.80.

open circles. For Na^{24} , these data indicate a value of $\sigma = 1.8$.

For the constant $\underline{a}$ in the relation $2\sigma^2 = a\tau$, Cameron⁴ gives the expression

$$a = 0.1181A^{5/3} [1 + 3.0052/A^{2/3} - 4.0298/A^{4/3}], \quad (2)$$

which for Na^{24} is 3.2. This leads to $\tau \approx 2$ Mev, which is close to the value⁵ found for Al^{28} .

and U is the excitation energy.

The quantity $2\sigma^2$ is given by

some authors as $2c\tau$ or $a\tau$,

where τ is the so-called nuclear

temperature. Equation (1) can

be used to compute the ratios of

the densities of levels for differ-

ent values of J to the density for

$J = 1$. Plots of these ratios for

three values of σ are shown in

Fig. 4. The experimental data

for the relative numbers in

Table IV are shown in the plot by

solid circles and for comparison

the data for Al^{28} are shown by

⁴ A. G. W. Cameron, Can. J. Phys. 37, 244 (1959).

⁵ C. T. Hibdon, Phys. Rev. 114, 179 (1959).

The level density $\rho(U)$ is given by Bloch³ in the form

$$\rho(U) = [\sigma U (96\pi)^{\frac{1}{2}}]^{-1} \exp[\pi(2U/3\delta)^{\frac{1}{2}}], \quad (3)$$

Fig. 5. Exponential distribution of the reduced neutron widths of Na^{24} .

where δ is the average level spacing of the nucleons in the nucleus. From the present measurements, the experimentally determined density of all levels is $\rho(U) = 239 \text{ Mev}^{-1}$. For a mean value of $U = 7.3 \text{ Mev}$ and the value of $\sigma = 1.8$ obtained from the distribution of the angular momenta, one obtains a value of $\delta = 0.40 \text{ Mev}$ compared with an expected theoretical value⁶ of about 0.50.

4. DISTRIBUTION IN THE SIZE OF THE NEUTRON WIDTHS

The reduced widths obtained from the neutron widths of the levels by the relation⁵ $\gamma^2 = \Gamma_n / (2P_l)$ were found to fluctuate violently among the levels of Na^{24} in a manner similar to the fluctuations of the reduced widths⁵ of Al^{28} . It is expected that the reduced widths will obey the Porter-Thomas⁷ distribution $x^{-\frac{1}{2}} \exp(-x/2)$ or possibly an exponential distribution e^{-x} , where the quantity $x = \gamma^2 / \langle \gamma^2 \rangle_{av}$ is evaluated for a given J and parity and γ^2 and $\langle \gamma^2 \rangle_{av}$ refer to a particular J and parity. In Fig. 5 the number of levels per interval Δx is plotted as a function of x

⁶ A. A. Ross, Phys. Rev. 108, 720 (1957).

⁷ C. E. Porter and R. G. Thomas, Phys. Rev. 104, 483 (1956).

for the present data for all of the levels of Na^{24} up to 630 kev.

The straight line shown in the figure is an exponential plot drawn for $c = 120$, where c is the value of the proportionality constant in the equation $y = c \exp(-x)$ and y is the number of levels per interval Δx .

Figure 6 shows a plot of the same data for a Porter-Thomas distribution. The

present data, then, appear to agree equally well with the exponential and Porter-Thomas distributions. It is important in nuclear theory and to nuclear engineering to know which of the two distributions, the one given by Porter and Thomas⁷ or the simpler exponential one, is more likely to be correct. Theoretical analyses⁷ show that the Porter-Thomas distribution is more reasonable on theoretical grounds and assign to the exponential distribution a small probability of being the correct one. A more accurate evaluation of the parameters of the levels may indicate a preference for one of the distributions.

Fig. 6. Porter-Thomas distribution of the reduced neutron widths of Na^{24} .

5. DISTRIBUTION OF THE LEVEL SPACINGS

The assumption has been made that the spacings between adjacent energy levels of the same spin and parity should obey an exponential distribution,⁵ i.e., the distribution function is

$$N = k_1 \exp(-\mathcal{S}), \quad (4)$$

where $\mathcal{S} = S/D$. The quantity S represents the level spacing and D the average level spacing for a given J and parity. The quantity k_1 is a

constant and N is the number of level spacings per interval $\Delta \mathcal{S}$. Figure 7 shows a plot of the number of level spacings per interval $\Delta \mathcal{S}$ for all of the levels of Na^{24} up to 630 kev. For comparison, the exponential distribution for a value of $k_1 = 100$ is shown by the solid line. This distribution appears to agree with the data.

An alternative distribution proposed by Wigner⁵ is

$$N = \frac{1}{2} \pi k_2 \mathcal{S} \exp(-\frac{1}{4} \pi \mathcal{S}^2)$$

or

$$\ln(N \mathcal{S}^{-1}) = -\frac{1}{4} \pi \mathcal{S}^2 + \ln(\frac{1}{2} \pi k_2) \quad (5)$$

This surmise was given on the basis that, for small values of S for zero-spin nuclei, the probability of finding a level in an interval dS is proportional to $(S dS/D)$. If this relation is also valid for large values of S , the Wigner surmise should agree with the experimental distribution of level

spacings. However, a plot of $\ln(N \mathcal{S}^{-1})$ vs $\mathcal{S}^2$ for the present data yields a curve instead of a straight line and therefore does not agree with the data.

6. STRENGTH FUNCTIONS

The strength function is given by the expression $\langle \gamma^2 \rangle_{av} / D$, the ratio⁵ of the average reduced neutron width to the average level spacing, where the reduced neutron width $\gamma^2 = \Gamma_n / (2 P_\ell)$ and the level spacing are averaged for a given value of ℓ . For the

Fig. 7. Distribution of the level spacings of Na^{24} .

s-wave levels in the present data, the strength function averaged over both values of J is 0.045; and averaged over all values of J for the p-wave levels it is 0.37, which is approximately eight times as large as for the s-wave levels. These results agree with the model of Feshbach, Porter, and Weisskopf⁸ who predict a p-wave maximum near $A = 25$ and a low value for s-wave levels for a nuclear well depth of 40 Mev. Moreover, the sum rule of Lane, Thomas, and Wigner⁹ suggests that the sum of the reduced widths of a given group of levels in an energy interval comparable with the spacings of giant resonances for a given value of l should not exceed $\hbar^2 / (\mu R^2)$. For the p-wave levels in the present measurements, this sum is 0.38 of the Wigner limit and further indicates that this interval of energy is near the maximum for the strength function for $l = 1$. Further, it should be noted that the strength function for the levels assigned to d-wave neutron interactions in the present measurements is 0.47 and that the sum of the reduced neutron widths far exceeds the Wigner limit. This value of the strength function is, then, about ten times the value for s-wave levels, although the two values might be expected to be of the same order of magnitude since the levels are of even parity. It was also found that the strength function for the f-wave levels is about 15, which is many times as large as the value for the p-wave levels. The strength function for the f-wave levels might be expected to show a peak near the peak of the p-wave levels but it should not be expected to exceed it by so large a factor. The large values for the d- and f-wave strength functions undoubtedly are attributable to one or more of the following factors: (a) the assignment of too many levels to values of $l = 2$ and 3, (b) a possible error in the expression for the penetrability factors P_2 and P_3 , or (c) a strong dependence of the reduced neutron width on l . The levels in this region are certainly expected to be composed of a number

⁸ H. Feshbach, C. E. Porter, and V. F. Weisskopf, Phys. Rev. 96, 448 (1954).

⁹ A. M. Lane, R. G. Thomas, and E. P. Wigner, Phys. Rev. 98, 693 (1955).

of d- and f-wave levels so a very large error in the assignments would be necessary to account for the large values of the strength functions.

7. DISTRIBUTION OF THE EXCITED NUCLEAR LEVELS

Figure 3 shows a plot of the virtual nuclear levels of Na^{24} with energies $\leq E_n$ as a function of the neutron energy E_n , but it is not known whether or not this curve would join on smoothly with a similar plot of the bound levels. Presumably, all of the bound levels have not been resolved and a discontinuity would be expected in the curve if the distribution shown in Fig. 3 included the bound levels. Then, in order to relate the number of virtual levels to the number of bound levels, one needs an expression for the total number of levels up to a given excitation energy U . The total number of levels in the energy interval from U_1 to U_2 is given by the expression

$$N(U) = \int \rho(U) dU, \quad (6)$$

where $\rho(U)$ is the density of all levels in the energy interval. The theoretical number of levels, then, depends on the form of $\rho(U)$. It is well known that $\rho(U)$ has an essentially exponential behavior and a number of expressions have been given for it. Here, the expression given by Bloch, Eq. (2) of the present paper, will be used. The integral, Eq. (6), then reduces to the form

$$N(U) = 2C \left[\ln x + ax + \frac{a^2 x^2}{2 \cdot 2!} + \frac{a^3 x^3}{3 \cdot 3!} + \dots \right], \quad (7)$$

where $x = U^{\frac{1}{2}}$, $C = [\sigma(96\pi)^{\frac{1}{2}}]^{-1}$, and $a = \pi(\frac{2}{3}\delta)^{\frac{1}{2}}$. The number of levels up to the excitation energy U , then, depends on the constant σ , which is proportional to the nuclear temperature (assumed to be constant for each nucleus), and on δ , the average level spacing of the individual nucleons in the nucleus.

Because of the first term in Eq. (7), the summation over the levels cannot begin with the ground level, whose excitation energy is $U = 0$, but instead must begin with some excited level. It was found that for a value of $\delta = 0.50$ Mev and a value of U as low as 0.10 kev, the value of N from Eq. (7) is a small negative number. By making this small correction for the lower limit, Eq. (7) should then reflect the distribution of all of the nuclear levels above the ground level for the proper values of δ and σ . If all of the bound levels of a nucleus were known up to say 5 Mev, a family of curves obtained from Eq. (7) would indicate the proper values of σ and δ for each nucleus. Apparently, the number of levels that have been resolved for any one nucleus is insufficient for an evaluation of σ and δ , but approximate values of these two constants for Na^{24} and Al^{28} have been determined from the distribution of the angular momenta.

Only about 20 of the bound levels¹⁰ of Na^{24} appear to have been resolved and this is really too few to be of much use for this purpose. However, approximately 100 bound levels¹⁰ are known for Al^{28} . This is the largest number of bound levels known for any odd-odd nucleus in this region and is therefore the most suitable nucleus for a check of Eq. (7). Figure 8 shows the number of bound levels of Al^{28} plotted against U , which is expressed in the center-of-mass system. A plot of Eq. (7) for values of δ of 0.50 or 0.60 Mev

Fig. 8. Distribution of the nuclear energy levels of Al^{28} . Curve A was obtained from Eq. (7) (times a factor of 1.8) for a value of $\delta = 0.50$ Mev and curve B for $\delta = 0.60$ Mev. The arrow indicates the binding energy.

¹⁰

P. M. Endt and C. M. Braams, Revs. Modern Phys. 29, 683 (1957).

Fig. 9. Distribution of the nuclear energy levels of Na^{24} . Curve A was obtained from Eq. (7) (times a factor of 1.8) for a value of $\delta = 0.50$ Mev and curve B for $\delta = 0.60$ Mev. The arrow indicates the binding energy, 6.956 Mev.

falls below the plot of the bound levels of Al^{28} and plots for smaller values of δ show steeper curves. It was found that a reasonable fit to the data, up to about 4 Mev, for $\delta = 0.50$ Mev occurs if Eq. (7) is multiplied by the constant 1.8. This plot is shown by curve A in Fig. 8. A similar plot is shown by curve B for $\delta = 0.60$ Mev. If curve A represents the correct distribution, it is evident that many of the bound levels above 4 Mev are still unresolved. Erickson¹¹ has shown that the number of levels up to an excitation energy U is the

product of the nuclear temperature τ and the density of levels, $N(U) = \tau \rho(U)$. By use of this relation, the point shown by a solid circle in Fig. 8 was obtained from the neutron resonances.⁵ This, then, suggests that the distribution of the nuclear levels is given by some such curve as A in Fig. 8. Figure 9 shows a similar plot of the 20 nuclear levels of Na^{24} . The trend of the levels up to about 2.5 Mev indicates that a value of 0.50 Mev for δ may also be about right for Na^{24} . The value of $N(U)$ calculated from Erickson's expression¹¹ from the level density of the neutron resonances and the nuclear temperature is shown by the solid circle in Fig. 9 and seems to further indicate that the value of δ is about 0.50 Mev. This value of $N(U)$ is somewhat above curve A, but it is believed that the value of the nuclear temperature used is too large.

¹¹ T. Erickson, Nuclear Phys. 11, 481 (1959).

Presumably, it may be too stringent a requirement to expect a plot (such as Figs. 8 and 9) of the first few nuclear levels of a nucleus to obey Eq. (7). However, plots have been made for the known levels of many nuclei and they all show that curves similar to the ones shown in Figs. 8 and 9 are followed surprisingly well. Families of curves were also plotted for a few values of δ . From these plots and the curves for various values of δ (not shown) a number of other trends were observed: (a) The larger values of δ are associated with nuclei that have small nuclear level densities. (b) The value of δ appears to be large for light nuclei (there being fewer levels for these nuclei) and decreases as one goes to heavier nuclei but shows peaks in the neighborhood of magic numbers and then decreases sharply again above these numbers. The value of δ appears to be the largest for even-even nuclei. (c) The distribution of the levels of the even-even nuclei may be given by Eq. (7) for a suitable choice of δ and of σ without multiplying the equation by a constant factor. If a multiplicative constant is needed, it is probably less than unity. (d) The distribution of the levels of the odd-even and even-odd nuclei apparently can be given by Eq. (7) if σ and δ are suitably chosen. (e) For the odd-odd levels, apparently Eq. (7) must be multiplied by a constant of the order of the value of σ . A more detailed study on the basis of the presently known levels is expected to confirm these trends. The larger values of δ for the lighter nuclei seem to agree with the trend for the theoretical values.⁶ The influence of the shell structure on the level density of a highly excited nucleus has been studied theoretically by Rosenzweig.¹² This study indicates trends similar to the ones stated above, particularly the trend noted in (b).

¹² N. Rosenzweig, Phys. Rev. 108, 817 (1957).

I-144-10

Investigation of Scintillators

(5230)

L. J. Basile, W. L. Buck, E. A. Mroz, and A. Weinreb

A. AUTOMATIC FILLING SYSTEM FOR A LIQUID-NITROGEN COLD TRAP

E. A. Mroz

An automatically-operated system for filling the cold trap of a vacuum line has been designed and constructed for use with the pulsed electron accelerator. Similar systems described in the literature¹ or used elsewhere at the Laboratory² either required materials not readily available or were not easily adaptable to our requirements.

The construction and capacity of the cold trap on the accelerator are such that a complete filling suffices for a period of 30 to 36 hr. A time switch can be used to turn on a filling device every 24 hr, but some means must also be provided to turn it off when the trap has become full.

The first system which was built used a crystal diode as the level-detecting element, utilizing the change in conductance of the diode with temperature. This system was unsatisfactory owing to the fact that the change in conductance at the temperature of liquid nitrogen was not sufficiently sharp. Cold vapors issuing from the trap during filling often would cool the diode sufficiently to stop the filling before completion. Attempts to correct this by adjustment of the sensitivity resulted only in unreliable operation.

The change in resistance of a typical carbon resistor on immersing it in liquid nitrogen differs from that in the crystal diode in two important respects; a significant change does not occur until some part of the resistor actually contacts the liquid, and the resulting change in resistance is small compared to that occurring in the diode. Typically the resistance at the temperature of liquid nitrogen is only about 1.6 times the resistance at room

¹

L. D. Miller and P. N. Petersen, Vacuum 9, 231-232 (1959).

²

B. G. Oltman, (private communication; M. A. Otavka, (private communication))

temperature.

A system which employs a transistor to amplify the result of this small change in resistance was built and has performed very reliably thus far.

Operation

A schematic diagram of the entire electrical system is shown in Fig. 10. The sole function of the time switch is to initiate the filling process. Although the usual commercial timer cannot be adjusted to remain "on" for a period less than about 15 min, the circuit is so designed that the timer does not affect the length of the filling time. The normally-closed 3-sec time-delay relay RL1 serves to prevent more than one filling of the trap during each "on" period of the timer.

To understand the operation of the system, consider first only the action taking place within the first 3 sec of each such "on" period. When the DPST timer switch closes, relay RL2 is energized through the normally-closed contacts of RL1. One set of contacts of RL2 energizes the solenoid valve which allows tank nitrogen to pressurize the liquid-gas container, thereby forcing liquid nitrogen through interconnecting tubing into the cold trap. The other set of contacts on RL2 activates the sensing circuit by applying 117 v ac to the transformer. The output of the transformer is rectified, filtered, and regulated at 15 v.

Fig. 10. The control circuit for the system to fill the cold trap automatically. The time switch and relay arrangement initiate the filling operation at a predetermined time. When a carbon resistor R4 senses a "full" condition of the trap, the filling operation is terminated. RL1 - Amperite 115C3T time-delay relay. RL2 - P. & B. MR11A relay. RL3 - Clare HGS 1003 or HGS 1048 relay, 4k coil. Solenoid valve - Skinner 16 660.

With the circuit values shown, and with the sensing resistor R4 at room temperature, the collector current of the transistor TR will be between 0.25 and 3.0 ma, depending on the setting of the "sensitivity" control R3. The pull-in current of RL3 is 1.6 - 1.8 ma. Hence R3 should be adjusted to make $I_C \approx 2$ ma. Relay RL3 is now energized, and closes the "latching" contacts.

Three seconds after the time switch closes, the time-delay relay RL1 activates and opens the contacts which originally allowed RL2 to be energized. However, RL2 is "latched" by the contacts of RL3, and the system continues to fill the trap.

The sensing resistor R4 is located inside and near the bottom of a plastic funnel which is in the filling opening of the cold trap. After the trap is completely filled, the level of liquid nitrogen will rise up into the funnel and immerse R4. About 1 sec after immersion, the resistance of R4 increases abruptly, reducing I_B of the transistor so that I_C falls to about 0.5 ma. Since the drop-out current of RL3 is about 1.2 ma, this relay de-energizes and the latching contacts open. Relay RL2 now opens, deactivating the gas-pressure solenoid and the sensing circuit.

This entire filling operation has taken about one minute and, since the "on" time of the timer is 15 min, the timer switch is still closed. However, the relay RL1 is holding its contact open and will continue to do so until the timer switch opens and allows the thermal unit of the relay to cool. At that time the circuit will be rearmed and ready for the next filling operation called for by the setting of the timer.

Resistor R3 serves to limit I_B in case the sensor leads are accidentally shorted together. Diode D3 short circuits the inductive high-voltage surge of the relay coil, which might otherwise damage the transistor.

If desired, the circuit may be rearranged so that RL3 is

unenergized when the sensing resistor is at room temperature and energized when the resistor is cooled. Such an arrangement is shown in Fig. 11.

Conservation of Liquid Nitrogen

Because of the limited space near the pulsed electron accelerator, the largest allowable size of the liquid-nitrogen container was considered to

be 15 l. Originally the liquid nitrogen was forced out of the reservoir through a length of copper tubing extending from the bottom of the reservoir up through the top. Owing to evaporation of liquid nitrogen as a result of heat conducted along this tubing, the 15-l capacity was barely sufficient for a 54-hr period (during which the trap was filled twice). After the copper tubing was replaced by one of plastic-bonded fiber, more than 5 l of liquid remained in the reservoir after such a 54-hr period. A separate test showed that evaporative loss of the coolant was reduced by a factor of at least 3 through use of the fiber tubing.

Fig. 11. An alternate sensing circuit in which the relay RL3 remains unenergized until the sensing resistor is cooled.

B. FLUORESCENCE SPECTRUM OF A COMMERCIAL PLASTIC SCINTILLATOR

W. L. Buck

The spectral distribution of the light emitted during a scintillation is an important consideration in the choice of suitable detectors, reflectors, and transparent media for use in conjunction with any particular scintillator. Knowledge of this spectrum may also be helpful in any attempt to understand the details of the scintillation process.

In view of the relatively feeble intensities of scintillation light which can be obtained by continuous irradiation of a scintillator with radioactive sources of convenient strengths, it is often more convenient to determine the spectrum of fluorescence excited by ultraviolet radiation. In the case of a solution-type scintillator, such a fluorescence spectrum should be a valid representation of the spectrum of scintillation light, providing that the exciting wavelength is such as to be absorbed predominantly by molecules of the solvent^{1,2} and that allowance is made for effects of reabsorption of emitted light within the scintillator.

As a result of a unique combination of desirable properties, plastic scintillators have proved to be useful in many applications of scintillation counting. One of the most widely used commercially-available scintillators of this type is known by the trade name Plastic Scintillator B.³ This product is understood to consist of a solid solution of p-terphenyl (TP) and diphenylstilbene⁴ (DPS) in polyvinyltoluene (PVT).

The fluorescence spectrum of a plastic scintillator of similar composition has been determined by Basile,² who found no evidence of emission in the region from 320 to 380 mμ such as is indicated in the advertised fluorescence spectrum of Plastic Scintillator B.⁵ The spectrum reported by Basile was observed by transmission through a $\frac{1}{2}$ -inch thickness of the sample, but the wavelength used for exciting the fluorescence was not recorded. Information is entirely lacking as to the experimental conditions under which the advertised fluorescence spectrum of the commercial plastic was measured.

¹ H. Kallmann and M. Furst, *Phys. Rev.* **81**, 853 (1951).

² L. J. Basile, *J. Chem. Phys.* **27**, 801 (1957).

³ Manufactured by Pilot Chemicals, Inc., 36 Pleasant St., Watertown 72, Mass.

⁴ Also known as trans-1,2-dibiphenylethylene.

⁵ Bulletin 591 (April 1959), Pilot Chemicals, Inc.

In an effort to clarify this situation, additional measurements of the fluorescence spectrum of Plastic Scintillator B have been under various experimental conditions. The results are shown in Fig. 12. Excitation was by ultraviolet light of selected wavelengths obtained by using a Bausch and Lomb grating monochromator (equipped with a mercury lamp) in conjunction with suitable filters. The spectral distribution of photons in the fluorescence was measured with a Beckman DK-2 spectrophotometer used as a spectroradiometer.⁶ The spectra shown in Fig. 12 have been corrected for the selective spectral sensitivity of the spectroradiometer, as determined with a calibrated tungsten-filament lamp.

Part a of Fig. 12 shows the fluorescence spectrum of Plastic Scintillator B, excited by 254-m μ radiation, as viewed by reflection (i.e., by directly viewing the surface illuminated by the exciting radiation). In

Fig. 12. Spectral distributions of photons in the fluorescence from Plastic Scintillator B (Pilot Chemicals, Inc.). Parts a and b show spectra obtained by directly viewing the surface illuminated by the exciting radiation. In part c the spectrum was viewed through a 4-mm thickness of the scintillator.

⁶ Thanks are due to Dr. I. B. Berlman, Radiological Physics Division, Argonne National Laboratory, for use of the spectrophotometer.

this case the exciting radiation is absorbed predominantly by the solvent. Comparison of this spectrum with unpublished fluorescence spectra of TP and of DPS in other solvents indicates that it is essentially a superposition of the molecular fluorescence spectra of TP and of DPS in PVT. Also, this spectrum is quite similar to that advertised by the manufacturer.⁵

Part b of Fig. 12 shows the fluorescence spectrum obtained with the same arrangement as in part a, except that 365-m μ excitation was used. Since TPB is the only constituent of the scintillator which absorbs strongly at wavelengths ≥ 365 m μ , this spectrum is believed to represent the molecular fluorescence of DPS in PVT. This view is supported by the unpublished study, mentioned above, of the fluorescence of DPS in other solvents.

In part c of Fig. 12 is shown the fluorescence spectrum as viewed by transmission through a 4-mm thickness of the plastic scintillator. In this arrangement essentially identical spectra were obtained with 254-m μ and 365-m μ excitation. This spectrum is believed to represent the fluorescence of DPS as modified by selective reabsorption of the shortest wavelengths observed in the molecular spectrum. Such reabsorption may probably be attributed to a certain amount of overlapping of the absorption and emission spectra of DPS. It appears that when 254-m μ excitation is employed, the shorter wavelength fluorescence (320-380 m μ) from TP molecules is entirely reabsorbed by the DPS in any thickness of the scintillator ≥ 4 mm. This spectrum resembles that obtained by Basile from a plastic scintillator of composition similar to Plastic Scintillator B.²

In a majority of the applications of plastic scintillators, most of the scintillation light is required to traverse a significant thickness of the scintillator before reaching the detector. In such a case, the spectrum of light seen by the detector may be expected to resemble that shown in part c of Fig. 12. Some additional suppression of the shortest wavelengths may be expected when very great thicknesses of the plastic are involved.

C. INFLUENCE OF TEMPERATURE ON THE ENERGY TRANSFER FROM NAPHTHALENE TO ANTHRACENE

A. Weinreb

The influence of temperature on the transfer efficiency in a solution of 20 g/l naphthalene and 0.5 g/l anthracene in paraffin oil has been investigated. When the solution is excited by wavelength 2650 Å, almost all the light is absorbed by naphthalene. The fluorescence emitted by the solution is that of anthracene, which is excited by transfer of energy from naphthalene. Irradiation of the solution by light of wavelength 3340 Å excites the anthracene directly since paraffin oil and naphthalene are practically transparent to this wavelength. From the fluorescent intensities obtained at both excitation wavelengths, the transfer efficiency is computed. The experimental determinations are as follows.

1. The intensity of the solution at both excitation wavelengths was measured as a function of temperature in the range from -5 to 80°C and the transfer efficiency computed. The transfer efficiency increases monotonically with temperature.

2. The viscosity of the solution was measured as a function of temperature. This allows the transfer efficiency to be plotted as a function of the diffusion parameter T/η , where T is the absolute temperature and η is the viscosity.

3. The transfer efficiency was measured as a function of cell thickness. The transfer efficiency does not increase beyond the thickness at which the absorption of the exciting light by naphthalene is complete. This shows that the transfer is nonradiative.

4. This last result is supported by the measurement of the fluorescent intensity of a solution of 20 g/l naphthalene in paraffin oil as a function of temperature. In changing the temperature from -5 to 80° the intensity decreases by a factor of about 1.75.

5. The transfer efficiency of the solution in paraffin oil was compared with that of a solution of 20 g/l naphthalene and 0.5 g/l anthracene in cyclohexane. The efficiency in cyclohexane is considerably higher than in paraffin oil. This result, as well as the increase of transfer efficiency with temperature, shows the diffusion dependence of the transfer process.

Publication of the more detailed results is contemplated.

V. THEORETICAL PHYSICS, GENERAL

V-9-1 Stripping Reactions and the Structure of Light and Intermediate Nuclei (5220)

M. H. Macfarlane and J. B. French*

Reported by M. H. Macfarlane

A reduced width connecting two nuclear levels contains information about the structure of the states involved. Techniques are described in this study whereby such information can be cast into usable form; the formalism so developed is then applied to an analysis of stripping widths.

A reduced width θ^2 is first defined and expressed as a product of two factors, $\mathcal{S}$ and θ_0^2 . The relative reduced width or spectroscopic factor $\mathcal{S}$ depends only on the wave functions of the nuclear states involved and contains the spectroscopic information we seek. The details of the reaction mechanism are embodied in the single-particle reduced width θ_0^2 .

Detailed analysis of the spectroscopic factor $\mathcal{S}$ establishes the theoretical framework for the entire study. Expressions for $\mathcal{S}$ are derived by use of a variety of model wave functions; most of this theoretical analysis involves some form of shell model although the rotational and vibrational collective models are also considered. Hole-particle theorems and sum rules for reduced widths are examined in detail. It should be emphasized that these formal considerations are independent of the means adopted to extract θ^2 and so are equally applicable, for example, in a study of resonant reduced widths.

Reduced widths are then extracted from the results of available stripping and pick-up reactions. Extensive tables are given of these empirical reduced widths. For this purpose the simple Butler formula is used, the

* University of Rochester.

relevant expressions for the differential cross sections being derived in an appendix. The quantity θ_0^2 is treated as an empirical parameter to be evaluated by direct comparison with experiment. In this study, the Butler formula is simply a convenient and appropriate way of reducing stripping data to usable form; deviations from the simple theory, including Coulomb and distortion effects, will find expression as dependences of θ_0^2 on its parameters.

The empirical reduced widths so obtained are next analyzed with the aid of explicit expressions for γ_j^2 derived earlier in the study. Transitions connecting states belonging to the ground-state configurations are discussed in terms of explicit nuclear models. The intermediate-coupling shell model gives a generally satisfactory description of the $l = 1$ reduced widths of low-lying levels in the lp shell, and, perhaps, of $l = 0$ and $l = 2$ reduced widths in nuclei for which $16 < A < 20$. In the middle of the ds-shell ($20 \leq A < 32$), the rotational model is more appropriate. Little is known about the structure and stripping widths of late ds-shell nuclei, with $32 < A < 39$. There is also a lack of data concerning nuclei with $39 \leq A < 70$, but there are indications that the jj-coupling shell model may be quite useful. The empirical reduced widths are used to set an upper limit on the closed-shell contributions to the Si^{28} and S^{32} ground-state wave functions and also to discuss core excitation in Ca^{40} . Transitions to states belonging to higher configurations than the groundstate form a separate topic, centering on the positions and fragmentation of single-particle levels. Such reactions are analyzed in terms of a weak-coupling formalism which relies less on explicit model wave functions and more on the observed level structure.

The various kinds of information about the structure of nuclei which can be obtained from an analysis of stripping widths are then reviewed and what is known about the single-particle reduced widths collected and

summarized. It is found that these empirical single-particle reduced widths behave in a reasonably consistent fashion as functions of their parameters and that, furthermore, their salient qualitative features can be interpreted in terms of a potential-well model of the process of nucleon transfer. The study closes with a discussion of a number of experiments of particular interest for future study.

The paper is to appear in the July 1960 issue of the Reviews of Modern Physics.

V-24-1 Imaginary Part of the Delbrück Scattering Amplitude (5220)

W. Zernik

The present calculations are based on the recent work of Kessler,¹ who was able to express the imaginary part of the scattering amplitude in the form of a five-dimensional integral. The imaginary part of the scattering amplitude arises, within the formalism of "old-fashioned" perturbation theory, from those transitions in which energy is conserved in the intermediate state. It is thus closely related to the cross-section for pair production; in fact, for forward scattering, the relation is trivial, being merely given by the "optical theorem." Kessler's work, therefore, may be regarded as a generalization of the optical theorem to finite scattering angles. The analytical evaluation of Kessler's integral does not appear to be feasible; but a few numerical results were obtained by Kessler by use of the Monte Carlo method.

Within the past three months, the analytical work of Kessler has been verified and some further numerical results have been obtained.

¹ P. Kessler, J. phys. radium 19, 739 (1958).

The method used was that of independent Gaussian quadrature. A program for this purpose was written for the IBM-704.

The scattering amplitudes were computed in units of $(Z\alpha)^2 r_0$, where r_0 is the classical electron radius. These units are the same as those used by Kessler. The amplitudes for gamma-ray polarization parallel and perpendicular to the scattering plane are denoted by $\underline{a}(\text{para})$ and $\underline{a}(\text{perp})$, respectively. In order to facilitate comparison with the approximate theory of Bethe and Rohrlich,² the amplitudes for small momentum transfer were computed for fixed momentum transfer rather than for fixed scattering angles. In this connection, it is convenient to define $\theta_c = mc^2/\hbar\omega$, where m is the mass of the electron and $\hbar\omega$ the gamma-ray energy.

The results of the computation for gamma ray energies of 2.62 and 6.14 Mev are given in Tables V and VI, respectively.

TABLE V. The imaginary part of the Delbrück scattering amplitude in units of $(\alpha Z)^2 r_0$ for gamma-ray energies of 2.62 Mev, as a function of the scattering angle θ .

θ	0	$\frac{1}{2}\theta_c$	θ_c	$\frac{3}{2}\theta_c$	$2\theta_c$	$3\theta_c$	30°	60°	90°	180°
$\underline{a}(\text{para})$	0.265	0.246	0.204	0.160	0.124	0.078	0.089	0.037	0.021	0.010
$\underline{a}(\text{perp})$	0.265	0.235	0.175	0.119	0.078	0.031	0.041	-0.002	-0.009	-0.010

TABLE VI. The imaginary part of the Delbrück scattering amplitude in units of $(\alpha Z)^2 r_0$ for gamma-ray energies of 6.14 Mev, as a function of the scattering angle θ .

θ	0	$\frac{1}{2}\theta_c$	θ_c	$\frac{3}{2}\theta_c$	$2\theta_c$	$3\theta_c$	30°	60°	90°	180°
$\underline{a}(\text{para})$	2.81	2.14	1.43	1.02	0.77	0.47	0.17	0.05	0.03	0.01
$\underline{a}(\text{perp})$	2.87	1.76	0.92	0.49	0.21	0.14	0.10	-0.02	-0.02	-0.01

²

H. A. Bethe and F. Rohrlich, Phys. Rev. 86, 10 (1952).

These results are believed to be correct to one or two percent. The results for 2.62 Mev at $\theta = 0$ agree with the previous calculations of Rohrlich and Gluckstern.³ The amplitudes for parallel and perpendicular polarization are equal in absolute magnitude, within the limits of computational error, at $\theta = 0$ and $\theta = \pi$ as is required on the basis of elementary symmetry considerations. The results at 2.62 Mev agree reasonably well with the less accurate calculations of Kessler¹ with the exception of $\underline{a}(\text{perp})$ at 60° . It should be noted that the angle θ used by Kessler is half the scattering angle while θ in the present discussion is the full scattering angle.

The approximate treatment of Bethe and Rohrlich² leads to a formula for the imaginary part of the scattering amplitude which may be written

$$a(\theta, \omega) = 0.2476 \frac{\hbar\omega}{mc^2} F_2(x) (Z\alpha)^2 r_0 ,$$

where

$$x = \theta \left(\frac{\hbar\omega}{mc^2} \right) .$$

This formula is expected to apply when $\hbar\omega \gg mc^2$ and

$$\left(\frac{mc^2}{\hbar\omega} \right)^2 < \theta < \frac{mc^2}{\hbar\omega} .$$

The quantity $F_2(x)$ has been computed and is tabulated in Table VII.

TABLE VII. The Bethe-Rohrlich function $F_2(x)$.

x	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.5	2.0
$F_2(x)$	2.920	2.227	1.826	1.542	1.325	1.149	1.003	0.8786	0.7712	0.6772	0.3447	0.1675

³ F. Rohrlich and R. L. Gluckstern, Phys. Rev. 86, 1 (1952).

Comparison of the exact results with the approximate theory of Bethe and Rohrlich² shows that the latter predicts results that are too large by a factor of about 8 at 2.62 Mev and by a factor of about 2 at 6.14 Mev.

The amplitudes given in Tables V and VI must be combined with the amplitudes for the other coherent processes mentioned above before the cross section may be calculated. However, in order to give a feeling for the relative magnitude of the Delbrück effect it is pointed out that, for the scattering of 6.14-Mev gamma rays from lead at a scattering angle of 30°, the "absorptive part of the differential cross section for Delbrück scattering," defined by

$$\frac{d\sigma}{d\Omega} = \frac{1}{2} [a^2(\text{para}) + a^2(\text{perp})] (aZ)^4 r_0^2 ,$$

is approximately equal to 0.29 mb/sterad, which is comparable to the experimental value.⁴

The presently available computer program is not too suitable for calculations for higher gamma-ray energies, since the number of points at which the integrand must be evaluated in order to get a reasonably accurate result becomes rather large and the amount of computing time required becomes excessive.

The reason for this may be qualitatively understood as follows. The five-dimensional integration is over the variables describing the intermediate state, i.e., the polar and azimuthal angles of the momentum vectors of the electron and positron and the energy of one of these particles. At high energies the integrand function becomes sharply "peaked" within small subspaces of the five-dimensional space, so it is necessary to use a finer grid in the numerical quadrature. Some of this peaking arises from the emission of the

⁴ S. G. Cohen, Nuovo cimento 14, 931 (1959).

pair into very small forward angles⁵; but this was dealt with by suitably dividing up the region of integration. The really troublesome peaks were apparently associated with the strong angular correlation of electrons with positrons at high energies. No simple way of dealing with this could be found.

It is felt that further progress along these lines might be made by employing more sophisticated methods of numerical quadrature.⁶ If the imaginary part of the scattering amplitude could be computed at high energies also, it would probably be possible to compute the real part with the aid of the dispersion relations for fixed momentum transfer.⁷

A paper on this subject is being prepared for publication.

⁵ W. Heitler, Quantum Theory of Radiation (Oxford University Press, 1954). Chapter 5.

⁶ J.C.P. Miller, Math. of Computation 14, 130 (1960).

⁷ A. Claesson, Kung. Fys. Säll. I. Lund. Forh. 27, 1 (1957).

V-45-15

Meson-Nucleon Interaction

(5210)

K. Tanaka

In a preprint entitled "Magnetic Moments of the Λ and Σ Hyperons," a relation among the magnetic moments of Σ_+ , Σ_0 , Σ_- and Λ hyperons is obtained as a consequence of the proposed symmetries of strong interactions, a minimal electromagnetic coupling for the electromagnetic interactions being assumed. The magnetic moments of the Λ and Σ hyperons are calculated with the aid of mass spectral representations in which only the contributions of the bound states are taken into account. The present calculation of these magnetic moments are compared with the results obtained from standard perturbation theory and with those of the cutoff theory. The theoretical value of μ_Λ is very small compared to that of the nucleon, if one assumes pseudoscalar K couplings.

PUBLICATIONS SINCE THE LAST REPORT

PAPERS

TECHNIQUES OF SLOW NEUTRON SPECTROSCOPY

- L. M. Bollinger.....(Project I-1)
Nuclear Spectroscopy, Part A, edited by Fay Ajzenberg-Selove
 (Academic Press, New York, 1960), Sec. III. B, pp. 342-357.

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- L. M. Bollinger.....(Project I-3)
Nuclear Spectroscopy, Part A, edited by Fay Ajzenberg-Selove
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- S. S. Hanna, J. Heberle, G. J. Perlow, R. S. Preston, and D. H.
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 Phys. Rev. 117, 1403-1406 (March 1, 1960)

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H. Toffer and R. L. Amrein.....(Project I-18)
 Rev. Sci. Instr. 31, 348-349 (March 1960)

 (α, t) REACTIONS NEAR $Z = 28$

J. L. Yntema.....(Project I-22)
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Leonard S. Goodman.....(Project I-80)
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John Swedlund.....(Project I-11)
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DETERMINATION OF ANGULAR MOMENTUM QUANTUM NUMBERS OF
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Robert A. Sporman.....(Project I-18)
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THE ORIGIN OF SCINTILLATIONS IN ORGANIC MATERIALS

Warren L. Buck.....(Project I-144)
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DECAY OF ${}_{66}^{\text{Dy}}{}^{166}$

R.G. Helmer and S. B. Burson.....(Project I-31)
Phys. Rev.

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Nuclear Spectroscopy, Part B, edited by Fay Ajzenberg-
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CROSS SECTION FOR FORMATION OF DOUBLY-IONIZED HELIUM BY
ELECTRON IMPACT

H. E. Stanton and J. E. Monahan.....(Project II-36)
Phys. Rev.

PERSONNEL CHANGES IN THE ANL PHYSICS DIVISION

NEW MEMBERS IN THE DIVISION

Resident Student Associate

Mr. Fumio Hirayama, graduate student, University of Michigan. Working with L. J. Basile on the mechanisms of energy transfer and of quenching in plastic scintillators. Came to Argonne on April 11, 1960.

Technicians

Mr. John G. McShane. Joined the Van de Graaff group on May 10, 1960.

Mr. Eugene Schultz. Joined the Van de Graaff group on May 11, 1960.

Secretary

Mrs. Christabel Fors. Joined the Physics Division as secretary in the theoretical wing on April 14, 1960.

DEPARTURES

Dr. David J. Meschi joined the Physics Division as a resident research associate on February 17, 1959. He has collaborated with W. A. Chupka and Joseph Berkowitz on mass spectroscopic studies of chemical equilibria at high temperatures (Project II-29). He terminated at ANL on April 15, 1960 to return to the University of California, Berkeley.