with the momentum distributions[9]:

$$q_p=0.64\ \mathrm{f}^{-1},\quad u=0.43,\quad K_p=0.53,$$
$$q_s=0.59\ \mathrm{f}^{-1},\quad v=0.33,\quad K_s=0.12,\quad K_s'=0.0027.$$

In Fig. 1 the calculated momentum distributions are compared with the momentum distributions deduced from experiment.[1] Taking into account that this is not a fit since fixed values are used for α_j, $\bar{\alpha}_j$, and β_j, the agreement seems to be satisfactory.

[9] The final expressions for the two form factors are $g_p(q)=0.54-0.043q^2/q_p^2+(0.46-0.9q^2/q_p^2+0.043q^4/q_p^4)F(1,\frac{3}{2};-\frac{1}{2}q^2/q_p^2)$, and $g_s(q)=(1-0.017q^2/q_s^2)\exp(-\frac{1}{2}q^2/q_s^2)$.

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Decay of Pm^{148}, Pm^{148m}, and Eu^{148}†

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The beta decay of Pm^{148} and Pm^{148m} (5.0 days and 45.5 days) and the electron capture of Eu^{148} (58 days) proceed to levels in Sm^{148}. These activities have been investigated with scintillation and magnetic spectrometers, and coincidence and directional correlation techniques. Pm^{148} (5 day) decays via three beta branches to levels at 1460 kev, 551 kev, and the ground state, with the available energy being 2460±20 kev. The decay of Pm^{148} (45.5 day) and Eu^{148} each populate levels of 551, 1181, 1596, 1908, and 2098 kev in Sm^{148}. The long-lived Pm populates additional levels at 2027 and 2197 kev, and Eu^{148} populates levels at 1886, 2148, 2201, 2697(?), and 2780 kev. The experimental data are consistent with the 45-day state being approximately 140 kev above the 5-day state. Decay schemes consistent with the experimental data are presented.

I. INTRODUCTION

Early investigators[1] established a 5.3-day activity associated with Pm^{148}. Long and Pool[2] also established a 48-day activity associated with Pm^{148}. They found beta particles of 1.7±0.1 and 0.6±0.1 Mev endpoints and a 0.54-Mev gamma ray. Folger, Stevenson, and Seaborg[3] found an activity in the products of the high-energy fission of uranium which had beta spectra with endpoints of approximately 2.3 and 0.5 Mev and a gamma ray of ~1 Mev associated with it.

Recently Bhattacherjee *et al.*[4] and Eldridge and Lyon[5] have investigated Pm^{148}. Bhattacherjee[4] found that the 4.2-day activity had γ rays of 560, 900, and 1460 kev associated with it, while the 46-day activity had γ rays of 105, 195, 295, 400, 560, 630, 720, 930, 1015, and 1200 kev. Eldridge and Lyon[5] further found that the 1200-kev photopeak could be almost fully accounted for by the "sum" of the 550- and 630-kev transitions. Both groups proposed decay schemes for Pm^{148} based on beta-gamma and gamma-gamma coincidences.

No decay scheme has been available for the electron capture of Eu^{148} to Sm^{148}. Mack and Pool[6] have bombarded enriched samarium isotopes with protons and found that Eu^{148} decayed with a 54-day half-life and had a 0.58-Mev gamma ray associated with it. Hoff, Rasmussen, and Thompson[7] reported that there was no evidence for positrons.

We have investigated the activities of Pm^{148} and Eu^{148} as part of a program to obtain as much information as possible on the nuclei in the so-called "transition" region ($A=143$ to 150) between spherical and strongly deformed nuclei.

II. EXPERIMENTAL PROCEDURE

The sources were obtained by bombarding enriched isotopes of Nd^{148} (81.7%) and Sm^{148} (83.1%) with protons in the 86-in. cyclotron at the Oak Ridge National

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‡ Now at the Physikalisches Institut der Universitat Basel, Basel, Switzerland.
[1] J. D. Kurbatov and M. L. Pool, Phys. Rev. **63**, 463 (1943).
[2] J. K. Long and M. L. Pool, Phys. Rev. **85**, 137 (1952).
[3] R. L. Folger, P. C. Stevenson, and G. T. Seaborg, University of California Radiation Laboratory Report UCRL-1195 (revised), May, 1951 (unpublished).
[4] S. K. Bhattacherjee, B. Sahai, and C. V. K. Baba, Nuclear Phys. **12**, 356 (1959).
[5] J. S. Eldridge and W. S. Lyon, Nuclear Phys. **23**, 131 (1961).
[6] R. C. Mack and M. L. Pool, Phys. Rev. **91**, 497(A) (1953).
[7] R. W. Hoff, J. O. Rasmussen, and S. G. Thompson, Phys. Rev. **83**, 1068 (1951).

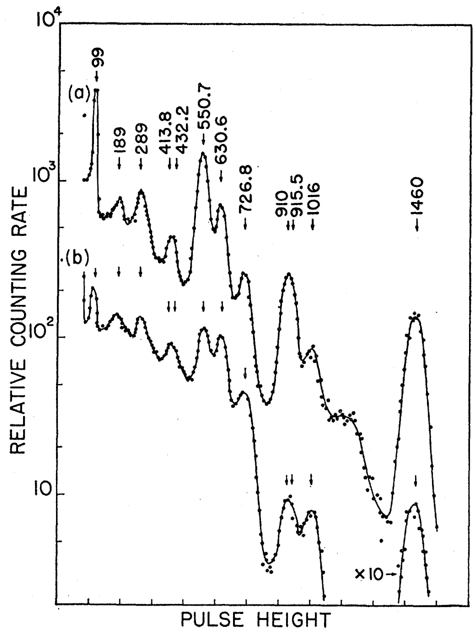

FIG. 1. Gamma-ray spectra of Pm^{148}. Curve (a) shows the 5-day and 45.5-day activities and curve (b) shows the 45.5-day activity.

Laboratory. Internal-conversion electron data were obtained from 180° permanent-magnet spectrographs and from an intermediate-image spectrometer of the Slätis-Siegbahn type. Beta spectra were taken with the intermediate-image spectrometer. The sources for the spectrographs were electroplated on 10-mil Pt wires and the data recorded on Eastman no-screen x-ray film. The intensities were obtained through a photometric analysis of the films.

A more accurate determination of the relative intensities of the conversion electrons was made with the intermediate-image spectrometer. The spectrometer sources were evaporated from an HCl solution onto a 1-mg/cm² Mylar film with an Al backing. The sources were ~3 mm in diameter and ~1 mg/cm² thick (momentum resolution ~3%).

The gamma-ray intensities were obtained from analysis of a gamma-ray spectrum taken with an integrally packaged 3×3 in. crystal and a 256-channel analyzer (resolution at 662 kev ~8%). The efficiency and peak-to-total corrections were obtained from the curves of Heath.[8]

Gamma-gamma coincidences were obtained by gating with a $1\frac{1}{2}$ in.×1 in. NaI crystal and displaying the coincident spectra on a $1\frac{1}{2}$ in.×2 in. crystal. The coincidence measurements were taken in a 90° geometry at a source distance of 4 cm from each crystal. A 10-g/cm² Pb absorber was placed between the crystals to minimize crystal-to-crystal Compton scattering.

Beta-gamma coincidences were obtained by displaying the beta spectra in coincidence with gamma-ray photopeaks. The beta detector was a $\frac{1}{4}$-in. thick Pilot B crystal approximately 2 cm in diameter (resolution of 624-kev K-conversion electron line ~14%). The source consisted of an oxide powder slurried onto a 2-mg/cm² Al backing. It was 5 mm in diameter and a few mg/cm² thick. The source was 1 cm from the beta counter and 2 cm from the gamma counter in 180° geometry. The resolving time of the conventional fast-slow coincidence circuit was 0.2 μsec.

The gamma-gamma directional correlation measurements were made with two 2×2-in. NaI crystals mounted on RCA 6342-A photomultipliers. The resolving time, 2τ, of the coincidence circuit was 18 nsec. The counters were shielded frontally with $\frac{1}{8}$-in. Al and laterally with 10-g/cm² Pb. The counters were 7 cm from the source which was in a solution of HCl in a lucite holder 1.2 cm high and 2 mm in diameter. The data were least-squares fitted using the method of Rose[9] and the geometrical finite solid-angle corrections were applied from the curves of Arns, Sund, and Wiedenbeck.[10]

III. EXPERIMENTAL RESULTS

a. Decay of Pm^{148}

Pm^{148} decays to levels in Sm^{148} with two activities, 5.0±0.5 days and 45.5±0.5 days, as measured with a Geiger-Muller counter. The data were taken both with and without a 0.08-g/cm² Cu absorber. Pm^{147} and Pm^{144} were impurities in the source.

Gamma-ray spectra of Pm^{148} are shown in Fig. 1. Curve (a) was taken 24 hr after proton irradiation and shows a predominance of the 5-day activity. There are

TABLE I. Relative gamma-ray intensities in the Pm^{148} decay.

Transition energy (kev)	Photon intensity	Multipolarity assignment[a]
5-day activity		
550.7	2500	$E2$
910	1980	$M1+E2$(~20%)
1460	3040	$E2$
45.5-day activity		
99.5	3940	
189	1660	
288.4	6050	$E2$[b]
413.8	~6000	
432.2	~6000	
550.7	43 200	$E2$
630.6	43 000	$E2$
726.8	16 000	$E2$
910	1450	
916.5	9000	
1016.0	10 000	
1460	2100	

[a] Multipolarities determined from directional correlation data.
[b] Based on I.C.C. of 0.042±0.006 as obtained from a comparison of γ-ray and K-conversion electron intensities of 289- and 631-kev transitions.

[8] R. L. Heath, Atomic Energy Commission Research and Development Report IDO-1640B (unpublished).

[9] M. E. Rose, Phys. Rev. **91**, 610 (1953).

[10] R. G. Arns, R. E. Sund, and M. L. Wiedenbeck (privately circulated report).

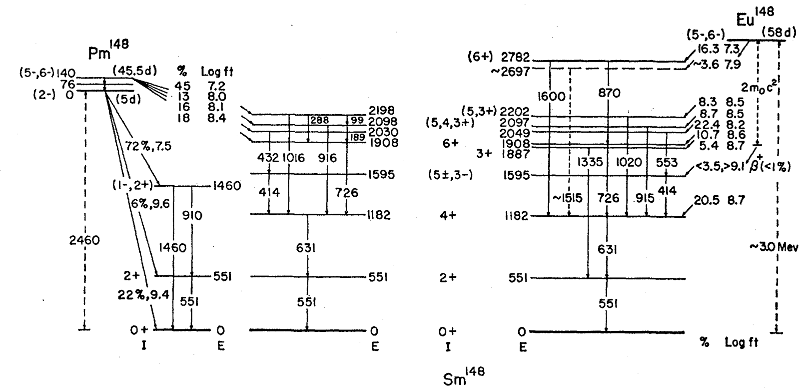

FIG. 2. Decay schemes for Pm^{148} and Eu^{148} to Sm^{148}. The two transitions in Pm^{148} are placed in cascade only on the basis of energy differences. The level shown at 2049 kev should be at 2149 kev. The level energies shown on the scheme are approximate and are slightly different than those quoted in the text. The 1016-kev transition in the Pm^{148} decay may proceed from the level at 2202 kev rather than the one at 2198 kev as discussed in the text.

three transitions associated with the 5-day activity (551, 910, and 1460 kev). Energies up to 800 kev are based on permanent magnet spectrograph measurements; the remainder of the energies were determined from γ-ray scintillation spectra.

Curve (b) shows the gamma-ray spectrum after the source had reached equilibrium. The 1460-kev transition showed a composite half-life. The beta branch from the Pm^{148} ground state to the Sm^{148} ground state had an endpoint of 2460 kev and the beta spectrum in coincidence with the 1016-kev gamma ray originating at a level at 2198 kev had an endpoint of $\sim$400 kev. This indicates that the isomeric level is $\sim$2595 kev above the Sm^{148} ground state or $\sim$135 kev above the Pm^{148} ground state. The intensity of the 1460-kev transition (fed by 5-day activity) relative to the 630-kev transition (fed by the 45-day activity) at equilibrium indicated an 8% branching to the Pm^{148} ground state through the isomeric level. Two low-energy transitions (62 and 76 kev)[11] which are internally converted in Pm were observed on the permanent magnet spectrograph films. The energies of the two transitions in cascade correspond to the energy difference in the Pm^{148} isomeric levels as determined by the beta-decay energies.

The relative photon intensities are given in Table I. The gamma-ray intensities associated with the 45.5 day activity were obtained after equilibrium had been reached. The gamma-ray intensities for the 5-day activity were obtained by subtracting out the longer-lived spectrum. A proposed level scheme for Sm^{148} consistent with relative photon intensities and coincidence measurements is shown in Fig. 2. Both the decay of Pm^{148} and Eu^{148} are shown in the figure for comparison purposes. The Eu^{148} decay will be discussed in Sec. III d.

b. Pm^{148} (5 day)

Our results for the level scheme for the 5-day activity are in agreement with the work of Bhattacherjee.[4] Analysis of the beta spectra taken with the spectrometer and the beta spectra in coincidence with the 551-kev gamma ray indicate three beta branches of 1020 kev (72%), 1900 kev (6%), and 2460 kev (22%) endpoints. Bhattacherjee reported a possible nonlinear Fermi plot for the high-energy branch as obtained with an anthracene crystal. The Fermi plot of the Pm^{148} beta spectrum taken with the intermediate-image spectrometer is shown in Fig. 3. The highest energy beta component (2460-kev endpoint) shows a definite deviation from a straight line. A unique first-forbidden shape factor was applied to the 2460-kev beta branch and the results are shown in Fig. 3. The reliability of the spectrometer to measure unique first-forbidden shape factors was checked with the beta spectrum of Y^{91}.

Evidence for the presence of a 1900-kev beta branch was indicated by the relative intensities of the 551- and 910-kev transitions and confirmed in a beta-gamma coincidence measurement made by gating on the 551-kev transition. Therefore the corrected high-energy Fermi plot was least-squares fitted from 2460 kev to 1900 kev. The 1900-kev beta component was then observed after subtraction of the high-energy component. The intensity of the 1900-kev beta branch with respect to the 2460-kev beta branch is consistent with gamma-ray intensities and beta-gamma coincidence measure-

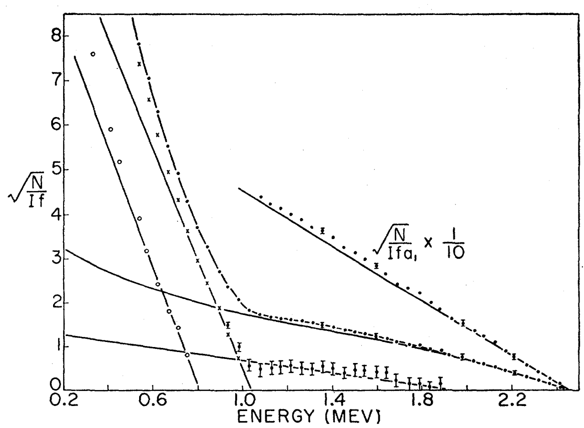

FIG. 3. Fermi plot of the Pm^{148} beta spectrum data as obtained with intermediate image spectrometer. Shown are the uncorrected Fermi plot, the corrected plot for the high-energy end, and the successive subtractions as described in the text.

[11] B. Harmatz, T. H. Handley, and J. W. Mihelich, Phys. Rev. **123**, 1758 (1961).

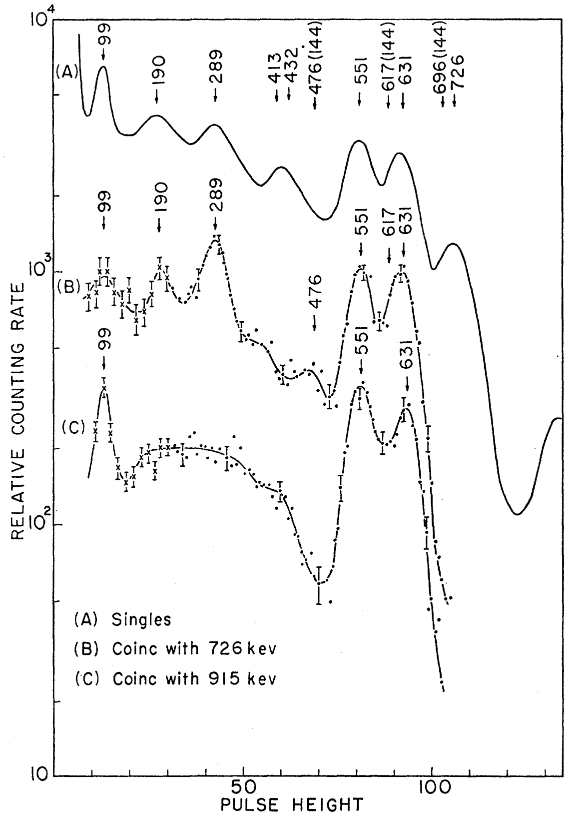

FIG. 4. Coincidence spectra obtained when gating with 726-kev and 915-kev photopeaks. The positions indicated at 476, 617, and 696 kev correspond to gamma-ray energies in Pm^{144} (an impurity).

ments [I(2460 kev)/I(1900 kev)=22/6]. The intense 1040-kev beta branch associated with the 5-day activity is evident, as well as the 780-kev beta branch associated with the Pm^{146} decay, another impurity in the source. The complex low-energy β transitions which depopulate the 45.5-day isomeric level are discussed below.

The logft values for the beta-decay branches are shown in Table II. These were obtained from Moszkowski's graphs,[12] using the measured branching ratios and half-lives. The unique first forbidden shape of the 2460-kev beta branch is consistent with the logft value of

TABLE II. Beta transition data for Pm^{148}.

Transition energy (kev)	Relative intensity (in equilibrium)	Logft
390±30	45 %	7.2[a]
490±30	13 %	8.0[a]
560±25	16 %	8.1[a]
680±20	18 %	8.4[a]
1020±15	5.8%	7.5[b]
1900±50	0.5%	9.6[b]
2460±20	1.7%	9.4[b]

[a] Transitions from isomeric level.
[b] Transitions from ground state.

[12] S. A. Moszkowski, Phys. Rev. 82, 35 (1951).

TABLE III. Gamma-gamma directional correlation data for Pm^{148}.

Correlation	Experimental results A_2	A_4
551 kev–631 kev	0.094±0.030	−0.009±0.043
551 kev–726 kev	0.096±0.024	0.038±0.040
631 kev–726 kev	0.091±0.024	−0.007±0.049
551 kev–910 kev	−0.21 ±0.07	0.001±0.098
Theoretical		
4(Q)2(Q)0 or 6(Q)4(Q)2	0.1020	0.0091
1(D)2(Q)0	−0.250	

9.4 and implies $\Delta J=2$, yes for this transition. This indicates that the ground-state spin of Pm^{148} is probably (2−). The shell model predicts an odd parity and a spin of between 1 and 6 since the 87th neutron is most likely in an $f_{7/2}$ state and the 61st proton in a $d_{5/2}$ state.

Coulomb excitation experiments by Heydenburg and Temmer[13] indicated that the 551-kev transition is $E2$ in character and hence the 551-kev level has a spin of 2+. In order to determine the spin of the 1460-kev level a gamma-gamma directional correlation measurement was made on the (551–910 kev) cascade. Since the (p,n) reaction produced a relatively small amount of the 5-day activity [I(5 day)/I(45 day)∼1, 24 hr after irradiation], the interference of the (551–916 kev) cascade introduced uncertainties in this measurement. The observed correlation coefficients were $A_2=-0.139\pm0.051$ and $A_4=0.003\pm0.082$. The interference correction was determined by a 916–631 kev correlation measurement with a source of Eu^{148}, assuming that the 916-kev transitions are the same in both sources and that the 916–631 kev and 916–551 kev correlations are identical. The corrected coefficients are listed in Table III together with the correlation data for the 45.5-day activity. They are consistent with either a spin of 1 or 2 for the 1460-kev level.

Recently Shirley[14] has aligned Pm^{148} nuclei using low-temperature techniques. The results of his angular distribution measurements on the 1460-kev gamma rays indicated that either (1) the spins of Pm^{148} (5 day) and the 1460-kev level of Sm^{148} are the same, or (2) beta decay to the 1460-kev level is practically all of the $L=2$ (B_{ij}) type.

c. Pm^{148} (45.5 day)

The 45.5-day scheme differs from that of Bhattacherjee[4] in regard to the placement of the 99-kev and 189-kev transitions, but is in agreement with that of Eldridge.[5] The gamma-gamma coincidences which determined their position in the decay scheme are shown in Fig. 4. Figure 4 shows the gamma-ray spectra in coincidence with the 726- and 916-kev transitions. Since a small portion of the 726-kev gate contained

[13] N. P. Heydenburg and G. M. Temmer, Phys. Rev. 100, 150 (1955).
[14] D. A. Shirley (private communication).

some of the photopeak of the 695-kev transition in Pm^{144} (an impurity), the 476- and 617-kev transitions in coincidence with the 696-kev transition can be seen. The 99-, 189-, and 288-kev transitions are placed high in the decay scheme from intensity considerations. The 1016-kev transition was found to coincide only with the 551- and 631-kev transitions and is placed directly above the 1181-kev level.

The sum of the energies of the 916.5- and 99.5-kev transitions is 1016 kev, which suggests the possibility that both the 99.5- and 1016-kev transitions proceed from the 2197-kev level. From the relative transition probabilities predicted by single-particle estimates, however, 99- and 1016-kev transitions of corresponding intensity [I(1016 kev)/I(99 kev)$\sim$2.5] would not be expected to proceed from the same level. This might imply two close-lying levels at about 2197 kev. The electron-capture decay of Eu^{148} supports this premise since no transitions of energy less than 413 kev were observed, whereas, a 1020-kev transition was found to depopulate a level whose energy is close to 2198 kev.

The permanent-magnet spectrographs indicated transitions of 413.8 and 432.2 kev. These transitions were shown to be in coincidence from gamma-gamma coincidence measurements. A beta-gamma coincidence measurement showed a single intense beta branch of endpoint energy 560±25 kev to be in coincidence with the composite 400-kev photopeak.

A typical coincidence beta spectrum obtained with a ¼-in. thick Pilot B crystal when gating on the 551-kev photopeak with a scintillation spectrometer is shown in Fig. 5. The 551-kev transition is in coincidence with beta branches of 1020, 680 kev, and several lower energy branches which were too complex to permit a good determination of their energy endpoints or intensities. The 1900-kev branch, which was observed on a coincidence measurement obtained when a large amount of the 5-day activity was still present, was too weak to be seen since the measurement shown was made after the source had reached equilibrium. [At equilibrium, I_β (1900 kev) $\sim$1% I_β (680 kev).] The results of all beta-gamma and gamma-gamma coincidences are summarized in Table IV.

TABLE IV. Results of beta-gamma and gamma-gamma coincidence measurements.

Gamma ray	Coincident γ-ray transitions (kev)	Coincident β-ray[a] transitions (kev)
413+432	413, 434, 551, 631	560, (many others weakly)
551	all except 551	690, 1020, 1900
631	all except 631	···
726	99, 189, 288, 551, 631	690, 1020 (weak)
910	551	1020
916	99, 551, 631	~500
1016	551, 631	~390
1460	···	1020

[a] Weak beta coincidences attributed to Compton distributions from higher energy transitions in gate.

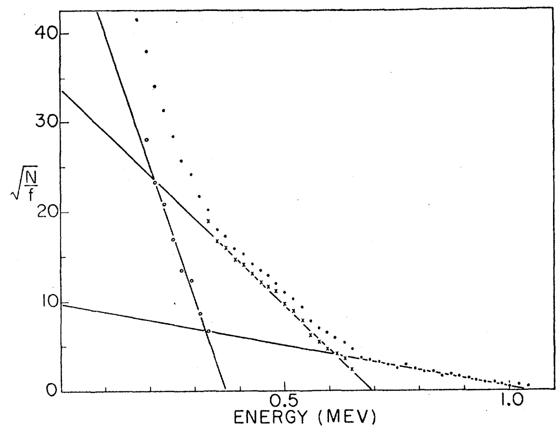

FIG. 5. Fermi plot of beta spectrum in coincidence with the 551-kev photopeak. A Pilot B phosphor was used as the beta detector. The branch ending at 380 kev is due in part to scattering of electrons out of the phosphor.

Gamma-gamma directional correlation measurements were carried out on the 726–631–551-kev cascade in order to determine the spin sequence. The correlation function coefficients, A_2 and A_4 for these measurements are shown in Table III. The results are in good agreement with a 6–4–2–0 spin sequence for the 1908-, 1182-, 551-kev, and ground-state levels, respectively. Correlation measurements involving the 413.8-kev transition were unfeasible because of the interference of the 432-kev transition. The source was too weak for any correlation measurements on the 916- or 1016-kev transitions. A composite correlation measurement obtained by gating both the 916- and 1016-kev gamma-ray photopeaks with one detector and the 631-kev photopeak with the other detector gave a 16% positive asymmetry.

Shirley[14] has measured the angular distribution functions for the 726-, 916-, and 1016-kev transitions. The data indicate a value of $F_2=-0.5\pm30\%$ for all three transitions, consistent with a spin of 4, 5, or 6 for the levels from which these transitions proceed. The tentative assignment of (6+) to the 1908-kev level is in agreement with these results.

The 413.8-kev transition is common to both the Pm^{148} and Eu^{148} decays. Since the 432-kev transition is not observed from the electron-capture side, this would place the 413-kev transition below the 432-kev transition. The Eu^{148} data permit a tentative assignment of (3−) for the 1596-kev level (as discussed below). The K-conversion electron intensities for the 413- and 432-kev transitions are approximately equal but since the gamma-ray photopeaks were not resolved a definite multipolarity for the 432-kev transition cannot be established at this time.

The spins of the upper levels which are populated by beta decay are probably high because: (1) the logft values of all the beta branches have approximately the same values (see Table II), and (2) the 1908-kev level probably has a spin of (6+). The logft values are consistent with first forbidden transitions ($\Delta J=0$, 1; yes)

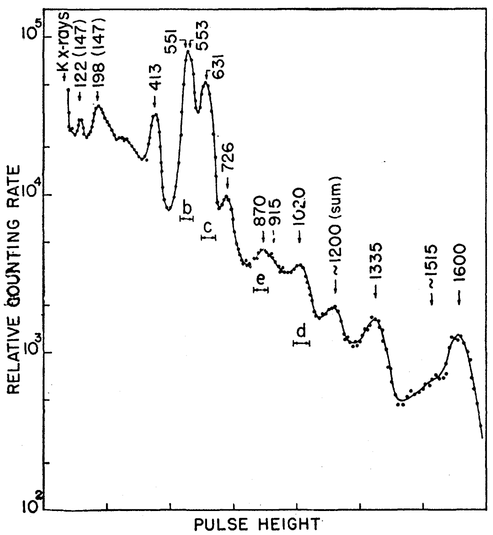

FIG. 6. Gamma-ray singles spectrum of Eu^{148}. Coincidence measurement gates for Fig. 8 are indicated.

but do not exclude allowed transitions ($\Delta J=0, 1$; no). This implies that the isomeric level in Pm^{148} has a high spin, probably 5 or 6. The multipolarities of the 62- and 76-kev transitions support this since the 62-kev transition is either $E3$ or $E4$ and the 76-kev transition is dipole.[11]

d. Decay of Eu^{148}

Eu^{148} decays via electron capture to levels in Sm^{148} with a 58 ± 3 day half-life, as measured with a Geiger-Müller counter. A gamma-ray spectrum taken with a scintillation spectrometer is shown in Fig. 6. This was taken several months after the source was received and hence contains very little Eu^{147} ($\sim5\%$ at the beginning of the experiments). Figure 7 shows a portion of the conversion electron spectrum taken with the intermediate-image spectrometer. The conversion electrons belonging to the Eu^{147} decay are indicated. Transitions of 550.7 and 553.2 kev were observed in the permanent-magnet spectrographs.

The proposed decay scheme for the electron capture of Eu^{148} consistent with relative gamma-ray intensities and gamma-gamma coincidence measurements is shown in Fig. 2. Some typical gamma-gamma coincidence measurements are shown in Fig. 8. The 1020-kev transition is in coincidence only with the 551- and 631-kev transitions, which were of equal intensity in the coincidence spectrum (see Fig. 8(d)). This coincidence spectrum was nearly identical to that obtained when gating the 915- and 1600-kev transitions. The 551-kev transition was assumed to be equal in intensity to the sum of the intensities of the 631- and 1335-kev transitions from branching considerations discussed below. The difference in the intensity obtained from the unresolved "550-kev" photopeak was then attributed to the 553-kev transition. Coincidences with the 553-kev transition were then established from the intensity of the 550-kev photopeak in the coincidence spectrum. No transition of energy less than 413 kev was observed in the Eu^{148} decay.

The fact that the 99- and 288-kev transitions are not observed in the Eu^{148} decay indicates two close-lying levels at about 2198 kev in Sm^{148} as discussed above. The question arises whether the 1016-kev transition in the Pm^{148} decay proceeds from the same level as the 1020-kev transition in the Eu^{148} decay. The 916-kev transition is probably common to both decays. If this is true, the Eu^{148} and Pm^{148} correlation data are consistent only if the 1016- and 1020-kev transitions are different.

The transition data for Sm^{148} from the electron capture of Eu^{148} are shown in Table V. The internal conversion coefficients (I.C.C.) were normalized to the 551-kev transition which was assumed to have a conversion coefficient equal to the theoretical value[15] for an $E2$ transition. The theoretical K-shell conversion coefficients are shown in Fig. 9.

A comparison of the measured I.C.C. with the theoretical curves (see Fig. 9) shows that the 631- and 726-

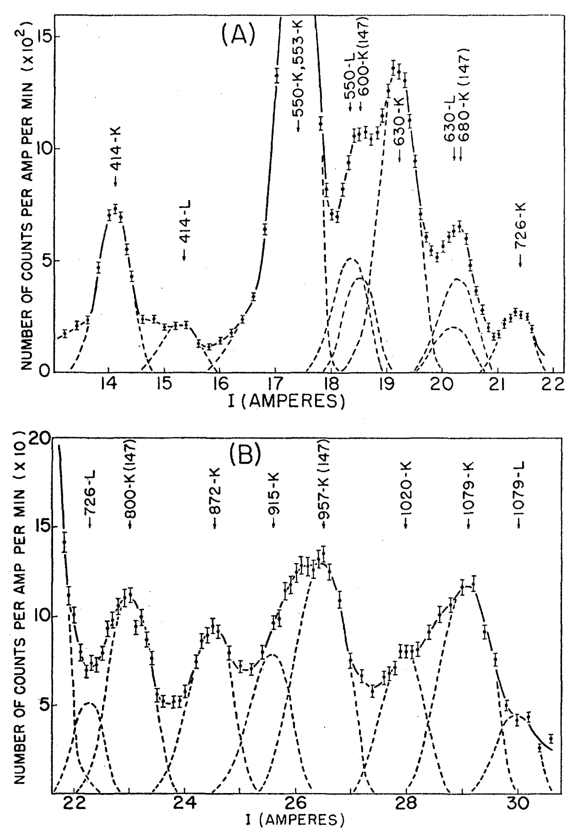

FIG. 7. Eu^{148} conversion electron spectrum taken with the intermediate-image spectrometer.

[15] M. E. Rose, *Internal Conversion Coefficients* (North Holland Publishing Company, Amsterdam, 1958). See also L. A. Sliv and I. M. Band, Report 57 ICC K1, Physics Department, University of Illinois, Urbana, Illinois.

TABLE V. Transition data for $Eu^{148} \rightarrow Sm^{148}$.

Transition energy (kev)	K-conversion e intensities[a]	Photon intensities	Exp I.C.C.[b]	Multipolarity from I.C.C.	Multipolarity assignments[c]
K x rays		200 000			
413.7	550	44 000	0.013 ±0.002	{~E2 {E1+(5.7–10%)M2	E2 E1+(<10%)M2
550.7	1390	172 000	0.0081	E2	E2
553.2	628	35 000	0.018 ±0.004	{M1+(0–10%)E2 {E1+(28–49%)M2	M1+E2
630.7	1000	163 000	0.0061 ±0.0006	{M1+(80–100%)E2 {E1+(12–17%)M2	E2
726.8	148	31 700	0.0047 ±0.0010	{M1+(55–100%)E2 {E1+(11–22%)M2	E2
870	67.1	13 500	0.0050 ±0.0014	{M1+(0–60%)E2 {E1+(32–57%)M2	M1+(15–45%)E2 E1+(32–45%)M2
915	64.3	15 300	0.0042 ±0.0012	{M1+(0–72%)E2 {E1+(19–43%)M2	M1+(<11%)E2
1020	57.8	14 400	0.0040 ±0.0012	{M1+(0–40%)E2 {E1+(26–59%)M2	M1+(<6%)E2
1335	19.5	9400	0.0021 ±0.0007	{M1+(0–67%)E2 {E1+(3–68%)M2	M1+(<10%)E2
~1515	~3.6	6100	0.0006 ±0.0002	{~E2 {E1+(0–11%)M2	E2 E1+(<11%)M2
1600	10.7	14 700	0.00073±0.00024	{M1+(60–100%)E2 {E1+(4–26%)M2	E2 E1+(<12%)M2

[a] Conversion electrons normalized to 1000 units for the 630.7-kev K-conversion line.
[b] I.C.C. normalized to theoretical E2 coefficient for 550.7-kev transition.
[c] Multipolarity assignments consistent with both I.C.C. and directional correlation data.

kev transitions are consistent with an E2 multipolarity assignment. This is in agreement with the 6–4–2–0 spin sequence observed in the Pm^{148} decay. The errors assigned to some of the measured I.C.C. do not allow an unambiguous multipolarity assignment. Gamma-gamma directional correlation measurements were performed in order to determine the spins of the higher energy levels and to remove the ambiguity in the multipolarity assignments.

The results of the directional correlations are shown in Table VI. The coefficients have been corrected for finite geometry[10] and interfering cascades. Correction for the interference due to other cascades was possible since correlations were carried out on all transitions with prominent photopeaks in the scintillation spectrum. The possible dipole-quadrupole mixtures for various spin assignments are shown in the table.

A comparison of the correlation data and the measured I.C.C. indicates that the 413-kev transition is E1+ (~3%) M2 and that the spin and parity of the 1595-kev level is then either (3−) or (5−). It is possible that the 413-kev transition is E2, in which case the 1595-kev level would be a 5+ state. The data for the 915-, 1020-, and 1335-kev transitions are consistent with M1+E2 mixtures shown in Table VI. The possible spin values for the levels from which these transitions proceed are indicated in the decay scheme. The correlation data for the 1600- 631-kev cascade are consistent with an assignment of E2 for the 1600-kev transition and a spin of (6+) to the 2780-kev level. A 1–3 correlation carried out on the 870- 631-kev cascade is in agreement with this assignment indicating that the 870- and 1600-kev transitions may both proceed from the 2780-kev level.

There is no appreciable electron capture to the 2+ level at 551 kev. Since electron capture apparently proceeds only to high spin states, the spin of the ground state of Eu^{148} may be 5− or 6−. The odd parity is assigned on the basis of the systematics of odd-odd isotopes of Eu. The shell model predicts an odd parity

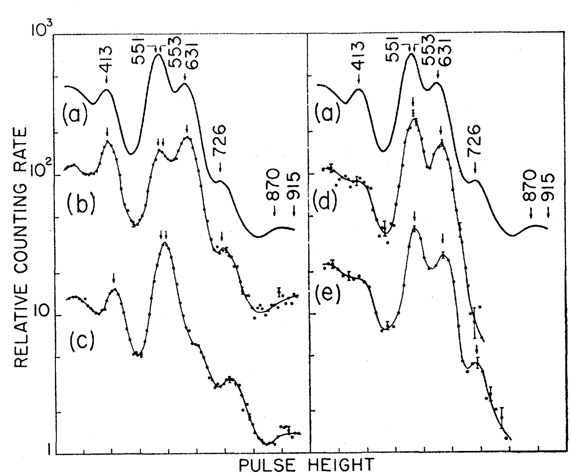

FIG. 8. Coincidence spectra obtained when gating the (b) 551-kev, (c) 631-kev, (d) 1020-kev, and (e) 870-kev photopeaks. The singles spectrum is shown as curve (a).

TABLE VI. Directional correlation data for Eu^{148} decay.

Correlation (γ kev-γ kev)	Experimental coefficients	Possible sequences $J_0(D,Q)J_1(Q)J_2$	Dipole-quadrupole mixtures
(1600–630)	$A_2=0.121\pm0.020$, $A_4=-0.01\pm0.03$	6–4–2	
		5–4–2	$D+(7\text{–}12\%)Q$
		4–4–2	$D+(3\text{–}8\%)Q$
		3–4–2	$D+(8-11\%)Q$
(1020–630)	$A_2=-0.215\pm0.060$, $A_4=0.01\pm0.03$	5–4–2	$D+(4\text{–}6\%)Q$
		3–4–2	$D+(<3\%)Q$
(915–630)	$A_2=0.110\pm0.030$, $A_4=0.02\pm0.05$	6–4–2	
		5–4–2	$D+(6\text{–}11\%)Q$; $D+(85\text{–}92\%)Q$
		4–4–2	$D+(3\text{–}11\%)Q$
		3–4–2	$D+(6\text{–}11\%)Q$
(726–630)	$A_2=0.083\pm0.020$, $A_4=0.02\pm0.04$	6–4–2	
		5–4–2	$D+(4\text{–}8\%)Q$
		4–4–2	$D+(8\text{–}12\%)Q$
		3–4–2	$D+(5\text{–}8\%)Q$
(414–630)	$A_2=-0.165\pm0.020$, $A_4=0.07\pm0.04$	5–4–2	$D+(2\text{–}3\%)Q$; $D+(99\text{–}100\%)Q$
		4–4–2	$D+(0\text{–}2\%)Q$
		3–4–2	$D+(<2\%)Q$
(1335–551)	$A_2=0.093\pm0.030$, $A_4=0.002\pm0.010$	4–2–0	
		3–2–0	$D+(3\text{–}7\%)Q$
		2–2–0	$D+(3\text{–}6\%)Q$
		1–2–0	$D+(7\text{–}10\%)Q$
1–3 correlation (870–630)	$A_2=0.170\pm0.030$, $A_4=0.02\pm0.04$	$6(D,Q)6(Q)4(Q)2$	$D+(<4\%)Q$; $D+(15\text{–}45\%)Q$

and a spin of between 1 and 6 since the 85th neutron is most likely in an $f_{7/2}$ state and the 63rd proton in a $d_{5/2}$ state.

Evidence for the existence of positrons was found on measurements made with the intermediate image spectrometer. Hoff *et al.*[7] had reported observing no appreciable positron branch. Furthermore, evidence for annihilation radiation was obtained by performing a 511–511 kev directional-correlation measurement. An estimate for the endpoint energy of the positrons of 800±100 kev is obtained from the spectrometer data. Since the lowest level to be populated appreciably by electron capture is that at 1182 kev, the positrons would be expected to populate this or higher levels. It is unlikely that the positrons would proceed to lower energy states, since the lower energy states are not directly populated by electron capture. The theoretical K-electron capture to positron branching ratio for a positron branch of endpoint energy 0.8 Mev is $K/\beta^+=35$.[16] This interpretation of the positron data indicates that the ground state of Eu^{148} is ~3.0 Mev above the Sm^{148} ground state. An energy difference of 2340 kev has been calculated by Cameron.[17]

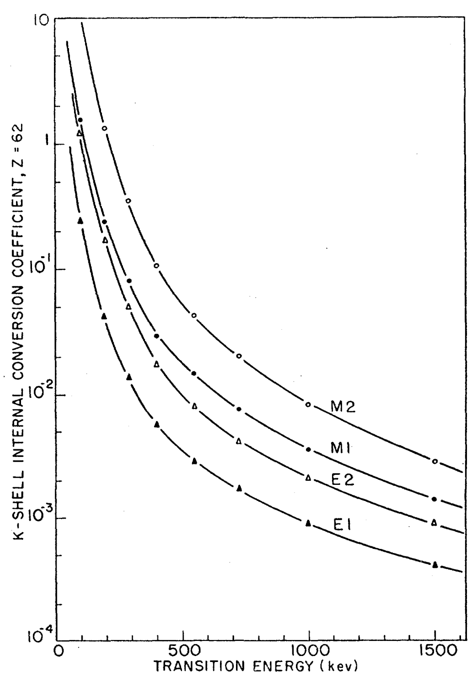

FIG. 9. K-shell internal conversion coefficients, $Z=62$ (taken from reference 15).

IV. DISCUSSION

One may remark on the levels of the odd-odd nucleus Pm^{148}. The ground state (5 day) has been designated as 2−, primarily on the basis of the experimental shape of the 2460-kev beta spectrum which is consistent with that expected for a unique first-forbidden transition. The isomeric state (45.5 day) of Pm^{148} decays via an 8% isomeric transition branch. The 62-kev transition has been assigned $E3$ or $E4$ character.[11] The former assign-

[16] P. F. Zweifel, Phys. Rev. **107**, 329 (1957).

[17] A. G. W. Cameron, Atomic Energy of Canada Limited Report AECL-433, 1957 (unpublished).

ment would indicate a retardation of 10^6 as compared to the single-particle estimate; the $E4$ assignment would indicate a retardation of <10. A second transition of 76 kev (dipole) is reported and may be the second transition of a two-step decay. Hence the spin sequence in Pm^{148} may be $2-$, $3\pm$, 5 or $6\pm$. The choice of 6 is most probable since no transition to the $4+$ level at 1182 kev is observed. Negative parity of the state would be consistent with the $\log ft$ value for the beta branch proceeding to the $6+$ level at 1908 kev. No beta transition from the Pm^{148} ground state to the $4+$ state at 1182 kev was observed. A lower limit for the $\log ft$ of this unique first-forbidden transition is ~ 9.8.

The $0+$, $2+$, $4+$, $6+$ sequence in Sm^{148} is the second such example in the transition region below the rare earths, the other case being Nd^{144}. The markedly different branching ratios to the upper levels of Sm^{148} for the decay of Pm^{148} and Eu^{148} indicate that the spins of these two nuclei are different, probably $6-$ and $5-$, respectively.

The nature of the level at 1595 kev in Sm^{148} is not quite clear. Directional-correlation measurements and the experimental value for the internal-conversion coefficient for the 414-kev transition are consistent with an assignment of $3-$ or $5\pm$ for this state. If it is $3-$, it is difficult to explain the absence of an allowed beta transition from the $2-$ Pm^{148} ground state, as well as the absence of an $E1$ transition of 1044 kev to the $2+$ first excited state; on the other hand, if it is a $5\pm$ state, it is difficult to explain the absence of direct transitions from either of the high-spin states of Pm^{148} or Eu^{148}. The least objectionable assignment is $5+$, although an almost pure $E2$ (414 kev) transition is then required between the $5+$ and $4+$ levels.

As mentioned previously, it is likely that the two states of 2097 and 2098 as populated in the beta decay and electron-capture decay, respectively, are one and the same since the 189-kev transition would probably have been unobserved in the Eu^{148} decay. However, it seems firm that the levels at 2198 and 2202 kev are different levels.

The level at 1887 kev is shown as $3+$ on the basis of the I.C.C. for the 1335-kev transition and the 1335-551 kev directional correlation. This state would then be populated with a unique first-forbidden electron capture from the Eu^{148} $(5-)$ ground state, a premise which is consistent with the $\log ft$ of 8.7.

The I.C.C. for the 915-kev transition and the directional correlation data are consistent with a $3+$, $4+$, or $5+$ assignment for the state at 2097 kev. The absence of a transition to the $2+$ state at 551 kev would indicate that $5+$ is the most likely value. The Pm^{148} alignment experiments of Shirley are consistent with spin values of 4, 5, or 6.

With regard to the level at 2202 kev, the I.C.C. for the 1020-kev transition and the 1020-631 kev directional correlation are consistent with an assignment of $3+$ or $5+$. Again, the absence of a crossover to the $2+$ level at 551 kev makes the higher spin value preferable.

The level at 2782 kev is tentatively designated as 5, $6\pm$ on the basis of the I.C.C. for the 1600-kev transition and the 1600–631 kev directional correlation, as well as the fact that the state is strongly populated in the electron capture of Eu^{148}. The absence of a transition to the 1595-kev level (probably $5+$) is difficult to explain.

The level at 1460 kev which is populated in the decay of Pm^{148} (5.0 day) has been designated $1-$ or $2+$. The assignment of $1-$ is somewhat preferable since recent directional-correlation measurements on the 910-551 kev γ-ray cascade by Reich, *et al.*,[18] are consistent only with spin 1 for this state. Furthermore, if the state were $2+$ the observed value (1.5) of the ratio of the intensities of the crossover and cascade transitions is considerably different than the usual value for similar states. If the $1-$ assignment is correct, then the beta decay to this state would be a somewhat retarded allowed transition.

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[18] C. W. Reich (private communication).