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Radioactive Decay of Pm^{148} and Pm^{148m}†

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The decay of the two Pm^{148} activities produced by neutron irradiation of fission-product Pm^{147} has been studied. The half-lives of these two activities have been measured to be 5.39 ± 0.06 days and 40.6 ± 0.4 days. The energies and relative intensities of the gamma radiation emitted in the decay of the 5.4-day activity were found to be 0.550 MeV (1.00), 0.910 MeV (0.55), and 1.46 MeV (0.77). Beta-ray absorption measurements and beta-ray scintillation spectra indicated the existence of a beta branch of ~2.6 MeV from the 5.4-day state in Pm^{148} to the Sm^{148} ground state. The decay of the 41-day activity gives rise to gamma rays in Sm^{148} whose energies and relative intensities are as follows: 0.098 MeV (0.032), 0.188 MeV (~0.01), 0.286 MeV (0.11), 0.309 MeV (0.05), 0.412 MeV (0.19), 0.431 MeV (0.08), 0.498 Mev (0.08), 0.548 MeV (0.99), 0.596 MeV (–), 0.627 MeV (1.00), 0.723 MeV (0.33), 0.913 MeV (0.20), and 1.011 MeV (0.21). The results of gamma-gamma and beta-gamma coincidence experiments, together with the gamma-ray energies and relative intensities, indicate the existence in Sm^{148} of levels at 0.55, 1.18, 1.46, 1.59, 1.90, 2.02, 2.09, and 2.19 MeV. Gamma-gamma directional correlation measurements were made on all the prominent gamma-ray cascades and provided spin assignments for many of the observed states. The conversion-electron spectrum of 41-day Pm^{148} gives evidence for the existence of transitions of 60 and 75 keV in Pm and thus establishes that the 41-day activity is an isomeric state. A $(6.5\pm1.7)\%$ isomeric-transition branch was observed for this state. Properties of the low-lying states of Pm^{148} are discussed. Decay schemes for both Pm^{148} activities are proposed.

I. INTRODUCTION

The excited states of Sm^{148} provide an interesting case for study since this nuclide lies in a region in which a transition is taking place from a spherical to a deformed nuclear equilibrium shape.[1] The level structure of nuclei in this region should provide information about the coupling between collective and independent particle motions as well as the nature of the collective motion itself.

Pm^{148} exhibits two activities, both of which decay to excited states in Sm^{148}. Since they excite states in Sm^{148} having a wide range of spins, a study of the decay of Pm^{148} should be especially interesting. Several studies of the decay of the Pm^{148} activities have appeared in the literature. A 5.3-day promethium activity was produced by proton bombardment of neodymium[2,3] and also by neutron irradiation[4] of fission product Pm^{147}. Long and Pool,[3] from a study of the activities produced by the proton bombardment of neodymium samples of different isotopic abundances, reported the existence of another, longer-lived (48-day) activity in Pm^{148}. This latter activity was also observed by Fischer,[5] who reported a value of 42 days for its half-life. Folger, Stevenson, and Seaborg[6] found a 43-day promethium activity among the products of the high-energy fission of uranium and assigned it to Pm^{148}. In addition to half-lives, these early investigators reported certain features of the beta and gamma radiations associated with these two activities.

Detailed studies of the decay of the two Pm^{148} activities have not appeared until recently. From a study of the beta and gamma radiation, Bhattacherjee, *et al.*[7] and Eldridge and Lyon[8] have proposed level schemes for the daughter nucleus Sm^{148}. The most recent work is that of Schwerdtfeger, Funk, and Mihelich,[9] who propose a level scheme based upon a study of the decay of Eu^{148} and both Pm^{148} activities.

As an outgrowth of the study of the activation cross sections[10] of Pm^{147} and Pm^{148}, a study of the decay of the two Pm^{148} activities was carried out at this laboratory. From this study, a level scheme for Sm^{148}, including spin and parity assignments for many of the observed states, has been proposed.

II. EXPERIMENTAL TECHNIQUES AND PROCEDURES

A. Source Preparation

The promethium activities were produced by neutron irradiation of fission product Pm^{147} obtained from the Oak Ridge Isotopes Division. The irradiations were made for about 15 days in a flux of 5×10^{14} neutrons/cm^2-sec in the Materials Testing Reactor. After irradiation, the samples were purified by coprecipitation with $La_2(C_2O_4)_3$ and by ion exchange using α-hydroxy isobutyrate elution from a heated Dowex-50 column.[11] In addition to the 2.65-yr activity from Pm^{147}, the purified samples contained 5.4- and 41-day activities

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† Work performed under the auspices of the U. S. Atomic Energy Commission.

[1] For general references on this subject see R. K. Sheline, Revs. Modern Phys. **32**, 1 (1960); and K. Alder, A. Bohr, T. Huus, B. Mottelson, and A. Winther, Revs. Modern Phys. **28**, 432 (1956).

[2] J. D. Kurbatov and M. L. Pool, Phys. Rev. **63**, 463 (1943).

[3] J. K. Long and M. L. Pool, Phys. Rev. **85**, 137 (1952).

[4] G. W. Parker, P. M. Lantz, M. G. Ingraham, D. C. Hess, Jr., and R. J. Hayden, Phys. Rev. **72**, 85 (1947).

[5] V. Kistiakowsky Fischer, Phys. Rev. **87**, 859 (1952).

[6] R. L. Folger, P. C. Stevenson, and G. T. Seaborg, University of California Radiation Laboratory Report UCRL-1195, 1951 (unpublished).

[7] S. K. Bhattacherjee, B. Sahai, and C. V. K. Baba, Nuclear Phys. **12**, 356 (1959).

[8] J. S. Eldridge and W. S. Lyon, Nuclear Phys. **23**, 131 (1961).

[9] C. F. Schwerdtfeger, E. G. Funk, and J. W. Mihelich, Bull. Am. Phys. Soc. **5**, 425 (1960); Phys. Rev. **125**, 1641 (1962).

[10] R. P. Schuman and J. R. Berreth, Nuclear Sci. and Engr. **12**, 519 (1962).

[11] G. R. Choppin and R. J. Silva, University of California Radiation Laboratory Report UCRL-3265, 1956 (unpublished).

from Pm^{148}, and the 53-hr activity from Pm^{149}. The 5.4-day Pm^{148} was the most abundant activity immediately after irradiation. After a period of several months, the samples contained mainly Pm^{147} with an appreciable amount of 41-day Pm^{148}.

B. Gamma-Ray Spectra

The gamma radiation emitted in the decay of the two Pm^{148} activities was studied using 3-in. diameter by 3-in. cylindrical NaI(Tl) crystals mounted on Dumont 6363 photomultiplier tubes. Sources were deposited on Scotch tape backings and covered with rubber hydrochloride films (0.5 mg/cm²) and were counted at various distances on the axis of the detector. Both beryllium and polystyrene were used as beta absorbers. Energy calibration of the scintillation spectrometer was accomplished using sources of Ce^{141}, Cs^{137}, and Zn^{65}. The method of "internal comparison" was applied to reduce the effect of rate-dependent gain fluctuations in the photomultiplier.

Typical gamma-ray spectra of the 5.4- and 41-day Pm^{148} activities are shown in Figs. 1 and 2, respectively. A spectrum of the 41-day activity, taken with an increased amplifier gain in order to obtain more detail in the low-energy region, is shown in Fig. 3. Values of the relative photopeak intensities were obtained by successive subtraction of calculated pulse-height distributions representing the response of the detector to monoenergetic radiation for the particular geometrical arrangement used in the measurements.[12] Relative emission rates of the gamma rays were then obtained using calculated detector efficiencies and experimentally determined peak-to-total ratios.[13] The spectrum that was analyzed to obtain the relative intensities of the gamma rays from the decay of the 5.4-day activity was taken at a source-detector distance of 10 cm. The results of this analysis are given in Table I.

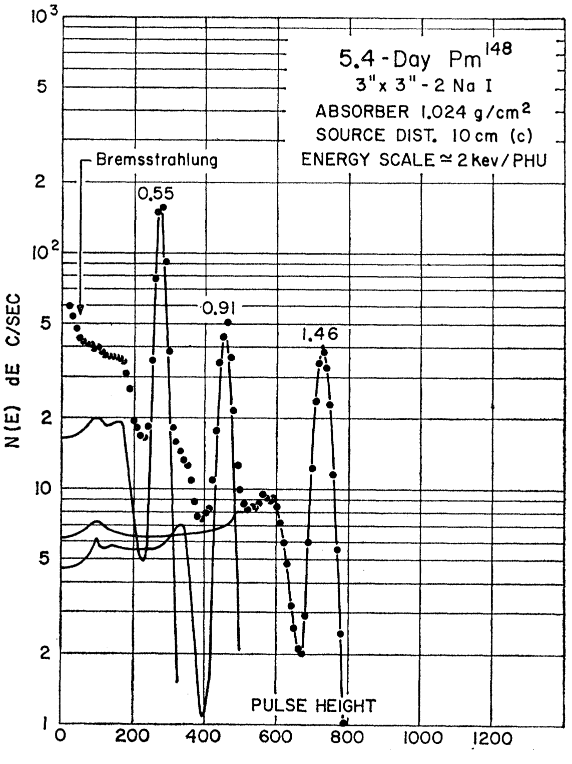

FIG. 1. Gamma-ray spectrum of 5.4-day Pm^{148}.

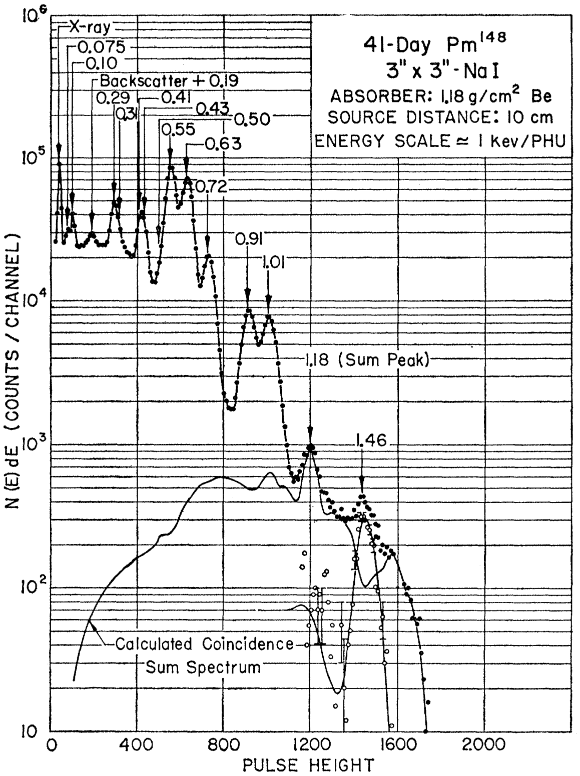

FIG. 2. Gamma-ray spectrum of 41-day Pm^{148}. The points designated by open circles in the region above ~1.1 MeV give the results of the subtraction of the coincidence sum spectrum, calculated as described in the text, from the experimental data. Typical statistical uncertainties are shown for these points. The shape of this resultant spectrum is quite well described by the 1.46-MeV gamma-ray shape shown in the figure.

TABLE I. Radiations from 5.4-day Pm^{148}.

Radiation	Energy (Mev)	Intensity (number per decay)
β^-	2.6 ±0.2	0.45±0.09
β^-	2.0 ±0.2	0.14[a]
β^-	1.1 ±0.2	0.41±0.09
γ	1.46 ±0.01	0.24±0.02
γ	0.910±0.005	0.17±0.02
γ	0.550±0.005	0.31±0.02

[a] Intensity inferred from the gamma-ray relative intensities.

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[12] R. L. Heath, in Proceedings of the Total Absorption Gamma-Ray Spectrometry Symposium, 1960, Atomic Energy Commission Report, TID-7594 (unpublished).

[13] S. H. Vegors, Jr., L. L. Marsden, and R. L. Heath, Atomic Energy Commission Report, IDO-16370 (unpublished).

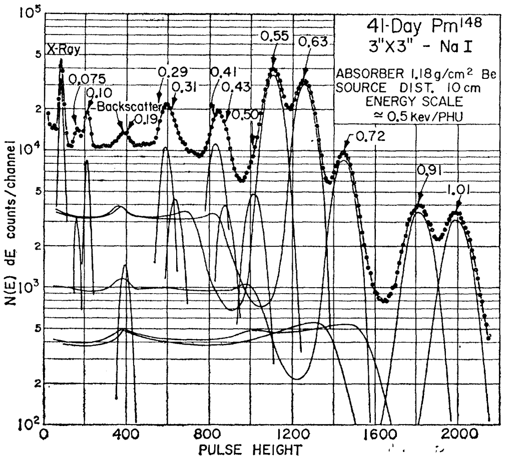

FIG. 3. A portion of the gamma-ray spectrum of 41-day Pm^{148} taken with an increased amplifier gain to show detail in the low-energy region. While the presence of a gamma ray at ~75 keV is clearly indicated, there is no evidence in the gamma-ray spectrum for a gamma ray at ~60 keV.

TABLE II. Radiations from 41-day Pm^{148}.

	Gamma radiation		
Energy (keV)	Intensity relative to 627-keV gamma ray	Intensity (transitions per decay)	Coincidencc relationships
x-ray	0.11 ±0.02[b]	...	...[g]
60.1	...[c]	...	...
74.6	0.011±0.004[b]	...[d]	none
98	0.032±0.004[b]	0.07[e]	0.55, 0.63, 0.91
188	~0.01	0.01	...[g]
286	0.11 ±0.02	0.10	0.55, 0.63, 0.72
309	0.05 ±0.02	0.05	...[g]
412	0.19 ±0.04	0.18	0.55, 0.63
431	0.08 ±0.03	0.08	
498	0.08 ±0.03	0.07	...[g]
548	0.99 ±0.05	0.91[f]	...[h]
596	...	...	...[g]
627	1	0.94	...[h]
723	0.33 ±0.03	0.31	0.29, 0.55, 0.63
913	0.20 ±0.02	0.18[f]	0.10, 0.55, 0.63
1011	0.21 ±0.02	0.20	0.55, 0.63
1460[a]	0.017±0.003	...[d]	none
	Beta radiation		
E_β[i] (MeV)	Intensity[i] (transitions per decay)		log *ft*
0.8	0.24		8.5
0.68	0.08		8.6
0.61	0.19		8.2
0.51	0.37		7.6

[a] Energy obtained from gamma-ray scintillation data.
[b] Contribution from escape peak included.
[c] Not observed in gamma-ray spectrum.
[d] See part B of the Discussion.
[e] Corrected for internal conversion ($M1$ assignment assumed).
[f] Contribution of 5.4-day Pm^{148} isomeric transition daughter removed.
[g] Not determined.
[h] All gammas except 0.060, 0.075, and 1.46.
[i] Energies and relative intensities inferred from decay scheme and gamma-ray relative intensities.

In addition to the gamma rays listed, there was some evidence for the existence of a gamma ray of ~2.26 MeV with an intensity of ~0.2% relative to that of the 1.46-MeV gamma ray.

In the gamma-ray spectrum of the 41-day activity, taken at a source-detector distance of 10 cm, the effects of summing[14] in the NaI crystal of coincident gamma rays must be taken into consideration, particularly in the determination of the relative intensity of the 1.46-MeV gamma ray. A computer program has been developed[15] which calculates the real sum spectrum arising from a particular gamma-ray cascade. This program performs a convolution of the spectral shapes representing the response of a detector to the individual members of the cascade. From a knowledge of the decay scheme of a radioactive nucleus, it is therefore possible to calculate the expected real sum spectrum. In order to obtain this composite sum spectrum for 41-day Pm^{148}, sum spectra were calculated for all cascades involving the prominent gamma rays assuming the decay scheme in Fig. 5 to be correct. The intensities of these spectra relative to the single gamma rays are uniquely determined from gamma-ray relative intensities, except for corrections for the directional correlation of the respective cascade. These corrections were made using the measured directional correlations (see Sec. G). The spectra were then added together to give the composite coincidence sum spectrum. This sum spectrum is shown in Fig. 2. Also shown is the result of the subtraction of this spectrum from the experimental data points in the region above ~1.1 MeV. This difference spectrum is quite well represented by the 1.46-MeV gamma-ray shape shown in the figure. These results demonstrate the precision with which a composite coincidence sum spectrum may be calculated, using the procedure outlined above. In order to provide an additional check on these results, the contribution of the coincidence sum spectrum was reduced by taking measurements at source-detector distances of 20, 39, and 100 cm. The analysis of these data indicated that, with the exception of the 1.46-MeV gamma-ray, the observed spectrum above ~1.1 MeV was entirely due to coincidence summing effects. The gamma-ray relative intensities are given in Table II and are averages of the results of the analysis of these spectra.

The precision with which the relative intensity of a gamma ray can be determined from an analysis of a gamma-ray singles spectrum depends on its position with respect to the other gamma rays in the spectrum. For this reason, a rather large uncertainty exists in the relative intensities of the unresolved pair of gamma rays at ~0.42 MeV and of the weak 0.31- and 0.50-MeV gamma rays. The uncertainties given for the relative intensities of these gamma rays are estimates based largely on the difficulties associated with the graphical "stripping" method employed in the intensity analysis. Since the weak 0.19-MeV gamma ray lies in the back-

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[14] R. L. Heath, Atomic Energy Commission Report, IDO-16408 (unpublished).

[15] E. C. Yates, R. L. Heath, and C. S. Pea, MTR–ETR Technical Branches Quarterly Report, July 1–September 30, 1960, IDO-16658 (unpublished), p. 31.

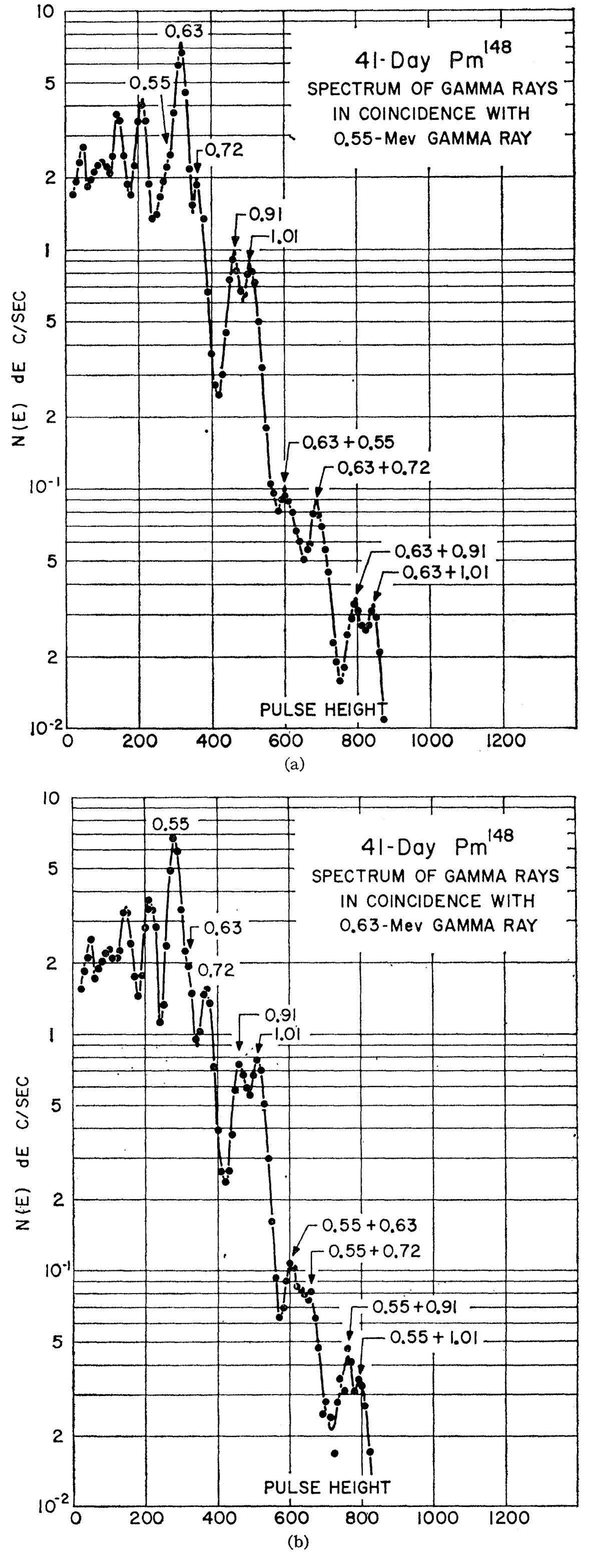
scattering peak, its quoted intensity should be considered to be highly uncertain. The 0.60-MeV gamma ray, whose existence was confirmed by the conversion-electron spectrum (discussed below), is weak, and no estimate of its intensity was provided by the graphical intensity analysis.

C. Gamma-Gamma Coincidence Measurements

Gamma-gamma coincidence measurements were made using a pair of 3×3-in. NaI(Tl) crystals. The detectors were positioned at 90 degrees with a shield placed to minimize Compton scattering between them. A source-detector distance of 5 cm was used in these measurements. The coincidence circuitry was of the fast-slow type with a resolving time of 6×10^{-7} sec. The coincidence spectrometer consisted of an automatic sliding-window single-channel analyzer operated in coincidence with either a 100-channel discriminator-type analyzer or a conventional 256-channel analyzer.

The coincidence relationships of the gamma rays from the 5.4-day activity indicated that the 0.91- and 0.55-MeV gamma rays were in cascade, while the 1.46-MeV gamma ray arose from a cross-over transition to the ground state. The coincidence relationships of the gamma rays from the 41-day activity are more complicated and are summarized in Table II.

Figures 4(a) and (b) show typical coincidence spectra. The two cases illustrated are for settings of the window of the single-channel analyzer on the photopeaks of the 0.55- and 0.63-MeV gamma rays, respectively. These spectra were chosen to illustrate the necessity for considering coincidence summing effects in the analysis of gamma-gamma coincidence measurements. Furthermore, the proper interpretation of coincidence sum peaks may provide additional information on the coincidence relationships in a complex decay scheme. In these two spectra the three peaks above 1.2 MeV do not represent single gamma rays, but arise from real coincidences between a given gamma ray (as selected by the single-channel analyzer) and the coincidence sum of the other two gamma rays of a triple cascade. All of these cascades contain both the 0.55- and 0.63-MeV gamma rays. Thus, when the 0.55-MeV gamma ray is selected by the single-channel analyzer, the sum peaks represent double sums between the 0.63-MeV gamma ray and the third member of the respective triple cascade. With the single-channel analyzer set on the 0.63-MeV gamma ray [Fig. 4(b)], the sum peaks correspond to coincidence summing with the 0.55-MeV gamma ray. In the two measurements the energies of these sum peaks are observed to differ by an amount equal to the energy difference between the 0.55- and the 0.63-MeV gamma rays (~0.08 MeV). Also present in both spectra is a sum peak at 1.18 MeV. This arises from summing between the 0.55- and 0.63-MeV gamma rays in coincidence with the Compton distributions from the higher energy gamma rays which



(a)

(b)

FIG. 4. (a) Spectrum of gamma rays from 41-day Pm^{148} in coincidence with the 0.55-MeV gamma-ray. (b) Spectrum of gamma rays from 41-day Pm^{148} in coincidence with the 0.63-MeV gamma ray.

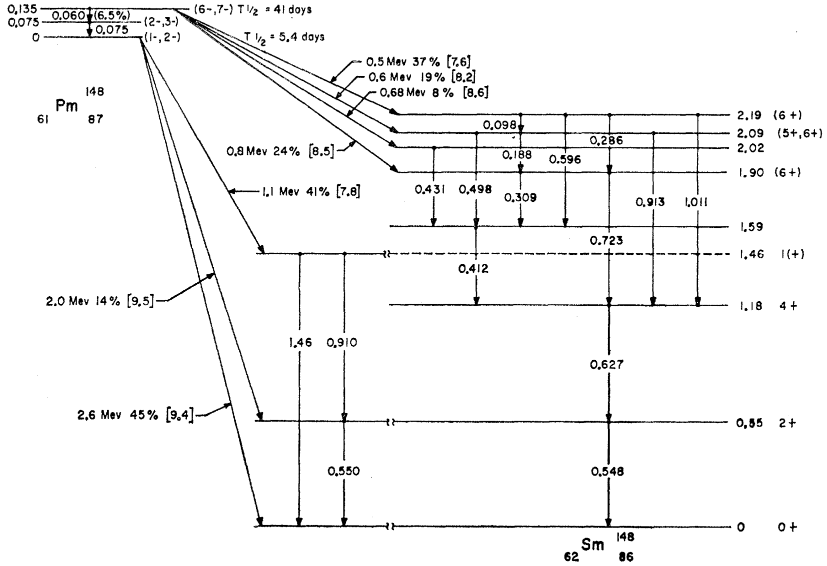


FIG. 5. Proposed decay scheme for the two Pm^{148} activities. The numbers in square brackets beside the β-ray transition intensities are the respective log ft values.

are included in the single-channel analyzer window. The only interpretation consistent with these results is that there exist in Sm^{148} levels at 1.18, 1.90, 2.09, and 2.19 MeV. (The measurements give no information, of course, on which one of the 0.55- and 0.63-MeV gamma rays is the ground-state transition.)

The interpretation of the gamma-ray spectra and the gamma-gamma coincidence measurements, as well as the measurements described below, makes it possible to propose a decay scheme for the two Pm^{148} activities. For convenience in discussing these measurements, the decay scheme is presented at this point (see Fig. 5). The position of the 0.19-, 0.31-, 0.50-, and 0.60-MeV gamma rays in the Sm^{148} level scheme is based on the agreement of their energies with the energy differences of Sm^{148} levels whose location had already been established from gamma-gamma coincidence measurements on the more prominent gamma rays. It was found that neither the 0.075- nor the 1.46-MeV gamma ray was in coincidence with any of the other gamma rays arising from the decay of the 41-day activity. The significance of this observation for establishing the relative energies of the two Pm^{148} activities will be discussed below (see Sec. III B).

D. Conversion-Electron Measurements

Because of the presence in the gamma-ray spectrum of 41-day Pm^{148} of a 75-keV gamma ray which exhibited no coincidence relationships, it was tentatively supposed that this gamma ray might be an isomeric transition in Pm^{148}. A rough calculation of the K-conversion coefficient of the 75-keV transition was made using its observed intensity in the gamma-ray spectrum and that of the K x-ray peak, corrected for the contributions of the known gamma rays in Sm^{148}. Where the multipole orders of the latter transitions could not be inferred from known level spins, probable multipolarities were provisionally assumed. If the residual intensity of the K x-ray peak were due to the 75-keV transition, the latter would then have a K-conversion coefficient of about 3±1.5. However (see Table III),[16,17] it is then evident that the multipolarity of this transition is probably $M1$ or $E2$, and in neither case is the half-life consistent with a 41-day isomeric state.

The 75-keV gamma ray might still be a transition in Pm^{148}, if it followed another gamma ray, as yet unobserved, which had a sufficiently high multipolarity to account for the half-life of the isomeric state. Such a gamma ray would be highly internally converted, hence unobservable in the gamma-ray spectrum.

To investigate the existence of such a transition, the conversion-electron spectrum of 41-day Pm^{148} was recorded photographically, using four 180° permanent magnet spectrographs, which cover an energy range

TABLE III. Theoretical conversion coefficients.

E (keV)	Multipole character	α_K [a]	α_{LI} [a]	α_{LII} [a]	α_{LIII} [a]	α_M [b] ($Z=60$)
60.1	$E2$	4.1	0.3	4.0	4.8	4.0
	$E3$	13	2.0	2.0×10^2	2.2×10^2	2.1×10^2
	$E4$	45	70	5.6×10^3	6.4×10^3	7×10^3
	$E5$	140	1.9×10^3	1.2×10^5	1.3×10^5	2.3×10^5
	$M3$	3.2×10^2	2.4×10^2	37	4.3×10^2	...
	$M4$	2×10^3	3.6×10^3	7.8×10^2	1.2×10^4	...
74.6	$E1$	0.5	0.05	0.01	0.01	0.02
	$E2$	2.5	0.2	1.3	1.4	1.2
	$M1$	3.1	0.4	0.03	0.01	0.1
	$M2$	34	6.4	0.7	1.5	3.4

[a] L. A. Sliv and I. M. Band, reference 16.
[b] M. E. Rose, reference 17.

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[16] From the calculations of L. A. Sliv and I. M. Band, *Coefficients of Internal Conversion of Gamma Radiation: K- and L-Shell* (Academy of Sciences of the USSR, Leningrad, 1956), issued in the United States as Reports 57 ICCKl and 58 ICCLl, P. Axel, Physics Department, University of Illinois.

[17] M. E. Rose, *Internal Conversion Coefficients* (North-Holland Publishing Company, Amsterdam, 1958).

from about 10 keV to 2 MeV. The sources were prepared by ruling the Pm activity, in HCl solution, on scotch tape. It should be noted that these sources, intended primarily for a rapid survey of internal conversion lines, were somewhat heavier and broader then are ideally suited to precision energy measurements. Based on the distribution from plate to plate of the measured energies for each conversion line, the uncertainties in gamma-ray energies are typically of the order of 0.1%. The systematic uncertainties, possibly arising from the sources used, are somewhat larger than this and are believed to be less than 0.4% for the higher energy transitions. For the lower energy transitions ($\lesssim$0.1 MeV), these uncertainties are somewhat larger.

In the low-energy region of the conversion-electron spectrum, L_{II}, L_{III}, M, and N lines were observed corresponding to a gamma ray of 60.1 keV, which was not observed in the gamma-ray spectrum of the 41-day activity. For the 74.6-keV transition, K and L_{I} lines were observed. Both groups of lines exhibited energy differences characteristic of Pm.

By visual estimate, the relative intensities of the L_{II} and L_{III} lines for the 60.1-keV transition were found to be approximately equal. This indicates that the 60.1-keV transition is an electric multipole (see Table III). The fact that only a single L line was observed for the 75-keV transition rules out the possibility that this transition is $E2$ (for which $L_{\mathrm{I}}:L_{\mathrm{II}}:L_{\mathrm{III}}=0.14:0.93:1.0$). The other possibilities ($E1$, $M1$, and $M2$) will be discussed later (see III B).

For those higher energy transitions for which both K and L internal conversion lines were observed, the energy differences were characteristic of Sm. Weaker transitions for which K lines only were recorded but whose energies correspond to transition energies between established levels in Sm^{148} are assigned to Sm on this basis. One additional weak line which could be interpreted as the K line of an $\sim$609-keV gamma ray in Sm suggests a transition which cannot be placed between established levels in the proposed level scheme.

E. Beta Energies, Relative Intensities, and Half-Lives

The beta radiation emitted by the promethium activities was studied using end-window proportional counters and anthracene scintillation detectors. The maximum energies of the beta rays emitted in the decay of the 5.4-day activity were determined both from aluminum absorption curves and from beta-ray scintillation spectra. An analysis of data from 5.4-day Pm^{148} indicated the presence of two beta groups having maximum energies of 2.6±0.2 MeV and approximately 1.1 MeV. The higher energy was determined by a comparison with beta rays from Y^{90} (2.26 MeV) and Pr^{144} (2.98 MeV).[18]

The intensities of the 5.4-day Pm^{148} beta groups were obtained from a comparison of the absolute beta disintegration rate obtained using a calibrated proportional counter with the absolute gamma disintegration rate obtained from a gamma-ray scintillation detector. The efficiencies of the end-window counter for detecting beta rays of various energies were determined by counting similarly mounted samples of Pm^{147}, Pm^{149}, and Y^{90} which had been standardized by 4π beta counting. The existence of a beta group feeding the 0.55-MeV state was inferred from the measured relative intensities of the gamma rays. The energies and relative intensities of the 5.4-day Pm^{148} beta rays are given in Table I.

Beta absorption measurements on the 41-day Pm^{148} were complicated by the presence of the much more intense beta rays (maximum energy 0.22 MeV) from the Pm^{147} present in the sample. A 2.6-MeV beta component with an intensity of $\sim$3% relative to that of the 0.55-MeV gamma ray was observed in the 41-day activity. This was interpreted as a transition to the Sm^{148} ground state from the 5.4-day Pm^{148} state produced following the isomeric transition. The intensity of this high-energy beta ray agrees well with the value for the isomeric-transition branch obtained from gamma-ray intensities. With the exception of the 2.6-MeV beta ray, the intensities of the 41-day Pm^{148} beta groups were inferred from the measured gamma-ray intensities.

In order to obtain half-lives for the Pm^{148} activities, the decay of the beta radiation from three samples was followed for periods up to approximately 400 days. In these measurements an aluminum absorber was used to absorb the beta rays from Pm^{147}. In addition to contributions from Pm^{148}, the decay curves contained contributions from Pm^{149} beta rays and bremsstrahlung arising from the Pm^{147} beta rays. The half-lives of the two Pm^{148} activities were obtained by a least-squares analysis of the decay data, assuming values of 53 h and 2.65 yr, respectively, for the half-lives of Pm^{149} and Pm^{147}. From this analysis, values of 5.39±0.06 days and 40.6±0.4 days were obtained for the half-lives of the two Pm^{148} activities.

F. Beta-Gamma Coincidence Experiment

In order to establish the position of the 0.43-MeV gamma ray in the level scheme, as well as to confirm certain features of the decay scheme, a beta-gamma coincidence experiment was performed. The gamma radiation was detected in a 3×3-in. NaI(Tl) crystal, and the beta radiation was detected in a $1\frac{1}{2}\times\frac{1}{4}$-in. anthracene crystal. Energy calibration of the beta detector was accomplished using the conversion electrons from Ba^{137m}. The random coincidence rate was less than 1% of the real coincidence rate. The single-channel analyzer was set to detect all beta radiation above a certain energy, and the spectrum of gamma radiation in coincidence with these beta rays

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[18] D. Strominger, J. M. Hollander, and G. T. Seaborg, Revs. Modern Phys. **30**, 585 (1958).

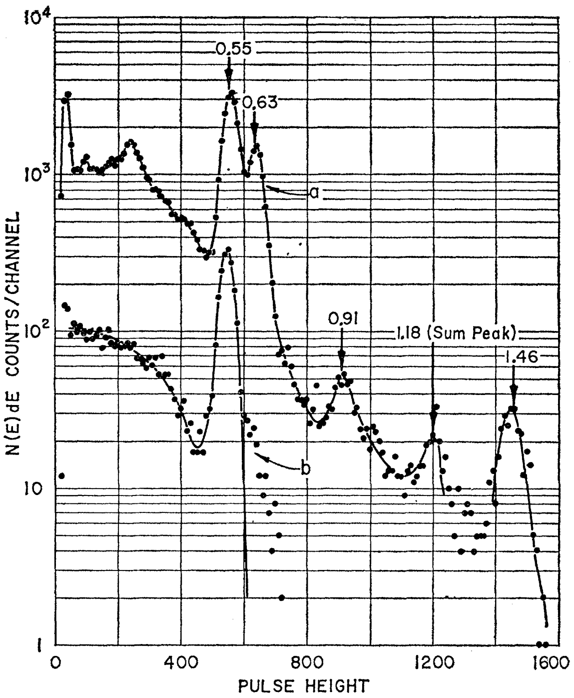

FIG. 6. Gamma-ray spectra taken in coincidence with beta radiation from 41-day Pm^{148}. Since the two spectra were taken for different counting times, the ordinates are not directly comparable. Spectrum (b) was taken with the single-channel analyzer set to count all beta radiation above ~1.2 MeV. Spectrum (a) was taken with the single-channel analyzer set to count all beta radiation above ~0.8 MeV.

was recorded on a 256-channel pulse-height analyzer. As the single-channel analyzer setting was decreased to include more of the beta spectrum, the appearance of the various gamma rays in the coincidence spectrum was observed. Approximately 20 coincidence spectra were taken in the range of single-channel analyzer settings from ~1.4 to ~0.4 MeV.

Two typical coincidence spectra are shown in Fig. 6. The spectrum (b), which represents coincidences with all betas above ~1.2 MeV, contains only the 0.55-MeV gamma ray. This gamma ray arises from beta feeding of the 0.55-MeV state through the Pm^{148} ground state. Spectrum (a) shows coincidences with betas above ~0.8 MeV. The 0.91- and 1.46-MeV gamma rays arise from the 1.46-MeV state fed through the Pm^{148} ground state. The 0.63-MeV gamma ray in the spectrum arises from the detection of 1.01- and 0.91-MeV gamma radiation by the anthracene crystal. The data did not provide conclusive evidence for a beta branch from the 41-day state in Pm^{148} to the 1.18-MeV state in Sm^{148}.

As the single-channel base line was decreased, the next gamma ray to appear in the spectrum was the 0.72-MeV gamma ray. Thus, no evidence for any appreciable beta feeding of a state in Sm^{148} in the region of 1.6 MeV was found. This information, together with the results of the gamma-gamma coincidence experiments, indicates that the 0.43-MeV gamma ray is in coincidence with the 0.41-MeV gamma ray and that it arises from a state at 2.02 MeV in Sm^{148}.

G. Directional Correlation Measurements

For the gamma-gamma directional correlation measurements, the Pm activity, in dilute HCl solution, was contained in thin-walled Lucite holders $\frac{1}{16}$-in. i.d. by $\frac{1}{4}$-in. high. The gamma-ray detectors were 3×3-in. NaI(Tl) crystals mounted on Dumont 6363 photomultiplier tubes. The source-detector distance was 10 cm. Data were taken every 9° in one quadrant from 90° through 180°.

The coincidence circuit was the fast-slow type. The pulses used to determine the fast coincidence relationship between the detectors were generated using a "cross-over pickoff gate."[19] This circuit generates a timing pulse from the zero cross-over point of the output pulse from a double differentiated linear amplifier. Since the position in time of the zero cross-over point of the differentiated pulse is relatively independent of input pulse amplitude over a wide range, much of the amplitude-dependent time jitter characteristic of conventional trigger circuits is eliminated. A resolving time of 8×10^{-8} sec was used in these experiments. Pulse-height analysis was performed using a single-channel analyzer with one detector and a 20-channel discriminator-type analyzer with the other. The coincidence circuit provided a gating pulse for the 20-channel analyzer whenever a coincidence occurred between two fast timing pulses and an output pulse from the single-channel analyzer. Thus the 20-channel analyzer recorded the spectrum of gamma rays in

TABLE IV. Directional correlation results for Sm^{148}.

Cascade (MeV)	Run	41-day Pm^{148} Experimental coefficients[a] $A2$	 $A4$
1.01–0.63–0.55	1	$+(0.0995\pm0.0034)$	$+(0.0073\pm0.0057)$
	2	$+(0.0970\pm0.0034)$	$+(0.0168\pm0.0051)$
	av	$+(0.0983\pm0.0024)$	$+(0.0121\pm0.0039)$
0.91–0.63–0.55	1	$+(0.0952\pm0.0044)$	$+(0.0030\pm0.0075)$
	2	$+(0.100\pm0.005)$	$+(0.0006\pm0.0078)$
	av	$+(0.0976\pm0.0032)$	$+(0.0018\pm0.0054)$
0.72–0.63–0.55	1	$+(0.0970\pm0.0065)$	$+(0.0122\pm0.0120)$
	2	$+(0.0892\pm0.0032)$	$+(0.0113\pm0.0041)$
	av	$+(0.0933\pm0.0037)$	$+(0.0117\pm0.0064)$
0.63–0.55		$+(0.0860\pm0.0077)$	$+(0.0120\pm0.0136)$
0.63–(0.41+0.43)		$-(0.0444\pm0.0082)$	$+(0.0069\pm0.0149)$
		5.4-day Pm^{148}	
0.91–0.55	1	$-(0.203\pm0.004)$	$+(0.0046\pm0.0071)$
	2	$-(0.191\pm0.005)$	$-(0.0069\pm0.0075)$
	av	$-(0.197\pm0.003)$	$-(0.0012\pm0.0052)$

[a] Corrected for the finite solid angle of the detectors.

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[19] E. Fairstein, Oak Ridge National Laboratory Instrumentation Division Annual Progress Report, ORNL-2480, 1957 (unpublished).

coincidence with radiation in the energy region spanned by the single-channel analyzer.

In each experiment, at least five determinations of the coincidence counting rate were made at each angle. This number of measurements allowed a meaningful comparison of the observed variance of the coincidence counting rate with that calculated from statistical uncertainties only. In all cases, the variances calculated in these two ways exhibited an agreement which was consistent with the statistical uncertainties involved.

The least-squares analysis of the data was carried out according to the method discussed by Rose.[20] The correction of the Legendre polynomial expansion coefficients for the finite solid angle of the detectors was carried out using experimentally determined correction factors,[21] which included the variation of the peak-to-total ratio across the face of the crystal.

41-Day Activity

In the directional correlation measurements of the 1.01–0.63–0.55-, the 0.91–0.63–0.55-, and the 0.72–0.63–0.55-MeV gamma-ray cascades, the single-channel analyzer was set to span the photopeak of the high-energy transition, and the 20-channel analyzer was set to span both the 0.63- and the 0.55-MeV gamma-ray photopeaks. Thus, two directional correlation measurements were carried out simultaneously. Since the 0.63- and the 0.55-MeV gamma rays are in cascade, the analysis of the directional correlation involving the 0.55-MeV gamma ray must take into account the fact there is an intermediate unobserved transition. Discussions of the form of the Legendre polynomial expansion coefficients in such cases have appeared in the literature.[22] A simultaneous measurement of the directional correlations of the 0.63-(0.41+0.43)- and 0.63–0.55-MeV gamma-ray cascades was made also, with the single-channel analyzer spanning the photopeak of the 0.63-MeV gamma ray and with the 20-channel analyzer spanning the photopeaks of the 0.55- and the (0.41+0.43)-MeV gamma rays. The results of all the directional correlation measurements are summarized in Table IV and discussed below.

The 1.01–0.63–0.55-MeV cascade. Two measurements of the directional correlation of this cascade were made. In each case, the random coincidence rate was about 3% of the gross coincidence rate. During the analysis of the coincidence spectra obtained from the first measurement, it became apparent that the intensity of the 0.63-MeV gamma ray relative to that of the 0.55-MeV gamma ray was the same at all angles. Thus, the directional correlations of the 1.01–0.63- and the 1.01–0.55-MeV cascades are essentially the same (see Fig. 7). From the form of the theoretical expressions for the Legendre expansion coefficients for a triple cascade, one may show that such a similarity depends only upon the spins of the final three nuclear levels involved and upon the multipole character of the final two transitions, and is *independent of the spin of the initial state and of the multipole character of the first transition.* Thus, the directional correlation of the 0.91–0.63-MeV cascade will be the same as that of the 0.91–0.55-MeV cascade; and the directional correlation of the 0.72–0.63-MeV cascade will be the same as that of the 0.72–0.55-MeV cascade. This feature of these particular triple cascades in Sm^{148} allows a considerable simplification in the analysis of the data. Since the relative intensity of the 0.55- and the 0.63-MeV gamma rays is independent of angle, it is not necessary to analyze each coincidence spectrum in order to obtain their intensities. The coincidence counting rate at a given angle can be obtained merely by summing all counts in the two photopeaks. This procedure was used in the analysis of all the directional correlation data involving the 0.63- and the 0.55-MeV gamma rays.

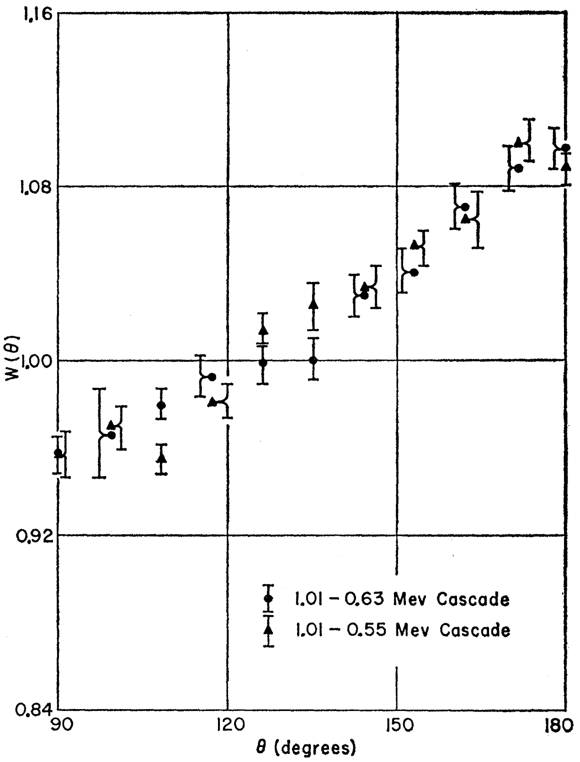

FIG. 7. The measured directional correlation functions of the 1.01–0.63- and the 1.01–0.55-MeV gamma-ray cascades in Sm^{148}. Both sets of data have been reduced to the form $W(\theta) = 1 + A_2P_2(\cos\theta) + A_4P_4(\cos\theta)$ and have been plotted to the same scale.

The 0.91–0.63–0.55-MeV cascade. Two measurements were made of the directional correlation of this cascade. The coincidence counting rates were obtained

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

[21] C. W. Reich, E. C. Yates, W. E. Page, and R. L. Heath, MTR–ETR Technical Branches Quarterly Report, Period Ending December 31, 1958, IDO-16532, p. 48 (unpublished).

[22] L. C. Biedenharn and M. E. Rose, Revs. Modern Phys. **25**, 729 (1953); L. W. Fagg and S. S. Hanna, Revs. Modern Phys. **31** 711 (1959).

as described above. With the single-channel analyzer setting used in the measurements, the contributions to the coincidence data from the 1.01–0.63–0.55-MeV cascade and the random coincidence rate were each approximately 3% of the gross coincidence rate. It was also necessary to correct for the 0.91–0.55-MeV gamma-ray cascade from 5.4-day Pm^{148}. These contributions were removed from the data before the least-squares analysis was performed.

The 0.72–0.63–0.55-MeV cascade. Two measurements of the directional correlation of this cascade were made. The analysis of the coincidence data was carried out as described above. The contributions from the 1.01–0.63–0.55-MeV cascade, the 0.91–0.63–0.55-MeV cascade, and the random coincidence rate were approximately 6%, 1%, and 1%, respectively, of the gross coincidence rate. These contributions were removed from the data before the least-squares analysis was performed.

The 0.63–(0.41+0.43)- and the 0.63–0.55-MeV cascades. One measurement of the directional correlation of these cascades was made. The first step in the analysis of the coincidence spectra was the removal of the contributions from the Compton distributions of the higher energy gamma rays. These contributions accounted for approximately 4% of the number of events in the 0.55-MeV photopeak and for approximately 15% of the events in the composite ~0.42-MeV peak. After these contributions had been removed, the relative intensities of both ~0.42- and 0.63-MeV peaks were obtained. In this analysis no attempt was made to obtain relative intensities of the 0.41- and 0.43-MeV gamma rays. The composite peak was treated as arising from a single gamma ray. The random coincidence rate for both correlations was less than 1% of the total coincidence rate.

5.4-Day Activity

The only cascade excited in the decay of this activity is the 0.91–0.55-MeV cascade. Two measurements of the directional correlation of this cascade were made. The analysis of the directional correlation data was complicated by the presence of a small amount of 41-day Pm^{148} in the sources. Since the 0.91-MeV gamma ray in the 41-day activity could not be resolved from the 0.91-MeV gamma ray under study, and since the former is also in coincidence with the 0.55-MeV gamma ray, the measured directional correlation of the 0.91–0.55-MeV cascade contained some contribution from the 41-day activity. Observation of the decay of the sources indicated that initially approximately 3% of the counting rate in the 0.91-MeV photopeak was due to the longer-lived activity. From this information and the measured directional correlation of the 0.91–0.63–0.55-MeV cascade, the contribution from the 41-day activity was removed. The effect due to random coincidences (approximately 3% of the gross coincidence rate in both experiments) was also removed. One of the measurements of the directional correlation of the 0.91–0.55-MeV gamma-ray cascade from 5.4-day Pm^{148} is shown in Fig. 8. The Legendre polynomial coefficients obtained from the least-squares analyses are listed in Table IV.

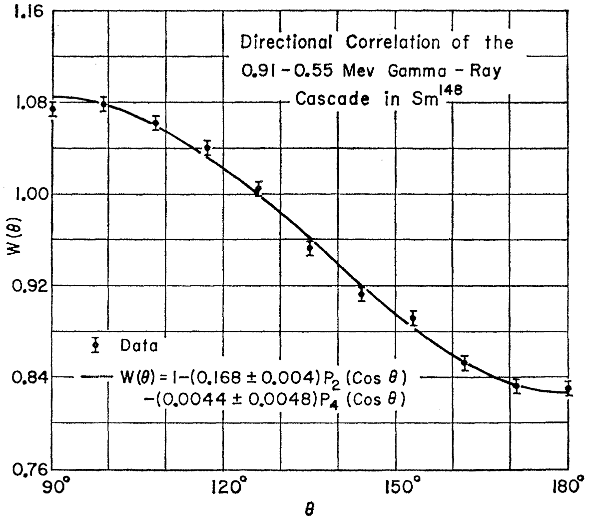

FIG. 8. One of the measurements of the directional correlation of the 0.91–0.55-MeV gamma-ray cascade arising in the decay of 5.4-day Pm^{148}. The solid curve gives the least-squares fit of the data of the form $W(\theta)=1+A_2P_2(\cos\theta)+A_4P_4(\cos\theta)$.

III. DISCUSSION

A. States in Sm^{148}

From Coulomb excitation using alpha particles, Heydenburg and Temmer[23] have established that the first excited state of Sm^{148} (0.55 MeV) has spin and parity 2+. From the gamma-ray relative intensities, log *ft* values for the beta transitions, and the interpretation of the directional correlation results based on this assignment, one can obtain spin and parity assignments for many of the levels excited in the decay of the Pm^{148} activities.

The 1.46-MeV state. Since the spins of the ground state and the 0.55-MeV state are known, the directional correlation of the 0.91–0.55-MeV cascade provides a unique spin assignment to the 1.46-MeV state. It is convenient to discuss the directional correlation results in terms of a graph whose coordinate axes are the coefficients A_2 and A_4 of Legendre polynomial expansion of the directional correlation function. On such a plot, a directional correlation of the form $1+A_2P_2(\cos\theta)+A_4P_4(\cos\theta)$ is represented by a point. For cascades in which one transition is a mixed multipole, the locus of possible directional correlations is a closed curve, each point of which corresponds to a particular value of the mixing parameter δ. Figure 9 gives an A_4 vs A_2 plot

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[23] N. P. Heydenburg and G. M. Temmer, Phys. Rev. **100**, 150 (1955).

appropriate for gamma-ray cascades in which the final transition takes place from a state of spin 2 to a state of spin 0. Also included in the figure are the experimental points for the 0.91–0.55- and the 0.63–0.55-MeV gamma-ray cascades in Sm^{148}. It is evident from an inspection of Fig. 9 that the directional correlation of the 0.91–0.55-MeV cascade is consistent with a spin assignment of either 1 or 3 to the 1.46-MeV state. The existence of a strong ground-state transition from this level rules out the possibility of spin 3. For a spin-1 assignment, the data require a δ of $+0.046$ for the 0.91-MeV gamma ray. A knowledge of the parity of this state is of interest, since from this one may hope to obtain some information concerning the nature of the excitation which gives rise to it. The small value of the mixing ratio of the 0.91-MeV transition does not provide a unique parity assignment. The log *ft* (7.8) of the beta transition to the 1.46-MeV state also does not provide a unique parity assignment, although this value suggests a first forbidden beta transition. In such a case, positive parity would be expected for the 1.46-MeV state since the parity of the ground state of Pm^{148} is presumably odd (see Sec. III B).

Recently, Shirley[24] has investigated the angular distribution of the 1.46-MeV gamma ray following the beta decay of aligned Pm^{148} nuclei. A preliminary analysis[24] of these data indicates that the spin of the 1.46-MeV state may be either 1 or 2. The data are apparently not consistent, however, with the assumption that the spin of the Pm^{148} parent is different from that of the 1.46-MeV state. Thus, it appears that a spin-1 assignment to the 1.46-MeV state would imply a spin-1 assignment to the 5.4-day ground state of Pm^{148}.

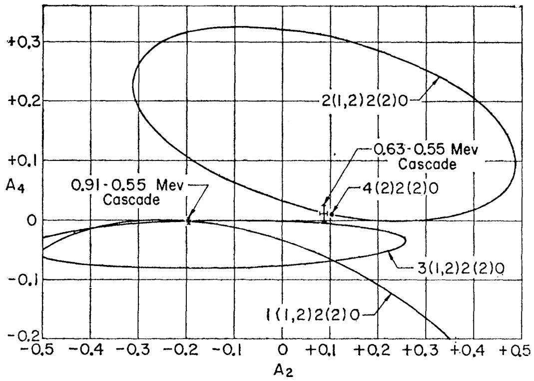

FIG. 9. Plot of A_4 vs A_2 for various spin sequences in which the final transition takes place from a state of spin 2 to a state of spin 0. The measured Legendre polynomial expansion coefficients, corrected for the finite solid angle of the detectors, are also indicated.

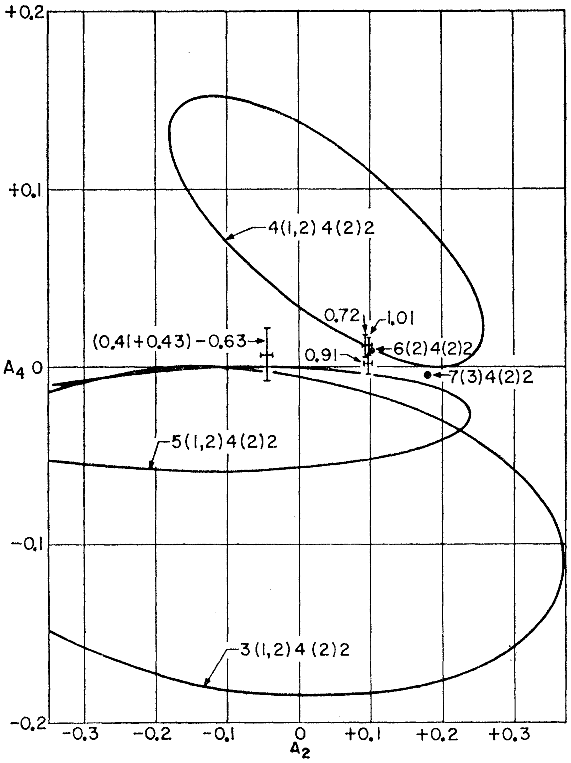

FIG. 10. Plot of A_4 vs A_2 for various spin sequences in which the final transition takes place from a state of spin 4 to a state of spin 2. The measured Legendre polynomial expansion coefficients, corrected for the finite solid angle of the detector, are also indicated. For those measurements involving a triple cascade, the data points are labeled by the energy of the first gamma ray in the cascade.

The 1.18-MeV state. The results of the directional correlation measurements of the 0.63–0.55- and the 1.01–0.63–0.55-MeV cascades require the assignment of spin 4 to this state. The parity is presumably even, since low-lying 4− states have not been observed in even-even nuclei. The measured directional correlation of the 0.63–0.55-MeV cascade is consistent with a 3(1,2)2(2)0 cascade with $\delta \cong -0.22$ in the first transition, a 2(1,2)2(2)0 cascade, also with $\delta \cong -0.22$, and a 4(2)2(2)0 cascade. The 3(1,2)2(2)0 sequence may be eliminated, since the corresponding value of δ requires that the Legendre polynomial coefficients in the directional correlation of the 1.01–0.63-MeV cascade have opposite signs from those of the 1.01–0.55-MeV cascade. The similarity of the directional correlations of these two cascades has already been noted (see Fig. 7). From the value of δ consistent with a 2(1,2)2(2)0 sequence, it may be shown that the value of A_2 in the directional correlation function of the 1.01–0.55-MeV cascade should be about twice as large as that in the directional correlation function of the 1.01–0.63-MeV cascade. The assignment of 2+ to the 1.18-MeV state is thus ruled out. A 4+ assignment, however, is consistent with the measured directional correlations. It is interesting to note that, if the 1.18-MeV state has spin 4, the directional correlation functions of the 1.01–0.63- and the 1.01–0.55-MeV cascades must be identical.

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[24] R. W. Grant and D. A. Shirley, Lawrence Radiation Laboratory, Berkeley, 1961 (unpublished).

Since the remaining directional correlations involve the 0.63-MeV, 4(2)2, transition as the second member of the cascade, their results may conveniently be compared and interpreted using the graph in Fig. 10. Also included on the graph are the experimental points for the various directional correlations. With the exception of the 0.63–(0.41+0.43)-MeV cascade, the directional correlation measurements include, as described above, both the 0.63- and 0.55-MeV transitions. In these latter cases, the experimental points are labeled by the energy of the first transition.

The 2.19-MeV state. The measured directional correlation of the 1.01–0.63–0.55-MeV gamma-ray cascade is consistent with the assignment to the 2.19-MeV state of either spin 6 or spin 4 with $\delta \cong -0.26$ in the 1.01-MeV transition. The assignment of spin 6 is more probable on the basis of the log *ft* of the beta transition to this state from the 41-day state in Pm^{148}. It will be shown below that the latter state is probably 6− or 7−. If the 2.19-MeV state were 4+, the beta transition feeding it would then be at least unique first forbidden and the log *ft* for such a transition should be higher than the observed value of 7.6. The absence of a crossover transition to the 2+ state at 0.55 MeV is also evidence in favor of a 6+ assignment.

The 2.09-MeV state. Information concerning the spin of this state is provided by the measured directional correlation of the 0.91–0.63–0.55-MeV gamma-ray cascade. The location of the experimental point (see Fig. 10) is such that spin assignments of 5, 6, and 4 to the 2.09-MeV state are possible. The assignment of 4 is not considered likely on the basis of the log *ft* (8.2) of the beta transition and the absence of a crossover transition to the 2+ first excited state. For a spin of 5, the value of δ consistent with the directional correlation data is ~ -0.26. Such a large value would favor an $M1$-$E2$ mixture in the 0.91-MeV transition rather than an $E1$-$M2$ mixture and would indicate a positive parity for the 2.09-MeV state. The log *ft* (8.2) of the beta transition feeding this state is consistent with the assumption that the two states involved have opposite parities.

The 1.90-MeV state. The directional correlation of the 0.72–0.63–0.55-MeV cascade is consistent with the assignment of either spin 4 or spin 6 to the 1.90-MeV state. The assignment of 6 is believed to be the more probable one from the absence of a crossover gamma-ray transition to the 2+ first-excited state. An even parity for this state was chosen on the basis of the log *ft* value (8.5) of the beta transition feeding it.

The 2.02- and the 1.59-MeV states. The data provide no definite spin assignments for these two states. Since the 1.59-MeV state is fed by gamma radiation from the 1.90-MeV state (6+) and from the 2.09-MeV state (5+, 6+), it is not probable that this state has a spin less than 4. Since there is no appreciable beta feeding of this state, it is also unlikely that its spin is greater than 5. The assignment of spin 4, while consistent with the absence of a beta branch to this state, would lead one to expect a crossover transition to the 2+ first excited state. While no transition of this energy (~1.05 MeV) was observed in either the gamma-ray spectrum or the conversion-electron spectrum, it is possible that a weak ($\lesssim 2\%$ of the intensity of the 0.63-MeV gamma ray) transition of this energy would not have been detected. If the spin of this state were 5, one might expect to observe some beta feeding of it. There is also some uncertainty in spin of the 2.02-MeV state. Since a beta branch to it is observed, its spin is probably either 5, 6, or 7. The directional correlation of the 0.63–(0.41+0.43)-MeV gamma-ray cascade provides no unique spin assignments for the two states. About all that one can conclude from this correlation is that it is consistent with the various spins previously mentioned.

B. States in Pm^{148}

The relative position of the 41- and 5.4-day states in Pm^{148} is established by the fact that the former state gives rise to transitions (60 and 75 keV) which exhibit internal conversion lines characteristic of Pm. This requires that the 41-day state be an isomeric state of Pm^{148}. The 5.4-day state is, then, the ground state. As indicated by the conversion-electron spectrum of these two transitions, the 75-keV transition has the lower multipole order. This is consistent with the assumption that the two transitions are in cascade, with the 60-keV (isomeric) transition preceding the 75-keV transition. The fact that, while the 75-keV gamma ray is present in the gamma-ray spectrum, no gamma rays of 60 keV are observed also supports this argument. The large internal-conversion coefficient expected for an isomeric transition of this energy would explain its absence in the gamma-ray spectrum. The existence of excited states in Pm^{148} at 75 and 135 keV is thus indicated. This is in agreement with the work of Harmatz, Handley, and Mihelich.[25]

The 1.46-MeV gamma ray in Sm^{148} is fed only through the decay of the 5.4-day Pm^{148} activity. Since the percentage of decays giving rise to this gamma ray is known (see Table I), its relative intensity in the gamma-ray spectrum of the 41-day activity may be used to calculate the percentage of decays of this activity that lead to the Pm^{148} ground state. This percentage is calculated to be $(6.5\pm1.7)\%$. One may also use the observed intensity of the 75-keV gamma ray to obtain the percentage of decays to the Pm^{148} ground state. Using the conversion coefficients in Table III, for an assumed $M1$ assignment for the 75-keV transition, one obtains a value of $(5.1\pm1.8)\%$ for this percentage. For $E1$ and $M2$ assignments, values of $(1.8\pm0.6)\%$ and $(52\pm19)\%$, respectively, are calcu-

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

lated for this percentage. An $E1$ or $M2$ assignment for this transition thus appears to be unlikely.

The lifetime of the isomeric state for gamma-ray emission may be calculated for any assumed multipolarity and compared with other experimental data as presented by Goldhaber and Sunyar.[26] Such a comparison indicates that the 60-keV transition is probably $E4$. If this transition were $E3$, its transition rate would be slower than that observed for other $E3$ transitions by a factor of $\sim 10^5$. If the 60-keV transition were $E5$, a transition rate $\sim 10^3$ faster than the single-particle estimate would be indicated. On the other hand, the observed transition rate for an $E4$ transition of 60 keV is in good agreement with the data presented by Goldhaber and Sunyar for other $E4$ transitions.

One may obtain information about the state of the 61st proton and the 87th neutron in Pm^{148} from the measured ground-state assignments of the neighboring odd-A nuclei ${}_{61}Pm_{86}{}^{147}$, ${}_{60}Nd_{87}{}^{147}$, and ${}_{62}Sm_{87}{}^{149}$. Cabezas *et al.*[27] have recently reported a $(7/2)+$ assignment for the ground state of Pm^{147}. The state of the 87th neutron in Pm^{148} is somewhat uncertain since the ground state of Nd^{147} has been reported[27,28] to be $(5/2)-$, while that of Sm^{149} has been reported[29] to be $(7/2)-$. The coupling of the odd proton and the odd neutron in these states could give rise to low-lying states in Pm^{148} having spins ranging from 0 to 7. Odd parity would be expected for such states. Since no appreciable beta feeding of the 4+ state at 1.18 MeV in Sm^{148} is observed, an assignment of either 6− or 7− to the 41-day isomeric state in Pm^{148} is indicated. The gamma decay of this state appears to involve only two cascade rays whose multipolarities are most likely $E4$ and $M1$. Since no crossover transition from the isomeric state to the ground state is observed, the spin of the 75-keV state is presumably one unit higher than that of the ground state. On this basis, a spin sequence of (1−, 2−, 6−) or (2−, 3−, 7−) would be expected for the three Pm^{148} states.

C. Summary

The choice of a 6+, rather than a 4+, assignment to the 1.90- and 2.19-MeV states in Sm^{148} was based on the following considerations. The spin of the 41-day state in Pm^{148} is large, probably 6 or 7. The inferred nature of the gamma transitions which de-excite this isomeric level, as well as the fact that it apparently does not directly excite the 4+ state at 1.18 MeV in Sm^{148}, makes an assignment of 5 or lower quite unlikely. The existence of beta branches to the 1.90- and 2.19-MeV states thus favors the 6+ assignments, although the log *ft* (8.5) of the former transition may be somewhat large for a first forbidden transition. Another argument which seems to favor 6+ assignments is the absence of crossover transitions to the 2+ state at 0.55 MeV. In any case, on the basis of the relative intensities of the gamma rays which de-excite (and excite, in the case of the 1.90-MeV state) these states, it seems quite reasonable to assign them an even parity.

It is also of interest to obtain an unambiguous parity assignment for the state at 1.46 MeV. As mentioned previously, the directional correlation measurements seem to require a spin of 1 for this state. With this assignment, however, the mixing ratio is sufficiently small ($\delta \sim +0.05$) that no choice of parity can be made on the basis of this measurement alone. A measurement of the linear polarization-direction correlation of the cascade which de-excites this state should provide a unique parity assignment.

With two possible exceptions, the log *ft* values of the beta transitions from both Pm^{148} activities appear to be somewhat large. In particular, the log *ft* values for the beta transitions from 5.4-day Pm^{148} to the ground state and 0.55-MeV 2+ state in Sm^{148} should be noted. If, as suggested by Schwerdtfeger *et al.*,[9] the 5.4-day Pm^{148} activity is 2−, then the ground-state beta transition would be unique first-forbidden, for which the observed log *ft* of 9.4 is not unreasonable. However, the transition to the 2+ state would then be ordinary first-forbidden, and one would have to explain the slowness of this transition. On the other hand, if the 5.4-day state is 1−, then both beta transitions should be ordinary first-forbidden. In this instance, the log *ft* values are considerably larger than one customarily observes for such transitions.

It would appear that any attempt to describe the observed levels in Sm^{148} in terms of a nuclear model must, at present, be somewhat inconclusive. With the exception of the 0.55-MeV state, there is no evidence for any other 2+ states below 2.2 MeV. There is also no evidence for any states of spin 3. The only state observed that is definitely 4+ is that at 1.18 MeV, although there is a possibility that any or all of the observed states above 1.5 MeV may have this assignment. On the basis of current ideas about nuclear structure,[30] several states having spins of 2, 3, and 4 might be expected to be present. It would be interesting to investigate this energy region of Sm^{148} using other techniques in an attempt to determine the position of such states, if they do indeed exist.

ACKNOWLEDGMENTS

The authors would like to acknowledge the assistance of Dr. R. G. Helmer of this laboratory for his assistance in the conversion-electron work as well as for discussions concerning various aspects of this work. They would

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(d,t) Reaction Studies on Iron and Nickel*

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Angular distributions and absolute cross sections have been measured for the (d,t) reactions on Fe^{54}, Fe^{58}, Ni^{58}, Ni^{60}, and Ni^{61} at a deuteron energy of 21.6 MeV. Sum rules are used to interpret the resulting reduced widths in terms of the average occupation numbers of the $1f_{7/2}$, $2p$, and $1f_{5/2}$ orbits in the various target ground states. The average occupation numbers so obtained are compared with the predictions of the pairing model of Kisslinger and Sorensen. We examine whether our conclusions are consistent with the results of (d,p) experiments on Ni^{58} and Ni^{60}.

1. INTRODUCTION

THIS paper is the third of a series[1,2] concerning (d,t) reaction studies of various nuclei in the $(1f,2p)$ shell. Angular distributions and absolute cross sections have been measured for the (d,t) reactions on Fe^{54}, Fe^{58}, Ni^{58}, Ni^{60}, and Ni^{61} at a deuteron energy of 21.6 MeV. The resulting reduced widths are interpreted in terms of the structure of the nuclear states involved, and the conclusions for the Ni isotopes are compared with the predictions of the pairing model of Kisslinger and Sorensen. The paper concludes with a general survey of the current experimental and theoretical situation concerning the neutron configurations of fp-shell nuclei, particularly the ground states. It reviews what has been learned in this connection from (d,t) reactions on nuclei between V^{51} and Zn^{68} and examines whether our conclusions are consistent with other experimental informaton. In particular, the implications of (d,p)-reaction studies of fp-shell nuclei are considered.

2. EXPERIMENTAL METHOD AND RESULTS

The experimental equipment and techniques have been described previously.[1] The experiment was performed in the 60-in. scattering chamber. The detector consisted of a 0.012-in. NaI(Tl) dE/dx crystal mounted on a 0.160-in. NaI(Tl) E crystal. The light from the E crystal was coupled directly to a photomultiplier, while the light from the dE/dx crystal was coupled to its photomultiplier via an air light pipe. The particles were identified by using a multiplier circuit whose inputs consisted of the E and dE/dx singals. After adjustment of the circuit, the output spectrum of the multiplier consisted of peaks corresponding to deuterons, protons, and tritons. The position of these peaks was independent of the energy of the incident particles. A single-channel analyzer set to accept only the triton peak gated a multichannel analyzer which recorded the E pulse. The targets were metallic foils, enriched in the desired isotopes and rolled to a thickness of about 0.0003 in. The energy calibration was obtained both from range-energy relations and reactions of known Q value. The calibration is accurate to roughly 100 keV. Relative cross sections are reliable to within the statistical error involved. Absolute cross sections have a possible error of less than 10%, resulting mainly from uncertainties in the target thickness.

Energy spectra were obtained at 3° intervals between 12° and 30° for all targets. In previous studies[1] of (d,t) reactions in the fp shell, it appeared that the desired information concerning l values and reduced widths could be obtained from the behavior of the differential cross section within this limited angular range.[3] This

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