previous definition and added to Fig. 1 as indicated in the caption. The prescription of Newson and Duncan predicts a ratio of integrated symmetric to asymmetric fission which is much larger than found experimentally. The predicted ratio has been reduced by the *same factor* for all six parts of Fig. 1. This factor corresponds to a correction for the relatively low excitation energy of the symmetric fragments[3] since they are formed at the expense of the energy (>4 Mev) to break up the double magic core ($_{50}Sn_{82}{}^{132}$) of the heavier asymmetric fragment. It seems reasonable to find the same factor for compound nuclei with about the same energy relative to fission threshold.

Only two parameters are needed to explain most of the fission yield data for all five cases where the compound nucleus is within one Mev or so of the fission threshold, but it is necessary to treat n as a free parameter for each curve to fit the small steep regions on each side of mass number $\frac{1}{2}A_0$. The qualitative agreement [Fig. 1(F)] for Ra^{226} is also interesting. One would expect a better fit in this case if the proton bombarding energy were closer to the threshold value. It is interesting to note that, according to our definition, asymmetric fission becomes impossible for $A_0<78+132=210$, which is in agreement with the fact that single maxima are always observed for the fission of Bi^{209} and lighter nuclides.[3] The interpretation of underthreshold (spontaneous) and over-threshold ($E_n>5$ Mev) fission will be discussed in a later paper.

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Gamma-Gamma Directional Correlations in Nd^{147}†*

ATAM P. ARYA‡
Department of Physics, The Pennsylvania State University, University Park, Pennsylvania
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Directional correlation measurements have been made on the 320- to 92-kev and 280-to 320-kev gamma-ray cascades in Pm^{147} following the decay of 11.1-day Nd^{147} with a coincidence scintillation spectrometer using NaI detectors. The observed correlation functions are: $W(\theta)=1-(0.1030\pm0.0298)\ P_2(\cos\theta)+(0.0107\pm0.0099)\ P_4(\cos\theta)$, and $W(\theta)=1+(0.0710\pm0.0162)\ P_2(\cos\theta)-(0.0126\pm0.0103)\ P_4(\cos\theta)$, respectively, for the two cascades. The energy levels of Pm^{147} at ground state, 92 kev, 410 kev, and 690 kev were found to be $\frac{7}{2}+$, $\frac{7}{2}+$, $\frac{7}{2}+$, and $\frac{5}{2}+$, respectively. It was found that the 92-kev gamma ray has a mixture of $(95\pm2)\%$ $M1$ and $(5\pm2)\%$ $E2$ with $\delta_{92}=+(0.229\pm0.143)$, the 320-kev gamma ray has a mixture of 1% $M1$ and 99% $E2$ with $\delta_{320}=+9.95\pm0.11$, and the 280-kev gamma ray has a mixture of 99% $M1$ and 1% $E2$ with $\delta_{280}=-0.11\pm0.11$.

INTRODUCTION

THE decay scheme of Nd^{147}, 11.1 day half-life, has been investigated by different authors[1–9] and is shown in Fig. 1. There is complete agreement in the decay schemes as proposed by Hans *et al.*[8] and Mitchell[6] on the one hand, and Cork[7] on the other hand, except for the level at 289 kev, the transition β_5^-, the gamma rays of energies 160 kev and 198 kev and the position of the gamma ray of energy 410 kev. But none of these discrepancies are involved in the present correlation studies. The gamma rays and the energy levels of interest are shown by boldface lines. The spin of the ground-state of Nd^{147} has been measured by Abraham[10] to be $\frac{5}{2}-$. Very recently the ground-state spin of Pm^{147} has been measured by Klinkenberg and Tomkins,[11] and by Cabezas *et al.*,[12] and is found to be $\frac{7}{2}$. All the β^- transitions from the ground state of Nd^{147} and feeding the excited states of Pm^{147} have been classified as first forbidden with a spin change of zero or one and with a change of parity.[2,3,5] Thus each excited level in Pm^{147} must have one of the following values: $\frac{3}{2}+$, $\frac{5}{2}+$, $\frac{7}{2}+$.

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* This work was based on a thesis to be submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy.
‡ Permanent home address: 3623 Chawri Bazar, Delhi-6, India.

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All the measured K/L ratios and K-shell conversion coefficients[3,6,13,14] favor identification of the 92-kev gamma transition as $M1$ with a small mixture of $E2$. The percentage of $E2$ in $M1$ found by different authors varies from 3 to 7% of $E2$.

The nuclear alignment experiments have been done by two different groups. The results of Ambler, Hudson, and Temmer[15,16] show that the 92-kev gamma ray is a mixture of 97% $M1$ and 3% $E2$ with $\delta=+0.17$ while the 530-kev gamma ray is a pure $E2$ transition. They explained their polar diagram with spin assignments of

$$Nd^{147}(92\text{-kev})\frac{9}{2}^{-}\xrightarrow{\beta^-}\frac{7}{2}^{+}\xrightarrow[(M1+E2)]{\gamma}\frac{5}{2}^{+},$$

$$Nd^{147}(530\text{-kev})\frac{9}{2}^{-}\xrightarrow{\beta^-}\frac{9}{2}^{+}\xrightarrow[E2]{\gamma}\frac{5}{2}^{+}.$$

The other group, Bishop and his associates,[17] have also interpreted their alignment results by taking the ground state of Nd^{147} as $9/2^-$, and the ground state of Pm^{147} as $\frac{5}{2}^+$. They obtained for the 92-kev gamma ray 96% $M1$ and 4% $E2$ with $\delta=-0.17\pm0.15$ and $P/\epsilon=+0.600$, where P is the polarizability and ϵ is the anisotropy, and have assigned a spin of $\frac{7}{2}^+$ to the 92-kev level; while for the 530-kev gamma ray they got a mixture of 56% $E2$ and 44% $M1$ with $\delta=+0.75\pm0.25$, $P/\epsilon=0.68$, and have assigned a spin value $\frac{7}{2}^+$ to the 530-kev level. These alignment experiments require reinterpretation.

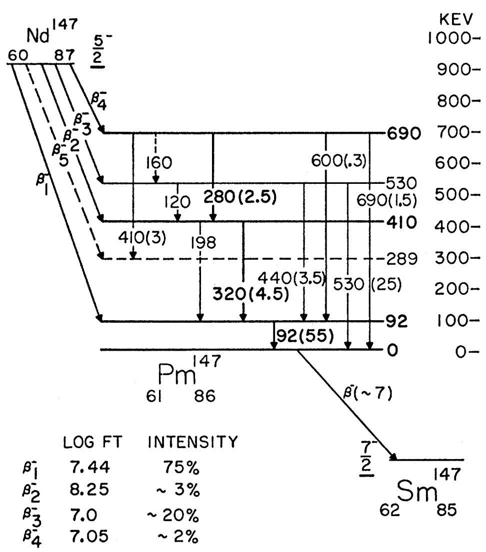

FIG. 1. Decay scheme of Nd^{147}. The numbers in parenthesis with the gamma rays are their relative intensities.

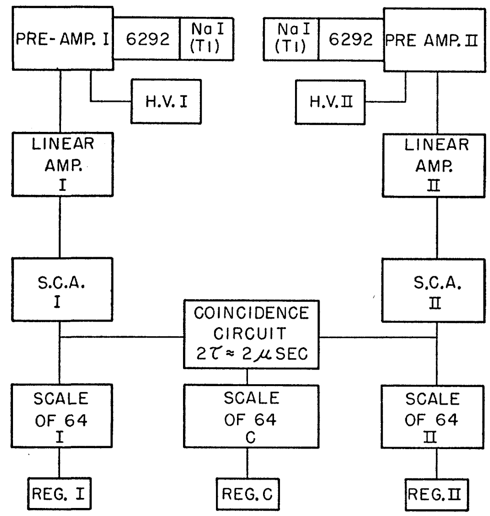

FIG. 2. Block diagram of the gamma-gamma coincidence counter.

The gamma-gamma directional correlations have been done on the 320- to 92-kev cascade by Lindqvist and Karlsson.[18] Their results are

$$W(\theta)=1-(0.097\pm0.007)P_2(\cos\theta)+(0.023\pm0.018)P_4(\cos\theta),$$

and explain the correlation as

$$\tfrac{5}{2}(D+Q)\xrightarrow{\gamma}\tfrac{7}{2}(D+Q)\xrightarrow{\gamma}\tfrac{5}{2},$$

with mixing ratio for the 92-kev transition

$$\delta(E2/M1)=+0.25\pm0.05,$$

which gives for the 92-kev gamma ray a mixture of $(94\pm2)\%$ $M1$ and $(6\pm2)\%$ $E2$. We have investigated this correlation and reinterpreted the data in view of the fact that the measured ground state spin of Pm^{147} is $\frac{7}{2}$ and not $\frac{5}{2}$. In addition, to ensure these spin assignments and to give a spin value to the level at 690 kev, we have investigated the correlation of the 280- to 320-kev gamma cascade.

The gyromagnetic ratio for the 92-kev level of Pm^{147} has been measured by Bodenstedt *et al.*[19] and the results interpreted in the Nuclear Data Sheets.[20] These results show that the spin value of $g_{7/2}$ is most probable for the 92-kev level.

EXPERIMENTAL PROCEDURE

The block diagram of the apparatus used is shown in Fig. 2. The slow coincidence circuit used had the resolving time $2\tau=2.1$ μsec. The scintillation counters consisted of $1\frac{3}{4}\times2$-in. NaI(Tl) crystals mounted on

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[18] Torsten Lindqvist and Erik Karlsson, Arkiv Fysik **12**, 519 (1957).
[19] E. Bodenstedt *et al.*, Z. Naturforsch. **13a**, 425 (1958).
[20] Nuclear Data Sheets, National Research Council, NRC 59-1-135 and 59-1-138.

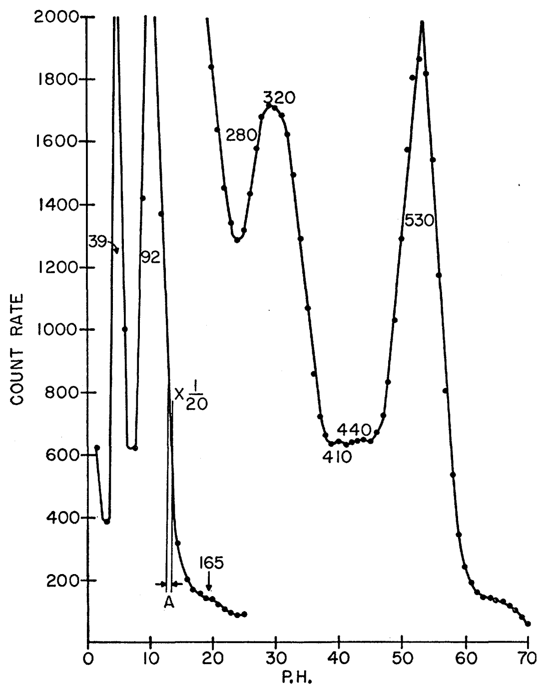

FIG. 3. Scintillation spectrum of gamma rays following the decay of Nd^{147}.

DuMont 6292 photomultipliers. Lateral lead shielding was used to eliminate coincidences due to scattering. A differential discriminator was used for energy selection.

Three neodymium samples, in the form of metallic fused chips 99.9% pure, were irradiated at different times in the thermal neutron flux of the Pennsylvania

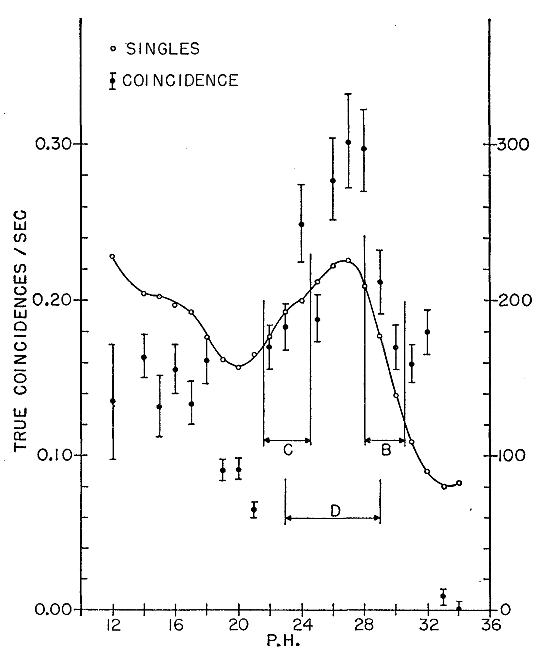

FIG. 4. Coincidence spectrum of 92-kev gamma ray with 320-kev gamma ray.

State University Research Reactor for different lengths of time varying from 75 to 130 hr. Because of the simultaneous production of $Nd^{149}(T_{\frac{1}{2}}=1.8\text{hr})$ and its daughter $Pm^{149}(T_{\frac{1}{2}}=50\text{hr})$, and $Pm^{151}(T_{\frac{1}{2}}=26\text{hr})$, irradiated samples were allowed to decay from three to six weeks in order to get rid of these short-lived activities. The correlation experiments were started only when the activity left was mainly Nd^{147}(11.1 day). The experiments for the 280–320-kev gamma cascade were repeated for the solution of Nd^{147} (fused chips dissolved in HCl acid), and no change in the correlation was observed. No necessity of repeating the experiment for the 320- to 92-kev gamma cascade was felt because the results of our solid sample agree with those of Lindqvist *et al.*[18] who did this correlation with solution sample.

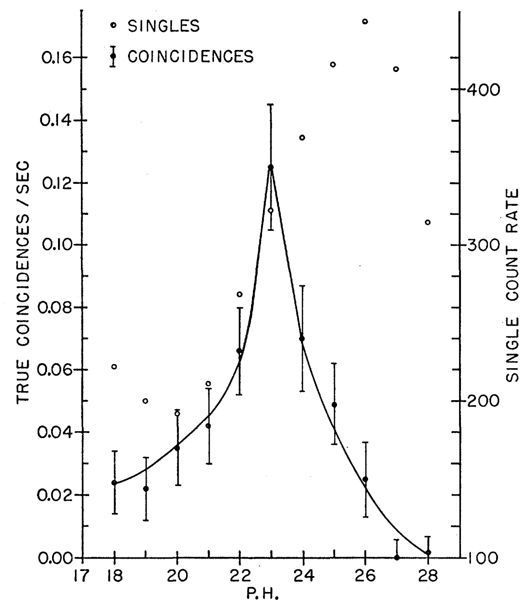

FIG. 5. Coincidence spectrum of 280-kev gamma ray with 320-kev gamma ray.

The half-life of the 92-kev level has been measured[21] to be $\sim 2.3\times 10^{-9}$ sec. Because of this and the fact that the result of solution and solid samples are the same, the measured correlation functions should not be attenuated due to extranuclear fields.

Figure 3 shows the single spectrum of Nd^{147} while Figs. 4 and 5 show the coincidence spectrum of the two cascades of interest. The data were taken at intervals of 15° from 90° to 180°. The angle between the detectors was changed after every five minutes. A very frequent check was made on the resolving time of the coincidence circuit. Decentering of the sample was not allowed to be more than 1%.

A least-squares fit of the data was made to the function $w(\theta)=1+a_2\cos^2\theta+a_4\cos^4\theta$, and the values of

[21] R. L. Graham *et al.*, J. of Phys. **31**, 377 (1953).

a_2 and a_4 were evaluated. Then, the corresponding values of the coefficients A_2' and A_4' in the expansion $W(\theta)=1+A_2'P_2(\cos\theta)+A_4'P_4(\cos\theta)$ were calculated. These values of the coefficients were corrected for the finite angular resolution[22] and the corrected values of A_2, A_4 were obtained.

RESULTS

320- to 92-kev Correlation

One differential discriminator was set at position A, shown in Fig. 3, bottom of the 92-kev gamma peak to avoid the amplifier drift, while the other differential discriminator was set at B as shown in Fig. 4, to the right of the 320-kev gamma-ray peak. This setting was made to avoid any contribution from the 280-kev gamma ray. It was found by extrapolation of the 280-kev gamma ray that the contribution from this peak was negligible for the setting at B. The correlation data are shown in Fig. 6. The solid curve is the least-squares curve and the error flags indicate the root-mean-square statistical errors of the experimental points. The experimental values of the expansion coefficients corrected for finite geometry are $A_2=-0.1030\pm0.0298$; $A_4=+0.0107\pm0.0099$ and the value of the anistropy $A=-0.1400\pm0.0314$, which are in agreement with the values obtained for these coefficients by Lindqvist.[18]

The mixing parameter δ is defined as the ratio of the reduced matrix elements β and α for quadrupole and dipole radiation, respectively.[23] If $\delta=\beta/\alpha$, then δ^2 is equal to the ratio of the intensities of quadrupole and dipole radiation. Q, the quadrupole content, will be equal to $\delta^2/(1+\delta^2)$, and the dipole content will be $(1-Q)$.

280- to 320-kev Correlation

The experiments on this correlation were divided into three parts. (1) The data were collected with solid sample by keeping one discriminator at position B and the other at C as shown in Fig. 4. (2) The experiments were repeated by keeping both the differential discriminators wide open ($\sim$6 v each) as shown by setting D in Fig. 4 so as to receive both the 280- and the 320-kev gamma rays in both the detectors. In this case also the solid sample was used. (3) The data were taken only at 180° and 90° with the liquid sample. No difference was observed as compared with the data taken in the above two cases, and so it was not necessary to carry it any further.

The data are shown in Fig. 7. The experimental value of the correlation obtained, corrected for finite geometry, is

$$W(\theta)=1+(0.0710\pm0.0162)P_2(\cos\theta)-(0.0126\pm0.0103)P_4(\cos\theta).$$

[22] M. E. Rose, Phys. Rev. **91**, 610 (1953).
[23] L. C. Biedenharn and M. E. Rose, Revs. Modern Phys. **25**, 729 (1953).

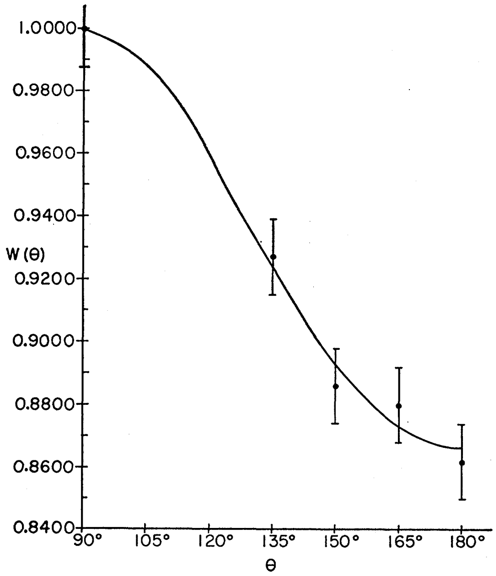

FIG. 6. Directional correlation of the 320 to 92-kev cascade. Solid line is the least-squares fit of the experimental points. Flags indicate the probable error.

Therefore,

$$A_2=+0.0710\pm0.0162, \quad A_4=-0.0126\pm0.0103,$$

and $A=+0.1028\pm0.0180$.

INTERPRETATION AND DISCUSSION

The ground state spin of Pm^{147} has been measured[11,12] and is found to be $\frac{7}{2}$. This agrees with the assignment of $g_{\frac{7}{2}}$ for the ground state of Pm^{147} from the nuclear shell model. This assignment of $\frac{7}{2}+$ is also consistent with the β^- transition from the ground state of Pm^{147} to Sm^{147} which has a logft value[5] $\sim$7 and has been classified as first forbidden[24] with a spin change of 0 or 1 while the measured spin[25] of the ground state of Sm^{147} is $\frac{7}{2}-$.

All the β^- transitions from the ground state of Nd^{147}

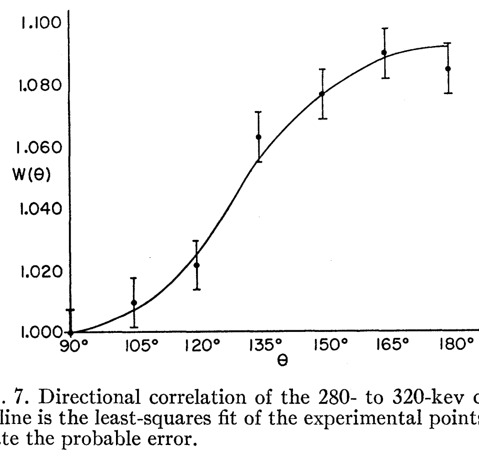

FIG. 7. Directional correlation of the 280- to 320-kev cascade. Solid line is the least-squares fit of the experimental points. Flags indicate the probable error.

[24] L. W. Nordheim *et al.*, Revs. Modern Phys. **23**, 315 (1951).
[25] Kiyoshi Murakawa, Phys. Rev. **93**, 1232 (1954).

(which has been measured to be $\frac{5}{2}^-$) leading to the excited states of Pm^{147} have been classified as first forbidden with a spin change of 0 or 1 and change in parity.[2,3,5] So each of the excited states of Pm^{147} will have one of the following values: $\frac{3}{2}^+$ $\frac{5}{2}^+$ $\frac{7}{2}^+$.

As the measured spin of the ground state of Pm^{147} is $\frac{7}{2}^+$, then the 92-kev level can be either $\frac{5}{2}^+$ or $\frac{7}{2}^+$. The assignment of $\frac{3}{2}^+$ to the 92-kev level is not possible because (1) the 92-kev gamma ray has some $M1$ radiation, and (2) this would require $A_4=0$ for the 320- to 92-kev gamma-gamma correlation, while experimentally it is found[18] that most probably $A_4\neq 0$.

Taking the 92-kev level to be $\frac{5}{2}^+$, we get from the polarization experiments of Bishop *et al.*[17] two values of δ for the 92-kev gamma ray:

$$\delta_{92}=+10 \quad \text{or} \quad \delta_{92}=+0.04.$$

The value of $\delta_{92}=+10$ is not possible because it requires the 92-kev gamma ray to be mostly $E2$ which is not consistent with the conversion coefficient and K/L ratio measurements. The value of $\delta_{92}=+0.04$ gives a mixture of 99.8% $M1$ and 0.2% $E2$ for the 92-kev gamma ray. This mixture of $E2$, though very low as compared with the conversion coefficient and K/L ratio measurements, may possibly be accepted as correct. Taking this value of $\delta_{92}=+0.04$, the 320- to 92-kev correlation cannot be explained by any assignment of $\frac{3}{2}^+$, $\frac{5}{2}^+$, or $\frac{7}{2}^+$ to the 410-kev level; because the assignment of $\frac{5}{2}^+$ requires A_4 to be negative while experimentally it is found to be positive, and the assignments of $\frac{3}{2}^+$ or $\frac{7}{2}^+$ do not satisfy the 320- to 92-kev gamma-gamma correlation. Also the assignment of $\frac{3}{2}^+$ to the 410-kev level requires $A_4=0$ for the 280- to 320-kev correlation, while experimentally it is found that probably $A_4\neq 0$.

The assignment of the $\frac{5}{2}$ value to the 92-kev level is also rejected on the basis of the gyromagnetic ratio measurements[20] which favor an assignment of $\frac{7}{2}$.

The only choice left is to take the 92-kev level to be $\frac{7}{2}^+$. The polarization experiments of Bishop *et al.*[17] give give two values for δ_{92}:

$$\delta_{92}=-7.4 \quad \text{or} \quad \delta_{92}=+0.25.$$

Again, the value $\delta_{92}=-7.4$ is not possible because it requires the 92-kev gamma ray to be mostly $E2$. $\delta_{92}=+0.25$ gives for the 92-kev gamma ray a mixture of 6% $E2$ and 94% $M1$ which is consistent with the conversion coefficient and K/L ratio measurements. We take the mean value, $(5\pm2)\%$ $E2$ and $(95\pm2)\%$ $M1$, as the mixture of the 92-kev transition. This gives the value $\delta_{92}=+0.229\pm0.143$.

In order to explain the 320- to 92-kev gamma-gamma correlation, the assignments of spins $\frac{3}{2}^+$ or $\frac{5}{2}^+$ to the 410-kev level is not very likely because these require A_4 to be negative while experimentally it is found to be positive. Also the assignment of $\frac{3}{2}^+$ requires (1) a mixture of octupole radiation for the 320-kev gamma ray which is not probable from the lifetime considerations, (2) $A_4=0$ for the 280- to 320-kev gamma-gamma correlation while experimentally it is found that probably $A_4\neq 0$. If we take the 410-kev level to be $\frac{7}{2}^+$, then the 320- to 92-kev correlation can be explained by the sequence

$$\frac{7}{2}^+ \xrightarrow[(D+Q)]{320} \frac{7}{2}^+ \xrightarrow[(D+Q)]{92} \frac{7}{2}^+ .$$

The only value of Q for the 320-kev gamma ray which is consistent with our experimental results and those of Lindqvist *et al.*[18] is

$$Q=0.99\pm0.01,$$

which gives for the 320-kev gamma ray

$$\delta_{320}=+9.95\pm0.11,$$
$$E2=(99\pm1)\%, \quad M1=(1\pm1)\%.$$

By taking this value of $\delta_{320}=+9.95$, any spin assignment to the 690-kev level must explain the 280- to 320 kev correlation. The three different sequences possible are

$$\frac{7}{2}^+ \xrightarrow[(D+Q)]{280} \frac{7}{2}^+ \xrightarrow[D+Q]{320} \frac{7}{2}^+ ,$$

$$\frac{5}{2}^+ \xrightarrow[(D+Q)]{280} \frac{7}{2}^+ \xrightarrow[(D+Q)]{320} \frac{7}{2}^+ ,$$

$$\frac{3}{2}^+ \xrightarrow[Q]{280} \frac{7}{2}^+ \xrightarrow[(D+Q)]{320} \frac{7}{2}^+ .$$

The first sequence is not probable because it requires A_4 to be positive while experimentally it is found to be negative. In the third sequence the assignment of $\frac{3}{2}^+$ requires a mixture of octupole radiation for the 280-kev gamma ray which is not probable. Hence the only sequence possible is

$$\frac{5}{2}^+ \xrightarrow[(D+Q)]{280} \frac{7}{2}^+ \xrightarrow[(D+Q)]{320} \frac{7}{2}^+ .$$

The values of Q and δ obtained from our experimental results of the 280- to 320-kev correlation are

$$Q=+(0.01\pm0.01),$$
$$\delta_{280}=-(0.11\pm0.11),$$

which gives for the 280-kev gamma ray a mixture of

$$M1=(99\pm1)\%, \quad E2=(1\pm1)\%.$$

The results of the above discussion are summarized in Table I.

It is to be noted that in the above discussion we have taken it for granted that there is a β^- transition from the ground state of Nd^{147} leading to the 410-kev excited level of Pm^{147}. Evans[9] did not find this β^- transition

which means that the 410-kev levels can also take the values 1/2, 9/2, 11/2, or higher. But any of these assignments to the 410-kev level do not satisfy the 320- to 92-kev gamma-gamma correlation. The assignment of $\frac{1}{2}$ requires (1) the 320-kev gamma ray to be $M3$ which is not probable, and (2) $A_2=0$ for the 280- to 320-kev correlation. The assignment of 9/2 requires A_4 to be negative while experimentally is found to be positive; and 11/2 requires a mixture of octupole radiation for the 320-kev gamma ray which is not probable. Spins higher than 11/2 require higher multipole radiations which are not probable.

SUMMARY AND CONCLUSION

With the known ground-state spins of Pm^{147}, Nd^{147}, and Sm^{147}, and the multipolarity of the 92-kev gamma ray, it has been possible with the help of the gamma-gamma directional correlations and the polarization measurements[16,17] to assign probable spins to the excited states of Pm^{147}. The ground state, the 92-kev level, the 410-kev level, and the 690-kev level have been assigned spins $\frac{7}{2}+$, $\frac{7}{2}+$, $\frac{7}{2}+$, and $\frac{5}{2}+$, respectively. The following are the multipolarities of different gamma rays which are consistent with the probable spin assignments given above: The 92-kev gamma ray has a mixture of $(95\pm2)\%$ $M1+(5\pm2)\%$ $E2$ with $\delta_{92}=+(0.229\pm0.143)$; the 320-kev gamma ray has a mixture of 1% $M1+99\%$ $E2$ with $\delta_{320}=+(9.95\pm0.11)$, and the 280-kev gamma ray has a mixture of 99% $M1+1\%$ $E2$ with $\delta_{280}=-(0.11\pm0.11)$.

The absence of a β^- transition leading from the ground state of Nd^{147} to the ground state of Pm^{147} is unexplained.

TABLE I. Summary of the discussion of spin assignments to Pm^{147}.

0	92 kev	410 kev	690 kev	Results
$\frac{7}{2}$				Experimentally found
	$\frac{3}{2}, \frac{5}{2}, \frac{7}{2}$	$\frac{3}{2}, \frac{5}{2}, \frac{7}{2}$	$\frac{3}{2}, \frac{5}{2}, \frac{7}{2}$	Because of β^- transition from $Nd^{147} \rightarrow Pm^{147}$
$\frac{7}{2}$	$\frac{3}{2}$			Not possible because (1) the 92-kev gamma ray has some $M1$ radiation; (2) requires $A_4=0$ for the 320- to 92-kev correlation, which is not likely
	$\frac{5}{2}, \frac{7}{2}$			Polarization and conversion coefficient measurements
	$\frac{5}{2}$	$\frac{5}{2}$		Not probable; requires A_4 to be negative for the 320- to 92 kev correlation
		$\frac{3}{2}$		(1) Does not satisfy the 320- to 92 kev correlation; (2) requires $A_4=0$ for the 280- to 320 kev correlation, which is not probable
		$\frac{7}{2}$		Does not satisfy the 320- to 92 kev correlation
	$\frac{7}{2}$	$\frac{5}{2}$		Requires A_4 to be negative for the 320- to 92 kev correlation
		$\frac{3}{2}$		Not possible; (1) requires $A_4=0$ for the 280- to 320 kev correlation, which is not likely; (2) requires a mixture of $M3$ for the 320-kev gamma ray
		$\frac{7}{2}$	$\frac{7}{2}$	Requires A_4 to be positive for the 280- to 320 kev correlation, and this is not probable
			$\frac{3}{2}$	Requires a mixture of octupole radiation for the 280-kev gamma ray
			$\frac{5}{2}$	Satisfies the 280- to 320 kev correlation
$\frac{7}{2}$	$\frac{7}{2}$	$\frac{7}{2}$	$\frac{5}{2}$	The probable spin sequence

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