This width is comparable with other $M1$ widths in light nuclei and also with the widths encountered for slow $E1$ transitions.

Comparison of Γ_0 with the result of the scattering experiment (3E) leads to a branching ratio $\Gamma_0/\Gamma=0.58\pm0.08$, in very good agreement with the ratio $\Gamma_0/\Gamma=0.57\pm0.05$ obtained from the analysis of the pulse-height distribution (IIB). For the total width of the level, one finally has

$$\Gamma=(0.42\pm0.06)\text{ eV},$$

corresponding to a mean life

$$\tau_{\text{level}}=1.57\times10^{-15}\text{ sec}.$$

C. Spin of the 4.504-MeV Level

The absence of appreciable resonance scattering from the 4.504-MeV level of Al^{27}, which falls within the range of the $N^{15}(p,\alpha)C^{12}$ gamma line, makes it rather probable that the 4.504-MeV level has either spin $\frac{1}{2}$ or a spin $\geq\frac{9}{2}$.

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Gamma-Gamma Directional Correlation in Pr^{143}

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The directional correlations of four γ–γ cascades in Pr^{143} fed from the decay of Ce^{143} have been studied. The correlation functions for the 293–57, 232–493, 591–293, and the 668–57-keV cascades are found to be: $W(\theta_{293-57})=1+(0.112\pm0.009)P_2(\cos\theta)+(0.000\pm0.014)P_4(\cos\theta)$, $W(\theta_{232-493})=1-(0.176\pm0.008)P_2(\cos\theta)-(0.001\pm0.012)P_4(\cos\theta)$, $W(\theta_{591-293})=1+(0.146\pm0.015)P_2(\cos\theta)+(0.003\pm0.026)P_4(\cos\theta)$, and $W(\theta_{668-57})=1+(0.063\pm0.018)P_2(\cos\theta)$, respectively. Knowing the spin of the ground state of Pr^{143} as $\frac{7}{2}^+$ and the recently measured spin of the ground state of Ce^{143} as $\frac{3}{2}^-$, and from the analysis of the angular-correlation results combined with the log ft values of β transitions from Ce^{143}, the levels of Pr^{143} have been assigned spins and parities as follows: ground state, $\frac{7}{2}^+$; 57 keV, $\frac{5}{2}^+$; 351 keV, $\frac{3}{2}^+$; 493 keV, $\frac{7}{2}^+$; 725 keV, $\frac{5}{2}^+$; 942 keV, $\frac{3}{2}^+$ or $\frac{5}{2}^+$; 1160 keV, $\frac{1}{2}^+$, $\frac{3}{2}^+$, or $\frac{5}{2}^+$; and 1395 keV, $\frac{3}{2}^-$ or $\frac{5}{2}^-$.

I. INTRODUCTION

THE energy levels of Pr^{143} populated from the decay of the 33-h Ce^{143} have been investigated recently by detailed scintillation and coincidence studies.[1] Excited states of Pr^{143} at 57, 351, 493, 725, 942, 1160, and 1395 keV were established. The measured spin[2] of the ground state of Pr^{143} from atomic-beam studies is $\frac{7}{2}$. In order to investigate further the properties of the excited states and the nature of the gamma transitions from these states, gamma-gamma angular-correlation measurements have been made.

The angular correlation of the 293–57-keV cascade has been measured previously by Rao and Hans[3] and by Bożek *et al.*[4] The results have been reanalyzed by Graham *et al.*[5] using the multipolarities of these transitions as determined from internal-conversion studies and the measured value of the spin of Pr^{143} as $\frac{7}{2}$. Since the contributions of the many higher-energy gamma rays,[1] in coincidence with the 293-keV γ ray, have not been taken into account by these authors, it was necessary to remeasure the angular correlation of the 293–57-keV cascade by minimizing these contributions.

From the systematics of the neighboring odd-neutron nuclei the spin of the ground state of Ce^{143} was expected to be $\frac{5}{2}^-$ or $\frac{7}{2}^-$ due to the coupling of three $f\frac{7}{2}$ neutrons outside the closed shell. Since the recent measurement[6] of the ground-state spin of Ce^{143} shows it to be $\frac{3}{2}$, the spins of the excited states of Pr^{143} inferred from the log ft values of the β transitions from Ce^{143} are to be revised. This has been discussed in Sec. III.

II. EXPERIMENTAL PROCEDURES AND RESULTS

The angular-correlation apparatus consisted of three scintillation detectors with NaI(Tl) crystals coupled to RCA 6810-A photomultipliers. Two of the counters were identical with 2-in.×2-in. crystals, while the third one was mounted with either a 1.5-in.×0.5-in. crystal when a 57-keV γ ray was detected or a 1.5-in.×1.5-in. crystal for the 232- and 293-keV γ rays. The three counters were mounted in a horizontal plane with their axes passing through the center where the source was kept. The distance of the detectors from the source was 7 cm in each case. The two identical detectors were kept fixed

[1] K. P. Gopinathan, M. C. Joshi, and E. A. S. Sarma, Phys. Rev. 136, B1247 (1964).
[2] B. Budick, I. Maleh, and R. Marrus, Phys. Rev. 135, B1281 (1964).
[3] G. N. Rao and H. S. Hans, Nucl. Phys. 41, 511 (1963).
[4] E. Bożek, A. Z. Hrynkiewicz, S. Ogaza, M. Rybicka, and J. Styczen, Phys. Letters 6, 89 (1963).
[5] R. L. Graham, J. M. Hollander, and P. Kleinheinz, Nucl. Phys. 49, 641 (1963).
[6] Isaac Maleh, Phys. Rev. 138, B766 (1965).

at 0° and 270° positions, respectively, and the third one could be moved between 90° and 180°. All the crystals were shielded at the sides by 8 mm of lead graded with cadmium and copper. A hollow lead cone was placed in front of the movable counter in order to avoid scattered radiation from the other crystals entering it. In the case of the 232–493- and the 591–293-keV cascades, ~3-mm-thick lead absorbers were placed in front of the crystals detecting the 493- and the 591-keV γ rays to prevent backscattered radiation from these crystals entering the other crystal. A two-channel fast-slow coincidence unit with a Simms-type fast coincidence circuit,[7] and having a resolving time $2\tau=20$ nsec, was used. Energy selection was made by use of single-channel analyzers. Coincidences were observed separately with pulses from either of the fixed counters and the movable counter as common channel. In this way two sets of observations at complementary angles were obtained simultaneously. This enabled us to obtain double the normal coincidence rate. The true-to-chance coincidence ratio was about 20 for the 293–57- and the 232–493-keV cascades. The chance coincidence rate was measured by introducing a delay of 120 nsec in the common channel and observing the chance coincidences for a sufficiently long time.

The observed coincidences were corrected for chance coincidences and the corrected coincidence rates at each angle were normalized by the singles count rates. The normalized coincidence rates, averaged over the corresponding angles of the two channels, were analyzed by the least-squares method[8] and fitted to the correlation function

$$W(\theta)=1+G_2A_2P_2(\cos\theta)+G_4A_4P_4(\cos\theta),$$

where G_2 and G_4 are the attenuation factors due to the finite solid angle of the detectors. Correcting for these

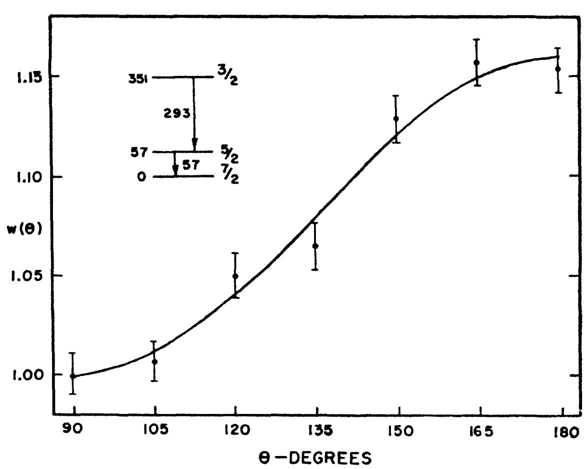

FIG. 1. The experimental results of the angular correlation of the 293–57-keV cascade. The solid line is the least-squares-fitted curve of the experimental points.

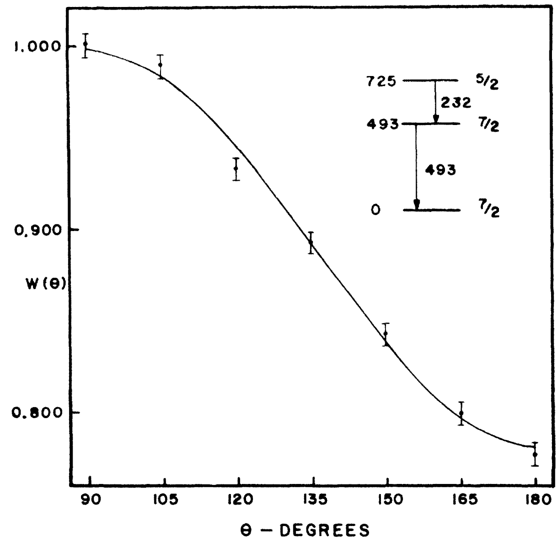

FIG. 2. Angular-correlation results of the 232–493-keV cascade with the least-squares-fitted curve.

factors from the curves given by Frauenfelder and Steffen,[9] and by Stanford and Rivers[10] for the appropriate geometries, the A_2 and A_4 coefficients were determined.

The performance of the setup was checked by measuring the angular correlation of the 1170–1330-keV cascade in Ni^{60}. The experimentally measured coefficients A_2 and A_4 for this cascade agreed with the theoretical values.

The source of Ce^{143} was made by irradiating a sample of 90% enriched Ce^{142} in the Canada India Reactor at Trombay for two days followed by chemical purification as described in Ref. 1. The final source was prepared in the form of a dilute solution of $CeCl_3$ in dilute HCl in a thin-walled tube of 2-mm diam×3-mm length. With the source in dilute solution form, any possible paramagnetic attenuation is minimized.

For the 293–57-keV cascade the use of the 1.5-in. ×0.5-in. crystal for the 57 keV γ rays minimized the contribution of the higher-energy γ rays. Absorbers of 100 mg/cm² each of tin and copper were used to absorb x rays without attenuating the 57-keV γ rays appreciably. Coincidences at seven angles were observed collecting at least 10 000 coincidence counts at each angle. The experimental points with the least-squares-fitted curve for this cascade are shown in Fig. 1. The correlation function corrected for finite solid angle was found to be

$$W(\theta)=1+(0.112\pm0.009)P_2(\cos\theta)+(0.000\pm0.014)P_4(\cos\theta),$$

in agreement with earlier measurements.[3,4]

In the case of the 232–493-keV cascade at least 20 000

[7] P. C. Simms, Rev. Sci. Instr. 32, 894 (1961).

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

[9] H. Frauenfelder and R. M. Steffen in *Alpha-, Beta-, and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (North-Holland Publishing Company, Amsterdam, 1965), p. 997.

[10] A. L. Stanford and W. K. Rivers, Rev. Sci. Instr. 30, 719 (1959).

coincidences were observed at each of the seven angles. The experimental results are shown in Fig. 2. The corrected correlation function was found to be

$$W(\theta)=1-(0.176\pm0.008)P_2(\cos\theta)-(0.001\pm0.012)P_4(\cos\theta).$$

The 591–293-keV cascade being a weak one, observations were made at four angles (Fig. 3) collecting about 6000 true coincidence counts at each angle. The true-to-chance coincidence ratio was 2 to 1 in this case. The chance coincidence rate was accurately measured by collecting a total of 5000 chance coincidences. The measured correlation function for this cascade is

$$W(\theta)=1+(0.146\pm0.015)P_2(\cos\theta)+(0.003\pm0.026)P_4(\cos\theta).$$

The 668–57-keV cascade is also a weak one and hence only about 3000 coincidence counts were observed at

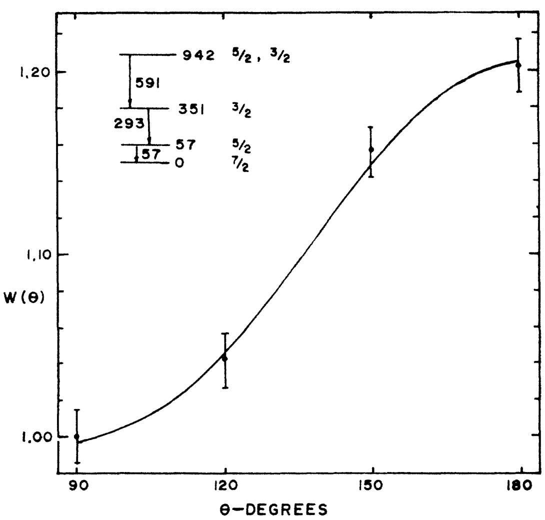

FIG. 3. The experimental angular-correlation results of the 591–293-keV cascade with the least-squares-fitted curve.

each of the four angles 90°, 120°, 150°, and 180°. The true-to-chance coincidence ratio was 2.5 in this case. Since the 57-keV γ ray is known to be very nearly pure $M1$ from internal conversion studies[5] and the 293–57-keV angular correlation, the A_4 coefficient in the correlation function of the 668–57-keV cascade is expected to be zero. Hence the least-squares fit was made with terms up to $P_2(\cos\theta)$ and the result was

$$W(\theta)=1+(0.063\pm0.018)P_2(\cos\theta).$$

III. DISCUSSION

The spins of the ground state and the 57-keV state of Pr^{143} are $\frac{7}{2}^+$ and $\frac{5}{2}^+$, respectively, as discussed in Ref. 1. Since the spin of the ground state of Ce^{143} is now measured to be $\frac{3}{2}$, this could be explained as due to the neutron configuration $(f_{7/2})^3$ or $(f_{7/2})^2(p_{3/2})^1$, indicating

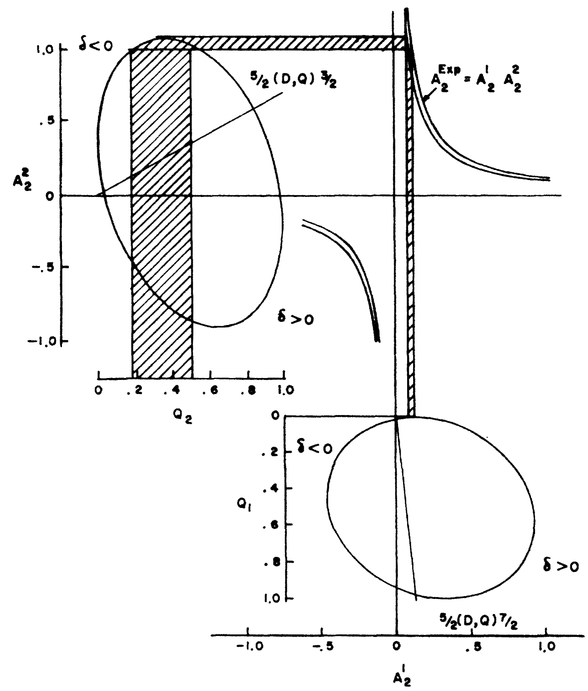

FIG. 4. The graphical analysis of the angular-correlation coefficients of the 293–57-keV cascade for the $\frac{3}{2}$(293)-$\frac{5}{2}$(57)-$\frac{7}{2}$ sequence. The hatched areas show regions of agreement with the internal-conversion measurements of Ref. 5 and the angular-correlation measurements. The sign of δ for the 293-keV transition is negative for this cascade.

the parity to be negative. The nonunique first-forbidden β transition[11] to the 57-keV level with $\log ft=7.7$ shows

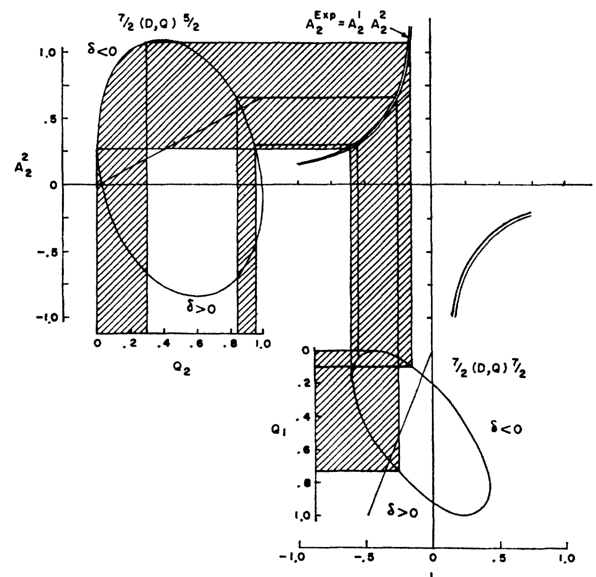

FIG. 5. The analysis of the 232–493-keV cascade for the sequence $\frac{5}{2}$(232)-$\frac{7}{2}$(493)-$\frac{7}{2}$. The hatched areas show values of Q_1 and Q_2 consistent with the experimental A_2 and A_4 coefficients.

[11] D. W. Martin, M. K. Brice, J. M. Cork, and S. B. Burson, Phys. Rev. **101**, 182 (1956).

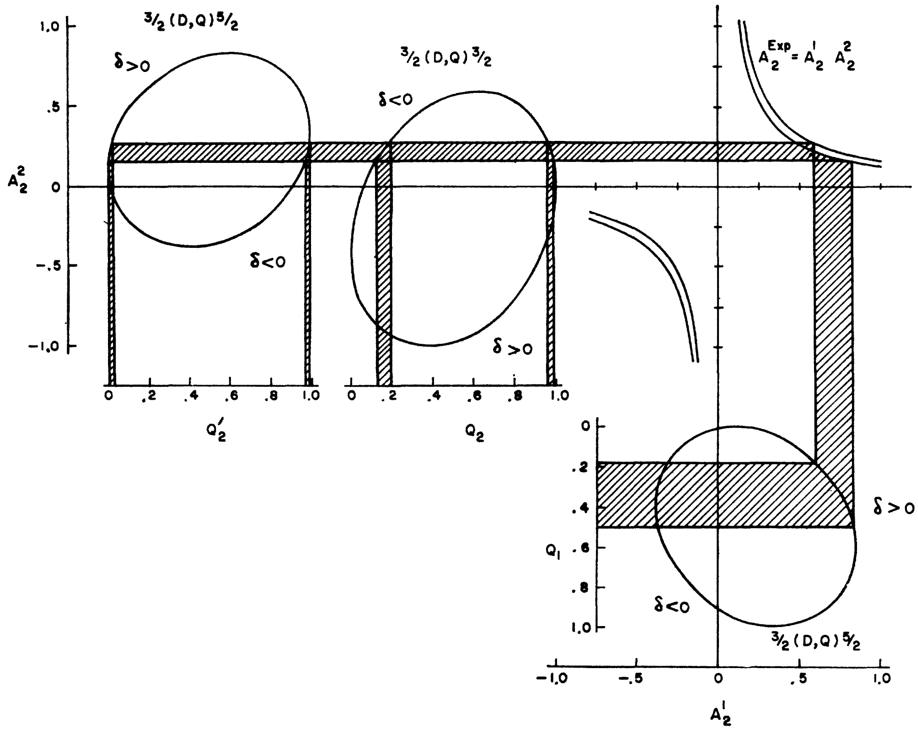

FIG. 6. The analysis of the 591–293-keV cascade for the sequences $\frac{3}{2}$-$\frac{3}{2}$-$\frac{5}{2}$ and $\frac{5}{2}$-$\frac{3}{2}$-$\frac{5}{2}$. The range of values of $A_2{}^1$ for the 293-keV transition, corresponding to the positive value of δ is taken for this cascade. The hatched areas show regions of consistency.

it to be considerably retarded. The log ft value 7.2 of the β transition to the 351-keV level shows that it is less retarded compared to the transition to the 57-keV level. It follows that this transition is also nonunique, first forbidden. Hence the possible spins of the 351-keV level are $\frac{3}{2}^+$ or $\frac{5}{2}^+$, as $\frac{1}{2}^+$ would not allow the observed intensity of the 351-keV transition to the $\frac{7}{2}^+$ ground state. The analysis of the angular correlation of the 293–57-keV cascade shows that the spin of the 351-keV level should be $\frac{3}{2}$ or $\frac{7}{2}$. Thus, combining the conclusions from the log ft value of β transition and the results of the angular correlation, we can uniquely fix the spin of the 351-keV state as $\frac{3}{2}^+$. The graphical analysis of the 293–57-keV cascade by the method of Arns and Wiedenbeck[12] for the sequence $\frac{3}{2}(293)$-$\frac{5}{2}(57)$-$\frac{7}{2}$ is shown in Fig. 4. From this analysis the mixing ratio δ, defined[13,14] as the ratio of the reduced matrix elements corresponding to multipole order $L+1$ to that corresponding to multipole order L, viz.,

$$\delta = \langle j_1 \| L+1 \| j \rangle / \langle j_1 \| L \| j \rangle, \quad \text{where } L=1 \text{ in this case,}$$

and the quadrupole fraction Q, given by

$$Q = \delta^2 / (1+\delta^2),$$

could be obtained for the 293- and the 57-keV transitions consistent with the internal conversion studies.[5] (See Table I.)

No β transition of observable intensity takes place to the 493-keV level. From the upper limit of the intensity of such a β transition, the log ft value should be $\gtrsim 8.2$. From this, the spin of the 493-keV level should be $\frac{7}{2}$ or more, assuming that the beta transition is not hindered because of any nuclear-structure effects. Since a γ transition of 142 keV is observed from the 493-keV to the $\frac{3}{2}^+$ 351-keV level, the spin of the 493-keV level can be only $\frac{7}{2}^+$.

The 725-keV level can be $\frac{3}{2}^+$ or $\frac{5}{2}^+$ from the log ft value of 7.0 of the β transition. The analysis of the results of the angular correlation of the 232–493-keV cascade, with $\frac{7}{2}$ as the spin of the 493-keV level, rules out the possibility $\frac{3}{2}^+$, but gives consistency with $\frac{5}{2}^+$ as shown in Fig. 5. The results of the 668–57-keV cascade also agrees with this assignment (figure not shown).

The analysis of the results for the 591–293-keV cascade is shown in Fig. 6. The range of values of δ for the 293-keV transition obtained from the results of the 293–57-keV cascade, in which it is the first transition, is $-1.0 \leq \delta \leq -0.47$. Since the 293-keV is the second transition for the 591–293-keV cascade, the sign of δ will be the opposite in this case, i.e., $1.0 \geq \delta \geq 0.47$. This change of phase of δ depending on the order of the transition in the cascade follows from the theory of Biedenharn and Rose[13,14] and has been experimentally demonstrated by Ofer.[15] This result was used in the analysis shown in Fig. 6. Both the possible spin values $\frac{3}{2}^+$ and

[12] R. G. Arns and M. L. Wiedenbeck, Phys. Rev. **111**, 1631 (1958).
[13] L. C. Biedenharn and M. E. Rose, Rev. Mod. Phys. **25**, 729 (1953).
[14] M. Sakai and T. Yamazaki, Institute for Nuclear Study, University of Tokyo Report No. INSJ-66, 1964 (unpublished).
[15] S. Ofer, Phys. Rev. **114**, 870 (1959).

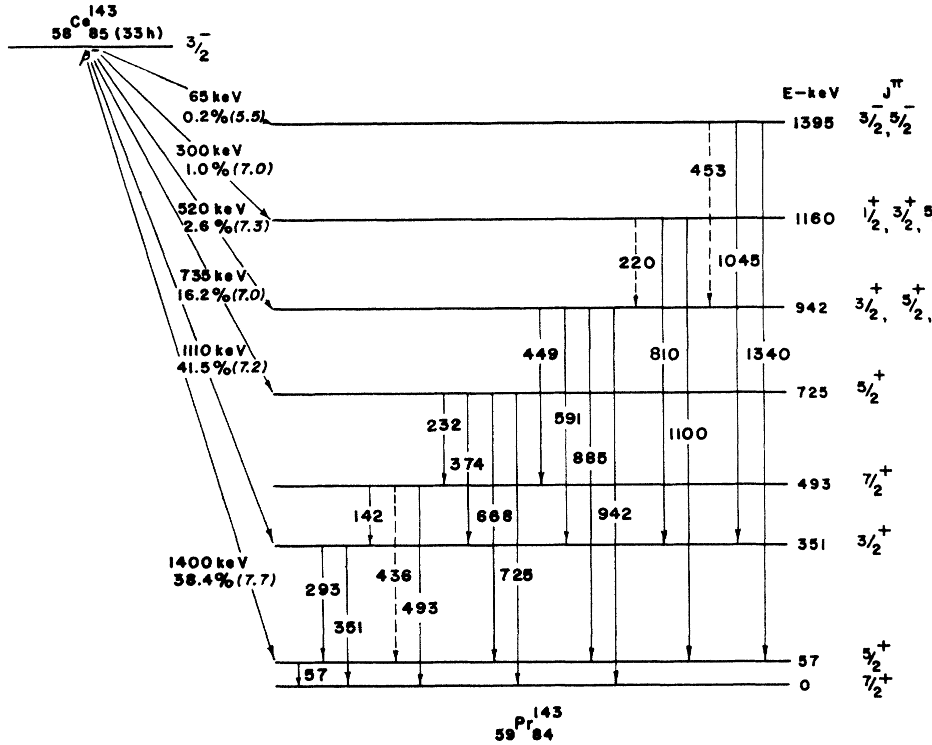

FIG. 7. The decay scheme of $Ce^{143} \rightarrow Pr^{143}$ consistent with the results of the angular-correlation studies.

$\frac{5}{2}^+$ for the 942-keV level agree with the experimental coefficients for the 591-293-keV cascade.

The interpretation of the results of the nuclear alignment experiments[16] in Ce^{143} will have to be revised in the light of the above conclusions based on the measured spin of the ground state of Ce^{143} as $\frac{3}{2}$.[17]

TABLE I. Results of the analysis of the angular-correlation functions.

Energy level (keV)	Spin	γ ray (keV)	%E2	Range of values of δ
0	$\frac{7}{2}$	...	...	...
57	$\frac{5}{2}$	57	0.01–0.08	$-0.01 \geq \delta \geq -0.03$
351	$\frac{3}{2}$	293	18–50	$\{-0.47 \geq \delta \geq -1.0^a$ $\{+0.47 \leq \delta \leq +1.0^b$
493	$\frac{7}{2}$	493	{ 0–10 {or 0–73	$-0.33 \leq \delta \leq +1.64$
725	$\frac{5}{2}$	232	{ 84–95 {or 0–30	$-2.3 \geq \delta \geq -4.4$ $0 \geq \delta \geq -0.66$
		668	46–96	$-0.92 \geq \delta \geq -4.9$
942	$\frac{3}{2}$	591	{ 12–19 {or 96–99	$-0.37 \geq \delta \geq -0.48$ $-4.9 \geq \delta \geq -10.0$
	or $\frac{5}{2}$	591	{ 0.5–2 {or 97–99	$+0.07 \leq \delta \leq +0.14$ $-5.7 \geq \delta \geq -10.0$

[a] For the 293–57-keV cascade.
[b] For the 591–293-keV cascade.

[16] J. N. Haag, D. A. Shirley, and D. H. Templeton, Phys. Rev. **129**, 1601 (1963).
[17] *Note added in proof*. The spin assignments shown in Fig. 7 are reported to be in agreement with nuclear alignment data. (D. A. Shirley, Lawrence Radiation Laboratory, Berkeley, private communication, 1964, quoted in Ref. 6.)

The values of δ and Q for the various transitions obtained from the analysis of the angular correlation data are given in Table I.

The spin of the 1160-keV level could be $\frac{1}{2}^+$, $\frac{3}{2}^+$, or $\frac{5}{2}^+$ from the log ft value of 7.0 for the β transition to this level and the observed γ transitions from this level. The log $ft = 5.5$ for the β transition to the 1395-keV level shows that it is an allowed transition and hence the parity of this level should be negative. From the relative strengths of the γ transitions from this level to the 351- and the 57-keV levels, the spin of the 1395-keV level can be either $\frac{3}{2}^-$ or $\frac{5}{2}^-$.

The decay scheme of $Ce^{143} \rightarrow Pr^{143}$ with the spins of the levels as inferred here is shown in Fig. 7.

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