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Energy Levels of Pr^{143}†

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The gamma rays of Pr^{143}, following the beta decay of Ce^{143}, have been studied with a scintillation coincidence spectrometer. The existence of levels at 57, 350, 725, 945, and 1167 keV has been confirmed. In addition, a level at 493 keV has been established. The directional correlation functions for the 668–57-keV, 232–493-keV, and 293–57-keV cascades in Pr^{143} have been measured. A spin of $\frac{5}{2}$ has been assigned to the 57 and 725-keV levels and a spin of $\frac{7}{2}$ to the 350-keV level. The spin of the 493-keV level may be either $\frac{5}{2}$ or $\frac{7}{2}$. The experimental level structure is compared with the theoretical predictions.

I. INTRODUCTION

THE prominent energy levels of Pr^{143} have been fairly well established by Martin *et al.*[1] Gopinathan *et al.*[2] have reported a new level at 1395 keV and some new weak gamma rays. In addition, they present evidence for the existence of a 493-keV level which was previously known to be either at 493 keV or 232 keV. Levy,[3] using a Ge(Li) detector, has found two new levels at 1057 and 448 keV. The present coincidence ex-experiments were undertaken in order to check the decay scheme as a prelude to directional correlation measurements. The decay scheme found in the present work is in basic agreement with those previously reported.[1–3] The relative intensities of the gamma rays, percent beta feeding of the Pr^{143} levels from Ce^{143}, and log *ft* values have been determined. Three directional correlation experiments were performed, from which the spin assignments and types of radiation were obtained for the levels and gamma rays involved. Much information is available about the low-lying excited states in Pr^{143} which was used in the analysis of the directional correlation measurements.

The ground-state spin of Pr^{143} has been measured to be $\frac{7}{2}$.[4] Graham *et al.*,[5] from *L*-conversion measurements, have placed limits on the *E*2 contents of the 57- and 293-keV transitions. In addition, they have measured the half-life of the 57-keV state and determined the upper limit for the half-life of the 350-keV state. Levy,[3] in his extensive work, has measured the 293–57-keV directional correlation, the half-life of the 57-keV state (which agrees reasonably well with the result of Graham *et al.*[5]), and the directional correlation of the 57-, 293-, and 350-keV gamma rays following the decay of aligned Ce^{143} nuclei. The 293–57-keV directional correlation has also been measured by Rao and Hans.[6] Their experimental results agree, within error, with those found in the present, and in Levy's work. Rao and Hans have also confirmed the decay scheme of Martin *et al.*[1] and have measured *K*-conversion coefficients for the 57-, 232-, and 293-keV transitions.

The present experimental data, together with results of previous investigators, are compared with the predictions of Kisslinger and Sorenson.[7]

† Supported by the National Science Foundation.

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

[2] K. P. Gopinathan, M. C. Joshi, and E. A. S. Sarma, Phys. Rev. **136**, B1247 (1964).

[3] R. M. Levy, Ph.D. thesis, Lawrence Radiation Laboratory Report No. UCRL-11663, 1964 (unpublished).

[4] B. Burdick, R. Marrus, W. M. Doyle, and W. A. Nierenberg, Bull. Am. Phys. Soc. **7**, 477 (1962); B. Burdick, R. Marrus, and I. Maleh, Phys. Rev. **135**, B1281 (1964).

[5] R. L. Graham, J. M. Hollander, and P. Kleinheinz, Nucl. Phys. **49**, 641 (1963).

[6] G. N. Rao and H. S. Hans, Nucl. Phys. **41**, 511 (1963).

[7] L. S. Kisslinger and R. A. Sorensen, Rev. Mod. Phys. **35**, 853 (1963).

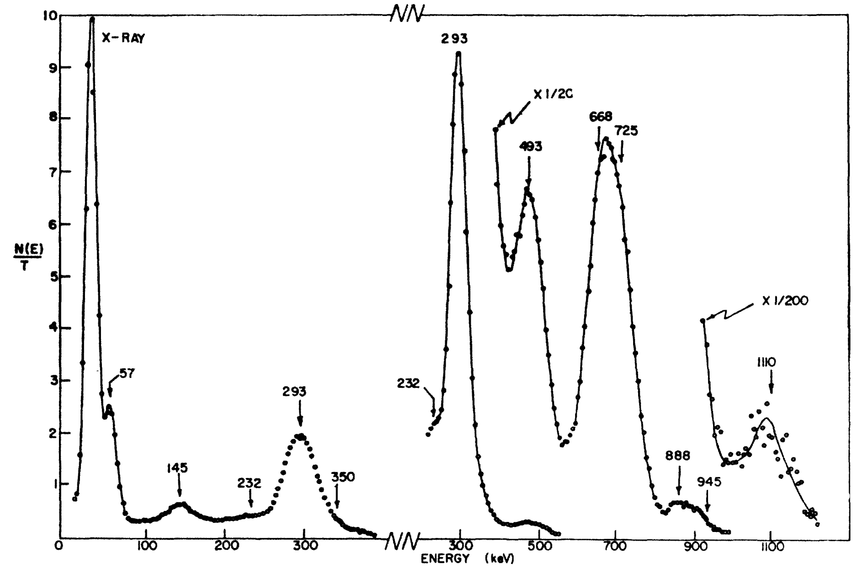

FIG. 1. Gamma-ray spectrum taken with a 2-in.×2-in. crystal using a 2-day-old source. The quantity, $N(E)/T$ on the ordinate axis refers to counts per channel per second in arbitrary units.

II. EXPERIMENTAL PROCEDURE

Sources used for the coincidence and directional correlation experiments were prepared by irradiating CeO_2, with the Ce electromagnetically enriched to 83.4% in Ce^{142}, in a slow neutron flux of $10^{12} n/cm^2$ sec for 8 to 50 h periods. The material was then disolved in concentrated HCl.

The coincidence measurements employed a fast-slow coincidence circuit with a resolving time of 50 nsec. Pulses coincident with an energy range, selected by a differential analyzer, were fed through a linear gate and recorded on a 256-channel analyzer. The detectors consisted of 2-in.×2-in. NaI(Tl) crystals mounted on RCA 6655-A phototubes. The coincidence spectra were taken with the detectors at 120 degrees and with a Compton shield placed between them. Random coincidences were measured and the coincidence spectra corrected accordingly.

The source-to-detector distance was 7 cm for the directional correlation measurements. The counting rates as a function of angle between the detectors were corrected for random coincidences, and the resulting data subjected to a least-squares fit.[8] The directional correlation function was then corrected for finite geometry.[9]

III. RESULTS

A. Gamma-Ray Spectrum

Figure 1 shows the gamma-ray spectrum of Pr^{143} taken with a 2-in.×2-in. crystal using a source which was 2 days old. The peak at 145 keV is mostly due to the presence of 33.4-day Ce^{141} which beta decays to Pr^{141}. The coincidence measurements (Sec. III B.) suggest that a gamma ray around 145 keV also exists in Pr^{143}. This has also been observed by Gopinathan *et al.*[2] and Levy.[3] The 1340-keV line reported in Ref. 2 was looked for in this work. Investigation of the gamma-ray spectrum with a 3-in.×3-in. crystal above 1000 keV showed a weak line at 1590 keV. This was attributed to a small amount of 40-h La^{140}. The Compton edge of the 1590-keV line is around 1355-keV, which is close to the 1340-keV line reported in Ref. 2. From these measurements, the relative intensity of a possible 1340-keV line in Pr^{143} would be less than 0.05% of the intensity of the 293-keV gamma ray.

B. Coincidence Measurements

The gamma-ray spectrum in coincidence with the energy range from 51 to 63 keV is shown in Fig. 2. Prominent peaks at 293, 668, 888, and 1110 keV, other coincidence measurements, and the singles gamma-ray spectrum confirm the existence of 57, 350, 725, 945, and 1167-keV levels. The structure around 595, 817, and 1045 keV is resolved in the gamma-ray spectrum in coincidence with the energy range around 293 keV (Fig. 3). The line at 143 keV may possibly arise through a transition from the 493-keV level (established by the spectrum in coincidence with the energy range around 493 keV, Fig. 4b) to the 350-keV level. Initially it was thought that the 143-keV peak was the result of random conicidences from the 145-keV gamma ray of Pr^{141}. The 143-keV line persists in the spectrum corrected for random coincidences. Allowing the 143-keV transition explains the weak line at 232-keV. The 1340–57-keV coincidence reported in Ref. 2 was sought but not observed in the present work.

The spectrum in coincidence with the energy range from 283 to 303 keV is shown in Fig. 3. The x-ray and 57-keV peaks confirm the 293–57-keV coincidence. A

[8] M. E. Rose, Phys. Rev. **91**, 610 (1953).
[9] R. G. Arns, R. E. Sund, and M. L. Wiedenbeck, University of Michigan Technical Report No. 2375-4-T, 1959 (unpublished).

small fraction of the x-ray and 57-keV intensities arises from Compton interference in the energy selector of the 668-, 888-, and 1110-keV gamma rays. The 143-keV line is consistent with the previously discussed 143-keV transition from the 493-keV level to the 350-keV level. Compton interference from the 493-keV gamma ray accounts for the 232-keV line and a small part of the x-ray peak. Lines at 375 and 595-keV are explained by transitions from the levels at 725 and 945-keV, respectively. The 817-keV line is a true coincidence arising through a transition from the 1167-keV level to the 350-keV level. The weak 315-keV line may be spurious and was not placed in the decay scheme. This line is not resolved in the spectrum uncorrected for random coincidences.

Figure 4(a) shows the gamma-ray spectrum in coincidence with the energy range from 220 to 244 keV. A 232–493-keV cascade from the 725-keV level explains the prominent 493-keV line. The structure around 436 keV has also been observed in Ref. 2. Since the other coincidence experiments do not resolve a line of 436 keV, no attempt has been made to place it in the decay scheme. The 293-, 232-, 57-keV peaks, and the x ray are explained by Compton interference in the energy selector. The 143-keV peak is consistent with its suggested position in the decay scheme.

The spectrum in coincidence with the energy range from 474 to 512 keV is shown in Fig. 4(b). The strong 232-keV line confirms the 232–493-keV cascade. The 493-keV level is established by the 452-keV peak which arises through a transition from the 945-keV level. Partial acceptance of the 452-keV gamma ray in the energy selector accounts for the 493-keV line. Most of the x-ray intensity, the 57-keV line, and the weak 293-keV line result from Compton interference in the energy selector.

Additional coincidence experiments were performed with the energy regions around 1110, 888, 668, and 595 keV. The results of these experiments are consistent with the coincidence spectra discussed and the decay scheme presented.

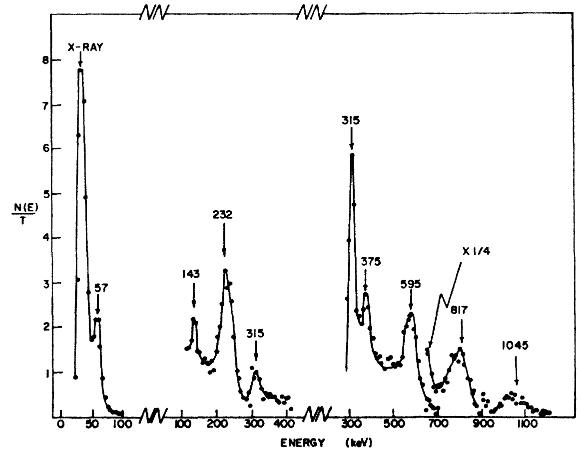

FIG. 3. Spectrum of gamma rays in coincidence with the energy range from 283 to 303 keV.

C. Decay Scheme

Figure 5 shows the decay scheme consistent with the coincidence measurements. Table I contains the gamma-ray relative intensities and estimated uncertainties. Comparing the measured K-conversion coefficients[1,6] for the 293-, 232-, and 57-keV transitions shows that most of the x-ray intensity arises from K-conversion of the 57-keV transition. In order to bring the percent beta feeding to the 57 and 350-keV levels, calculated from the gamma-ray relative intensities, into agreement with the results of Martin *et al.*[1] it is necessary to take the K/L ratio for the 57-keV transition ≈ 1. This is

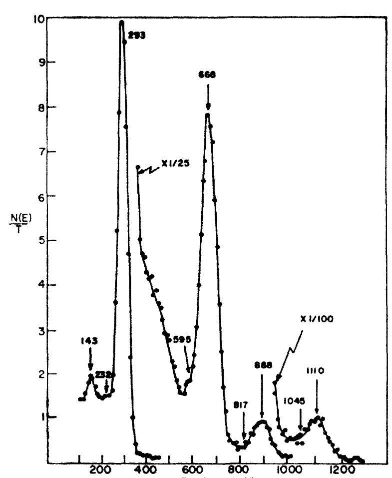

FIG. 2. Spectrum of gamma rays in coincidence with the energy range from 51 to 63 keV.

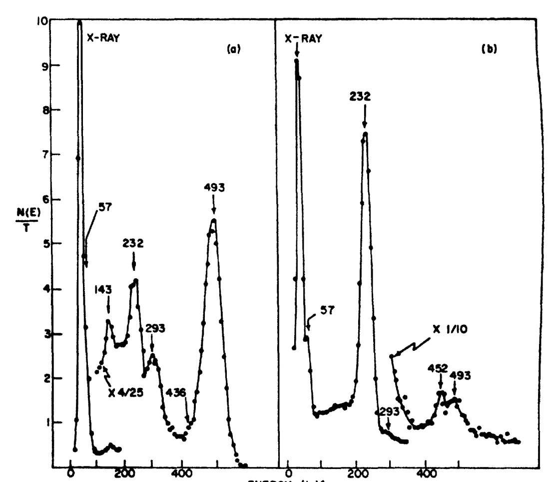

FIG. 4. Spectra of gamma rays in coincidence with the energy ranges (a) from 220 to 244 keV and (b) from 474 to 512 keV.

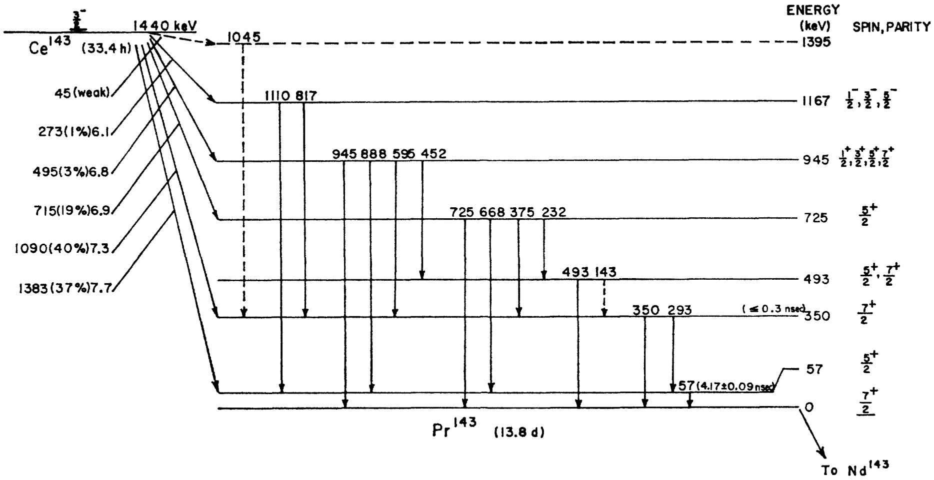

FIG. 5. Decay scheme of Ce[143]. The ground-state spin of Ce[143] has been measured by Maleh (Ref. 12). The half-life of the 57-keV state and upper limit for the half-life of the 350-keV state have been measured by Graham *et al.* (Ref. 5). The percent beta feeding to the 57-keV and 350-keV levels has been adopted from Martin *et al.* (Ref. 1). Other beta-intensity data have been deduced from the gamma intensities measured in the present work. The ground-state spin of Pr[143] has been measured by Burdick *et al.* (Ref. 4).

consistent with previously reported ratios.[10] Since there has been no recent measurement to check K/L for the 57-keV transition, the percent beta feeding to the first two excited states has been adopted from Martin *et al.*[1] and the feeding to the higher levels calculated from the gamma-ray relative intensities measured in this work.

The only evidence found in the present work for the existence of a 1395-keV level is the 1045-keV gamma ray in coincidence with the energy range around 293 keV. The 1395-keV level and the 1045-keV transition are shown as dashed lines in the decay scheme. The other levels in the decay scheme have been established previously[1–3,6] and have been confirmed in this work.

D. The 293–57-keV Directional Correlation

The directional correlation function for the 293–57-keV cascade measured in the present work is $W(\theta) = +(0.123\pm0.011)\ P_2(\cos\theta)$. The $A_4{}^{(\mathrm{exp})}$ term is zero within experimental error. This agrees, within experimental error, with $A_2{}^{(\mathrm{exp})}=0.132\pm0.019$ reported in Ref. 6 and with $A_2{}^{(\mathrm{exp})}=0.133\pm0.007$ reported in Ref. 3. From L-conversion measurements, Graham *et al.*[5] have found the mixing ratio ($\delta^2=E2/M1$) for the 57-keV gamma ray to be $\leq 0.3\%$ and the $E2$ content of the 293-keV gamma ray to be $34\pm16\%$.

The interpretation of the directional correlation function by Rao and Hans[6] was based on the assumed ground-state spin of $\frac{5}{2}$ for Pr[143]. Graham *et al.*[5] interpreted the results of Rao and Hans using the measured ground-state spin[4] of $\frac{7}{2}$ for Pr[143]. They have shown that the only spin assignments consistent with the directional correlation function and their L-conversion data are $\frac{5}{2}$ for the 57-keV level and either $\frac{3}{2}$ or $\frac{7}{2}$ for the 250-keV level. This has been confirmed in the present work. The spins $\frac{3}{2}$ and $\frac{7}{2}$ for the 350-keV level are also consistent with the nuclear alignment data of Levy.[3] For the $\frac{3}{2}$, $\frac{5}{2}$, $\frac{7}{2}$ sequence the sign of δ for the 293- and 57-keV gamma rays are both negative and for the $\frac{7}{2}$, $\frac{5}{2}$, $\frac{7}{2}$ sequence both signs are positive (cf., Fig. 6).

TABLE I. Gamma-ray relative intensities and estimated uncertainties. The intensities are compared to the 293-keV gamma-ray intensity.

Energy (keV)	Relative intensity
x ray	82 ±20
57	23 ± 5
143	6 ± 3
232	4 ± 2
293	100
350	9 ± 8
375	0.4± 0.2
452	0.1± 0.1
493	4 ± 2
595	2.2± 0.5
668	13 ± 3
725	12 ± 3
817	0.7± 0.4
888	2 ± 1
945	0.4± 0.4
1045	0.4± 0.4
1110	0.8± 0.2

E. The 668–57-keV Directional Correlation

The directional correlation function for the 668–57-keV cascade was measured to be

$$W(\theta)=1+(0.075\pm0.011)P_2(\cos\theta).$$

The $A_4{}^{(\mathrm{exp})}$ term is zero within experimental error.

The 725-keV level was assumed to have spins from $\frac{1}{2}$ to $\frac{7}{2}$ and positive parity, based on the log ft value of the beta decay from Ce[143] and its measured ground-state spin[11] of $\frac{3}{2}$ and negative parity. With the established spin of $\frac{5}{2}$ for the 57-keV level, there are four possible spin sequences for the 725- and 57-keV levels and the ground state. Of these, only the $\frac{5}{2}$, $\frac{5}{2}$, $\frac{7}{2}$ and $\frac{7}{2}$, $\frac{5}{2}$, $\frac{7}{2}$ sequences are allowed by the directional correlation result and the L-conversion work of Graham *et al.*[5] Further, the negative $A_4{}^{(\mathrm{exp})}$ term in the 232–493-keV

[10] H. G. Keller and J. M. Cork, Phys. Rev. **84**, 1079 (1951); E. Kondaiah, Arkiv Fysik **4**, 811 (1952).

[11] I. Maleh, Phys. Rev. **138**, B766 (1965).

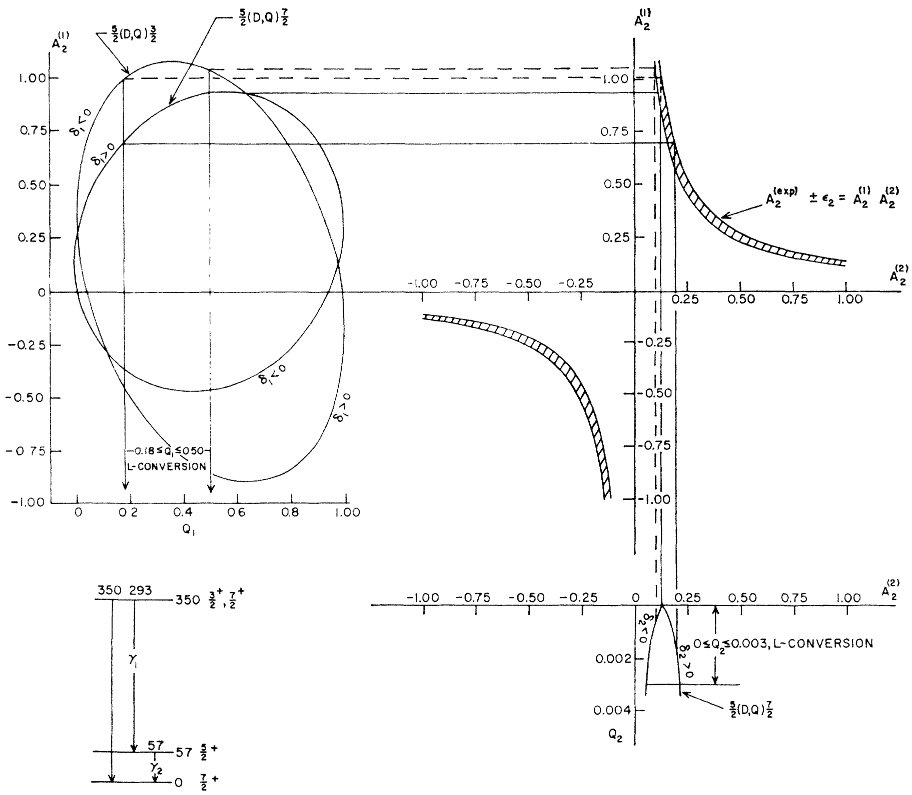

FIG. 6. Analysis of the 293–57-keV directional correlation function according to the method of Ref. 11. The two spin sequences allowed by the $A_2^{(\mathrm{exp})}$ term and the *L*-conversion work of Graham *et al.* (Ref. 5) are $\frac{3}{2}$, $\frac{5}{2}$, $\frac{7}{2}$ and $\frac{7}{2}$, $\frac{5}{2}$, $\frac{7}{2}$. In the notation $j(D,Q)j'$, j is the spin of the intermediate state and j' is the spin of the initial or final state. The symbols "*D*" and "*Q*" refer to dipole and quadrupole, respectively.

directional correlation function (Sec. III.F.) does not allow a spin of $\frac{7}{2}$ for the 725-keV level. Therefore, the $\frac{5}{2}$, $\frac{5}{2}$, $\frac{7}{2}$ sequence is favored for the 725- and 57-keV levels and the ground-state, respectively.

For the allowed $\frac{5}{2}$, $\frac{5}{2}$, $\frac{7}{2}$ assignments, the $E2$ content, determined by the method of Ref. 12, of the 668-keV gamma ray is between 40% and 98% ($\delta<0$) with the $E2$ content of the 57-keV gamma ray $\leq 0.3\%$ ($\delta>0$) as shown in Fig. 7. Since the 57-keV gamma ray is the second transition in both the 668–57- and 293–57-keV cascades, the sign of δ (57), determined from both directional correlation measurements, must be the same.[13] Therefore, the spin $\frac{7}{2}$ assignment is favored for the 350-keV level. The spin $\frac{7}{2}$ assignment to the 350-keV level does not fit well with the log ft value of 7.3 for the beta decay to that level (Fig. 5). The log ft values have been determined from half-life, energy, and relative intensity data.

F. The 232–493-keV Directional Correlation

The directional correlation function for the 232–493-keV cascade was found to be

$$W(\theta)=1+(-0.227\pm0.016)P_2(\cos\theta)+(-0.035\pm0.028)P_4(\cos\theta).$$

[12] R. G. Arns and M. L. Weidenbeck, Phys. Rev. **111**, 1631 (1958).

[13] L. C. Biedenharn and M. E. Rose, Rev. Mod. Phys. **25**, 729 (1953).

The spin and parity of the 493-keV level were assumed to range from $\frac{3}{2}$ to $\frac{11}{2}$. There are two spin sequences, for the 725- and 493-keV levels and the ground state, consistent with the directional correlation measurement and the K-conversion coefficient for the 232-keV transition (measured by Rao and Hans[6] to be 0.12 ± 0.02). These are $\frac{5}{2}$, $\frac{5}{2}$, $\frac{7}{2}$ and $\frac{5}{2}$, $\frac{7}{2}$, $\frac{7}{2}$. There is no experimental evidence to suggest which of the two sequences is more probable. For the $\frac{5}{2}$, $\frac{5}{2}$, $\frac{7}{2}$ sequence, the $E2$ content of the 232-keV gamma ray is between 16% and 47% ($\delta>0$) with the 493-keV gamma ray pure $E2$. For the $\frac{5}{2}$, $\frac{7}{2}$, $\frac{7}{2}$ sequence the corresponding ranges of quadrupole contents for the 232-keV and 493-keV gamma rays are

$$2\%\leq E2(232)\leq 50\%(\delta<0),$$
$$62\%\leq E2(493)\leq 80\%(\delta>0)$$

or

$$20\%\leq E2(232)\leq 50\%(\delta>0),$$
$$47\% E2(493)\leq 100\%(\delta<0).$$

IV. DISCUSSION

As was discussed by Graham *et al.*,[5] the level structure of Pr^{143} is of particular interest in order to learn if the $\frac{5}{2}+$ and $\frac{7}{2}+$ states have crossed between Pr^{141} and Pr^{143}. The results of Refs. 3 and 5 and of this work confirm the crossing of these states. The theoretical calculations of Kisslinger and Sorenson[7] do not predict the

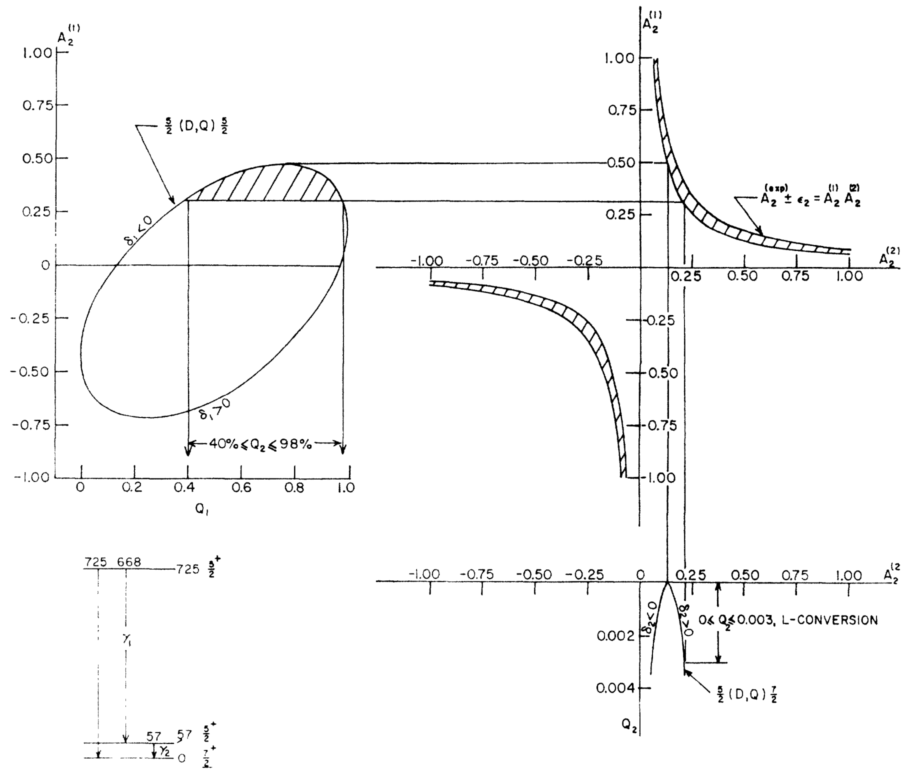

FIG. 7. Analysis of the 668–57-keV directional correlation function. The spin sequence is $\frac{5}{2}$, $\frac{5}{2}$, $\frac{7}{2}$. Spin $\frac{7}{2}$ is not allowed for the 725-keV level by the negative $A_4^{(\mathrm{exp})}$ in the 232–493-keV directional correlation function.

crossing of the $\frac{5}{2}+$ and $\frac{7}{2}+$ states between Pr^{141}. The quadrupole force which determines the relative position of the $\frac{5}{2}+$ and $\frac{7}{2}+$ states in the theoretical predictions, only depresses the $\frac{7}{2}+$ state in going from Pr^{141} to Pr^{143}.

From the measured half-life of the 57-keV state[5] and the K-conversion coefficient,[1,6] K/L ratio ≈ 1 and the upper limit of[5] 0.3% for the $E2$ content of the 57-keV transition the partial $E2$ lifetime shows no $E2$ enhancement of the 57-keV gamma ray over the single-particle (Weisskopf) estimate. This is consistent with the interpretation that the $\frac{5}{2}+$ state is mostly particle in nature and with recent $E2$ transition-rate calculations of Sorensen.[14] The partial $M1$ half-life of the 57-keV state indicates an $M1$ retardation factor around 550 for the 57-keV transition. In a similar manner, using the upper limit of[5] 0.3 nsec for the half-life of the 350-keV state, the partial $E2$ and $M1$ lifetimes of the 293-keV gamma decay indicate an $E2$ enhancement factor of 6 ± 3 and an $M1$ retardation factor of 625_{-115}^{+200} compared to the single particle estimates.

The 350-keV state and higher excited states may possibly be interpreted as collective in nature, resulting from the coupling of the spin 2 phonon with either the $\frac{5}{2}+$ or $\frac{7}{2}+$ quasiparticle states. The expected spins may range from $\frac{1}{2}$ to $\frac{11}{2}$. Kisslinger and Sorensen have predicted several states with these spins in this energy region. However, as they point out, their method may not give accurate results when even a few neutrons are added to the 82-neutron shell because of the approaching deformed region. Additional experiments aimed at determining the extent of the deformation of Pr^{143} would be worthwhile. It would also be worthwhile to further investigate the quadrupole force which affects the crossing of the $\frac{5}{2}+$ and $\frac{7}{2}+$ states between Pr^{141} and Pr^{143}.

Note added in proof. K. P. Gopinathan, Phys. Rev. **139**, B1467 (1965), has reported directional correlation measurements on the cascades reported here. The experimental results are in reasonable agreement. However, Gopinathan assigns a spin of $\frac{3}{2}$ to the 350-keV level.

[14] R. A. Sorensen, Phys. Rev. **133**, B281 (1964).