Decay of Ce^{143}

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The decay of 33-h Ce^{143} has been investigated using scintillation and coincidence spectrometers. The analysis of the singles γ-ray spectrum showed 36- (x ray), 57-, 142-, 232-, 293-, 351-, 450-, 493-, 591-, 668-, 725-, 810-, 885-, 942-, 1045-, 1100-, and 1340-keV γ rays. All the γ rays except the 142-keV γ ray were found to follow a half-life of 33 h. The 142-keV γ ray, which was thought to be entirely due to Ce^{141}, has also been shown to be present in Ce^{143} by γ-γ coincidences. The 1340-keV γ ray was newly observed in this investigation. Extensive γ-γ coincidences showed the presence of previously unreported weak transitions of energy 220, 374, 436, 449, 453, 810, and 1045 keV. The level at 493 keV has been established, and evidence for a new level at 1395 keV has been obtained. A revised decay scheme consistent with these observations and the previous β-ray measurements has been presented with excited states in Pr^{143} at 57, 351, 493, 725, 942, 1160, and 1395 keV.

I. INTRODUCTION

SEVERAL investigations on the levels in Pr^{143} populated by the β decay of 33-h Ce^{143} have been reported.[1–4] The properties of the 57- and 351-keV levels were investigated in greater detail.[5–11] But the cascade relationship of the various γ rays was not established by detailed γ-γ coincidences. A 232–493-keV cascade arising from the 725-keV level was known from the previous investigations,[4] but the sequence of emission of these γ rays was not known. The β spectrum was studied earlier by Martin *et al.*[4] using a double-focusing β-ray spectrometer and the end-point energies and relative intensities of the β groups were measured. The reported relative intensities of β and γ transitions are not in agreement.[12]

The spin of the ground state of Pr^{143} has been directly measured to be $\frac{7}{2}$ by the atomic beam magnetic resonance method.[13] Since Ce^{142} shows a vibrational spectrum up to the two-phonon state,[14] the low-lying levels in Pr^{143} could arise from coupling of the $g_{7/2}$ particle state to the quadrupole vibrations[15] of the even-even core of Ce^{142}. It would be instructive to examine the nature of the excited states of Pr^{143} from this stand point. It was found necessary to study systematic γ-γ coincidences to establish the decay scheme in greater detail. In Sec. II we describe the detailed scintillation spectrometer studies including γ-γ coincidences and in Sec. III we discuss the level structure of Pr^{143} from the point of view of the coupling mentioned above.

II. MEASUREMENTS AND RESULTS

1. Preparation of Source

In the present investigations Ce^{143} was produced by irradiating 90% enriched Ce^{142} in the reactor "Apsara" at Trombay for 24 h. The sample was chemically purified[16] by dissolving in hydrochloric acid and coprecipitating CeF_3 on LaF_3 and separating cerium from lanthanum by oxidation to Ce^{4+} and precipitating $Ce(IO_3)_4$. Two cycles of such precipitations gave good decontamination from all rare earths and other possible impurities. The source was finally obtained as $CeCl_3$ solution and a few drops of this solution were evaporated on a thin Perspex source holder. The Pr^{143} grown from Ce^{143} did not interfere with the γ-ray studies since it is a pure β emitter. The only other contaminant in the Ce^{143} source was 33-day Ce^{141} produced by neutron activation of Ce^{140} present to the extent of $\approx 10\%$ in the target material. Since its radiations are well known, their contribution could be corrected for.

2. Study of Gamma Spectrum

The γ-ray spectrum was studied with a scintillation spectrometer consisting of a 3-in.×3-in. NaI(Tl) crystal coupled to a Dumont 6363 photomultiplier, in conjunction with a 512-channel pulse-height analyzer. The resolution of the spectrometer was 7.5% for the 662-keV γ ray of Cs^{137}. The Ce^{143} source was placed at a distance of 15 cm from the detector. To reduce bremsstrahlung

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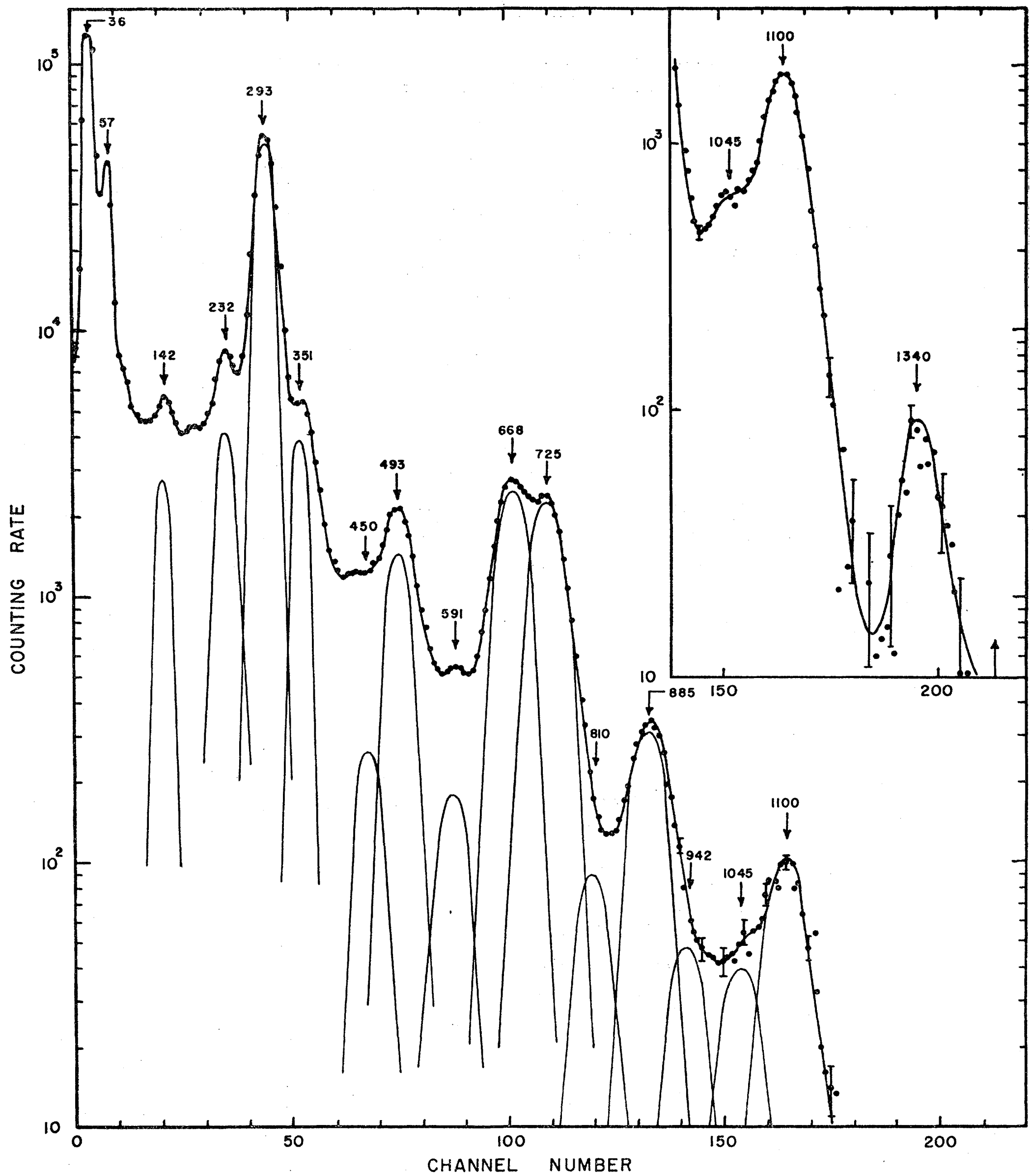

FIG. 1. The γ-ray spectrum of Ce^{143} taken in a 3-in.×3-in. NaI(Tl) crystal. The inset shows the high-energy portion of the spectrum with 8 mm of lead absorber. The γ-ray energies are shown in keV. The upward arrow in the inset shows the position of the background peak at 1460 keV due to K^{40}.

due to the stopping of high-energy β rays, the β absorber of 0.5-in. Perspex was placed half-way between the source and the crystal. The observed γ spectrum, corrected for background, is shown in Fig. 1. The high-energy portion of the γ spectrum was studied by filtering the γ rays through 8 mm of lead covered with cadmium and copper to absorb low-energy γ rays and x rays. The distance of the source from the crystal was made 6 cm in this case. The analysis of the spectrum showed γ rays at 36 (x ray), 57, 142, 232, 293, 351, 450, 493, 591, 668, 725, 810, 885, 942, 1045, and 1100 keV. The high-energy portion of the spectrum shown in the inset of Fig. 1, had a peak at 1340 keV. The peak counting rate due to this γ ray was $\approx$100 counts/40 min, while the background in this energy region was 100 counts/40 min. The γ-ray peak of 1340 keV was well resolved from the peak in the background at 1460 keV due to K^{40}. The position of the latter is shown by the upward arrow in the figure. Gamma rays of energy 450, 810, 942, 1045, and 1340 keV were newly observed in this study. The presence of these γ rays in the decay of Ce^{143} was confirmed by γ-γ coincidences. The decay of the spectrum was followed for six half-lives of Ce^{143}. All the γ rays except the 142 keV were found to decay

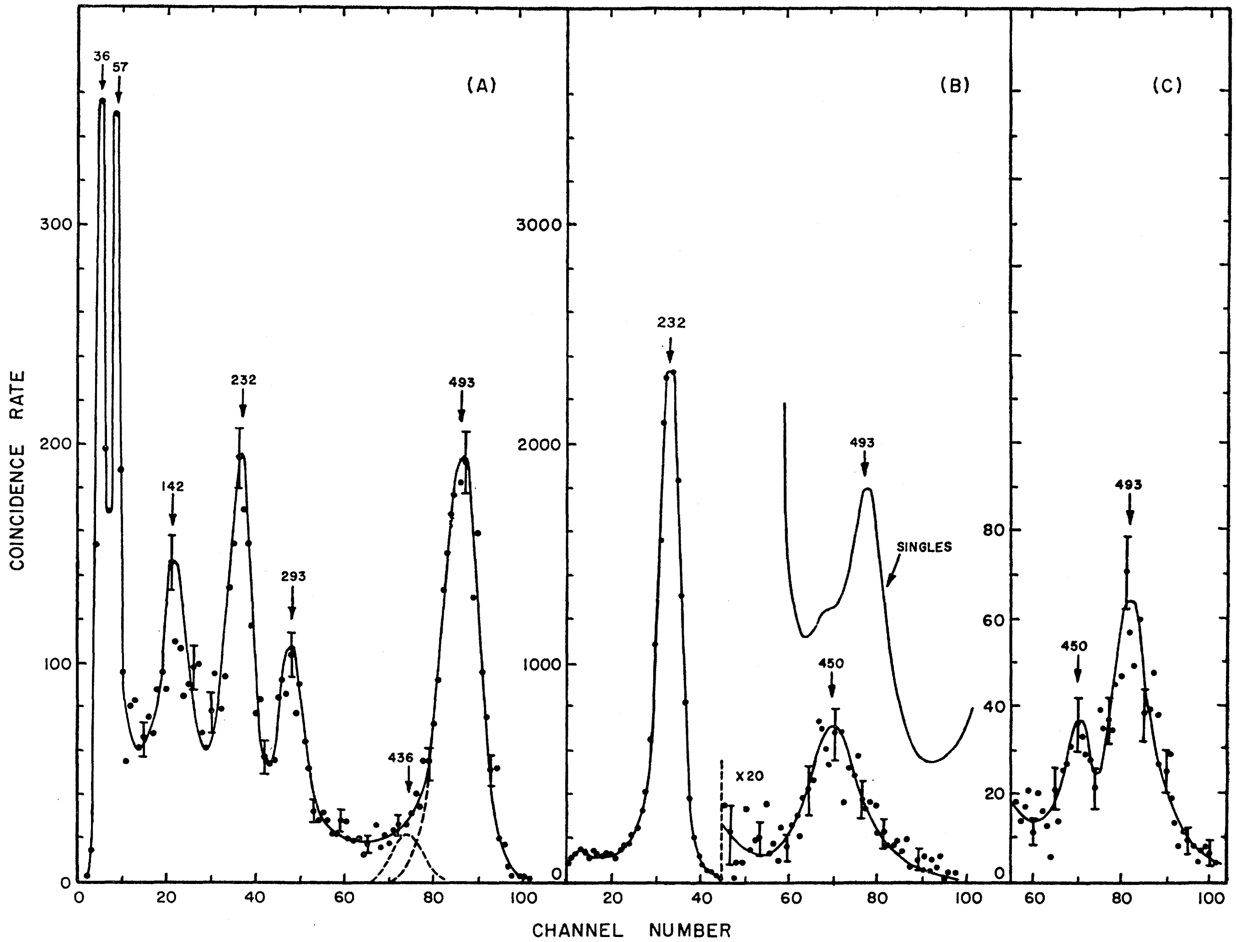

FIG. 2. The γ spectra in coincidence with: (A) 232-keV; (B) 493-keV; (C) 440-keV region. The γ-ray energies are given in keV.

with the same half-life of 33 h, showing that they belonged to Ce^{143} decay. The 142-keV peak was found to be largely due to a small amount of 33-day Ce^{141} present in the Ce^{143} source. A part of it is also found to be present in Ce^{143}. This was confirmed from coincidences. The relative intensities of the γ rays are given in Table I.

3. Gamma-Gamma Coincidences

Gamma-gamma coincidences were studied with the use of two NaI(Tl) crystals mounted on RCA 6810-A photomultipliers and a 512-channel pulse-height analyzer. One of the crystals was of size 1.5 in.×1.5 in. while the second one was 2 in.×2 in. The smaller size crystal was used as the gate detector when coincidences with low-energy γ rays were studied, and when high-energy γ rays were taken in the gate the larger crystal was used for gate detector. The fast-slow coincidence unit, with a Simm's-type[17] transistorized fast coincidence circuit, had a resolving time $2\tau=30$ nsec. The two detectors were placed at 90° with an anti-Compton shield in

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TABLE I. Relative intensities of γ rays in Ce^{143} decay.

E_γ keV	Singles γ spectrum	Coincidence with 293-keV γ ray	Coincidence with 493-keV γ ray
36			
57	25		
142		1.1	
220	...		
232	7		7
293	100		
351	9		
374		0.9	
436, 449, 453	0.8		0.4
493	5.3		
591	3	2.5	
668	15.1		
725	17.1		
810	0.7	1.0	
885	3.0		
942	0.5		
1045	0.4	0.4	
1100	1.4		
1340	0.1		

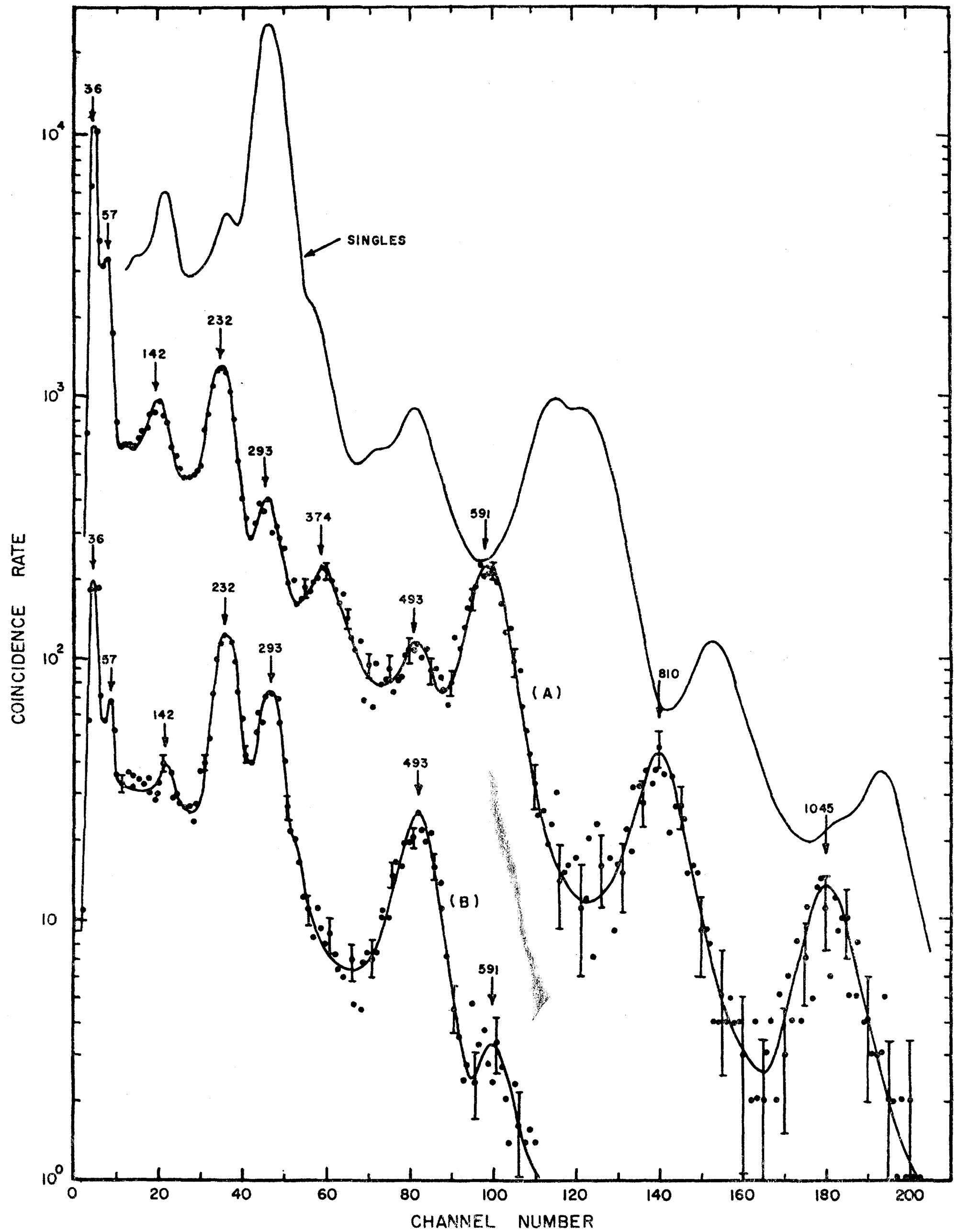

FIG. 3. The γ spectra in coincidence with: (A) 293-keV γ ray; and (B) 142-keV γ ray. The energies of the photopeaks are shown in keV.

between. To look for weak coincidences, observations of 800-min duration were taken. The stability of the system was checked from the singles spectra. A shift in pulse height of more than 0.5 V in the gate channel over the period of observation was not permitted.

The γ spectrum in coincidence with 232-keV γ ray is shown in Fig. 2(A). Photopeaks at 36 (x ray), 57, 142, 232, 293, and 493 keV were observed in the coincidence spectrum. The 232–493-keV coincidence is very strong. The analysis of the coincidence spectrum showed that the 232-keV peak is due to the Compton of 493-keV γ ray and a small part due to the Compton of 293-keV γ ray accepted in the gate. The coincidences of the 232-keV with the 142- and 293-keV γ rays are newly observed. The rising portion of the 493-keV photopeak indicated the presence of a weak 436-keV γ ray in the coincidence spectrum. By subtracting the contribution of the 493-keV γ ray using the line shape of the 510-keV γ ray from Na^{22}, the contribution of the 436-keV γ ray was calculated [Fig. 2(A)]. The coincidence spectrum was observed over two half-lives of Ce^{143}, and all the observed γ rays were found to decay with the same half-life.

These coincidences indicate that there is a level at 493 keV from which the 142-, 436-, and 493-keV transitions take place to the 351- and 57-keV levels and the ground state, respectively (Fig. 5). The 232-keV transition can be shown to take place between the 725- and the 493-keV levels. The 232- and 293-keV transitions come in coincidence through the 142-keV transition.

When 493 keV was taken in the gate, the coincidence spectrum showed a strong 232-keV peak and a weak coincidence with a γ ray of approximately 450 keV [Fig. 2(B)]. To confirm this the 440-keV region was accepted in the gate and the coincidence spectrum scanned. This coincidence spectrum showed 450- and 493-keV peaks with the 450-keV peak relatively larger in height [Fig. 2(C)] than in the coincidence with 232 keV. These observations indicate weak 436–450-keV and 493–450-keV cascades which are explained by a 449-keV transition from the 942- to the 493-keV level. The relatively larger intensity of the 450-keV peak in the coincidence spectrum with the 440-keV region in gate is due to the mutual coincidence of 449- and 436-keV γ rays.

The coincidence with 293 keV was studied by using the 1.5-in.×1.5-in. crystal as the gate detector and the 2-in.×2-in. crystal as the scanner detector. Two coincidence runs of 800-min duration were taken over two half-lives of Ce^{143} to follow the decay of the various γ rays in the spectrum. The observed coincidence spectrum [Fig. 3(A)] showed peaks at 36, 57, 142, 232, 293, 374, 493, 591, 810, and 1045 keV. After correcting for coincidence due to Compton of higher energy γ rays and a small contribution of the 232-keV γ rays in the 293-keV gate, peaks at 36, 57, 142, 232, 374, 591, 810, and 1045 keV were found to be due to coincidences with 293-keV γ ray. From the decay of the coincidence spectrum it was found that all the observed γ rays belonged to 33-h Ce^{143}. The coincidence was repeated with a lead absorber of 5 mm thickness lined with cadmium and copper, inserted in front of the scanner detector to absorb low energy γ rays. This observation confirmed the coincidences mentioned above.

The 374-, 591-, and 810-keV transitions are shown from the 725-, 942-, and 1160-keV levels, to the 351-keV level. These transitions explain the observed coincidences. The 293–1045-keV coincidences are explained by proposing a level at 1395 keV and showing a 1045-keV transition from this level to the 351-keV level.

The spectrum of γ rays in coincidence with 142 keV [Fig. 3(B)] showed peaks at 36, 57, 142, 232, 293, 493, and 591 keV. The 591-keV peak can be accounted for by the Compton of 293-keV γ ray and the 493-keV by the Compton of 232-keV γ ray accepted in the gate. A part of 232-keV peak was due to the Compton of 493 keV accepted in the gate. After taking these contributions into account, the 232- and 293-keV γ rays were found to be in coincidence with the 142-keV γ ray. This established the level at 493 keV.

TABLE II. Gamma-gamma coincidences in the decay of Ce^{143}.

γ ray in gate (keV)	γ rays in coincidence (keV)
142	36, 57, 232, 293
232	36, 57, 142, 293, (436), 493
293	36, 57, 142, 232, 374, 591, 810, 1045
450	36, 57, 232, 293, 450, 493
493	232, 450
810	293, 351
885	220, 453

When 885-keV region was taken in the gate and the coincidence spectrum scanned, it showed weak coincidences with 220- and 453-keV. These are explained by proposing a weak 220-keV transition from the 1160- to the 942-keV level and a 453-keV transition from the 1395- to the 942-keV level. When 810-keV region was taken in the gate the coincidence showed 293 keV, which confirmed the 293–810-keV cascade mentioned earlier.

The summary of γ-γ coincidences is shown in Table II. The intensities of γ rays observed in coincidences were calculated from the analysis of the coincidence spectra and they are given in Table I. The angular dependence of the coincidence rate was not taken into account in these calculations.

4. Total Absorption Gamma-Ray Spectrum

The γ-ray spectrum of Ce^{143} was studied in 4π geometry by keeping the source in the well of size $\frac{1}{4}$ in. diam $\times 1\frac{1}{2}$ in. deep in a 3-in.×3-in. NaI(Tl) crystal. To study the effect of absorption of x rays and the 57-keV γ rays, the source was surrounded by tubes of $\approx$1-mm copper and $\approx$2-mm cadmium, respectively. The spectra are shown in Fig. 4. The observed sum-peaks are consistent with the γ-γ coincidences described above. The highest energy portion of the spectrum with the source inside the well showed an enhancement of the 1340-keV peak as compared with the spectrum with the source at 15 cm. With 1 mm of copper surrounding the source, the peak is at 1340 keV [Fig. 4(B)] as also with 2 mm of cadmium around the source [Fig. 4(C)], indicating summing of cascades up to 57-keV level. With only Perspex surrounding the source, the peak tends towards the higher energy side [Fig. 4(A)] indicating summing of x rays and the 57-keV γ rays. This confirms the highest energy level at 1395 keV. The spectrum with the source surrounded by cadmium tube shows the 493-keV peak higher than with the source in copper tube [Fig. 4(B), (C)]. This has not been explained.

III. DECAY SCHEME AND DISCUSSION

From these results a consistent decay scheme as shown in Fig. 5 can be constructed. The 493-keV level

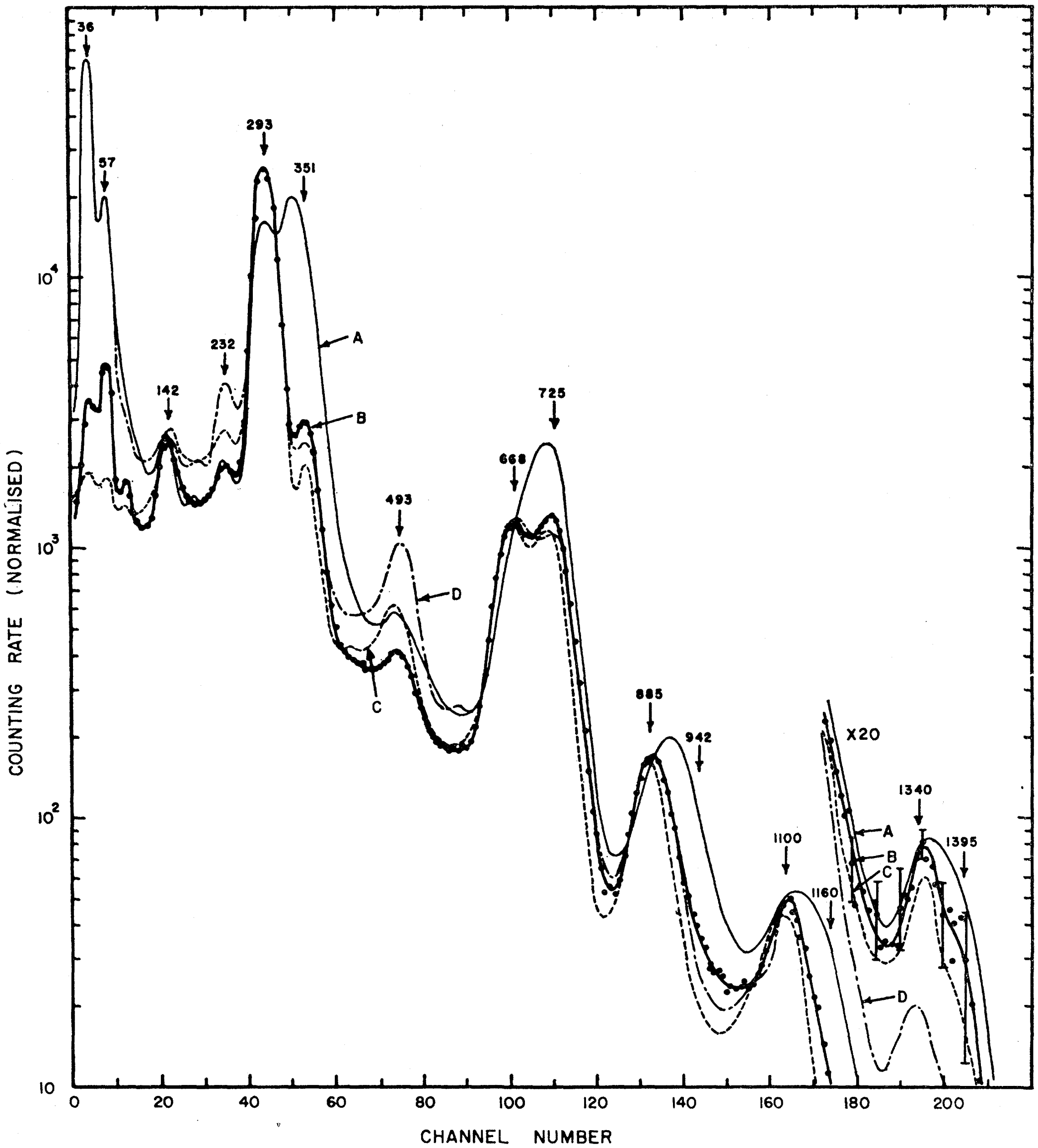

FIG. 4. The γ spectrum in 4π geometry with the source inside the well of $\frac{1}{4}$ in.$\times 1\frac{1}{2}$ in. size in a 3-in.$\times$3-in. crystal. (A) The source surrounded by Perspex; (B) with 1-mm-thick copper surrounding the source; (C) with 2-mm-thick cadmium around the source; (D) the spectrum with the source at 15 cm from the crystal.

is established in the present study consistent with the coincidences of the 232- and the 293-keV γ rays with 142 keV. The 1395-keV level is suggested by the highest energy sum-peak observed in the total absorption spectrum and the 1045–293-keV and the 453–885-keV cascades observed in γ-γ coincidences and the 1340-keV γ ray observed in the singles γ spectrum.

The relative intensities of the two highest energy β groups from the magnetic spectrometer studies of Martin *et al.*[4] are 37 and 40. The relative intensities of the lower energy β transitions will not be accurate because of the contribution of Pr^{143} and Ce^{141} in the source. So the relative intensities of these β groups were calculated from γ-ray intensities obtained from singles and coincidence spectra. These calculated relative intensities and the logft values are given in the decay scheme (Fig. 5).

Pr^{143} with 59 protons is considered a nearly spherical nucleus with the Ce^{142} even-even core susceptible for quadrupole vibrations. In the case of Ce^{140} where $N=82$ corresponds to a closed neutron shell and $Z=58$ corresponds to a closed subshell ($g_{7/2}$) of protons, the nucleus is more rigidly spherical and is not subjected to quadrupole vibrations. This is observed from the excited states of Ce^{140} where the lowest excited state[18] is at 1596

[18] *Nuclear Data Sheets*, compiled by K. Way *et al.* (Printing and Publishing Office, National Academy of Science, National Research Council, Washington 25, D. C.), NRC 59-1-84.

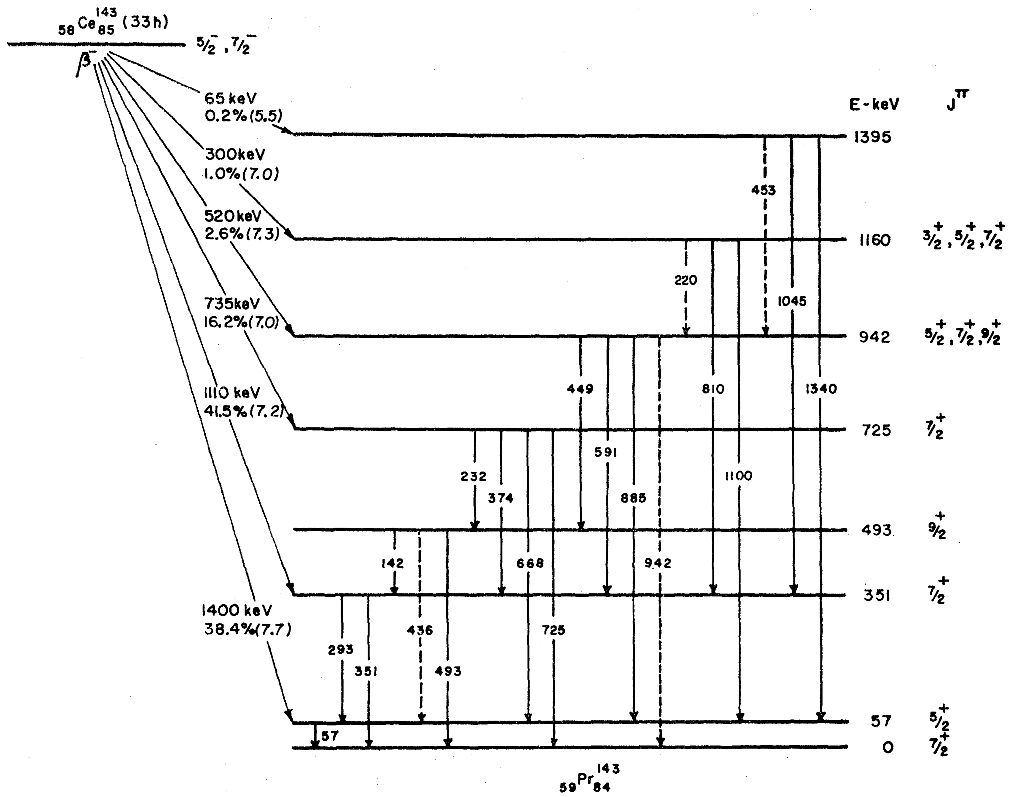

FIG. 5. Decay scheme of Ce^{143} from the present investigations.

keV which has a particle character. In the case of Ce^{142} the first excited state[14] is at 630 keV (2^+) and the second excited state at 1500 keV (4^+) indicating vibrational character up to the two-phonon state. Now if we compare the level spectra of Pr^{141} and Pr^{143}, the former can be considered a spherical nucleus with a rigid core of 58 protons and 82 neutrons, and an odd proton in the $d_{5/2}$ shell as predicted by the shell model. This is found to be the case from the measured spin of the ground state of Pr^{141} as $\frac{5}{2}$ from paramagnetic resonance[19] and from atomic beam magnetic resonance.[20] The first excited state at 142 keV can be explained as $(g_{7/2})^{-1}(d_{5/2})^2$ proton configuration. In the case of Pr^{143} with two neutrons outside the closed shell of 82 and nine protons outside the closed shell of 50, as a result of the residual interaction of these particles the ground-state configuration becomes $(g_{7/2})^{-1}(d_{5/2})^2$ which is in accordance with the direct measurement[13] of the ground-state spin of Pr^{143} as $\frac{7}{2}$.

Since as mentioned above, the excited states of the even-even Ce^{142} show vibrational character, the low-lying energy levels of Pr^{143} could be explained as due to the coupling of the odd proton with its available single-particle states $g_{7/2}$ and $d_{5/2}$ to the quadrupole vibrations of the even even core.[15] One can expect various levels in the low-energy region with spins $\frac{1}{2}^+$ to $11/2^+$. In other words collective character of excitation should be expected in the energy spectrum of Pr^{143}.

The 57-keV transition from the first excited state of Pr^{143} is found to be mainly $M1$ with $E2$ admixture $\lesssim 0.3\%$ by measurement of L_I/L_{II} and L_I/L_{III} conversion ratios and by the 293–57-keV γ-γ angular correlation.[10,11] From the measurement of the lifetime of the 57-keV level[6–8,11] the $M1$ transition from this to the ground state is found to be retarded. This indicates the l-forbidden $M1$ character of the transition between $d_{5/2}$ state (57 keV) and $g_{7/2}$ ground state.

The 351-keV level can have spin and parity $\frac{3}{2}^+$ or $\frac{7}{2}^+$ consistent with the previous measurements of the 293–57-keV angular correlation and the measurement of the conversion coefficient and K/L ratio of the 293-keV transition.[10,11] The 493- and the 725-keV levels are assigned spins $\frac{9}{2}^+$ and $\frac{7}{2}^+$, respectively, from our preliminary results of γ-γ angular-correlation study involving the 232–493-keV cascade. One of these transitions is mainly $E2$ in character while the other is $M1+E2$. Since there is a 142-keV transition from the $\frac{9}{2}^+$ 493-keV level to the 351-keV level with appreciable intensity compared to the transition to the 57-keV level, it favors a $\frac{7}{2}^+$ assignment for the 351-keV level. There is a ground-state transition from the 942-keV level, but the transition to the 57-keV level is more intense. So the probable spin and parity of this state are $\frac{5}{2}^+$, $\frac{7}{2}^+$, or $\frac{9}{2}^+$. Similarly the 1160-keV level could be assigned $\frac{3}{2}^+$, $\frac{5}{2}^+$, or $\frac{7}{2}^+$.

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Ground State of Ce^{143}

In ${}_{58}Ce_{85}{}^{143}$ the three neutrons outside the major closed shell of 82 neutrons, are expected to be in the $f_{7/2}$ orbital. These can couple to a resultant spin of either $\frac{7}{2}$ or $\frac{5}{2}$, the parity being negative. This is supported by the direct measurement of the spins of the neighboring nuclei with $N=83$ to 87.

The $\log ft$ values of β transitions from Ce^{143} to most of the levels of Pr^{143} indicate that they are of the first forbidden type ($\Delta J=0, \pm 1$, yes). This shows that these levels have even parity. The absence of the first-forbidden β transition to the ground state of Pr^{143} cannot be explained. It can only be mentioned that similar cases are present in the β decay of Nd^{147} and Nd^{149} where the ground-state β transition from $\frac{5}{2}^-$ to $\frac{7}{2}^+$ is absent or highly retarded.[21,22]

ACKNOWLEDGMENTS

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Nuclear Matrix Elements for First-Forbidden β Decay*

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The first-forbidden β decay from the ground states of odd-odd nuclei to the quadrupole vibrational states of even-even nuclei is studied. It is found that the collective motions introduce particle-hole correlations and thereby lead to cancellations, which is the dominant feature of these processes. The region of proton number between 50 and 60 is treated in detail.

I. INTRODUCTION

Although β decay has long played an important part in the study of nuclear structure, and the classification into allowed and forbidden transitions was correlated with nuclear shell model soon after it was proposed,[1] it has been only recently that experimental techniques have been adequate to determine the nuclear matrix elements of the operators leading to forbidden transitions. There is still uncertainty in some of the experimental results, but systematics are gradually being collected which are hard to understand in either the shell model or the collective model.

The first-forbidden β decays involve six matrix elements, all with parity change. There are two matrix elements (in the standard notation[2] $\int\gamma_5$ and $\int\boldsymbol{\sigma}\cdot\mathbf{r}/i$) for which the spins of the initial and final states must be the same ($\Delta J=0$), three $\Delta J=1$ matrix elements ($\int i\mathbf{r}$, $\int\boldsymbol{\sigma}\times\mathbf{r}$, and $\int\boldsymbol{\alpha}$), and $\int iB_{ij}$ for which the spin change can be as large as two. The single-particle estimates for the relativistic matrix elements $\int\gamma_5$ and $\int\boldsymbol{\alpha}$ are roughly 0.1, while for the other matrix elements they are roughly the nuclear radius R.

The experimental values are always considerably less than these. Typical experimental results are 1–10% of the single-particle estimate for the $\int iB_{ij}$ and $\frac{1}{10}$% for the other matrix elements. Moreover, there seem to be rapid variations in the matrix elements from isotope to isotope.

In this work we study the transitions from odd-odd to even-even spherical nuclei, the only ones for which there is experimental data, in terms of the shell model with particle correlations in order to try to learn what aspects of nuclear structure can lead to these unusual results. These decays are especially interesting from a nuclear structure point of view since the final states are collective states. The detailed calculations are restricted to the isotopes with proton number 50–60, a region in which many properties of the low-lying states have been successfully interpreted in terms of the modes of motion derived from a system of shell-model particles interacting with pairing and quadrupole forces.[3] We use these methods to calculate the first forbidden beta transitions to low-lying collective states, giving numerical results for the β^+ and β^- transitions to the first 2^+ states from the 2^- and 3^- states in the odd-odd nuclei.

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