Thermal neutron capture on ^{142}Ce

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The γ ray spectrum from thermal neutron capture on ^{142}Ce has been studied from 100 keV to 6.4 MeV. The γ rays were studied in singles and coincidence with Ge(Li) detectors. The results obtained together with information from the ^{142}Ce$(d,p)^{143}$Ce reaction indicate the population by neutron capture of levels in ^{143}Ce with energies 18.4±0.5, 42.4±0.6, (56.4±1.0), 632.5±0.5, 808.2±0.3, 862.1±0.3, 1154.1±0.3, 1172.5±0.3, 1572.4±0.5, 1620.5±0.4, 1628.7±0.4, 1835.2±0.8, 1913.4±1.1, 1945.4±0.6, 1993.3±0.6, 2027.4±0.8, 2061.5±0.6, 2202.0±0.6, 2215.9±0.6, 2232.1±0.7, 2272.7±1.0, 2313.9±0.8, 2488.6±1.0, and 2537.3±0.8 keV. The neutron separation energy of ^{143}Ce was determined to be 5145.9±0.5 keV, which is in poor agreement with values obtained from currently available mass tables. The ^{143}Ce level scheme was found to be similar to that of other even Z, $N=85$ nuclei with a small group of levels close to the ground state separated by 600–700 keV from the next level. Below 1600 keV it is possible to identify levels in ^{143}Ce excited in both the (n,γ) and (d,p) reactions. For those levels which have been assigned $l_n=1$ in the (d,p) reaction, it was found that the strengths of excitation in the (n,γ) and (d,p) reactions are strongly correlated as in the neighboring $N=83$ nuclei ^{139}Be and ^{141}Ce. This result is interpreted as indicating that direct capture plays an important role in the mechanism of the ^{142}Ce$(n,\gamma)^{143}$Ce reaction.

[NUCLEAR REACTIONS ^{142}Ce(n,γ) E=thermal: measured E_γ, I_γ, $\gamma\gamma$-coin. ^{143}Ce deduced levels, transitions, J, π, Q.]

I. INTRODUCTION

It has long been known that 82 neutrons constitute a closed shell but it is only recently that we have begun to accumulate detailed information about the level structure and level properties of nuclei near this closed shell. Studies[1–32] of nuclei with 83 neutrons and an even number of protons have revealed the strikingly simple structure associated with a single neutron outside the closed shell. ^{143}Ce has three neutrons outside the closed shell and a knowledge of the level structure of this nucleus is important for the light it sheds on how the relatively simple structure of the $N=83$ nuclei is modified by the addition of more neutrons. Accordingly, we have studied the γ rays from the ^{142}Ce$(n,\gamma)^{143}$Ce reaction and the results are reported here.

To date, our knowledge of the properties of levels in ^{143}Ce is very limited. The γ rays from the β decay of 14 min ^{143}La have been studied by Fritze, Kennett, and Prestwich.[33] These authors measured the energies and intensities of the γ rays from ^{143}La but did not propose a decay scheme. The ^{142}Ce$(d,p)^{143}$Ce, ^{142}Ce$(p,p)^{142}$Ce, and ^{142}Ce$(p,p')^{142}$Ce reactions have been studied by Lessard, Gales, and Foster.[23] They reported a large number of levels and assigned l values and spectroscopic factors to them from a distorted wave Born approximation analysis of the angular distributions of the outgoing protons. Some information on these levels was also obtained by Fulmer, McCarthy, and Cohen,[3] from measurements of the (d,p) reaction on natural cerium.

Prior to the present work little was known about the electromagnetic decay of levels in ^{143}Ce. Groshev *et al.*[34] reported the energies and intensities of four primary γ rays observed in thermal neutron capture. Pingel[35] made measurements on the $(d,p\gamma)$ reaction on natural cerium and reported the decay of a number of low-lying levels in ^{143}Ce.

We present here detailed information on the γ ray decay of the low-lying levels in ^{143}Ce which are populated in the ^{142}Ce$(n,\gamma)^{143}$Ce reaction. The energies and relative intensities of the ^{143}Ce γ rays were measured with Ge(Li) detectors (see Sec. II B). γ-γ coincidences were studied with a Ge(Li)-Ge(Li) detector combination (Sec. II C). A level scheme for ^{143}Ce was then constructed on the basis of all the available information (Sec. III). This level scheme is discussed and compared with those of neighboring nuclei in Sec. IV B. In Sec. IV A possible correlations between the strengths of excitation of levels in ^{143}Ce in the (d,p) and (n,γ)

reactions are discussed in terms of the neutron capture reaction mechanism.

II. EXPERIMENTAL METHODS AND RESULTS

A. Equipment

The principal target used in these experiments consisted of 6.14 g of CeO_2 enriched in ^{142}Ce with the following isotopic composition[36]: $<0.05\%$ ^{136}Ce, $<0.05\%$ ^{138}Ce, 7.89% ^{140}Ce, and 92.11% ^{142}Ce. In thermal neutron capture the contribution of ^{142}Ce to the capture cross section of this sample is $\simeq 95\%$. The sample was enclosed in a Teflon capsule. This target was irradiated in an external, filtered, thermal neutron beam[37] from the Brookhaven high flux beam reactor with an intensity of $\simeq 7\times10^7$ neutrons/sec cm^2 and a Cd ratio of $\simeq 2\times10^4$.

A target of natural CeO_2 was used to study the γ ray spectrum from thermal neutron capture on natural cerium under the same conditions. The γ ray spectrum obtained with a sample of graphite in the target position was also studied to obtain a measure of the background radiation.

The γ ray singles spectra were measured with a Ge(Li) detector of $\simeq 40$ cm^3 active volume. Coincidences between γ rays were studied with this detector and a 15 cm^3 Ge(Li) detector with both detectors at right angles to the neutron beam. $^6Li_2CO_3$ absorbers were placed in front of the detectors to prevent scattered neutrons from reaching them.

B. Energy and intensity measurements

The γ ray singles spectrum from the ^{142}Ce(n,γ)^{143}Ce reaction was measured over the energy range 100 keV–6.4 MeV in several runs of different dispersion and energy range. In order to assign lines correctly to ^{143}Ce the γ ray spectrum from a natural CeO_2 target was studied under the same conditions. Careful comparisons of these spectra allowed the assignment of γ rays to the ^{142}Ce(n,γ)^{143}Ce reaction and these are listed in Table I. The lower half of Fig. 1 shows an example of part of the γ ray spectrum from the enriched target from $\simeq 3300$ to 4800 keV. This spectrum was accumulated in two days with the beam collimated to a diameter of 3.0 mm. It may be compared with the spectrum from the natural CeO_2 target taken under identical conditions which is shown in the upper half of the figure. The energies of peaks assigned to ^{143}Ce are given in keV and single and double asterisks indicate one- and two-escape peaks, respectively.

The energies of the ^{143}Ce γ rays were measured from the spectra recorded with the natural Ce target and the target enriched in ^{142}Ce. At intervals during the measurement of these spectra the electronic pulses were routed into a separate section of the analyzer memory and a set of pulser peaks from a precision pulser[38] was superimposed on the γ ray spectrum. This allowed us to compare the energies of the ^{143}Ce γ rays with the previously measured energies of the ^{141}Ce capture γ rays,[19] the γ rays from the decay[39] of ^{143}Ce, and the hydrogen capture γ ray.[40] The energy separations between the ^{143}Ce γ ray lines and the calibration lines were first determined in units of pulse height from the pulser. The pulse height differences were then converted into energy differences by comparison with the known energy differences between the calibration lines. It should be noted that this procedure assumes that there is a linear relationship between the pulse heights from the γ ray detector and the pulser, and between pulse height and the channel number of the observed peak over the short regions between peaks. The measured energies of the ^{143}Ce γ rays obtained in this way are shown in column 1 of Table I.

The relative intensities of the ^{143}Ce γ rays were measured and are given in column 2 of Table I. These intensities were obtained with the use of a relative efficiency curve for the 40 cm^3 Ge(Li) detector which was obtained in the manner described by Kane and Mariscotti.[41]

C. γ-γ coincidence measurements

γ-γ coincidences were measured with two Ge(Li) detectors. A standard fast-slow coincidence circuit was used. The two linear signals from the Ge(Li) detectors were analyzed with two 4096 channel analog to digital converters and a PDP-11 computer and recorded in event-by-event mode on IBM compatible magnetic tape. An off-line analysis program allowed the reconstruction of coincidence spectra by setting digital windows on the peak of interest. Gates of identical width were set on adjacent featureless parts of the spectrum to identify coincidences with the underlying Compton continuum. Delayed coincidences were also recorded to determine the random coincidence counting rate. It was found to be very small compared with the total coincidence rate.

Figure 2 shows an example of the results obtained. The upper part shows the spectrum from 470 to 850 keV in coincidence with the double-escape peak of the prominent 4337.8 keV primary γ ray. This may be compared with the singles γ ray spectrum recorded with the same dispersion which is shown in the lower half of the figure. The information obtained from the coincidence measurements is summarized in Table II.

TABLE I. Energies, relative intensities, and assignments of γ rays from the $^{142}Ce(n,\gamma)^{143}Ce$ reaction.

E_γ (keV)	I_γ (rel.)	Level From	Level To
5145.5±0.7 [a]	0.28±0.07	5145.9	g.s.
4513.0±0.7	0.43±0.12	5145.9	632.5
4337.8±0.6 [a]	100±5	5145.9	808.2
4283.9±0.6 [a]	9.8±1.5	5145.9	862.1
3991.7±0.6	7.2±1.0	5145.9	1154.1
3973.1±0.7	0.7±0.2	5145.9	1172.5
3573.1±0.7	4.3±0.5	5145.9	1572.4
3525.7±1.0	2.9±0.3	5145.9	1620.5
3517.0±1.0	2.9±0.3	5145.9	1628.7
3310.4±0.8	3.2±0.4	5145.9	1835.2
3232.5±0.6	4.1±0.5	5145.9	1913.4
3200.2±0.5	2.6±0.4	5145.9	1945.4
3153.1±0.5	3.8±0.4	5145.9	1993.3
3118.9±0.8	1.2±0.3	5145.9	2027.4
3084.0±1.0	5.1±0.5	5145.9	2061.5
2943.4±1.0	0.8±0.2	5145.9	2202.0
2930.6±1.0	0.8±0.3	5145.9	2215.9
2913.4±0.6	1.7±0.3	5145.9	2232.1
2873.2±1.0	1.4±0.2	5145.9	2272.7
2831.7±1.0	0.9±0.1	5145.9	2313.9
2657.6±0.8	1.1±0.2	5145.9	2488.6
2608.5±0.6	1.1±0.2	5145.9	2537.3
2596.5±1.0	0.7±0.2	...	
2568.1±1.0	0.6±0.2	...	
2538.0±1.0	1.3±0.2	2537.3	g.s.
2494.5±0.8	0.5±0.3	2537.3	42.4
2453.2±1.5	0.6±0.3	...	
2446.8±1.5	0.6±0.3	2488.6	42.4
2433.6±1.0	0.2±0.1	2488.6	56.4
2305.5±1.5	0.4±0.2	...	
2276.0±1.5	0.3±0.2	...	
2271.2±1.5	0.2±0.07	2272.7 2313.9	g.s. 42.4
2244.1±0.8	0.5±0.2	...	
2231.3±0.8	0.2±0.1	2232.1 2272.7	g.s. 42.4
2201.8±0.4	1.1±0.3	2202.0	g.s.
2190.3±0.5	0.8±0.3	2232.1	42.4
2174.0±0.6	0.7±0.3	2215.9	42.4
2061.3±0.6	1.3±0.3	2061.5	g.s.
2042.9±0.8	0.7±0.3	2061.5	18.4
2027.9±0.8	1.6±0.3	2027.4	g.s.
2018.8±0.4	3.2±0.6	2061.5	42.4
1993.2±0.4	0.6±0.1	1993.3	g.s.
1949.9±0.2	3.4±0.3	1993.3	42.4
1928.0±1.5	0.3±0.2	1945.4	18.4
1922.6±0.8	0.8±0.3	...	
1912.2±0.8	1.5±0.5	1913.4	g.s.
1902.8±0.5	0.9±0.3	1945.4	42.4
1883.4±1.5	0.3±0.2	...	
1843.2±0.6	0.9±0.2	...	
1835.8±0.6	1.1±0.3	1835.2	g.s.
1782.1±0.5 [b]	0.6±0.2	...	
1757.0±0.5	0.6±0.1	...	
1748.7±0.5	0.8±0.2	...	
1736.8±0.5	0.4±0.2	...	
1681.3±0.8	0.8±0.3	2313.9	632.5
1674.9±0.8	0.3±0.1	2537.3	862.1
1662.9±0.5	0.6±0.2	...	
1650.9±0.3	1.3±0.3	...	
1628.5±0.6	1.1±0.3	1628.7	g.s.
1620.5±0.5	0.8±0.2	1620.5	g.s.
1586.0±1.0	0.3±0.1	1628.7	42.4
1578.6±0.8	1.1±0.3	1620.5	42.4
1572.2±0.5	5.7±0.6	1572.4 1628.7	g.s. 56.4
1557.6±0.6	0.4±0.1	...	
1546.2±0.6	0.3±0.1	...	
1529.1±0.6	0.8±0.2	1572.4	42.4
1521.3±0.7	0.4±0.1	...	
1515.3±0.7	0.2±0.1	1572.4	56.4
1505.9±0.7	0.6±0.2	2313.9	808.2
1434.2±0.5	0.7±0.1	...	
1347.2±0.2	1.0±0.2	...	
1278.3±0.8	0.5±0.1	...	
1259.4±0.2	1.4±0.1	...	
1217.6±0.3	0.9±0.2	...	
1185.7±0.6	0.4±0.1	1993.3	808.2
1172.3±0.4	2.0±0.3	1172.5	g.s.
1165.2±0.5	1.2±0.2	2027.4	862.1
1154.1±0.3	8.8±0.3	1154.1	g.s.
1146.1±0.4	1.5±0.4	...	
1136.0±0.4	2.1±0.4	(1154.1	18.4)
1130.2±0.4	1.5±0.3	1172.5	42.4
1123.1±0.5	0.4±0.1	...	
1117.4±1.0	0.2±0.1	2272.7 1172.5	1154.1 56.4
1106.3±0.5	1.5±0.3	1913.4	808.2
1093.9±1.0	0.9±0.2	...	
1047.3±0.8	0.3±0.1	...	
1026.8±0.7	1.3±0.2	1835.2	808.2
988.3±0.5	0.5±0.1	1620.5	632.5
972.3±0.6	1.7±0.2	1835.2	862.1
963.2±0.5	0.8±0.1	...	
915.2±0.7	0.5±0.1	2488.6	1572.4
862.2±0.3 [a]	14.8±2.0	862.1	g.s.
853.3±0.8	0.4±0.1		
830.8±0.8	0.3±0.1	...	
820.8±1.0	0.2±0.1	1628.7 1993.3	808.2 1172.5
808.3±0.3 [a]	34.2±3.0	808.2	g.s.
789.4±0.3	16.1±1.2	808.2	18.4
766.0±0.5	47.2±2.5	808.2	42.4

TABLE I. *(Continued)*

E_γ (keV)	I_γ (rel.)	Level From	Level To
741.6 ± 0.6 } 738.4 ± 0.6 }	0.8 ± 0.2	1913.4 / 2313.9	1172.5 / 1572.4
731.6 ± 0.8	0.6 ± 0.1	···	
696.9 ± 0.3	0.3 ± 0.1	···	
645.5 ± 0.8	0.3 ± 0.1		
632.3 ± 0.4	0.3 ± 0.1	632.5	g.s.
489.8 ± 0.3	0.7 ± 0.3	2061.5	1572.4
393.8 ± 0.2	0.1 ± 0.05	···	
345.4 ± 0.7	0.1 ± 0.05	1154.1	808.2
283.3 ± 0.3	0.4 ± 0.1	···	

[a] The measured energies of these γ rays were used to determine the neutron separation energy.
[b] Unresolved doublet.

III. CONSTRUCTION OF THE LEVEL SCHEME

The level scheme of ^{143}Ce, which is shown in Fig. 3, was constructed from the results of Table I, the γ-γ coincidence measurements, and the information available from the (d,p) reaction and proton scattering studies of Lessard *et al.*[23]

The assignment of the intense γ rays of 4337.8 and 4283.9 keV energy as primary transitions to levels at 808.2 and 862.1 keV provides a sound basis for the construction of the level scheme. These assignments are based on the following arguments.

(a) The (d,p) and (p,p') reaction studies indicate the existence of levels in ^{143}Ce at 0, 21, 40, 815, and 869 keV with angular momentum transfers $l=1$, 3, (1), 1, and 1, respectively, in the (d,p) reaction. Since the capture state has spin and parity $\frac{1}{2}^+$ one may expect $E1$ primary transitions to the levels with $l=1$, namely the ground state and the states at 40, 815, and 869 keV. The differences in energy between the 5145.5, 4337.8, and 4283.9 keV γ rays are consistent with their assignment as primary transitions to the ground state and excited states at 808.2 and 862.1 keV.

(b) In the low energy region of the ^{143}Ce γ ray spectrum, we observe intense γ rays of energies 808.3 and 862.2 keV. These energies are in excellent agreement with the differences in energy of the highest energy γ ray (5145.5 keV) and 4337.8 and 4283.9 keV γ rays, and support their placement as ground state transitions from the levels at 808.2 and 862.1 keV.

(c) The coincidence measurements (see Fig. 2 and Table II) show clearly that the 4337.8 keV γ ray is in coincidence with the γ rays of energies 808.3, 789.4, and 766.0 keV which are consistent with the assignment of the 4337.8 keV γ ray as a primary γ ray to a level at 808.2 keV which decays to the ground state and levels at 18.4 and 42.4 keV. Similarly the observed 4283.9-862.2 keV coincidences confirm the placement of the 4283.9 keV transition.

It should be noted that the errors on the level energies reported[23] in the (d,p) reaction are large and the arguments outlined above do not eliminate the possibility that all of the levels are displaced by a few keV from the true ground state. No evidence was found for such a possibility.

These observations establish the levels at 808.2 and 862.2 keV. The remainder of the level scheme was then constructed as follows:

The neutron separation energy for ^{143}Ce was determined from the 4337.8-808.3 keV and 4283.9-862.2 keV cascades and the energy of the primary transition to the ground state. The weighted average value of the neutron separation energy, corrected for the energy of nuclear recoil, was found to be 5145.9 ± 0.5 keV. This is in very poor agreement with the value of 5178 ± 7 keV given in the mass tables of Wapstra and Gove.[42] This discrepancy reflects the lack of precise information on neutron separation energies in this region.

It was assumed that each of the observed high energy γ rays down to an energy of 2600 keV was a primary γ ray. Secondary γ rays were placed in the level scheme on the basis of the energy combination principle supported in some cases by the coincidence results. Below 1600 keV the existence of the observed levels was also supported by evidence from the (d,p) reaction studies. With the exception of the low-lying levels at 18.4, 42.4, and 56.4 keV at least one incoming and one outgoing transition was observed for each of the levels finally placed.

Comments on the properties of the individual levels in ^{143}Ce follow.

A. Ground state, 18.4 ± 0.5, 42.4 ± 0.6, and 56.4 ± 1.0 keV levels

A group of four low-lying levels was observed by Lessard *et al.*[23] in the ^{142}Ce$(d,p)^{143}$Ce reaction with $l_n=1$, 3, (1), and 3, respectively. The ground state spin has been measured[43] to be $\frac{3}{2}^-$. Lessard *et al.* assigned spin and parity $\frac{7}{2}^-$ to the level at 21 keV on the basis of the measured spectroscopic factor.

The capture state in ^{143}Ce following thermal neutron capture (s wave) has spin and parity $\frac{1}{2}^+$. It is expected to decay via $E1$ primary transitions to levels with $l_n=1$. A weak primary transition of 5145.5 keV is observed to the ground state but no

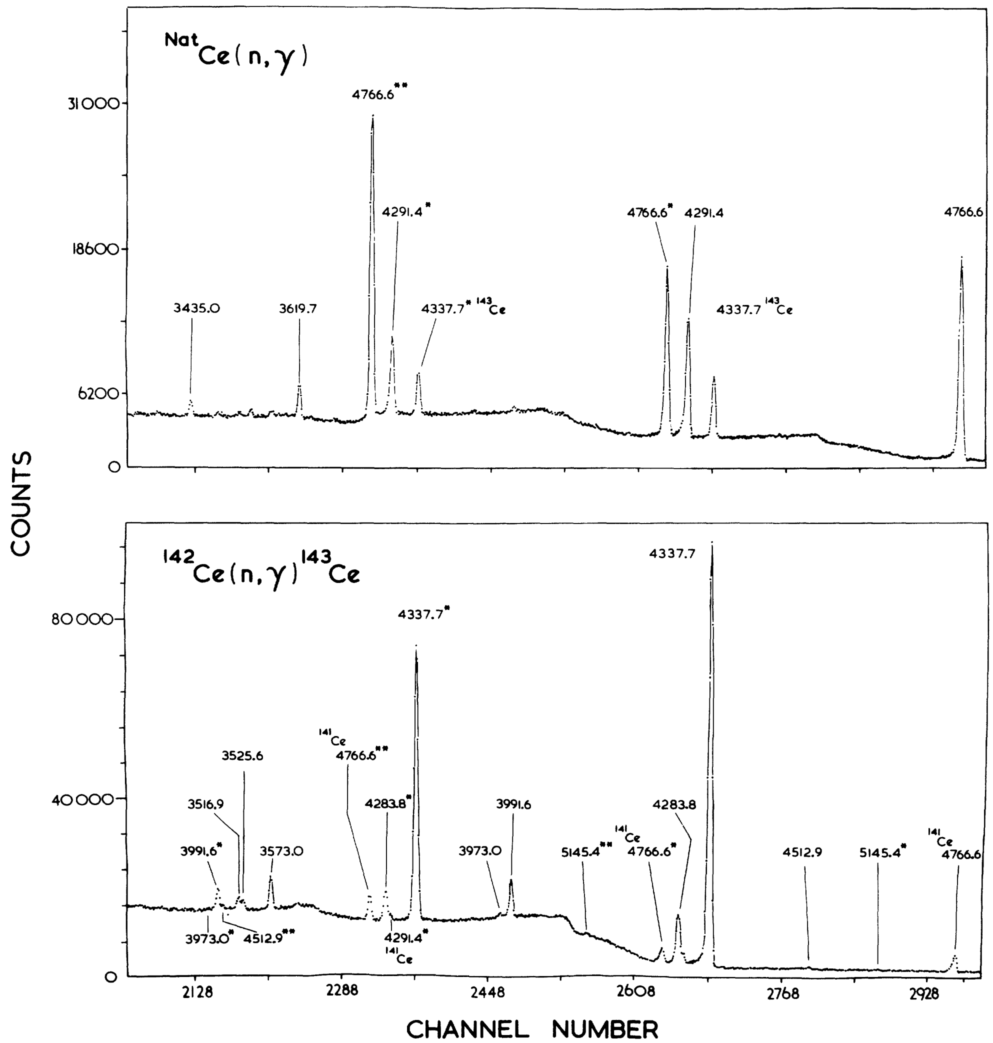

FIG. 1. This figure shows a small portion of the γ ray spectra from a natural CeO_2 target (upper half) and a CeO_2 target enriched in ^{142}Ce. The spectra were taken under identical conditions and cover the same energy range, 3300–4800 keV. Single- and double-escape peaks are marked with one and two asterisks, respectively. The targets were irradiated in an external, filtered thermal neutron beam at the Brookhaven high flux beam reactor. The lower spectrum was accumulated in approximately two days. Comparisons of spectra like these and spectra taken with a graphite scatterer allowed the assignment of γ rays to the $^{142}Ce(n, \gamma)^{143}Ce$ reaction (see Sec. II B).

primary transition is observed to the other three levels discussed here.

The levels at 18.4 and 42.4 keV are clearly established by the observation of the strong 4337.8-789.4 and 4337.8-766.0 keV γ ray cascades in the coincidence measurements. In both cases, several other γ rays were also found to fit between the level and higher excited states. Unfortunately, it was not possible to study the γ ray spectrum below 60 keV so no information was obtained about the decay of these levels.

The existence of the level at 56.4 keV is less certain. No firm evidence was obtained from the coincidence studies for any γ ray feeding such a level. Four weak γ rays were found to fit as transitions to a level at this energy from the levels at 1172.5, 1572.4, 1628.7, and 2488.6 keV. These γ rays do not fit elsewhere in the level scheme. Without more conclusive evidence, it is not clear that this level is populated in the (n,γ) reaction.

B. Level at 632.5 ± 0.5 keV

A level at this energy is fed by the weak primary γ ray of 4513.0 keV energy. It decays to the ground state via the 632.3 keV transition. It may be identified with the level reported[23] in the (d,p) reaction at 637 keV with $l_n = 1$. The direct feeding

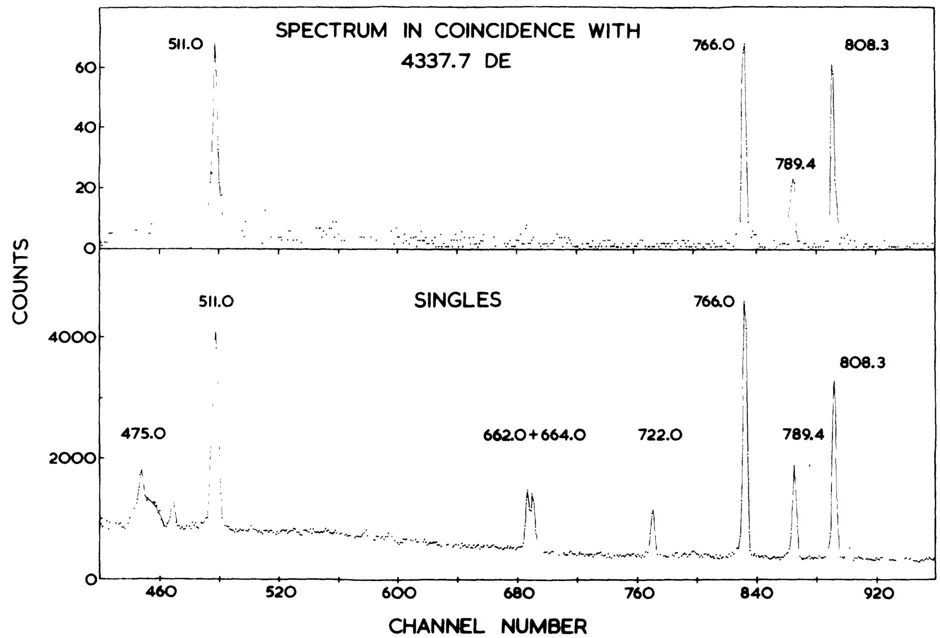

FIG. 2. The upper half of the figure shows a portion of the Ge(Li) detector spectrum in coincidence with the double-escape peak of the strong 4337.8 keV γ ray. For comparison the corresponding part of the singles spectrum in the same detector is shown in the lower half of the figure. It is clear from these spectra that the double-escape peak of the 4337.8 keV γ ray is in coincidence with the 511.0, 766.0, 789.4, and 808.3 keV γ rays. (See Sec. III).

from the $\frac{1}{2}^+$ capture state and the assigned angular momentum transfer in the (d,p) reaction indicate spin and parity $\frac{1}{2}^-$ or $\frac{3}{2}^-$.

C. Level at 808.2 ± 0.3 keV

This level is fed by the very intense 4337.8 keV primary γ ray and decays by the strong 808.3, 789.4, and 766.0 keV γ rays to the ground state and the levels at 18.4 and 42.4 keV. It is also populated by secondary transitions of 345.4, 1026.8, 1106.3, 1185.7, and 1505.9 keV from the levels at 1154.1, 1835.2, 1913.4, 1993.3, and 2313.9 keV. It may be identified with the level at 815 keV reported by Lessard *et al.*[23] to be strongly populated in the (d,p) reaction.

The direct feeding from the $\frac{1}{2}^+$ capture state and decay to levels with spins and parities $\frac{7}{2}^-$ and $\frac{3}{2}^-$ indicate that this state has spin and parity $\frac{3}{2}^-$ since the choice of $\frac{1}{2}^-$ would require a very enhanced $M3$ transition to the 18.4 keV state to compete with the $M1$ ground state transition.

TABLE II. Results of the γ-γ coincidence measurements.

γ ray (keV)	Coincident γ rays (keV)
4337.8	766, 789 and 808
4283.9	862
3991.7	1154
1154.1	3991
862.2	972, 4283 [a]
808.2	4337, [a] (1026)
789.4	4337, [a] 1026
766.0	4337, [a] 1026

[a] The double- and single-escape peaks and the photopeak were seen in coincidence in this case.

D. Level at 862.1 ± 0.3 keV

Lessard *et al.*[23] reported a level at 869 keV which was strongly excited in the (d,p) reaction with $l_n = 1$. It was tentatively assigned spin and parity $\frac{1}{2}^-$ on the basis of the measured spectroscopic factor.

This same level is populated by the intense 4283.8 keV primary γ ray and decays to the ground state by a transition of 862.2 keV energy. γ rays of 972.3, 1130.2, 1165.2, and 1674.9 keV also fit as populating this level from the levels at 1835.2, 1993.3, 2027.4, and 2537.3 keV. The 1130.2 keV transition also fits elsewhere in the level scheme.

The present results are consistent with spin and parity $\frac{1}{2}^-$ but $\frac{3}{2}^-$ cannot be ruled out.

E. Level at 1154.1 ± 0.3 keV

This level is populated by the 3991.6 keV primary γ ray. The 1154.1, 1136.0, and 345.4 keV transi-

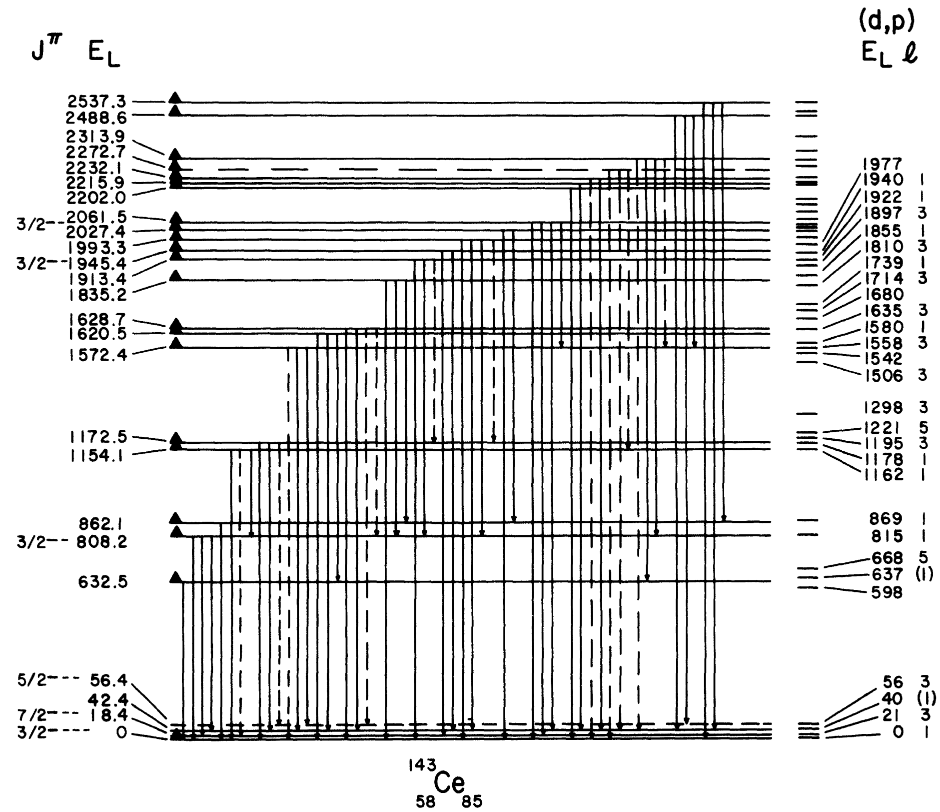

FIG. 3. This figure shows the level scheme of ^{143}Ce based on the present work and the results of the (d, p) studies of Lessard *et al.* (Ref. 23). Level energies in keV (E_L) and assigned spins and parities (J^π) are shown on the left of each level. Those levels not assigned a definite spin and parity have spin $\frac{1}{2}$ or $\frac{3}{2}$. The solid horizontal lines represent established levels and the vertical lines transitions between them. Where a line appears dashed it represents a transition which may be placed in more than one place in the level scheme. The results of the (d, p) reaction studies are summarized on the right. The measured level energy in keV (E_L) and orbital angular momentum transfer (L) are given on the right of each level.

tions fit in energy between this level and the ground state, 18.4, and 808.2 keV levels. The coincidence measurements show clearly that this is the correct placement for the 1154.1 keV γ ray, but show no positive evidence for 3991.0-1136.0 keV coincidences, indicating that only a fraction of the 1136.0 keV transition intensity belongs here.

The level may be identified with the level seen at 1162 keV in the ^{142}Ce$(d,p)^{143}$Ce reaction and assigned $l_n = 1$, and with the level seen as an isobaric analog resonance at an effective energy of 1158 keV in the inelastic scattering of protons from ^{142}Ce. Lessard *et al.*[23] tentatively assigned spin and parity $\frac{1}{2}^-$ to this level. This assignment is consistent with the present results, but $\frac{3}{2}^-$ spin and parity cannot be ruled out.

F. Level at 1172.5 ± 0.3 keV

The 3973.0 keV primary γ ray feeds this level as do the 741.6, 820.8, and 853.3 keV transitions from levels at 1913.4, 1993.3, and 2027.4 keV. Only the last of these three secondary γ rays does not fit elsewhere in the level scheme. The level decays by the 1172.3, 1130.2, and 1117.4 keV γ rays to the ground state, 42.4, and 56.4 keV levels.

Lessard *et al.*[23] report a level at 1178 keV with $l_n = 1$ which they identify with an isobaric analog resonance at 1198 keV of assigned spin and parity $\frac{1}{2}^-$. The identification with the isobaric analog resonance is somewhat suspect since the difference in the observed energy from the level energy in the (d,p) reaction is very much larger than for all the other observed resonances. The present results are consistent with this assignment but they do not rule out the $\frac{3}{2}$ assignment.

G. Level at 1572.4 ± 0.5 keV

The primary γ ray of energy 3573.1 keV feeds this level which decays by the 1572.2, 1529.1, and 1515.3 keV transitions to the ground state, 42.4, and 56.4 keV states. The secondary transitions of 489.8, 741.6, 915.2, and 963.2 keV also fit as populating this level, although the 741.6 and 915.2 keV transitions fit elsewhere in the level scheme.

This level may be identified with the 1580 keV level observed by Lessard *et al.* and assigned $l_n=1$ in the (d,p) reaction. All of these results are consistent with spin and parity $\frac{3}{2}^-$ or $\frac{1}{2}^-$ for this level.

H. Levels above 1600 keV

Above an excitation energy of 1600 keV levels at 1620.5, 1628.7, 1835.2, 1913.4, 1945.4, 1993.3, 2027.4, 2061.5, 2202.0, 2215.9, 2232.1, (2272.7), 2313.9, 2488.6, and 2537.3 keV are observed to be populated by primary capture γ rays. Unfortunately, these levels cannot be positively identified with the levels reported by Lessard *et al.*[23] in the (d,p) reaction because of the limited energy resolution in their experiment and the increasing level density at higher excitation energy.

Most of these levels have been assigned spin $\frac{1}{2}$ or $\frac{3}{2}$ because they are fed directly from the $\frac{1}{2}^+$ capture state and because of their observed decay pattern. No experimental evidence is available concerning the parity of these levels although most are expected to have odd parity because of the orbital angular momentum of the neutron single particle orbits in this region. The 1945.4 and 2061.5 keV levels, however, have been assigned spin and parity $\frac{3}{2}^-$ because they are fed from the $\frac{1}{2}^+$ capture state and decay to the $\frac{7}{2}^-$ level at 18.4 keV. A $\frac{1}{2}^-$ assignment is ruled out since it is highly unlikely that an $M3$ transition to the 18.4 keV level would compete with dipole transitions to other levels. Similarly $\frac{5}{2}^-$ is ruled out since an $E2$ primary transition is unlikely to compete with the observed $E1$ primary capture γ rays.

IV. DISCUSSION

A. (n,γ)-(d,p) correlations

One of the most striking features of the neutron capture γ ray spectra from even Z, $N=82$ targets is the intense feeding of the low-lying p states from the s-wave capture states. The same feature is apparent here, where the target nucleus has $N=84$.

In the case of the $N=82$ targets this feature of the spectra has been investigated in some detail.[16,19,44,45] It was found[44,45] that for ^{140}Ce and ^{138}Ba there is a very strong correlation between the strengths of excitation of levels in the (d,p) and (n,γ) reactions. This correlation is clear evidence of the nonstatistical behavior of the neutron capture reaction. It has been shown[44] that this behavior is consistent with the common unique parent assumption of Lane and Wilkinson[46] and with the predominance of direct capture in the (n,γ) reaction mechanism. It has been suggested[47] that the occurrence of direct capture is enhanced by the availability of the $4s\rightarrow 3p$ transition in this region.

Since we expect the low-lying states of ^{143}Ce to be of relatively simple character and bear some relationship to the low-lying levels in ^{141}Ce it is natural to enquire whether there is any correlation between the strengths of excitation in the (d,p) and (n,γ) reactions for levels in ^{143}Ce with $l_n=1$.

The relevant results for a comparison of the strengths of excitation in the (d,p) and (n,γ) reactions on ^{142}Ce are summarized in Table III. The comparison is limited to levels below 1600 keV because it is not possible to equate levels seen in the two reactions above this energy. For s-wave neutron capture followed by $E1$ primary γ rays $G_{n\gamma}$, the relative strength of excitation in the (n,γ) reaction, is given by $I_\gamma/E_\gamma{}^3$. The values of $G_{n\gamma}$

TABLE III. Comparison of the strengths of excitation of levels in ^{143}Ce in the (n,γ) and (d,p) reactions. All of the levels assigned $l_n=1$ below 1600 keV are listed. The results of the (d,p) reaction are taken from Lessard *et al.* (Ref. 23). The energy resolution in their experiment is too poor to allow any comparison above 1600 keV. The first two columns give the level energy E_L (in keV) and the spins and parities of the states of interest. The third, fourth, and fifth columns give the primary γ ray energy in keV, its intensity relative to the 4337.8 keV γ ray intensity, and $G_{n\gamma}$ $(=I_\gamma/E_\gamma{}^3)$, the strength of excitation in the (n,γ) reaction. $G_{n\gamma}$ has been normalized so that $\overline{G}_{n\gamma}=\overline{G}_{dp}$ for the states considered. The strength of excitation in the (d,p) reaction, $G_{dp}=(2J_f+1)S$, is given in column 6. The final column gives $G_{n\gamma}/G_{dp}$.

E_L (keV)	J_f^π	E_γ (keV)	I_γ	$G_{n\gamma}$	G_{dp}	$G_{n\gamma}/G_{dp}$
0	$\frac{3}{2}^-$	5145.5	0.28 ± 0.07	0.004	0.13	0.031
42.4	$\frac{1}{2},\frac{3}{2}$	···	···	···	0.08	···
632.5	$\frac{1}{2},\frac{3}{2}$	4513.0	0.43 ± 0.12	0.009	···	···
808.2	$\frac{3}{2}^-$	4337.8	100 ± 5	2.40	2.00	1.2
862.1	$\frac{1}{2}(\frac{3}{2})^-$	4283.9	9.8 ± 1.5	0.25	0.60	0.42
1154.1	$\frac{1}{2},\frac{3}{2}$	3991.7	7.2 ± 1.0	0.24	0.13	1.84
1172.5	$\frac{1}{2},\frac{3}{2}$	3973.1	0.7 ± 0.2	0.022	0.09	0.24
1572.4	$\frac{1}{2},\frac{3}{2}$	3573.1	4.3 ± 0.5	0.18	0.13	1.38

are taken from the present work and appear in column 6. The corresponding strength of excitation in the (d,p) reaction is given by $G_{dp}=(2J+1)S$ where S is the spectroscopic factor. The values of G_{dp} are given in column 6. These results are taken from the work of Lessard *et al.*[23] It should be noted that the values of $G_{n\gamma}$ have been normalized so that $\overline{G}_{n\gamma}=\overline{G}_{dp}$. Figure 4 summarizes the comparison of $G_{n\gamma}$ and G_{dp} for a number of nuclei with $N=83$ and 85. In the case of ^{143}Ce it is readily ap-

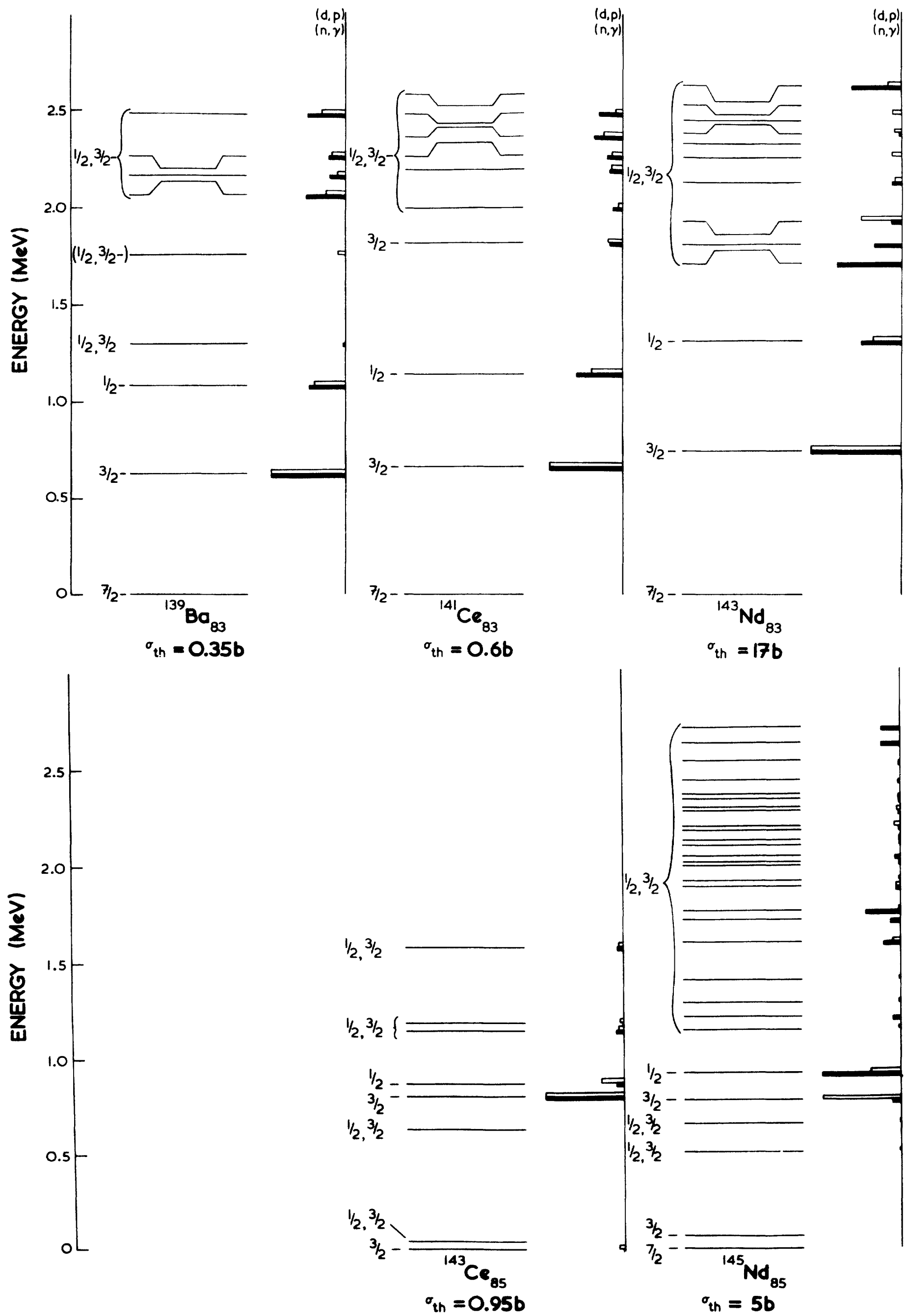

FIG. 4. A comparison of the strengths of excitation in the (d,p) and (n,γ) reactions of levels assigned $l_n=1$ in the (d,p) reaction for some nuclei with even Z, $N=83$ (^{139}Ba, ^{141}Ce, and ^{143}Nd) and even Z, $N=85$ (^{143}Ce and ^{145}Nd). An energy scale is shown on the left. The spin and parity are shown on the left of each level. The strengths of excitation obtained in the (n,γ) and (d,p) reactions, are shown graphically on the right of each level scheme by solid and open bars, respectively. The thermal capture cross section is given below the appropriate level scheme.

parent that there is a strong correlation between these two quantities. This is borne out by the calculated correlation coefficient of 0.97 which has a very small probability of being consistent with zero correlation. This must be interpreted with some caution, however, since the level at 42.4 keV is not seen to be populated in the (n, γ) reaction and, although the 632.5 keV level is seen in the (d, p) reaction, no value for the spectroscopic factor was reported. This is not unexpected since the 632.5 keV level is only very weakly populated in the (n, γ) reaction. This result is thus consistent with the observed correlation. In addition the results are incomplete because it is limited to levels below 1600 keV. Nevertheless the evidence seems clear that there is a significant correlation in this case. This may be interpreted[44] as indicating that direct capture plays an important part in the mechanism of the ^{142}Ce$(n, \gamma)^{143}$Ce reaction.

It is interesting to look at the other $N = 83$ and $N = 85$ nuclei in the light of this result. Figure 4 summarizes the values of $G_{n\gamma}$ and G_{dp} for all levels with $l_n = 1$ in ^{139}Ba, ^{141}Ce, ^{143}Nd, ^{143}Ce, and ^{145}Nd, the only cases where sufficient results are available for such a comparison. In three cases, ^{139}Ba, ^{141}Ce, and ^{143}Ce there is a very strong correlation.

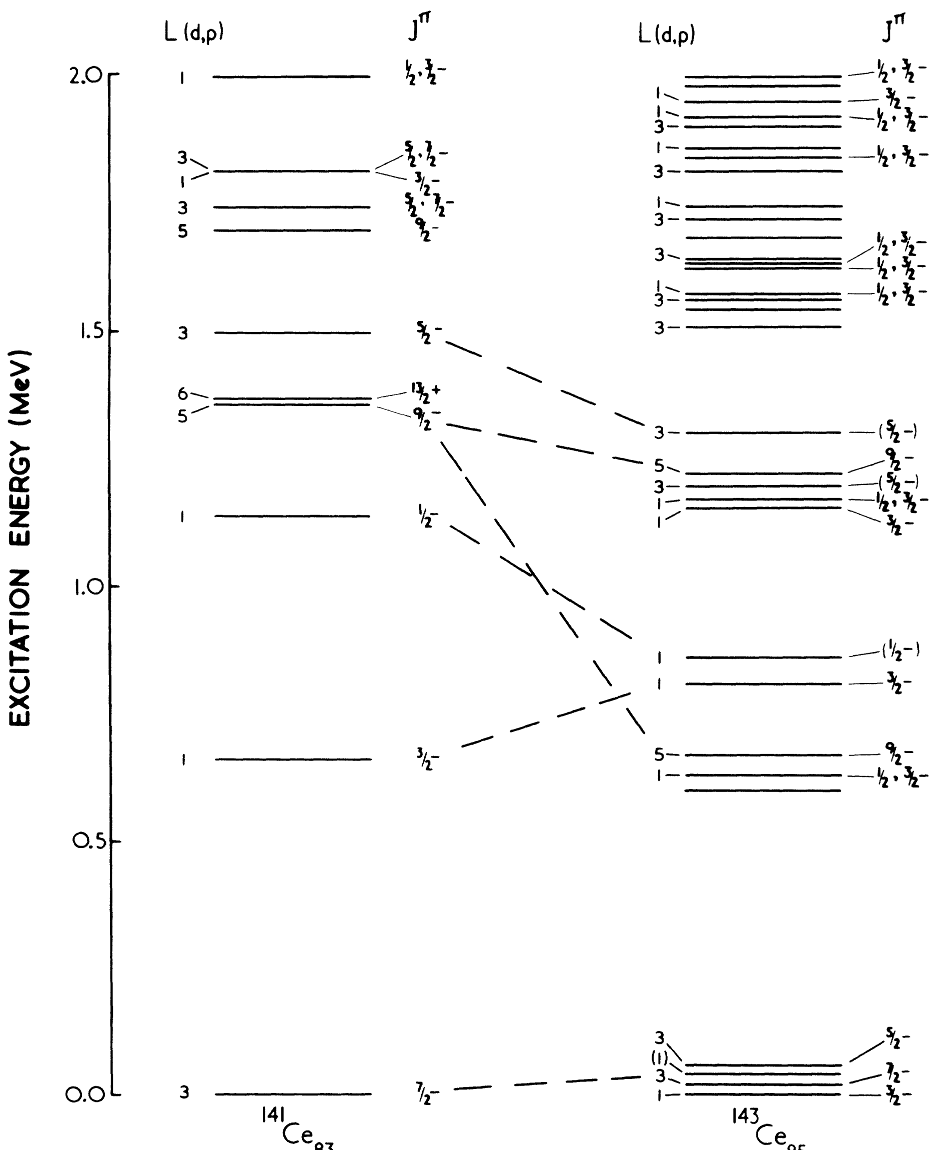

FIG. 5. Comparison of the energy level spectra of ^{141}Ce and ^{143}Ce. The energy scale is shown on the left. The measured angular momentum transfer in the (d, p) reaction is shown on the left of the level in each case. Where the spin and parity have been assigned they are given on the right of the level. The levels connected by the dashed lines are thought to be of similar character.

For ^{143}Nd and ^{145}Nd there is no correlation. The major difference between these two groups of nuclei is the thermal capture cross section which is 1 b or less for the first group and 18 and 5 b for the two Nd nuclei. The first group has cross sections consistent with those expected for direct capture alone but it is evident that there is a major contribution from a bound state or a resonance in the other two cases. As one would expect under such circumstances any contribution from direct capture is masked by the predominant, resonance capture with its statistical behavior. Taken overall it is quite clear that direct capture is favored in this region by the strong nuclear structure effect of the $N=82$ closed shell and the availability of the $4s \to 3p$ single particle transition.

B. Comparison with level schemes of neighboring nuclei

The level scheme of ^{143}Ce may be compared with that of other neighboring nuclei. Figure 5 compares the level schemes of ^{141}Ce and ^{143}Ce. Not unexpectedly the level structure of ^{143}Ce is considerably more complicated than that of ^{141}Ce. The level structure of ^{141}Ce is particularly simple with the lowest-lying levels being largely due to the single neutron outside the $N=82$ shell in the $f_{7/2}$, $p_{3/2}$, $p_{1/2}$, $h_{9/2}$, $f_{5/2}$, and $i_{13/2}$ orbits. At slightly higher energies one expects levels due to the coupling of the single neutron to the 2^+ first excited state of the ^{140}Ce core. The decay pattern[19] of the 1808.7 keV level in ^{141}Ce indicates that it may indeed be described as being mainly due to the $f_{7/2}$ neutron coupled to the 2^+ state of the core. As one would expect, the addition of two more neutrons causes much more fragmentation in ^{143}Ce, although one finds the same number of states with large spectroscopic factors in the two nuclei. These are identified by the dashed lines in Fig. 5.

A comparison may also be made with the other even Z, $N=85$ nuclei, ^{147}Sm and ^{145}Nd. As is readily apparent from Fig. 6 there is a close corres-

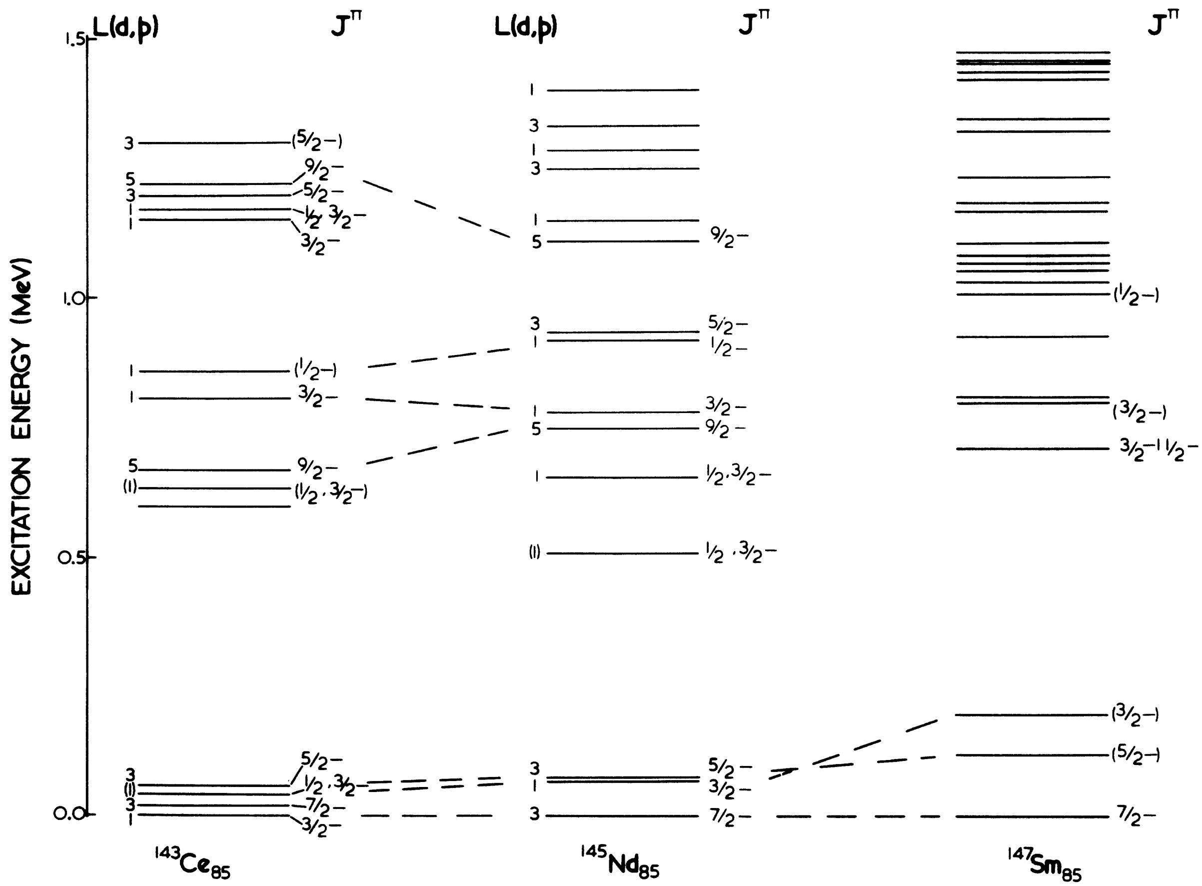

FIG. 6. Comparison of the energy level spectra of the three even Z, $N=85$ nuclei, ^{143}Ce, ^{145}Nd, and ^{147}Sm. The energy scale is shown on the left. The measured angular momentum transfer in the (d,p) reaction is shown on the left of each level. Where the spin and parity have been assigned they are given on the right of each level. Levels thought to be of similar character are connected by the dashed lines.

pondence between the properties of the three nuclei. In Nd and Sm the ground state has spin and parity $\frac{7}{2}^-$ and the corresponding state occurs at 18.4 keV in ^{143}Ce. All three nuclei are characterized by a small group of levels close to the ground state separated from the next level by about 600–700 keV. These levels may be interpreted as being due to the coupling of the three neutrons in the $f_{7/2}$ shell. Alternatively, they may be described in terms of the coupling of the $f_{7/2}$, $p_{3/2}$, $p_{1/2}$, etc. neutron single particle states to the 2^+ state of the ^{142}Ce core. In both cases we might expect the $\frac{3}{2}^-$ and $\frac{5}{2}^-$ states to lie very low in energy as is observed. Unfortunately, our knowledge of the properties of these levels is still too limited to allow any sensible test of these or other nuclear models.

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