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Structure of $N = 81$ nuclei: Levels of ^{141}Nd and ^{139}Ce populated in beta decay

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The nuclear level structure of ^{141}Nd and ^{139}Ce has been investigated by studying the decay of 20.9-min ^{141}Pm produced via the ^{141}Pr(^{3}He, $3n$) reaction and the decay of 4.5-h ^{139}Pr produced by the ^{140}Pr(γ, n)^{139}Pr reaction. For the ^{141}Pm decay, singles and anti-Compton γ-ray spectra and γ-γ coincidence measurements were used to deduce a decay scheme that includes nine previously unreported levels in ^{141}Nd and incorporates 67 of the 70 γ rays attributed to the decay of ^{141}Pm. Singles and anti-Compton spectra were taken as a function of time in order to confirm assignment of the ^{139}Pr γ rays. The level structures of ^{141}Nd and ^{139}Ce are compared to recent measurements in other $N = 81$ isotones. The results of this work are in good agreement with theoretical predictions based on the hole-vibrational coupling model for levels below 1.3 MeV. There exist more levels between 1.3 and 2.0 MeV than are predicted by this model, but these excess levels can be explained qualitatively within a weak coupling framework.

[RADIOACTIVITY ^{141}Pm [from ^{141}Pr(^{3}He, $3n$)] and ^{139}Pr [from ^{140}Pr(γ, n)] measured E_γ, I_γ, γ-γ coin; deduced ^{141}Nd and ^{139}Ce levels, J, π, and $\log ft$ values. Natural target, Ge(Li) detectors, anti-Compton spectrometer.]

I. INTRODUCTION

The energy levels of ^{141}Nd and ^{139}Ce, nuclei with a single hole in the $N=82$ neutron shell, are of particular interest because they are expected to be well characterized by the particle-core vibrational coupling model. In this description the lower-lying states are expected to be essentially pure neutron-hole configurations while the higher levels may be described as single neutron-hole states coupled to an excited closed-shell core. However, it has been shown that in ^{133}Te and ^{135}Xe [1-3] there are deviations from this simple hole-vibration picture as calculated by Heyde and Brussard.[4] It is hoped that a better understanding of the discrepancies with the hole-vibration description will emerge by studying the energy level systematics of $N=81$ nuclei with increasing proton number.

The levels in ^{141}Nd have been the subject of several recent reaction studies employing the (p,d) and (d,t) reactions.[5-7] These levels have also recently been investigated via the radioactive decay of 20.9-min ^{141}Pm.[8] The levels of ^{139}Ce have also been studied in reaction[5,9] and decay scheme[10,11] spectroscopy.

In this work the decay of ^{141}Pm and ^{139}Pr to the levels of ^{141}Nd and ^{139}Ce, respectively, have been investigated using anti-Compton spectrometry and (for ^{141}Pm) γ-γ coincidence techniques. The results reported here are in general agreement with previous studies but include many previously unreported γ-ray transitions and several new levels in ^{141}Nd and ^{139}Ce. The levels of ^{141}Nd and ^{139}Ce are also compared to recent results in neighboring $N=81$ nuclei.[1-3,5,7,12,13]

II. EXPERIMENTAL

A. Decay of ^{141}Pm

Sources of 20.9-min ^{141}Pm were produced via the ^{141}Pr(^{3}He, $3n$)^{141}Pm reaction by bombarding 99.95% natural praesodymium foils with a ^{3}He beam from the Washington University cyclotron. For the singles measurements the targets were bombarded for 10 μA min with a 4-μA beam of 28-MeV ^{3}He ions. In the coincidence experiments, a 32-MeV ^{3}He beam of 1-μA intensity and 4-sec duration was used. The higher projectile energy was used in the coincidence experiment so that coincidence relationships in ^{140}Pm could be investigated simultaneously.[14] The difference in source strength was due to the different geometries in the two experiments (see Ref. 14). In all experiments the ^{141}Pr foils were irradiated using a manual target removal system that allowed sample changes in less than 45 sec. Counting began 6–12 min after bombardment in order to minimize the contribution of short-lived components in the γ-ray spectrum.

γ-ray spectra were obtained using a Ge(Li)-NaI(Tl) anti-Compton spectrometer described in Ref. 15. The Ge(Li) detector used in this work was a $5\frac{1}{2}$% true coaxial crystal with energy resolution of 1.9 keV (full width at half maximum) at 1332 keV. Timed γ-ray spectra were accumulated with a 4096-channel pulse height analyzer for each of 17 samples. Each set of 17 individual spectra were added together off line to determine the decay properties of the γ rays. All spectra were added together for γ-ray energy and intensity determination. The sum spectrum of ^{141}Pm γ rays taken with the anti-Compton spectrometer is shown in Fig. 1.

The energies of the more intense ^{141}Pm γ rays were determined by counting simultaneously with γ-ray standard sources (^{137}Cs, ^{125}Sb, ^{60}Co, and ^{56}Co). The energies of the weaker ^{141}Pm transitions were then determined by interpolation from the calibrated ^{141}Pm γ rays. γ-ray intensities were determined from detector efficiency curves obtained using ^{226}Ra, ^{133}Ba, ^{56}Co, ^{154}Eu, ^{125}Sb, and ^{60}Co sources as calibration standards.

γ-γ coincidence spectra were obtained using the previously described Ge(Li) detector and a 6.7% coaxial closed-end Ge(Li) spectrometer with similar energy resolution. A 4096-channel pulse height analyzer interfaced to a PDP-8/L computer with an IBM 360 compatible magnetic tape drive was used for two-parameter data acquisition. A total of 4×10^7 coincidence events stored event by event in 4096×4096 channel resolution on magnetic tape were analyzed with an IBM 360/65 computer program SCAN[16] which selected the desired

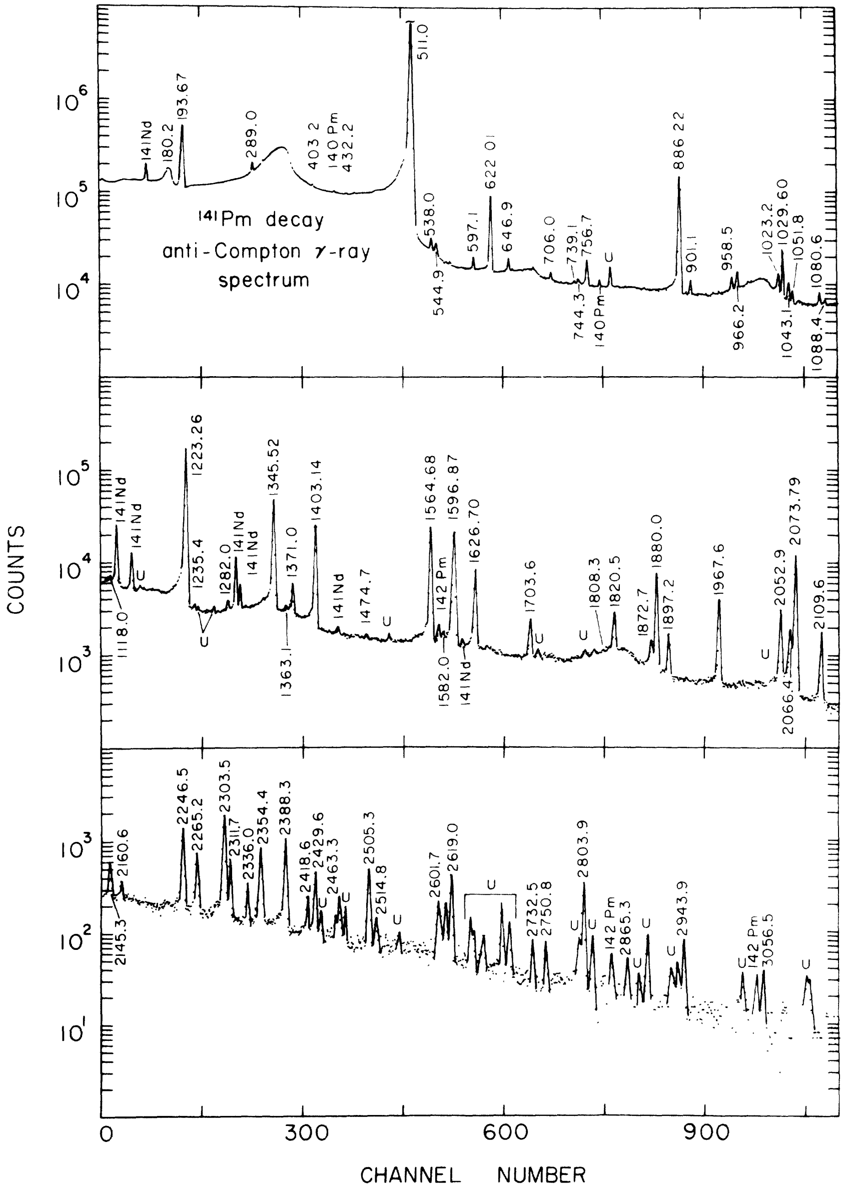

FIG. 1. Spectrum of ^{141}Pm γ rays taken with the anti-Compton spectrometer. Peak energies are given in keV. Peaks labeled with the letter U are unassigned.

γ-ray gates and generated the corresponding coincidence spectra.

B. Decay of ^{139}Pr

Sources of 4.5-h ^{139}Pr were produced via the ^{140}Pr(γ,n)^{139}Pr reaction by irradiating 99.99% natural praesodymium with bremsstrahlung radiation from a 50-MeV electron beam at the Lawrence Livermore Laboratory linac. The bombarding times were typically 8 h with a 4-h delay before counting began. Both singles and anti-Compton γ-ray spectra were studied as a function of time after irradiation. For the singles spectra 2-cm^3 planar and 50-cm^3 true coaxial Ge(Li) detectors were used. Spectra from the latter detector were taken with varying absorber thicknesses up to 1.3 cm of lead. The anti-Compton spectra were determined with a 7-cm^3 Ge(Li) crystal and an NaI(Tl) annulus described elsewhere.[17] The ^{139}Pr γ-ray energies were calibrated in the manner used for the ^{141}Pm source.

III. RESULTS AND DECAY SCHEMES

A. Decay of ^{141}Pm

The energies and relative intensities of γ rays assigned to ^{141}Pm are given in Table I. These values are weighted averages of at least two singles determinations using the anti-Compton spectrometer. γ-γ coincidence data determined in this work are given in Table II. Three of the coincidence spectra are shown in Fig. 2. From the above information, the decay scheme shown in Figs. 3 and 4 was constructed. All but three of the 70 γ rays attributed to ^{141}Pm were placed in this scheme. The unassigned γ rays have energies of 646.9, 966.2, and 2418.6 keV. The 966.2-keV transition was observed in coincidence with the 1345.52-keV γ ray but could not be assigned to the decay of any of the proposed levels.

The log*ft* values and the electron capture-positron intensity ratios given in Table III were calculated for the levels in ^{141}Nd using the tables of Gove and Martin,[18] the Q_β value of 3730 ± 40 keV measured by Charvet *et al.*,[19] and assuming that 90% of the ^{141}Pm decays to the ground state of ^{141}Nd.[20]

The work of Yap *et al.*[8] is in general agreement with this work and was useful in characterizing the states below 2500 keV. Only significant deviations and additions from the previous work are discussed here.

New levels at 3056.5, 2463.3, and 2944.4 keV have been constructed on the basis of observation of a transition to the ground state and one or more crossover transitions to well-known levels. A

TABLE I. Energies and relative intensities of γ-ray transitions from ^{141}Pm decay.

Energy[a] (keV)	Relative intensity[b]	Transition	
		From	To
180.2 (1)	0.68	2246.5	2066.4
193.67 (5)	33.9	193.7	g.s.
289.0 (2)	3.2	2109.6	1820.5
403.2 (2)	0.45	1967.6	1564.7
432.2 (2)	0.31	2505.3	2073.8
538.0 (2)	1.4	2505.3	1967.6
544.9 (1)	1.1	2109.6	1564.7
597.1 (1)	1.2	1820.5	1223.3
622.01 (5)	18.0	1967.6	1345.5
646.9 (1)	1.4		
706.0 (1)	0.5	2303.4	1596.9
739.1 (1)	0.59	2303.4	1564.7
744.3 (1)	0.9	1967.6	1223.3
756.7 (1)	1.8	756.7	g.s.
886.22 (5)	51.4	2109.6	1223.3
901.1 (1)	1.2	2246.5	1345.5
958.5 (1)	1.4	2303.4	1345.5
966.2 (1)	1.9		
1023.2 (1)	3.1	2246.5	1223.3
1029.60 (5)	7.0	1223.3	193.7
1043.1 (1)	0.8	2388.3	1345.5
1051.8 (1)	2.1	1808.3	756.7
1080.6 (1)	1.1	2303.4	1223.3
1088.4 (1)	0.32	3056.5	1967.6
1118.0 (1)	0.27	2463.3	1345.5
1223.26 (5)	100	1223.3	g.s.
1235.4 (1)	0.15	3056.5	1820.5
1282.0 (1)	0.44	2505.3	1223.3
1345.52 (5)	28.0	1345.5	g.s.
1363.1 (1)	0.08	2944.4	1582.0
1371.0 (1)	2.3	1564.7	193.7
1403.14 (6)	15.9	1596.9	193.7
1474.7 (1)	0.13	3056.5	1582.0
1564.68 (7)	17.8	1564.7	g.s.
1582.0 (1)	0.22	1582.0	g.s.
1596.87 (7)	16.7	1596.9	g.s.
1626.70 (7)	6.0	1820.5	193.7
1703.6 (1)	1.2	1897.2	193.7
1808.3 (1)	0.03	1808.3	g.s.
1820.5 (1)	1.6	1820.5	g.s.
1872.7 (1)	0.56	2066.4	193.7
1880.0 (1)	6.9	2073.8	193.7
1897.2 (1)	1.0	1897.2	g.s.
1967.6 (1)	3.6	1967.6	g.s.
2052.9 (1)	2.6	2246.5	193.7
2066.4 (1)	1.5	2066.4	g.s.
2073.79 (9)	13.3	2073.8	g.s.
2109.6 (1)	1.6	2109.6	g.s.
2145.3 (2)	0.36	2145.3	g.s.
2160.6 (2)	0.18	2354.4	193.7
2246.5 (1)	1.5	2246.5	g.s.
2265.2 (2)	0.72	2265.2	g.s.
2303.5 (1)	2.4	2303.4	g.s.

TABLE I *(Continued)*

Energy [a] (keV)		Relative intensity [b]	Transition From	To
2311.7	(2)	0.49	2505.3	193.7
2336.0	(2)	0.25	2336.0	g.s.
2354.4	(2)	0.89	2354.4	g.s.
2388.3	(2)	1.2	2388.3	g.s.
2418.6	(2)	0.16		
2429.6	(2)	0.55	2429.6	g.s.
2463.3	(2)	0.27	2463.3	g.s.
2505.3	(2)	0.59	2505.3	g.s.
2514.8	(2)	0.09	2514.8	g.s.
2601.7	(2)	0.27	2601.7	g.s.
2619.0	(2)	0.55	2619.0	g.s.
2732.5	(2)	0.07	2732.5	g.s.
2750.8	(2)	0.06	2944.4	193.7
2803.9	(4)	0.46	2803.9	g.s.
2865.3	(4)	0.05	2865.3	g.s.
2943.9	(5)	0.12	2944.4	g.s.
3056.5	(5)	0.05	3056.5	g.s.

[a] Uncertainties are given in parentheses.

[b] The uncertainties in intensity are ± 5% for $I_\gamma > 15$, ± 10% for $0.5 < I_\gamma < 15$, and ± 20% for $I_\gamma < 0.5$.

TABLE II. Results of ^{141}Pm γ-γ coincidence measurements.

γ-ray gate (keV)	Coincident γ rays (keV)
193.67	289.0, 886.22, 1029.60, 1371.0, 1403.14, 1626.7, 1872.7, 1880.0, 2052.9
622.01	538.0, 1345.52
886.22	193.67, 1029.60, 1223.26
1029.60	193.67, 886.22
1223.26	886.22, 1023.2, 1080.6
1345.52	193.67, 622.01, 901.1, 958.5, 966.2
1403.14	193.67
1564.68	403.2
1626.70	193.67, 289.0
1880.0	193.67
2052.9	193.67

level at 1582.0 keV has been proposed based on the presence of a γ ray of that energy and the observation of crossover transitions from the 3056.5- and 2944.4-keV levels to the 1582.0-keV level.

We tentatively propose a level at 1808.3 keV based on the observation of the 1051.8-keV γ ray proposed as a crossover transition to the 756.7-keV isomeric state. A level with similar decay properties exists in the $N=81$ nucleus ^{135}I.[2,3] A γ ray of 1808.3 keV was observed but its placement as a transition from an 1808-keV level to the ground state is questionable (see Sec. III B). Tentative levels at 2336.0, 2514.8, 2732.5, and 2865.4 keV are proposed based on the existence of γ rays of those energies which decay with the correct half-life. These γ rays were not observed in coincidence with any other transitions.

The observation of previously unreported γ rays at 1043.3 and 2160.6 keV supports the existence of levels previously considered as tentative at 2388.3 and 2354.4 keV, respectively. The 1043.1-keV γ ray was also observed in coincidence with the 1345.52-keV transition which strengthens this placement. Several previously unreported γ transitions at 403.2, 432.2, 739.1, and 744.3 keV have been incorporated in the ^{141}Pm decay scheme between established levels in ^{141}Nd on the basis of precise energy differences. In addition, the 403.2-keV γ ray was observed in coincidence with the 1564.68-keV γ ray. The placement of the 432.2-keV γ ray is considered tentative because the en-

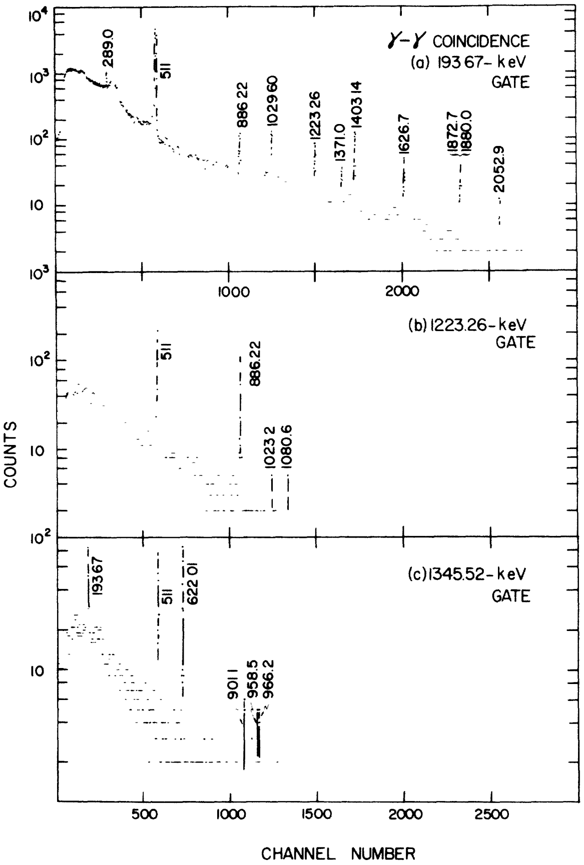

FIG. 2. Typical γ-γ coincidence spectra from ^{141}Pm decay.

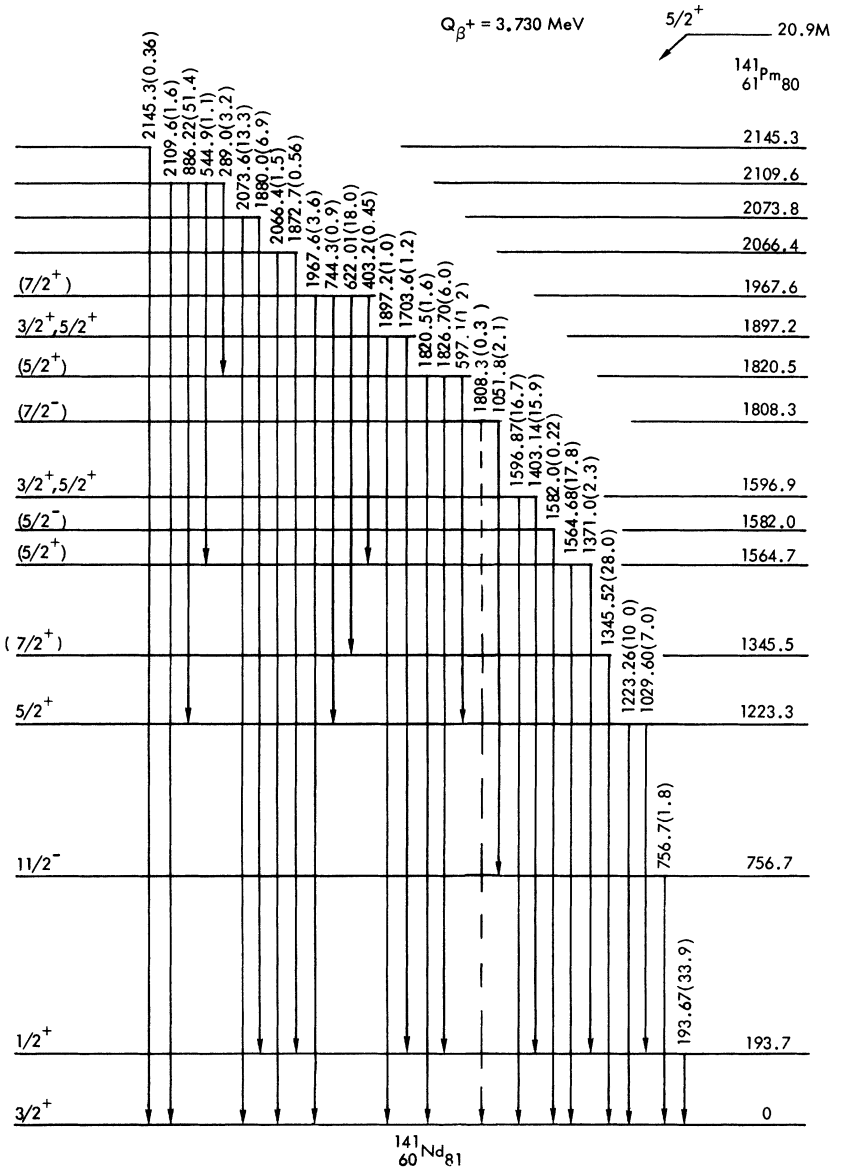

FIG. 3. Partial decay scheme of ^{141}Pm showing transitions from low-lying levels.

ergy balance for this transition is not as good as for the other cases.

The previously reported but unassigned γ rays at 958.5 and 1282.0 keV are now placed in the decay scheme. The 958.5-keV γ ray was observed in coincidence with the 1345.52-keV γ ray and was placed deexciting the 2303.4-keV level. The 1282.0-keV γ ray was seen in the 1967.6-keV γ-ray coincidence spectrum and was assigned to depopulate the 2505.3-keV level.

Low-intensity γ rays at 2985.5, 2690.3, and 2612.3 keV reported by Yap *et al.*[8] are assumed to be due to impurities. The first γ ray was not seen in this work and the latter two transitions were observed to decay with half-lives much longer than 20.9 min. As a result, we have ruled out the possibility of a 2986-keV level tentatively proposed by Yap *et al.*[8]

B. Assignment of spins and parities for levels in ^{141}Nd

Several levels have previously been assigned spin and parity (J^π) values. The J^π of the ground state has been established from atomic beam measurements to be $\frac{3}{2}^+$ (Ref. 21). The 193.7- and 756.7-keV levels have been assigned J^π values of $\frac{1}{2}^+$ and $\frac{11}{2}^-$, respectively, from reaction work.[2-4] The 1223.3-, 1564.7-, and 1820.5-keV levels have all been assigned spins and parities of $\frac{5}{2}^+$. These

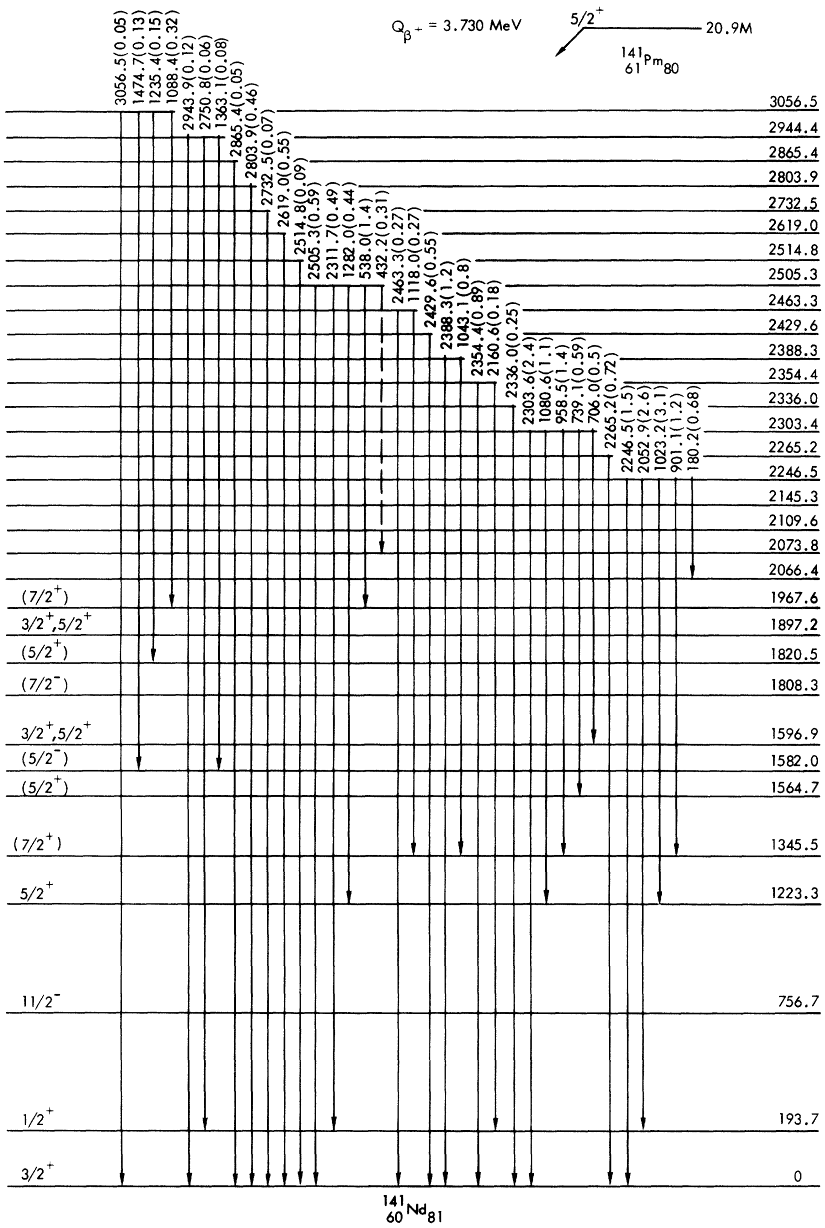

FIG. 4. Partial decay scheme of ^{141}Pm showing transitions from higher-lying levels.

levels are populated in allowed or first forbidden β decay and they decay to both $\frac{3}{2}^+$ and $\frac{1}{2}^+$ states limiting their possible spins to $\frac{3}{2}^+$ or $\frac{5}{2}^+$. The $l=2$ angular distributions and spectroscopic strengths of these levels determined in reaction studies[5-7] indicate a J^π assignment of $\frac{5}{2}^+$ for these levels.

A tentative spin and parity of $\frac{7}{2}^+$ is proposed for the 1345.5-keV level since this state decays to the $\frac{3}{2}^+$ ground state but not the $\frac{1}{2}^+$ 193.7-keV level and is populated in allowed or first forbidden β decay. This assignment is supported by the (p,d) studies of Foster, Dietzsch, and Spalding[6] in which $l=4$ angular distributions were observed for this state.

The 1582.0-keV level has the highest log*ft* value (≥ 9.9) of any ^{141}Nd level populated in β decay of ^{141}Pm. This is characteristic of first forbidden or allowed β decay indicating that it may be a negative parity state. This level decays to the $\frac{3}{2}^+$ ground state but to neither the $\frac{1}{2}^+$ first excited state nor the $\frac{11}{2}^-$ isomeric state. Therefore, a spin and parity of $\frac{5}{2}^-$ is tentatively proposed.

The 1596.9- and 1897.2-keV levels are populated in allowed or first forbidden β decay and decay to $\frac{3}{2}^+$ and $\frac{1}{2}^+$ states but not the 1345.5-keV $\frac{7}{2}^+$ level. Therefore the spins and parities of these states are limited to either $\frac{3}{2}^+$ or $\frac{5}{2}^+$ similar to the assignment given by Yap *et al.*[8]

The 1808.3-keV level has a log*ft* of 7.5 which is indicative of allowed or first forbidden β decay. This state decays predominately to the $\frac{11}{2}^-$ level but not the $\frac{1}{2}^+$ state, suggesting a spin and parity of $\frac{7}{2}^-$. A γ ray of 1808.3 keV is observed with relative intensity of 0.03. This could represent an $M2$ transition to the ground state. However, such a transition is not expected.

A $\frac{1}{2}^+$ level at 1870 keV has been identified in reaction studies. However, we find no evidence for this level being populated in γ decay from higher-lying levels.

TABLE III. Summary of level energies, β^+ and electron capture intensities, and log*ft* values for the levels in ^{141}Nd, assuming $Q_{\beta^+}=3.730$ MeV [A. Charvet, R. Duffait, A. Emsallem, and R. Chery, J. Phys. (Paris) 31, 737 (1970)]. Electron capture to positron ratio and log*ft* values are calculated according to Gove and Martin [Nucl. Data Tables 10, 206 (1971)].

Level energy (keV)	I_{β^+} (%)	I_{ec} (%)	log*ft*
0[a]	51	39	5.5
193.7			
756.7			
1223.3	0.4	1.7	6.5
1345.5	0.03	0.2	7.3
1564.7	0.06	0.7	6.7
1582.0		≤0.0004	≥9.9
1596.9	0.1	1.2	6.5
1808.3	0.003	0.09	7.5
1820.5	0.007	0.2	7.1
1897.2	0.002	0.09	7.5
1967.6	0.02	0.9	6.4
2066.4	0.001	0.06	7.6
2073.8	0.008	0.8	6.4
2109.6	0.05	2.3	5.9
2145.3		0.02	8.1
2246.5	0.001	0.4	6.7
2265.2		0.03	7.7
2303.4	0.0004	0.2	6.8
2336.0		0.01	8.3
2354.4		0.04	7.5
2388.3		0.08	7.3
2429.6		0.02	7.8
2463.3		0.01	8.1
2505.3		0.1	6.9
2514.8		0.004	8.5
2619.0		0.02	7.6
2732.5		0.003	8.5
2803.9		0.02	7.5
2865.3		0.002	8.6
2943.9		0.01	7.7
3056.5		0.03	7.2

[a] Ground state feeding taken as 90% from Ref. 20.

TABLE IV. Energies and relative intensities of γ-ray transitions from ^{139}Pr decay.

Energy[a] (keV)	Relative intensity[a]	Transition From	To
255.11 (2)	498 (14)	254	g.s.
354.00 (10)	25 (5)	1984	1630
511.00 (–)	35000 (800)		
587.37 (15)	15 (5)	1907	1320
664.60 (15)	8 (2)	1984	1320
696.01 (10)	9 (5)	2016	1320
754.24 (8)	30 (5)	754	g.s.
1065.32 (20)	7 (4)	1320	254
1088.70 (10)	22 (5)	1843	754
1320.24 (2)	147 (2)	1320	g.s.
1341.50 (9)	10 (5)	1596	254
1347.33 (1)	1000	1347	g.s.
1375.56 (3)	325 (15)	1630	255
[1517.20 (35)]	[5 (27)]	(1774	254)
1563.38 (2)	88 (5)	1818	254
1596.58 (2)	72 (6)	1596	g.s.
1630.67 (2)	725 (20)	1630	g.s.
1652.58 (2)	82 (5)	1907	254
[1678.53 (26)]	[3 (1)]		
1710.27 (24)	3.6 (9)	1966	254
1729.89 (9)	19 (3)	1984	254
1818.30 (4)	65 (4)	1818	g.s.
1907.61 (5)	36 (4)	1907	g.s.
1965.66 (44)	1.2 (5)	1965	g.s.
1985.04 (29)	1.6 (5)	1985	g.s.
2016.25 (4)	25 (3)	2016	g.s.

[a] Uncertainties are given in parentheses.

TABLE V. Summary of level energies, electron capture intensities, and log*ft* values for the levels in ^{139}Ce.

Level energy (keV)	I_{ec} (%)	log*ft*
0	91.1[a]	5.6
255	···	···
754	···	···
1320	0.046	8.0
1347	0.38	7.1
1597	0.031	7.8
1631	0.39	6.6
1818	0.058	7.0
(1843)	0.0084	7.8
1907	0.051	6.8
1966	0.0018	8.1
1985	0.021	7.1
2016	0.013	6.5

[a] 7.9% positron branch taken from Ref. 12.

No spin and parity assignments were made for levels above 2 MeV. All of these levels are populated in allowed or first forbidden β decay; those that populate the $\frac{1}{2}^+$ first excited state are limited to spins of $\frac{3}{2}$ or $\frac{5}{2}$ based on this γ decay. However, we suggest that either the 2066.4- or 2073.8-keV levels correspond to the $l=2$ level observed in the (p,d) studies of Jolly and Kashy[5] who give a $\frac{5}{2}^+$ assignment for this level.

C. Decay of ^{139}Pr and levels of ^{139}Ce

The energies and intensities of γ rays assigned to the ^{139}Pr decay are given in Table IV. In Fig. 5 we show a decay scheme for ^{139}Pr to the levels of ^{139}Ce which was constructed from reaction studies[5,9] as well as this and other decay scheme studies.[10,22] The log*ft* values are given in Table V.

The decay scheme we present is somewhat improved over that given in the Nuclear Data Sheets.[22] The latter is essentially that presented by Beery, Kelly, and McHarris.[10] We do observe the 754.24-keV γ ray which presumably comes from the decay of the known 56.2-sec $\frac{11}{2}^-$ isomer.[22] We suggest that the $\frac{11}{2}^-$ level is populated by γ-ray cascade and we place the 1088.70-keV γ ray that we observed as representing the decay of a level at 1842.9 keV similar to that in the ^{141}Pm case. The other new level reported here is at 1965.5 keV, suggested by

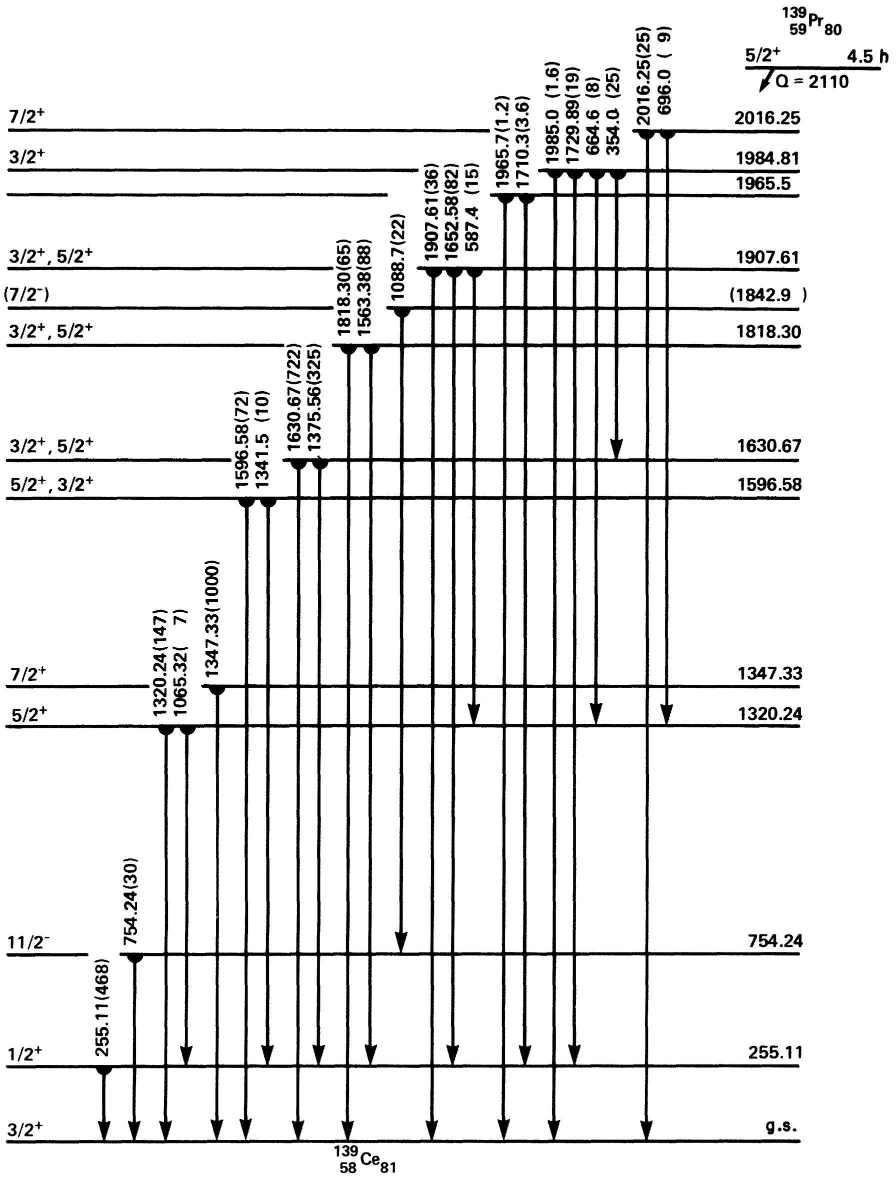

FIG. 5. Decay scheme of ^{139}Pr.

the observation of 1965.7- and 1710.3-keV γ rays with an energy difference of 255.4 keV. We also observe low-intensity γ rays of 354.0 and 587.4 keV which represent transitions between previously known levels.

IV. DISCUSSION

The nuclei with 81 neutrons provide an interesting class of nuclei to study because they represent one hole in the 82 neutron closed shell. At low energies, these nuclei should be limited to excitations of the single neutron hole and its coupling to the closed shell $N=82$ vibrational core. The following discussion concerns the level properties of the heavier $N=81$ nuclei studied here as a test of the particle- (hole) vibration model.

The three lowest levels in the $N=81$ nuclei have properties consistent with the excitation of a single neutron hole. The lowest $\frac{1}{2}^+$, $\frac{3}{2}^+$, and $\frac{11}{2}^-$ levels shown in Fig. 6 have been shown to have strong hole character by transfer reaction studies[5-7,9]; however, the same studies showed that the $d_{5/2}$ and $g_{7/2}$ transfer strength was spread over many levels. Further support for the $h_{11/2}$ and $d_{3/2}$ levels comes from the $M4$ interlevel transition. The calculation of the rate of this transition agrees well with the measured half-life of the $\frac{11}{2}^-$ level in these nuclei.[4]

The calculations of Heyde and Brussard[4] using a hole-vibration model, agree with most of the experimentally observed levels and their properties. They correctly predict the lowest single-hole $\frac{1}{2}^+$, $\frac{3}{2}^+$, and $\frac{11}{2}^-$ levels as well as the hole-vibration coupled levels up to 2 MeV. They also predict the correct branching ratios from the hole-vibration states; for example, a branching ratio of 0.066 is predicted for the decay of the $\frac{5}{2}^+$ level at 1320-keV in ^{139}Ce, whereas we measure a value of 0.048. Similar agreement can be found for ^{141}Nd and ^{143}Sm as observed in this work and that of Kennedy, Giejrathi, and Hinrichsen.[23] However, in ^{139}Pr we

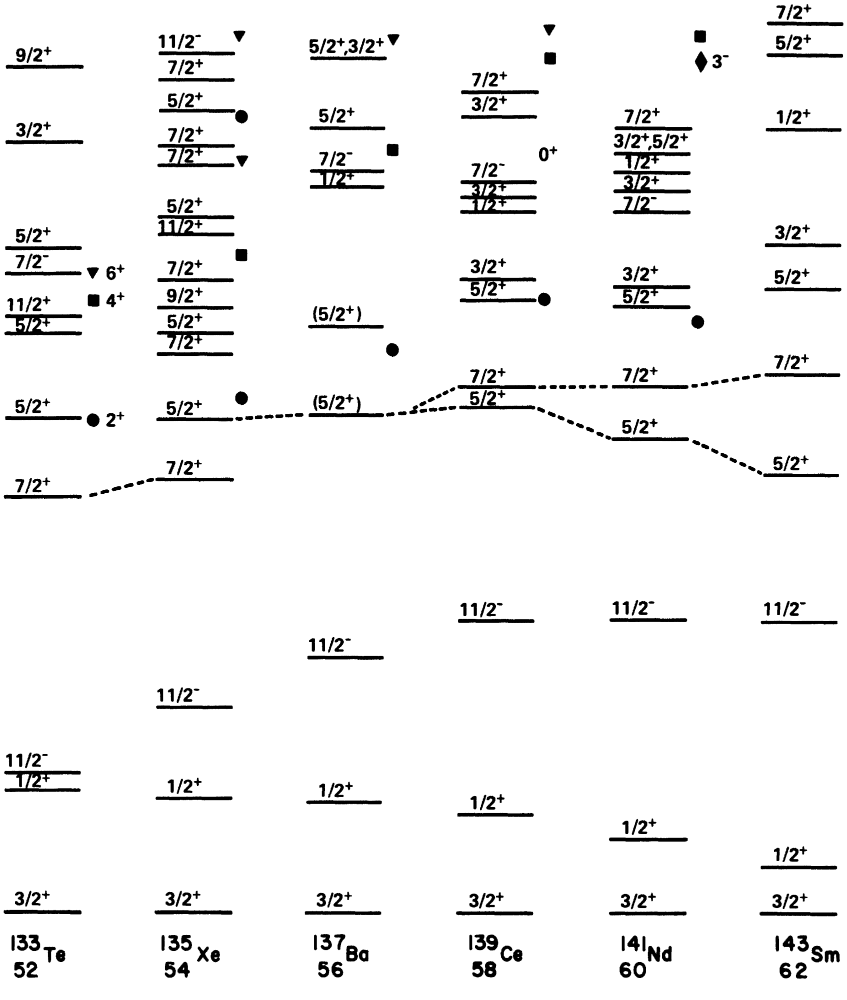

FIG. 6. Comparison of the energies, spins, and parities of the levels of $N=81$ isotones, ^{135}Xe (Refs. 1 and 2), ^{137}Ba (Refs. 5 and 7), ^{139}Ce (Ref. 12 and this work), ^{141}Nd (Refs. 5–7 and this work), and ^{143}Sm (Refs. 5, 7, and 13). The circles, squares, and triangles represent the low-lying 2^+, 4^+, and 6^+ levels, respectively, of the neighboring even-even core.

observe four more levels below 2 MeV than predicted on the basis of a simple hole-vibration model and five more in ^{141}Nd. This can be seen in Fig. 7 where we compare the observed levels from 1.2 to 2.0 MeV with the predictions of Heyde and Brussard.[4]

The excess levels with respect to the hole-vibration model may be accounted for if the ^{140}Ce core excitations are taken into account. Besides the 2^+ level at 1596 keV, a level with J^π of 0^+ at 1903 keV has been observed in the ^{140}Ce even-even core nucleus. The $\frac{3}{2}^+$ level at 1984.81 keV in ^{139}Ce may be the coupling of the $\frac{3}{2}^+$ ground state to the 0^+ core excitation. If we assume the observed transitions have $M1$ multipolarity then decay of the 1984.81-keV level gives the following relative experimental transition probabilities in parentheses: →1630 keV (1.00); →1320 keV (0.05); →255 keV (0.007); →g.s. (0.000 36). The highly hindered transition to the ground state and the $\frac{3}{2}^+$ level at 255 keV is expected if the 1984.81-keV level is predominantly core coupled. These transitions would have to occur via single-hole components of the 1984.81-keV wave function which are presumably small. The transitions to the 2^+ core coupled states would be expected to be less hindered. Note that any $E2$ admixtures would give rise to even greater relative hindrances. The

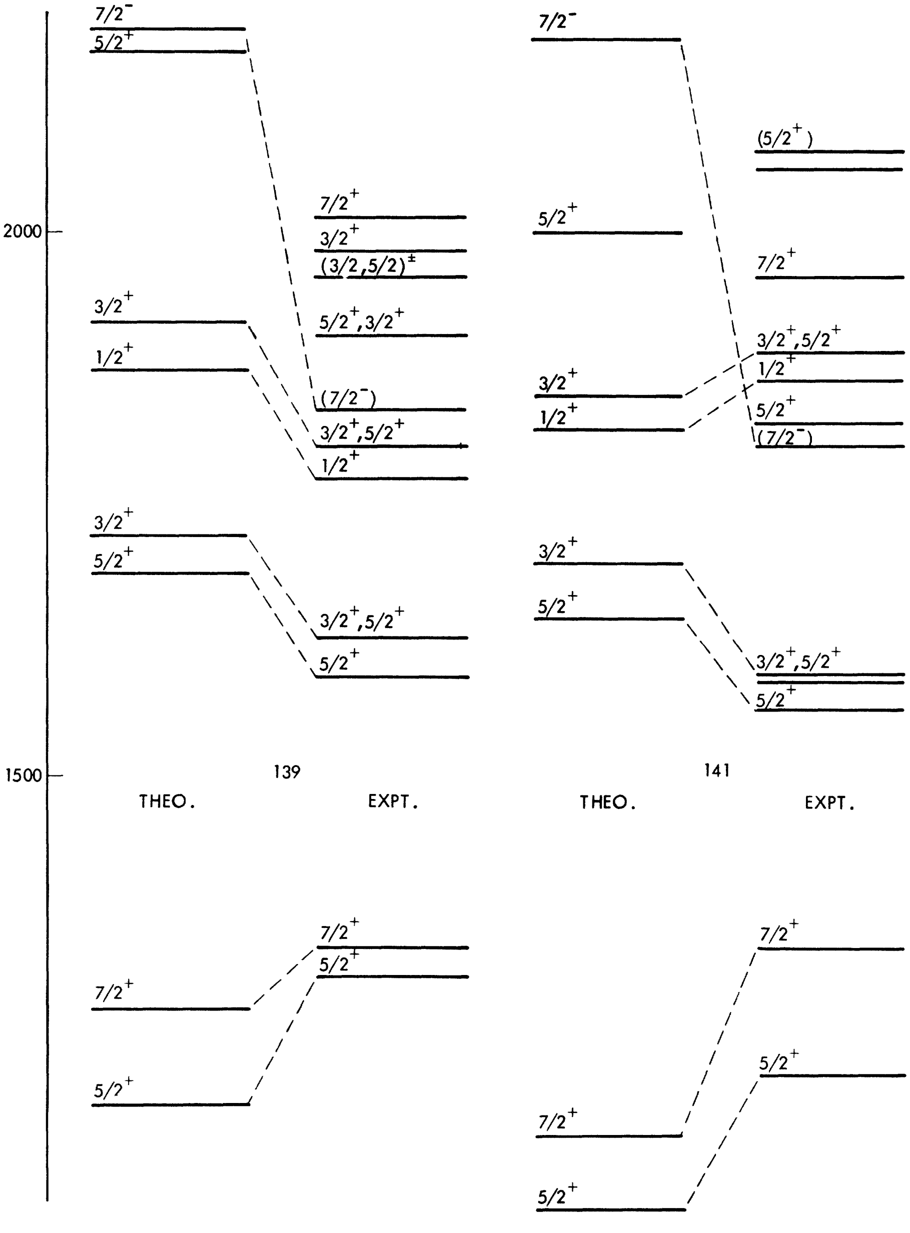

FIG. 7. Comparison of levels of ^{139}Pr and ^{141}Nd between 1.2 and 2.1 MeV with the theoretical hole-vibration calculations of Heyde and Brussard (Ref. 4).

detection of an $E0$ component in the 1984.81-keV transition would establish a $d_{3/2}\otimes 0^+$ configuration for this level. It may be possible to detect such a transition with a device which can separate positrons from electrons.

A pair of levels at 1907.61 and 2016.25 keV in ^{139}Ce and a pair at 1820.5 and 1967.6 keV in ^{141}Nd may correspond to the coupling of the $s_{1/2}$ and $d_{3/2}$ hole to the 4^+ level in the corresponding even-even core. None of these four levels is predicted by Heyde and Brussard. However, both pairs of levels preferably decay to the 2^+ core coupled levels at approximately 1.3 MeV.

The 3^- octupole excitation in the even-even core may give rise to extra negative parity levels in ^{141}Nd and ^{143}Sm. Such levels would not be expected to be at low excitation in the lighter $N=81$ nuclei because the 3^- octupole state is at 3.2 MeV in the ^{134}Xe; however, the octupole state occurs at 2.1 MeV in ^{140}Nd and 1.8 MeV in ^{142}Sm. If the 1582.0-keV level does have J^π of $\frac{5}{2}^-$ it could be a candidate for such a level.

V. SUMMARY AND RECOMMENDATIONS

We have compared our results on the decay of ^{139}Pr and ^{141}Pm to the levels of ^{139}Ce and ^{141}Nd with a hole-vibration model. We find good agreement with the calculations of Heyde and Brussard using this model for the description of the levels up to 1.3 MeV. However, we find an excess level below 2 MeV which can be qualitatively accounted for if the known even-even core excitations are taken into account. Further conversion electron work is suggested in order to search for $E0$ strength in the decay of levels which may be $d_{3/2}\otimes 0^+$ core excitations in ^{139}Ce.

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