States in $N = 81$ ^{141}Nd populated by the decay of ^{141}Pm

F. Y. Yap,* R. R. Todd,† and W. H. Kelly
Cyclotron Laboratory‡ and Department of Physics, Michigan State University, East Lansing, Michigan 48824

Wm. C. McHarris§ and R. A. Warner
Department of Chemistry,¶ and Cyclotron Laboratory,‡ and Department of Physics, Michigan State University, East Lansing, Michigan 48824
(Received 24 April 1974)

The decay of 20.90-min ^{141}Pm has been studied with Ge(Li) and NaI(Tl) γ-ray detectors in a variety of singles and coincidence configurations, including Ge(Li)-Ge(Li) two-parameter "megachannel" coincidence experiments, anticoincidence experiments, and pair ($\gamma^{\pm}$-γ) experiments to determine the relative β^+ feedings. Fifty-two γ rays were identified from this decay, and 43 of these (> 99% of the γ intensity) were placed in a decay scheme containing 23 levels in ^{141}Nd. J^π assignments or limits were made for all of the states. The structures of the lower-lying states in ^{141}Nd are discussed in terms of the shell model, and possible structures are also suggested for many of the higher-lying states. We compare our results with those of previous studies and also with particle-transfer data.

[RADIOACTIVITY ^{141}Pm; measured E_γ, I_γ, $\gamma\gamma$ coin, $\gamma^{\pm}\gamma$ coin, deduced α_K; ^{141}Nd deduced levels, J, π.]

I. INTRODUCTION

^{141}Pm is twice removed from stability on the neutron deficient side of the $N=82$ closed shell and decays with a 20.9-min half-life to 2.5-h $^{141}_{60}Nd_{81}$. The character of ^{141}Nd is such that the decay of ^{141}Pm might be expected to populate rather low-lying neutron-hole states in the daughter which exhibit significant single-particle properties. This is indeed the case, and it is possible to compare the β-decay results presented here with the results of recent particle-transfer experiments. These include ^{142}Nd$(p,d)^{141}$Nd by Jolly and Kashy[1] and a similar (p,d) study by Chameaux *et al.*[2] as well as the results of Foster, Dietsch, and Spalding[3] from studies of the ^{142}Nd$(d,t)^{141}$Nd reaction and those of Yagi, Sato, and Aoki[4] on the ^{143}Nd(p,t)-^{141}Nd reaction.

The first positive identification of ^{141}Pm was made in 1952 by Kistiakowsky Fischer.[5] She produced it by bombarding isotopically enriched samples of $^{142}Nd_2O_3$ with 20–30-MeV protons. The half-life was determined to be 22 ± 2 min, in good agreement with our results of 20.90 ± 0.2 min. Prior to 1967, little else had been published about the decay of ^{141}Pm. Then Bleyl, Munzel, and Pfinning[6] reported the half-life to be 20.9 ± 0.05 min, identified several of the strong transitions, and compared their results with the study of Arl't *et al.*[7]; no attempt was made to construct a decay scheme. More recently, Hesse[8] observed 11 transitions that he identified with the decay of ^{141}Pm. These were identified as a by-product of his study of the decay of ^{141}Sm^m. To date the most complete study has been performed by Charvet *et al.*[9] This study identified 24 transitions arising from the decay of ^{141}Pm. Of these 24 transitions, 19 were placed in a decay scheme containing 11 levels.

The present investigation was undertaken as a part of a series of studies of the decay schemes of the neutron deficient $A = 141$ isobaric chain. We have identified a total of 52 γ transitions as being associated with the 20.9-min ^{141}Pm decay. Using a variety of coincidence techniques, we place 43 of these in a consistent decay scheme having 23 states. These results are compared with the γ-ray work of previous investigators[7-9] and with the particle transfer experiments.[1-4]

II. SOURCE PREPARATION AND IDENTIFICATION

Most of the 20.9-min ^{141}Pm activity was produced by the ^{142}Nd$(p,2n)$ ^{141}Pm reaction on targets of Nd_2O_3, with the neodymium enriched to $\approx 90\%$ ^{142}Nd. The bombarding times were typically 1–2 min with ≈ 1-μA beams of 24-MeV protons from the Michigan State University sector-focused cyclotron. Counting began within 2 min of the end of the bombardment, and each source was not counted longer than 50 min.

A study of the excitation function was made by varying the incident beam energy in ≈ 3-MeV steps from below the 14-MeV threshold of the $(p,2n)$ reaction to 30 MeV, which is 5 MeV above the threshold for the $(p, 3n)$ reaction.

^{141}Pm sources were also produced via the reaction $^{141}Pr(^3He, 3n)^{141}Pm$ ($Q = -14.7$ MeV) at 25 MeV. However, this reaction did not yield as pure ^{141}Pm samples as those produced in the $(p, 2n)$ reaction. The ^{141}Pm activity has also been produced through the decay of ^{141}Sm.[10] Several of the strong γ rays observed in the decay $^{141}Pm \xrightarrow{\epsilon/\beta^+} {}^{141}Nd$ are identifiable with decays of levels excited in previous reaction studies,[1-4] and in essentially all cases our results confirm the state assignments suggested by the reaction work.

III. EXPERIMENTAL RESULTS

A. γ-ray singles spectra

The energies and intensities of γ-ray transitions observed in the decay of ^{141}Pm were determined with the aid of a Ge(Li) detector having a relative full-energy peak efficiency of 2.5% and a typical resolution of 2.2 keV FWHM (full width at half-maximum) for the 1332.48-keV line of ^{60}Co. The quoted efficiency is relative to that of a 7.6×7.6-cm NaI(Tl) detector with both detectors 25 cm from the source.

With the exception of the 193.8-keV transition, the energies of the stronger lines in the ^{141}Pm spectrum were determined in a study[11] of the decay of $^{141}Sm^m$, which is its parent. These lines were in turn used to determine the energies of the weaker transitions. Previously measured lines in $^{141}Sm^m$ decay (Table I) were used as energy calibration standards for this study. The results of this method were checked by subsequently observing the strong lines in ^{141}Nd decay[12] and using the ^{141}Pm decay energies to determine these energies. These latter results proved accurate to within the quoted error limits. The energy of the 193.8-keV transition was determined by counting the ^{141}Pm activity in the presence of ^{57}Co, ^{192}Ir, and ^{243}Cm.[13] The results from several different spectra were then averaged, yielding an energy of 193.8 ± 0.1 keV for this transition.

Transitions belonging to the decay of ^{141}Pm were identified by their relative intensities in successive spectra. Starting 2 min after bombardment, five successive 10-min spectra were accumulated. The process was repeated following the irradiation of each of several samples, and the spectra in the corresponding time intervals were added. Those γ rays which maintained a constant intensity relative to that of the 1223.3-keV γ in each of the five 10-min spectra were identified as belonging to ^{141}Pm. The first and fifth of these spectra are displayed in Fig. 1. Table II contains the energies and intensities of the 52 γ rays observed in this study.

TABLE I. Energies and relative intensities of γ rays from the decay of ^{141}Sm.

Energy (keV)	Intensity
196.6 ± 0.3	184 ± 18
431.8 ± 0.1	100 ± 5
538.5 ± 0.3	20.9 ± 1.4
628.7 ± 0.1	6.6 ± 0.20
684.6 ± 0.2	19.6 ± 1.5
725.7 ± 0.5	3.6 ± 0.6
750.3 ± 0.3	3.9 ± 0.60
777.4 ± 0.3	50.3 ± 2.0
785.9 ± 0.1	16.9 ± 1.0
805.9 ± 0.1	8.8 ± 1.6
837.1 ± 0.2	8.87 ± 0.30
875.0 ± 0.1	3.1 ± 0.1
896.5 ± 0.1	3.6 ± 0.4
911.3 ± 0.3	22.8 ± 0.6
924.7 ± 0.1	5.7 ± 0.8
983.3 ± 0.3	18.0 ± 0.8
1009.1 ± 0.4	7.2 ± 0.6
1117.6 ± 0.2	8.0 ± 0.6
1145.1 ± 0.2	21.6 ± 0.8
1463.4 ± 0.6	4.5 ± 0.8
1490.3 ± 0.1	22.9 ± 1.5
1786.4 ± 0.4	27.1 ± 1.1
2073.7 ± 0.2	3.53 ± 1.2

B. Coincidence studies

Several prompt-coincidence experiments were performed. These included two-parameter "megachannel" coincidence experiments using Ge(Li) spectrometers,[14] an anticoincidence experiment, and 511-511-keV-γ triple coincidence experiments[15] utilizing a Ge(Li) detector in an 20.3 $\times$ 20.3-cm NaI(Tl) split annulus. The two-parameter coincidence results are summarized in Table III, while the results of the other coincidence experiments appear in Table IV.

The two-parameter coincidence experiments employed Ge(Li) detectors having relative efficiencies of 4.5 and 10.4% and capable of 2.0 and 2.2-keV resolution (FWHM), respectively, at 1332 keV. The detectors were placed face to face, separated by a graded absorber to reduce Compton scattering from one detector into the other. The source was placed off the axis of the detectors in order to reduce coincidences between the annihilation photons. Addresses of the coincident events were recorded, one pair to a word, on a magnetic tape using an XDS Sigma-7 computer with the data taking program EVENT.[16] This yielded a 4096×4096-channel array of prompt coincidences. The resolving time was $2\tau \approx 120$ nsec. The integrated (total) coincidence spectrum is shown in Fig. 2(a). The various gated spectra are shown in Figs. 2(b)–2(c). Because the ^{141}Pm decay proceeds ≈ 90% of the time to the ground state of ^{141}Nd and the half-life is 21 min, the two parameter Ge(Li)-Ge(Li) coincidence experiment was difficult. The data displayed in Fig. 2 were accumulated over a period of 12 h, and a total of 10^6 coincidence events were obtained. The sample was replenished frequently and the old source replaced by a new source every 40 to 50 min. Despite the few events, these spectra were invaluable in the construction of the decay scheme.

The anticoincidence spectrum shown in Fig. 3 was obtained with a Ge(Li) detector [having 2.0-keV resolution (FWHM) and a relative efficiency of 0.4% at 1332 keV] placed in the tunnel of the annulus with the ^{141}Pm source in the annulus center. The Ge(Li) detector was operated in anticoincidence with γ rays above 100 keV in the annulus ($2\tau \approx 100$ nsec; a true-to-chance ratio of ≈100/1), resulting in the enhancement of those transitions not in prompt coincidence with other γ rays or with β^+ emission. This spectrum was particularly useful in placing transitions to the ground state or to a metastable state.

511-keV-511-keV-γ coincidence spectrum shown in Fig. 4 was obtained using absorbers of sufficient thickness to insure annihilation of all the positrons near the source. In this experiment the single-channel analyzers associated with each half of the annulus had their windows adjusted to accept only the 511-keV region. A triple coincidence ($2\tau \approx 100$ nsec) was required for Ge(Li) pulses to be analyzed. Thus, only double-escape peaks and transitions from levels fed by β^+ decay appear in the spectrum. These and various other coincidence results are summarized in Table IV.

IV. ^{141}Pm DECAY SCHEME

The ^{141}Pm decay scheme we have constructed is illustrated in Fig. 5. All transition and level

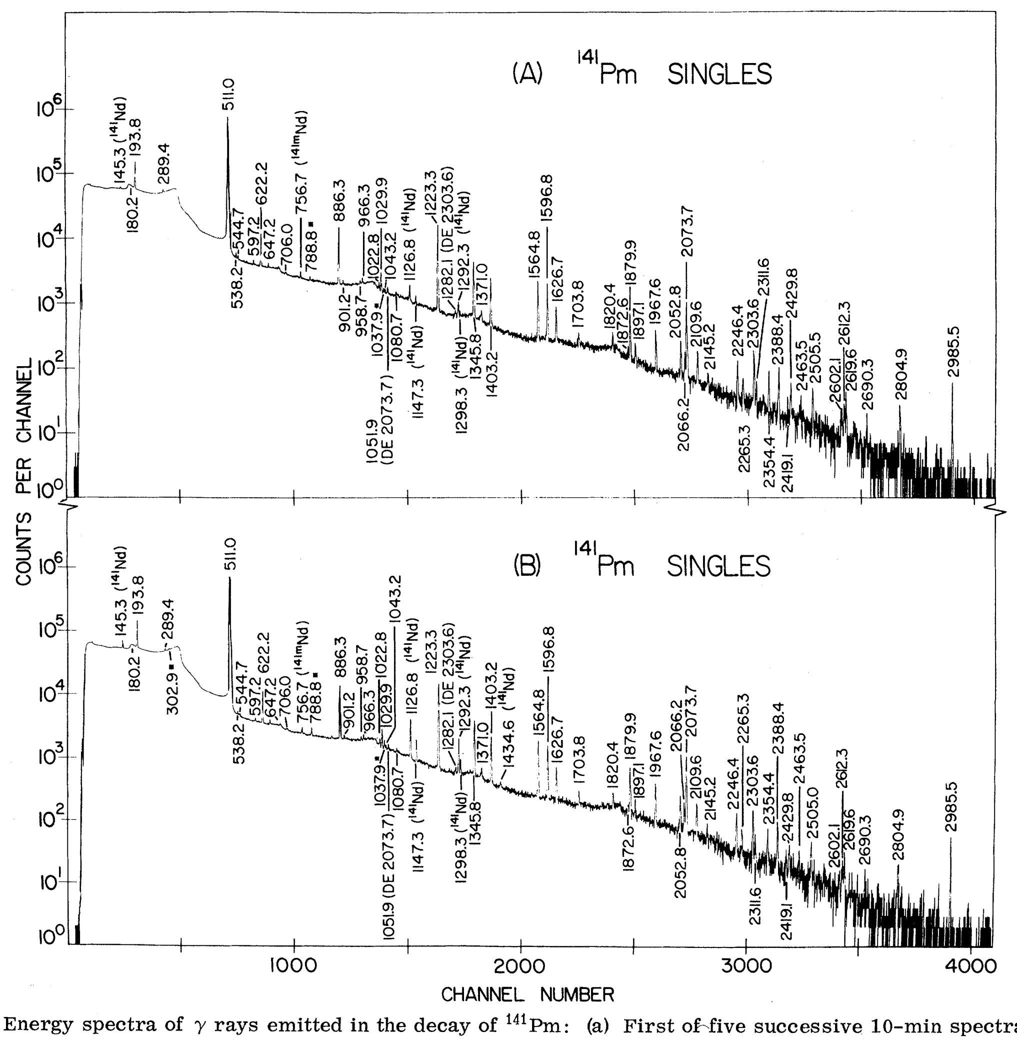

FIG. 1. Energy spectra of γ rays emitted in the decay of ^{141}Pm: (a) First of five successive 10-min spectra; (b) Fifth of five successive 10-min spectra.

TABLE II. Energies and relative intensities of γ rays from the decay of ^{141}Pm.

This work		Charvet *et al.*[a]		Hesse[b]	
Energy (keV)	Relative intensity	Energy (keV)	Relative intensity	Energy (keV)	Relative intensity
180.2 ± 0.4	0.6 ± 0.2				
193.8 ± 0.1	34.9 ± 1.7	193.7 ± 0.3	32 ± 3		
289.4 ± 0.3	3.6 ± 0.6				
538.2 ± 0.3	1.7 ± 0.4				
544.7 ± 0.4	1.4 ± 0.4				
597.2 ± 0.3	1.2 ± 0.3				
622.2 ± 0.4	18.9 ± 1.0	622.0 ± 0.1	20 ± 2	621.2 ± 0.5	19.8 ± 2.3
647.2 ± 0.3 [c]	1.3 ± 0.3				
706.0 ± 0.8	1.0 ± 0.3				
756.7 ± 0.4	1.7 ± 0.4				
886.3 ± 0.3	52.5 ± 2.6	886.1 ± 0.2	52 ± 5	886.0 ± 0.5	56.7 ± 7.0
901.2 ± 0.4	1.1 ± 0.5				
958.7 ± 0.4 [c]	1.3 ± 0.4				
966.3 ± 0.3 [c]	2.0 ± 0.5				
1022.8 ± 0.4	2.8 ± 0.5				
1029.9 ± 0.4	7.8 ± 0.5	1029.6 ± 0.5	7 ± 0.7	1028.5 ± 0.8	7.8 ± 3.1
1051.9 ± 0.6 [c]	2.0 ± 0.5				
1080.7 ± 0.6	1.0 ± 0.2				
1223.3 ± 0.5	≡100	1223.3 ± 0.1	≡100	1222.9 ± 0.5	≡100
1282.1 ± 0.6 [c]	0.9 ± 0.4				
1345.8 ± 0.4	27.6 ± 1.4	1345.4 ± 0.2	30 ± 3	1345.0 ± 0.7	49.4 ± 11
1371.0 ± 0.6	2.2 ± 0.7	1370 ± 1.0	3 ± 0.5		
1403.2 ± 0.5	16.0 ± 1.0	1403.2 ± 0.3	16 ± 2	1403.1 ± 0.7	17.7 ± 4
1564.8 ± 0.5	17.9 ± 1.0	1564.7 ± 0.2	17 ± 2	1563.7 ± 0.5	21.3 ± 4.7
1596.8 ± 0.5	16.1 ± 1.0	1596.9 ± 0.2	13.6 ± 1.5	1597.7 ± 0.7	20.6 ± 4
1626.7 ± 0.5	5.8 ± 0.6	1626.5 ± 0.7	6 ± 1		
1703.8 ± 0.6	1.2 ± 0.2	1703.3 ± 1	1 ± 0.2		
1820.4 ± 0.7	1.6 ± 0.4	1820.2 ± 1	1.7 ± 0.3		
1872.6 ± 0.6	0.5 ± 0.2				
1879.9 ± 0.5	6.9 ± 0.7	1879.8 ± 0.5	8 ± 2	1879.9 ± 0.8	9.8 ± 2.3
1897.1 ± 0.5	1.1 ± 0.3	1897.0 ± 1	0.9 ± 0.2		
1967.6 ± 0.5	3.6 ± 0.4				
2052.8 ± 0.5	2.6 ± 0.4	2053.3 ± 1	2.4 ± 0.5		
2066.4 ± 0.6	1.3 ± 0.2				
2073.7 ± 0.5	13.4 ± 1.0	2073.5 ± 0.4	12 ± 2	2072.9 ± 0.6	18.4 ± 3.1
2109.6 ± 0.5	1.8 ± 0.2				
2145.2 ± 0.9	0.3 ± 0.1				
2246.4 ± 0.6	1.5 ± 0.4	2247 ± 1.5	1.4 ± 0.3		
2265.3 ± 0.8	0.7 ± 0.1	2266 ± 1.5	1 ± 0.2		
2303.6 ± 0.6	2.4 ± 0.2	2305 ± 1.5	1.5 ± 0.5		
2311.6 ± 0.6	0.5 ± 0.1				
2354.4 ± 0.6	1.0 ± 0.2	2355 ± 2	0.8 ± 0.2		
2388.4 ± 0.5	1.3 ± 0.2	2389 ± 2	1 ± 0.2		
2419.1 ± 1.0 [c]	0.2 ± 0.1				
2429.8 ± 1.0	0.6 ± 0.1				
2505.0 ± 1.0	0.6 ± 0.2	2505 ± 2	0.5 ± 0.1		
2602.1 ± 1.0 [c]	0.1 ± 0.05				
2612.3 ± 1.0	0.3 ± 0.1				
2619.6 ± 1.0	0.4 ± 0.1				
2690.3 ± 1.0 [c]	0.2 ± 0.1				
2804.9 ± 1.0	0.5 ± 0.1	2804 ± 2	0.4 ± 0.1		
2985.5 ± 1.0	0.9 ± 0.2				

[a] Reference 9.
[b] Reference 8.
[c] These transitions belong to ^{141}Pm, but we were unable to place them in the decay scheme.

energies are given in keV, and $Q_\epsilon = 3.73$ MeV is the value determined by Charvet *et al.*[9] The electromagnetic transition intensities are given in percent of the disintegrations of ^{141}Pm, as are the $\epsilon + \beta^+$ intensities. The logft values were calculated using 20.9 min for the half-life of ^{141}Pm.

The amount of total β feeding $(\epsilon + \beta^+)$ directly to the ground state of ^{141}Nd was determined from knowledge of the total β^+ intensity obtained from a γ-ray spectrum of a source enclosed in aluminum of sufficient thickness to stop all the positrons emitted. The β^+ feedings to all levels other than the ground state were calculated from the intensity balance at each level and theoretical ϵ/β^+ ratios. This number was then subtracted from the total β^+ intensity obtained in the total annihilation measurement. The result is expected to be the amount of positron intensity arising solely from decay to the ^{141}Nd ground state. The total $(\epsilon + \beta^+)$ feeding to the ground state was then calculated from the theoretical ϵ/β^+ value.

A level is placed at 193.8 keV for a number of reasons. The 193.8-keV line is the third strongest in the spectrum and is not observed in coincidence with either of the two strongest lines at 1223.3 and 886.3 keV. A large number of other transitions are observed in coincidence with it (cf Fig. 2), however, and seven of these have energies corresponding to the differences between the energies of other lines and 193.8 keV. In addition, a level of about this energy has been observed in (p,d) and (d,t) reaction studies.[1-3]

The placement of levels at 1223.3, 1345.8, 1564.8, and 1596.8 keV is suggested by the enhancement of γ rays at these energies in both the anticoincidence (Fig. 3) and 511-keV-511-keV vs γ triple coincidence spectra (Fig. 4). The levels at 1968.0, 2073.7, 2109.6, 2246.6, 2303.4, 2354.4, and 2388.4 keV are proposed because the peaks at these energies are enhanced in the anticoincidence spectrum. Levels are placed at 1820.4, 1897.1, 2066.4, and 2265.3 keV because transitions of these energies are enhanced in the anticoincidence spectrum, and other transitions from these states are in coincidence with the 193.8-keV transition.

Making use of energy sums we postulate levels at 2506 and 2805 keV. We note that the transitions of 2311.6 and 2612.3 keV add with the 193.8-keV transition to give energies of 2505.4 and 2806.1 keV, which suggests that they may depopulate the 2506- and 2805-keV levels, respectively. The low efficiencies of the Ge(Li) detectors for high energies prevented these coincidences from being readily observed.

The other proposed levels, at 2145.2, 2430, 2620, and 2986 keV, are suggested solely by the observation of transitions of these energies in the singles experiments and our inability to relate them to other transitions via energy sums. These transitions are of sufficiently low intensity that it is not surprising that they are unobserved in the anticoincidence and triple-coincidence experiments.

In addition to these states, we show the level at 756.7 keV, which is the well known 60-sec $\frac{11}{2}^-$ isomeric state in ^{141}Nd. In the first spectrum in Fig. 1, accumulated in the interval from 6 to 16 min after bombardment, the 756.7-keV transition appears quite intense. This is attributed mostly to the direct production of ^{141}Nd^m via the reaction ^{142}Nd$(p,p'n)^{141}$Nd ($Q \leq -7.1$ MeV). The 756.7-keV intensity drops quite rapidly in subsequent spectra, in agreement with this assumption. However, the second spectrum in Fig. 1, which was also taken for an elapsed time of 10 min, beginning 54 min after bombardment, shows that the 756.7-keV transition still has a measureable intensity. In fact, the relative intensity of this line in the last four of the five successive ten minute spectra is relatively constant, with an average value of 1.7 (normalized to the 1223.3-keV line). This would seem to indicate that there is some indirect feeding of this level in the decay of ^{141}Pm, or that there is another transition in the decay scheme with nearly the same energy. There is no indication that a 756.7-keV γ ray is in coincidence with any other transition. Auble[17] has suggested that the ≈1420-keV state, observed to have $l = 0$ in the (p,t) reaction,[4] may actually lie at 1403.9 keV

TABLE III. Summary of γ-γ two parameter coincidence results for ^{141}Pm decay.

Gate energy (keV)	Energies of γ rays in the gated spectra (keV) Strong	Medium to weak
193.8	289.4, 1029.9, 1371.0, 1403.2, 1626.7, 1703.8, 1879.9, 2052.8	886.3
289.4		193.8, 597.2, 1223.3, 1626.7, 1820.4
538.2		622.2, 1345.8
597.2		1223.3
622.2	1345.8	
886.3		193.8, 1223.3
1022.8		1223.3
1029.9		193.8, 886.3
1223.3	886.3	
1345.8	622.2	
1371.0		193.8
1403.2	193.8	
1626.7	289.4	193.8
1703.8		193.8
1820.4		289.4
1879.9	193.8	
2052.8		193.8

TABLE IV. γ-ray intensities observed in ^{141}Pm coincidence experiments.

Energy (keV)	Relative intensities Singles	Anticoinc.	Integral coinc.	193.8-keV gate	511-keV-511-keV vs γ triple coinc.
180.2	0.6				
193.8	34.9	26.4	574.1		7.5
289.4	3.6		39.6	1.9	
511.0	2385				65.6
538.2	1.7		7.4		
544.7	1.4				
597.2	1.2		4.7		
622.2	18.9	7.3	58.7		4.6
647.2	1.3				
706.0	1.0				
886.3	52.5	20.5	114.3	3.3	4.2
901.2	1.1				
958.7	1.3		2.1		
966.3	2.0		3.4		
1022.8	2.8		4.7		
1029.8	7.8	1.9	17.3	6.9	5.3
1051.9	2.0				12.6
1080.7	1.0				
1223.3	≡100	56.1	≡100		≡100
1282.1	0.9				3.3
1345.8	27.6	9.0	39.3		8.6
1371.0	2.2		2.7	2.8	
1403.2	16.0	5.8	17.5	≡16.0	6.6
1564.8	17.9	13.9	6.5		16.9
1596.8	16.1	≡16.1	3.2		19.4
1626.7	5.8		7.1	5.8	
1703.8	1.2		0.7	0.6	
1820.4	1.6	2.0	1.0		
1872.6	0.5		0.8	1.3	
1879.9	6.9	3.8	4.2	6.0	
1897.1	1.1				
1967.6	3.6	3.4			
2052.8	2.6			2.5	
2066.4	1.3				
2073.7	13.4	16.0			1.8
2109.6	1.8	2.5			
2145.2	0.3				
2246.4	1.5	2.5			
2265.3	0.7				
2303.6	2.4	2.5			
2311.6	0.5				
2354.4	1.0	1.1			
2388.4	1.3	1.5			
2429.8	0.6	0.3			
2505.0	0.6	0.5			
2602.1	0.1				
2619.6	0.4	0.3			
2690.3	0.2	0.1			
2804.9	0.5	0.3			
2985.5	0.9				

and have $J^{\pi}=\frac{7}{2}^{-}$. This state could then decay to the 756.7-keV level via the weak 647.2-keV γ, which is as yet unplaced. The relative intensities of the 756.7- and 647.2-keV γ rays are comparable within the errors of the measurements and would correspond to a logft of 7.6 for β decay to a 1403.9-keV state, i.e., either a first forbidden or an allowed transition. Unfortunately, we do not have any direct evidence that this is correct, so we have omitted the 1403.9-keV state from the decay scheme.

V. SPIN AND PARITY ASSIGNMENTS

A. Ground states

The ground-state spin of ^{141}Nd has been determined[18] by the atomic beam method to be $\frac{3}{2}$. Results of (p,d) and (d,t) reaction studies[1-3] have confirmed a $\frac{3}{2}^+$ assignment for this state, and this suggests that it is primarily a $(\nu d_{3/2})^{-1}$ configuration.

Our results show that 89% of the ϵ/β^+ decay of ^{141}Pm populates the $\frac{3}{2}^+$ ground state of ^{141}Nd. The logft value for the transition is 5.4 and suggests an allowed decay. This limits the possible spin assignments for the ground state of ^{141}Pm to $\frac{1}{2}^+$, $\frac{3}{2}^+$, or $\frac{5}{2}^+$. The systematics of known odd-proton–odd-mass nuclei in the $51 \leq Z \leq 63$ region indicate an additional restriction on the possible spins. These nuclei all exhibit ground-state spins of $\frac{5}{2}^+$ or $\frac{7}{2}^+$. The ground-state spins of ^{143}Pm and ^{145}Pm are $\frac{5}{2}^+$, while the heavier Pm isotopes, beginning with ^{147}Pm, have $\frac{7}{2}^+$ ground-state spins. The possibility of a $\frac{7}{2}^+$ spin for the ^{141}Pm ground state can be eliminated since the ground-state $\rightarrow$ ground-state β transition has log$ft = 5.4$. Hence, we will assume in our following arguments that the ground-state spin-parity of ^{141}Pm is $\frac{5}{2}^+$ and that its configuration is primarily $\pi d_{5/2}$.

B. 193.8-keV state

We observed no direct decay ($\lesssim 0.3\%$, corresponding to log$ft \gtrsim 7.9$) to the 193.8-keV state in ^{141}Nd. This is consistent with the $s_{1/2}$ assignment from the (p,d) and (d,t) reaction studies.[1-3] Charvet *et al.*[9] determined the half-life to be 1.17 ± 0.15 nsec and the $E2/M1$ mixing ratio for the 193.8-keV transition, δ^2, to be 0.15 ± 0.04.

C. Other states in ^{141}Nd

The logft values for transitions to the remaining states in ^{141}Nd range from 5.9 to 8.1, with all but two of them lying between 6.4 and 7.7. These suggest allowed or, at most, first forbidden non-unique transitions and limit the possible spins to $\frac{3}{2}$, $\frac{5}{2}$, and $\frac{7}{2}$. In the following discussion we use the results of the (p,d) and (d,t) studies[1-3] to eliminate some of these possibilities. For convenient reference, we include the conversion electron work of Charvet *et al.*[9] in Table V, together with our photon intensities, which enable us to deduce some of the multipolarities. (Comparisons were made with the theoretical conversion coefficients of Hager and Seltzer.[19]) Unfortunately, we were not able to make much use of these electron data, for there appear to be large errors associated with them, probably caused by the difficulties in subtracting out the large positron continuum on which the conversion lines rode. The assigned multipolarities for the more intense, lower-energy transitions are probably correct, but there is considerable uncertainty in those for the weaker, higher-energy transitions; for example, the $M2$ and $M3$ assignments are inconsistent with the rest of the decay scheme and are undoubtedly wrong.

In Table VI we compare our proposed state energies and J^π assignments with those of Refs. 1–3 and 9.

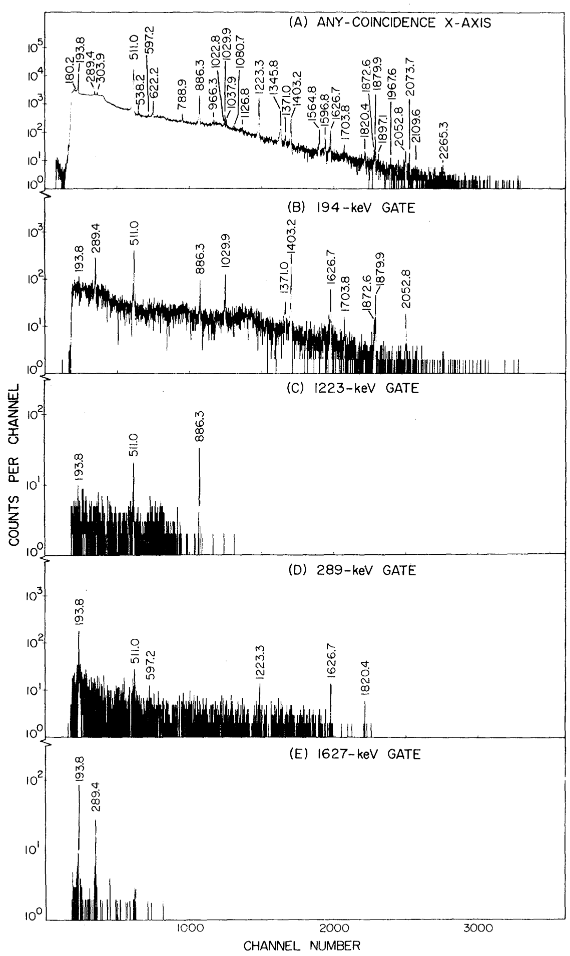

FIG. 2. Coincidence spectra recovered from gated portions of the two-parameter data. Coincidences with the Compton continuum have been subtracted. (a)–(e) compare an integral coincidence spectrum with spectra obtained in coincidence with gates set at 194, 1223, 289, and 1627 keV. (f)–(k) compare spectra obtained in coincidence with gates set at 622, 597, 538, 1029, 1022, and 886 keV. (l)–(r) compare spectra obtained in coincidence with gates set at 1403, 1371, 1345, 2052, 1879, 1820, and 1703 keV.

1223.3-keV state

The ϵ/β^+ transition to the state we have placed at 1223.3 keV has a log*ft* of 6.4, suggesting J^π values of $\frac{3}{2}^+$, $\frac{5}{2}^+$, or $\frac{7}{2}^+$. This state feeds both the $\frac{3}{2}^+$ ground state and the $\frac{1}{2}^+$ state at 193.8 keV, making $\frac{7}{2}^+$ quite unlikely. Also, the multipolarity of the 1223.3-keV transition is one of the more trustworthy, and it appears to be $E2$ with little if any $M1$ mixing, consistent with a $\frac{3}{2}^+$ or $\frac{5}{2}^+$ assignment. The level is tied down to $\frac{5}{2}^+$ because of the $l = 2$ angular momentum transfer in the reaction studies.[1-3]

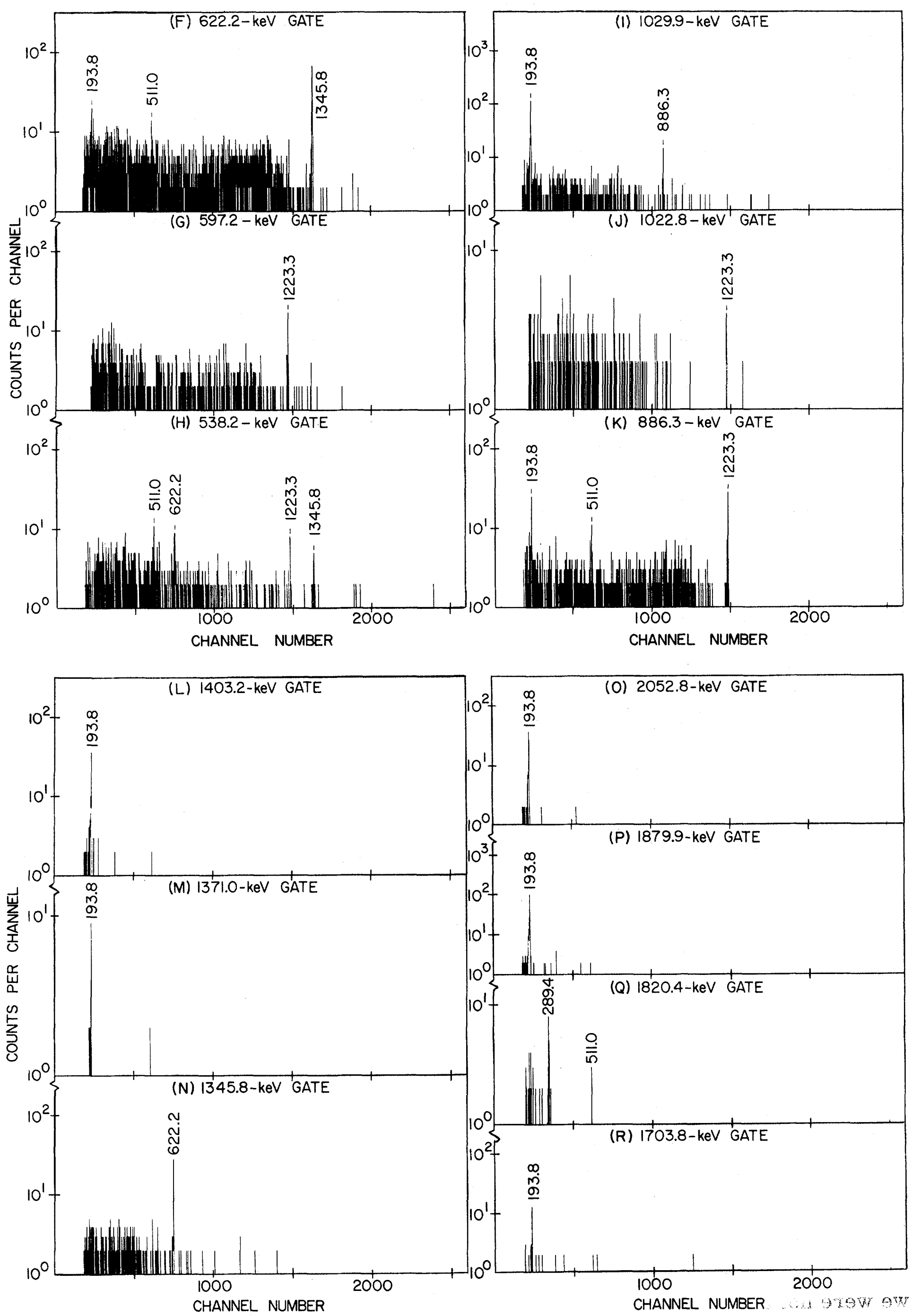

FIG. 2 (*Continued*)

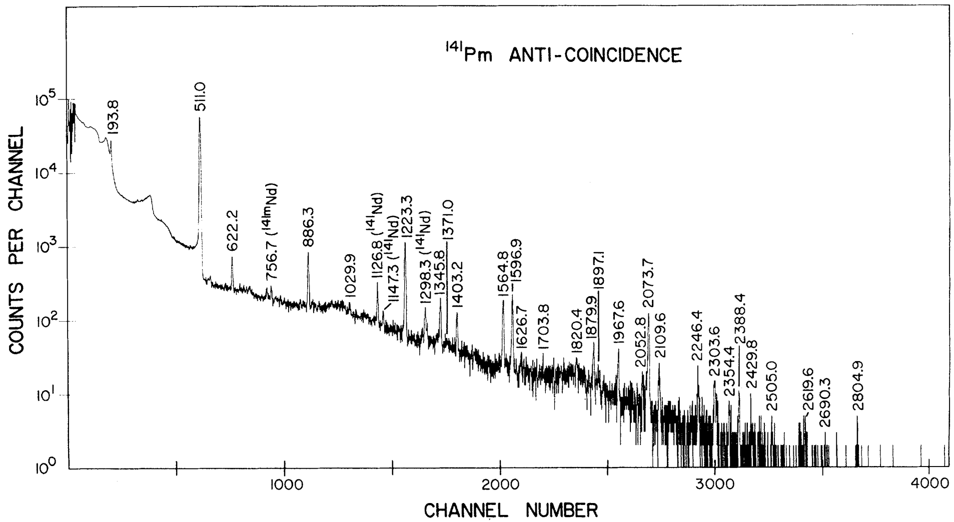

FIG. 3. γ rays from ^{141}Pm decay detected in a Ge(Li) counter in anticoincidence with a NaI(Tl) annulus.

1345.8-keV state

The state at 1345.8 keV deexcites only to the $\frac{3}{2}^+$ ground state. As no transition is observed between this state and the $\frac{1}{2}^+$ first excited state, a $\frac{3}{2}$ assignment seems somewhat unlikely, although $\frac{3}{2}$, $\frac{5}{2}$, and $\frac{7}{2}$ are all certainly possible. The parity of this state is undetermined from our data because the logft value of 7.2 could result from either an allowed or a first-forbidden transition.

A state has been observed at this excitation energy in the (p,d) and (d,t) reaction studies on ^{142}Nd, and the results[1,2] suggest $\frac{7}{2}^+$ for the spin and parity. Charvet *et al.*[9] assign $\frac{7}{2}^-(\frac{5}{2}^-)$ to the state, but this is based on a (possibly mistaken) $M2$ assignment for the 1345.8-keV γ transition.

The corresponding states of the neighboring even-Z $N=81$ nuclei can also be considered, although this is weaker evidence. A $\frac{7}{2}^+$ state has been identified[20,21] at 1347.7 keV in ^{139}Ce, and a $\frac{7}{2}^+$ state is seen[1,22] at 1369.0 keV in ^{143}Sm. All in all, even though there is some conflicting evidence, the $\frac{7}{2}^+$ assignment is most likely, but $\frac{7}{2}^-$, $\frac{5}{2}^+$, and even $\frac{3}{2}^+$ cannot be absolutely ruled out.

1564.8-keV state

The level at 1564.8 keV is populated by β decay with a logft of 6.7. This suggests an allowed transition, indicating possible spins of $\frac{3}{2}^+$, $\frac{5}{2}^+$, and $\frac{7}{2}^+$. Transitions are observed from this state to both the $\frac{1}{2}^+$ state at 193.8 keV and the $\frac{3}{2}^+$ ground state. The $\frac{7}{2}^+$ assignment can be eliminated because this would require the 1371.0-keV γ ray to the first excited state to be an $M3$ and the 1564.8-keV γ ray to the ground state an $E2$, which would not be expected to compete favorably. The

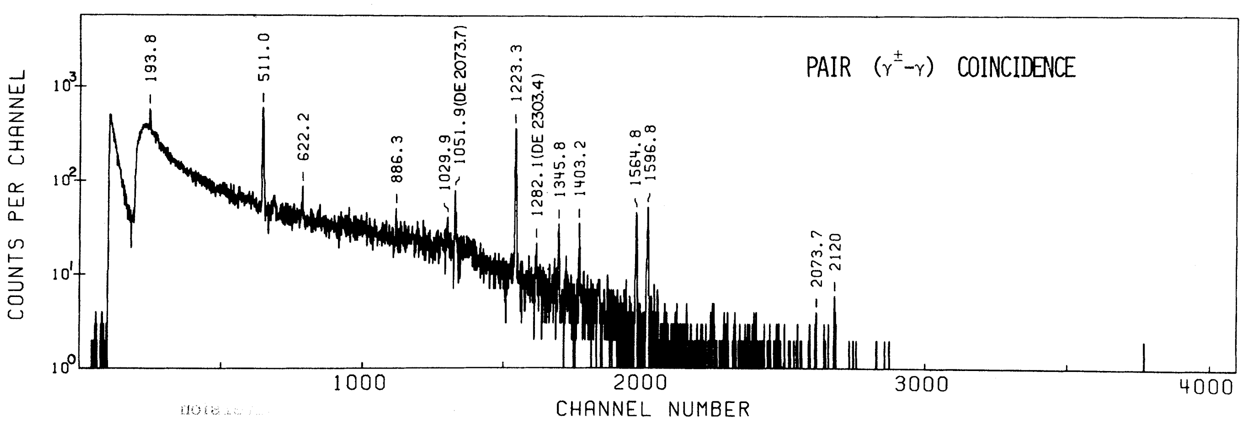

FIG. 4. Ge(Li) γ-ray spectrum in coincidence with two 511-keV quanta detected simultaneously in each half of the NaI(Tl) annulus.

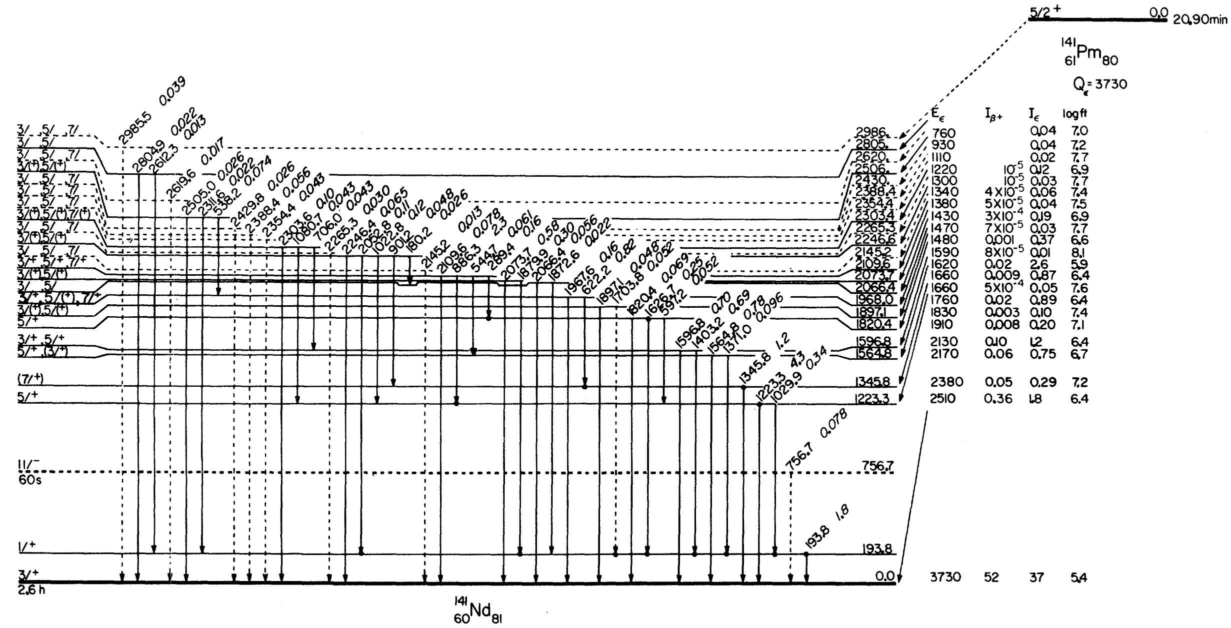

FIG. 5. Decay scheme of ^{141}Pm. Dashed levels have been placed solely on the basis of a single transition and are hence questionable.

$\frac{5}{2}^+$ assignment remains a possibility as some degree of $E2$ enhancement and $M1$ retardation are observed in nearby nuclei.

The conversion-electron results of Charvet *et al.* indicate the multipolarity of the 1564.8-keV transition may be $M3$. The Moskowski single-particle estimate for the partial half-life of such a transition is ≈ 7 μsec. We have not measured the half-life of this state; however, this transition appears in the 511-keV-511-keV vs γ triple coincidence experiment (resolving time ≈ 100 nsec) with a relative intensity nearly the same as that seen with no coincidence requirement, suggesting a half-life less than a few hundred nsec, and casting considerable doubt on the $M3$ interpretation. The conversion coefficient of the 1564.8-keV transition can be explained if there is an $E0+M1+(E2)$ mixture. If $E0$ is present, then the 1564.8-keV state must be $\frac{3}{2}^+$. The existing data leave this assignment uncertain, however.

The (p,d) and (d,t) reactions populate a state at this excitation energy, which is characterized by

TABLE V. Multipolarity assignments for selected γ transitions from ^{141}Pm decay.

Energy (keV) (this work)	Photon relative intensity (this work)	K conversion relative intensity (Ref. 9)	Experimental $10^3\alpha_K$	Deduced multipolarity [a]
193.8± 0.1	34.9± 1.7	≡100	≡180 [b]	$M1+E2$
622.2± 0.4	18.9± 1.0	$1.2^{+0.5}_{-0.3}$	$4.0^{+1.2}_{-0.6}$	$E1$ (or $E2$?)
886.3± 0.3	52.5± 2.6	1.7 ± 0.2	2.0± 0.5	$E2$
1223.3± 0.5	≡100	2.1 ± 0.6	1.3± 0.4	$E2$
1345.8± 0.4	27.6± 1.4	1.6 ± 0.3	3.6± 1.0	$M2$
1403.2± 0.5	16.0± 1.0	0.4 ± 0.2	1.6± 1	$E2$, $M1$
1564.8± 0.5	17.9± 1.0	1.4 ± 0.3	4.9± 1.0	$M3$
1596.8± 0.5	16.1± 1.0	0.36± 0.2	1.4± 0.8	$E2$ or $E3$
1879.9± 0.5	6.9± 0.7	<0.2	<1.8	$E2$, $M1$, or $E1$
2073.3± 0.5	13.4± 1.0	<0.25	<1.2	$E2$, $M1$, or $E1$

[a] Based on comparison of experimental α_K values with the theoretical values of Ref. 19.

[b] The value of $\alpha_K = 0.180$ serves as the fiducial value for the determination of conversion coefficients. This can be done for this mixed transition because the $E2/M1$ mixing ratio presumably is known.

TABLE VI. ^{141}Nd level scheme comparisons.

Present work		Charvet *et al.* (Ref. 9)		Jolly and Kashy (Ref. 1)		Chameux *et al.* (Ref. 2)		Foster *et al.* (Ref. 3)	
Energy (keV)	J^π assignment	Energy (keV)	J^π assignment	Energy (keV)	J^π assignment	Energy (keV)	J^π assignment	Energy (keV)	J^π assignment
0	$\frac{3}{2}^+$	0	$\frac{3}{2}^+$	0	$\frac{3}{2}^+$	0	$\frac{3}{2}^+$	0	$\frac{3}{2}^+$
193.8	$\frac{1}{2}^+$	193.7	$\frac{1}{2}^+$	190	$\frac{1}{2}^+$	222	$\frac{1}{2}^+$	193	$\frac{1}{2}^+$
756.7 [a]	$\frac{11}{2}^-$	756.8	$\frac{11}{2}^-$	760	$\frac{11}{2}^+$	755	$\frac{11}{2}^-$	756	$\frac{11}{2}^-$
1223.3	$\frac{5}{2}^+$	1223.3	$(\frac{5}{2}^+)$	1200	$\frac{5}{2}^+$	1220	$\frac{5}{2}^+$	1221	$(\frac{5}{2}^+)$
1345.8	$(\frac{7}{2}^+)$	1345.4	$\frac{7}{2}^-(\frac{5}{2}^-)$	1330	$(\frac{7}{2}^+)$	1370	...	1343	$(\frac{7}{2}^+)$
1564.8	$\frac{5}{2}^+(\frac{3}{2}^+)$	1564.7	...	1560	$(\frac{5}{2}^+)$	1560	$\frac{5}{2}^+$	1561	$(\frac{5}{2}^+)$
1596.8	$\frac{3}{2}^+, \frac{5}{2}^+$	1596.9	$\frac{3}{2}^+(\frac{5}{2}^+)$	...	...	...	...	...	...
1820.4	$\frac{5}{2}^+$	1820.2	...	1800	$(\frac{5}{2}^+)$	1840	$\frac{5}{2}^+$	1817	$(\frac{5}{2}^+)$
...	...	...	...	1870	$\frac{1}{2}^+$	...	...	1887	$\frac{1}{2}^+$
1897.1	$\frac{3}{2}^{(+)}, \frac{5}{2}^{(+)}$	1897.0	...	...	...	...	...	...	...
1968.0	$\frac{5}{2}^{(+)}, \frac{7}{2}^{(+)}$	1967.4	$(\frac{7}{2}^+)$	...	...	...	...	...	...
2066.4	$\frac{3}{2}, \frac{5}{2}$	...	...	2050	$(\frac{5}{2}^+)$	...	...	...	...
2073.7	$\frac{3}{2}^{(+)}, \frac{5}{2}^{(+)}$	2073.5	$\frac{3}{2}^+(\frac{5}{2}^+)$	2090	$(\frac{5}{2}^+)$	2090	$\frac{5}{2}^+$	...	...
2109.6	$\frac{3}{2}^+, \frac{5}{2}^+, \frac{7}{2}^+$	2109.4	$(\frac{5}{2}^+)\frac{7}{2}^+$	...	...	...	...	...	...
2145.2	$\frac{3}{2}, \frac{5}{2}, \frac{7}{2}$	...	...	...	...	...	...	...	...
...	...	...	...	2190	$\frac{11}{2}^-$	...	...	...	...
...	...	...	...	...	...	2210	$\frac{7}{2}^+$	...	...
2246.6	$\frac{3}{2}^{(+)}, \frac{5}{2}^+$	...	...	...	...	...	...	...	...
2265.3	$\frac{3}{2}, \frac{5}{2}, \frac{7}{2}$	...	...	...	...	...	...	...	...
2303.4	$\frac{3}{2}^{(+)}, \frac{5}{2}^{(+)}, \frac{7}{2}^{(+)}$	...	...	2300	$(\frac{7}{2}^+)$	2310	...	...	...
2354.4	$\frac{3}{2}, \frac{5}{2}, \frac{7}{2}$	...	...	...	...	...	...	...	...
2388.4	$\frac{3}{2}, \frac{5}{2}, \frac{7}{2}$	...	...	...	...	...	...	...	...
2430	$\frac{3}{2}, \frac{5}{2}, \frac{7}{2}$	...	...	...	...	...	...	...	...
2506	$\frac{3}{2}^{(+)}, \frac{5}{2}^{(+)}$	...	...	...	...	...	...	...	...
2620	$\frac{3}{2}, \frac{5}{2}, \frac{7}{2}$	...	...	2590	...	...	...	...	...
2805	$\frac{3}{2}, \frac{5}{2}$	2804	...	2800	...	...	...	...	...
...	...	...	...	2910	...	2910	$\frac{5}{2}^+$	...	...
2986	$\frac{3}{2}, \frac{5}{2}, \frac{7}{2}$	...	...	...	...	...	...	...	...
...	...	...	...	3090	$\frac{7}{2}^+$	3100	...	...	...
...	...	...	...	3370	$\frac{5}{2}^+$	3350	...	...	...

[a] It is not yet completely clear whether the 756.7 $\frac{11}{2}^-$ state in ^{141}Nd is populated in the decay of ^{141}Pm, although data are presented in this paper that suggest it may be fed indirectly via higher energy states.

an $l=2$ angular momentum transfer, resulting in an assigned spin and parity of $\frac{5}{2}^+$. This is probably the same state that we observe in the β decay.

As a result of this evidence, $\frac{5}{2}^+$ and $\frac{3}{2}^+$ are possible J^π assignments for the 1564.8-keV state.

1596.8-keV state

The state at 1596.8 keV deexcites to the $\frac{1}{2}^+$ first excited state, and the $\frac{3}{2}^+$ ground state. The logft value (6.4) suggests an allowed transition and, therefore, positive parity. The conversion coefficients (Table V) indicate that the 1403.2-keV transition from this level to the $\frac{1}{2}^+$ first excited state and the 1596.8-keV ground-state transition may be $E2$ and/or $M1$, and these assignments seem consistent with the observed branching ratios. Thus, $\frac{5}{2}^+$ and $\frac{3}{2}^+$ assignments appear equally likely. A $\frac{7}{2}^+$ assignment can be ruled out because the consequent 1403.2-keV $M3$ transition would not be expected to compete favorably with the $E2$ transition feeding the ground state.

Higher excited states in ^{141}Nd

The logft for the β transition to the 1820.4-keV state is 7.1, which implies $J=\frac{3}{2}$, $\frac{5}{2}$, or $\frac{7}{2}$ but does not allow the determination of this state's parity. This state deexcites to three lower-lying states, the $\frac{5}{2}^+$ 1223.3-keV state, the $\frac{1}{2}^+$ 193.8-keV state, and the $\frac{3}{2}^+$ ground state. The spin assignment can be limited to $\frac{3}{2}$ or $\frac{5}{2}$ on the basis of the preferential deexcitation to the $\frac{1}{2}^+$ state. A level is observed at this excitation in the (p,d) and (d,t) studies and has been assigned $\frac{5}{2}^+$, which is consistent with our data.

The logft for the transition to the 1968.0-keV state is 6.4, which probably indicates an allowed transition. This state feeds the 1345.8-keV state strongly and also populates the $\frac{3}{2}^+$ ground state. The 1968.0-keV state is thus most likely $\frac{3}{2}^+$, $\frac{5}{2}^+$, or $\frac{7}{2}^+$, although $\frac{5}{2}^-$ cannot be completely ruled out.

The states at 1897.1, 2066.4, and 2805 keV are fed by β transitions that have logft values of 7.4, 7.6, and 7.2, respectively. These states have similar deexcitation patterns to the $\frac{1}{2}^+$ 193.8-keV state and the $\frac{3}{2}^+$ ground state. Consequently, we can limit the probable spin assignments to $\frac{3}{2}$ or $\frac{5}{2}$. The parities remain uncertain.

The states at 2073.7 and 2506 keV are fed by β transitions with respective logft values of 6.4 and 6.9, which give weak arguments for positive parity. Since both states depopulate to the $\frac{1}{2}^+$ 193.8-keV state and the $\frac{3}{2}^+$ ground state, the assignments can be narrowed to $\frac{3}{2}^{\pm}$ or $\frac{5}{2}^{(+)}$.

The logft of 5.9 for the transition to the 2109.6-keV state is a stronger argument for that state having positive parity. The deexcitation pattern of this state, however, does not allow any narrowing of the spin assignments, so we are left with $\frac{3}{2}^+$, $\frac{5}{2}^+$, or $\frac{7}{2}^+$.

With a logft of 8.1, the β transition to the 2145.2-keV state could be either first forbidden or (hindered) allowed, so the assignment must remain $\frac{3}{2}^{\pm}$, $\frac{5}{2}^{\pm}$, or $\frac{7}{2}^{\pm}$.

The state at 2246.6 keV feeds states having $J^\pi=\frac{1}{2}^+$, $\frac{3}{2}^+$, $\frac{5}{2}^+$, and $\frac{7}{2}^+$ (or possible $\frac{7}{2}^-$). The logft value of 6.6 is consistent with allowed β decay, so we are left with an assignment of $\frac{3}{2}^{(+)}$ or $\frac{5}{2}^{(+)}$ for this state.

With the exception of the states at 2303.4 and 2986 keV, the remaining states (at 2265.3, 2354.4, 2388.4, 2430, and 2620 keV) are fed by β transitions having logft values ranging between 7.4 and 7.7, so we can only say their spins are $\frac{3}{2}^{\pm}$, $\frac{5}{2}^{\pm}$, or $\frac{7}{2}^{\pm}$. The lower logft values for the transitions to the 2303.4- and 2986-keV states (6.9 and 7.0, respectively) are weak arguments for positive parity, making their probable assignments $\frac{3}{2}^{(+)}$, $\frac{5}{2}^{(+)}$, or $\frac{7}{2}^{(+)}$.

VI. DISCUSSION

The ground state and the first two excited states in ^{141}Nd can be characterized in shell-model terms as being primarily $(\nu d_{3/2})^{-1}$, $(\nu s_{1/2})^{-1}$, and $(\nu h_{11/2})^{-1}$, respectively. These states appear to be of rather pure single-particle nature as characterized by the large spectroscopic factors associated with their population in the (p,d) and (d,t) studies.[2,3]

We determined that 89% of the β^+/ϵ decay of ^{141}Pm populates the ground state of ^{141}Nd with a logft of 5.4. This is consistent with the transformation of a $d_{5/2}$ proton into a $d_{3/2}$ neutron. A similar $(\pi d_{5/2})\to(\nu d_{3/2})$ decay is observed[21] in the case of $^{139}\mathrm{Pr} \xrightarrow{\beta^+/\epsilon} {}^{139}\mathrm{Ce}$, in which 99% of the β decay goes directly to the ground state of ^{139}Ce and has a logft of 5.6.

The first excited state at 193.8 keV receives no apparent β^+/ϵ feeding (<0.3%), and the log$ft>7.9$ is consistent with a $(\nu s_{1/2})^{-1}$ description. The 193.8-keV γ ray from this state is primarily an l-forbidden $M1$ transition $(s_{1/2}\to d_{3/2})$. The results of Charvet *et al.*[9] indicate the multipolarity is (87% $M1$ +13% $E2$). These values correspond to an $M1$ retardation factor of 51 (with respect to a Moskowski single-particle estimate) and an $E2$ enhancement factor of 4.

The state of 756.7 keV is the well-known isomer of ^{141}Nd ($t_{1/2}=60$ sec).[12] This state is one of a long series of $\frac{11}{2}^-$ metastable states found in the $N=81$ isotones.[22] These isomers are characterized as $(\nu h_{11/2})^{-1}$ neutron states and all are of a relatively pure single-particle character. They are characterized by half-lives ranging from 55.4 min for $^{133}Te^m$ to approximately 60 sec for the isotones $^{139}Ce^m$, $^{141}Nd^m$, and $^{143}Sm^m$. These states decay via $M4$ transitions directly to the ground states. We discussed earlier the apparent observation of the indirect feeding of the 756.7-keV level from states at higher excitation. This indirect feeding suggests that higher-lying negative parity states of spin $\frac{9}{2}$ or $\frac{7}{2}$ are populated in the ^{141}Pm decay, e.g. the $\nu h_{9/2}$ or the $\nu f_{7/2}$ states. It would be of interest to learn whether similar feedings can be observed in the decay of ^{143}Eu to states in ^{143}Sm.

According to the reaction studies, the state at 1223.3 keV contains approximately one-half to one-third of the $2d_{5/2}$ single-particle strength, indicating that the $d_{5/2}$ single-particle state is highly fractionated. In ^{141}Pm decay the 1223.3-keV state is fed by four higher-lying states in ^{141}Nd at 1820.4, 2109.6, 2246.6, and 2303.4 keV, with the 886.3-keV transition from the state at 2109.6 keV being the second strongest line in the γ-ray spectrum. The $\frac{5}{2}^+$ state observed in the (p,d) studies at 2.09 MeV,[1,2] which may correspond to the level seen at 2109.6 keV in the β decay, could be another fraction of the $d_{5/2}$ state.

The state at 1345.8 keV ($\log ft = 7.2$) is somewhat of a puzzle. It is tempting to conclude from the (p,d) and (d,t) data of Jolly and Kashy[1] and Foster *et al.*[3] that it contains some $(\nu g_{7/2})$ component in its wave function. Similar $\frac{7}{2}^+$ states have been observed in ^{139}Ce at 1347.4 keV[19] and in ^{143}Sm at 1369.5 keV,[23] with respective $\log ft$ values of 7.0 and 6.5. It should be noted that this $\frac{7}{2}^+$ assignment depends on large-l single-nucleon transfer data, and angular distributions of this kind are difficult to interpret unambiguously.

Preliminary calculations for states below 2 MeV in ^{141}Nd have been done by Reehal[24] using the pairing-plus-quadrupole Hamiltonian of Kisslinger and Sorensen.[25] The three lowest states turn out to be nearly pure single-particle states. The lowest $\frac{5}{2}^+$ state seems to have significant admixture of $\frac{1}{2}^+$ and $\frac{3}{2}^+$ single-particle states coupled to one phonon. Similarly, the lowest $\frac{7}{2}^+$ state appears to arise mainly from coupling $\frac{3}{2}^+$ to one phonon and has little single-particle character. The character of several of the higher-lying states apparently arises from coupling $\frac{1}{2}^+$ and $\frac{3}{2}^+$ single-particle states to one phonon. A more detailed analysis of the higher-lying states await more complete shell-model calculations.

ACKNOWLEDGMENTS

We would like to thank Dr. H. Blosser and the staff of the Michigan State University Cyclotron Laboratory for their assistance in the operation of the cyclotron and computer. Our thanks also go to Dr. Dwight Beery for helping with the initial stages of this work, and to Dr. R. Goles, Mr. Wm. B. Chaffee, Dr. R. E. Eppley, and Dr. L. Samuelson, who aided in the data collection and analysis.

---

*U. S. National Science Foundation Summer Research Participant. Permanent address: Physics Department, Wilson College, Chambersburg, Pennsylvania 17201.

†Present address: Department of Physics, Western Michigan University, Kalamazoo, Michigan 49001.

‡Work supported in part by the U. S. National Science Foundation.

§Alfred P. Sloan Fellow, 1972–1976.

¶Work supported in part by the U. S. Atomic Energy Commission.

[1]R. K. Jolly and E. Kashy, Phys. Rev. C 4, 887 (1971).
[2]A. Chameaux, G. Bruge, H. Faraggi, and J. Picard, Nucl. Phys. A164, 176 (1971).
[3]J. L. Foster, Jr., O. Dietzsch, and D. Spalding, Nucl. Phys. A169, 187 (1971).
[4]K. Yagi, K. Sato, and Y. Aoki, Phys. Lett. 37B (1971); K. Yagi, Y. Aoki, and K. Sato, J. Phys. Soc. Jpn. 28, 1583 (1970).
[5]V. Kistiakowsky Fischer, Phys. Rev. 87, 259 (1952).
[6]J. Bleyl, M. Munzel, and G. Pfinning, Radiochim. Acta 6, 200 (1967).
[7]R. Arl't, N. Bonch-Osmolovskaya, J. Vrzal, J. Liptak, and J. Urbanec, Dubna Report No. JINR-P-2618, 1966 (unpublished).
[8]K. Hesse, Z. Phys. 220, 328 (1969).
[9]A. Charvet, R. Duffait, A. Ernsallem, and R. Chery, J. Phys. (Paris) 31, 737 (1970).
[10]R. R. Todd, R. E. Eppley, R. A. Warner, Wm. C. McHarris, and W. H. Kelly, unpublished.
[11]R. E. Eppley, R. R. Todd, R. A. Warner, Wm. C. McHarris, and W. H. Kelly, Phys. Rev. C 5, 1084 (1972).
[12]D. B. Beery, W. H. Kelly, and Wm. C. McHarris, Phys. Rev. 171, 1283 (1968).
[13]R. E. Eppley, Ph.D. thesis, Michigan State University (unpublished) [COO-1779-32 (1970)].
[14]R. E. Doebler, Wm. C. McHarris, and W. H. Kelly, Phys. Rev. C 2, 2422 (1970).
[15]R. L. Auble, D. B. Beery, G. Berzins, L. M. Beyer, R. C. Etherton, W. H. Kelly, and Wm. C. McHarris, Nucl. Instrum. Methods 51, 61 (1967).
[16]G. C. Giesler, Wm. C. McHarris, R. A. Warner, and W. H. Kelly, Nucl. Instrum. Methods 91, 313 (1971).
[17]R. L. Auble, Nucl. Data B10, 151 (1973).
[18]S. S. Alpert, B. Budick, E. Lipworth, and R. Marrus, Bull. Am. Phys. Soc. 7, 239 (1962).
[19]R. S. Hager and E. C. Seltzer, Nucl. Data A4, 1 (1968).
[20]R. H. Fulmer, A. L. McCarthy, and B. L. Cohen,

Phys. Rev. 128, 1302 (1962).
[21]D. B. Beery, W. H. Kelly, and Wm. C. McHarris, Phys. Rev. 188, 1875 (1969).
[22]G. Jansen, M. Morinaga, and C. Signorini, Nucl. Phys. A128, 245 (1969); D. B. Beery, W. H. Kelly, and Wm. C. McHarris, Phys. Rev. 188, 1851 (1969); R. E. Eppley, Wm. C. McHarris, and W. H. Kelly, Phys. Rev. C 2, 1929 (1970); R. E. Eppley, R. R. Todd, R. A. Warner, Wm. C. McHarris, and W. H. Kelly, *ibid.* 5, 1084 (1972).
[23]R. B. Firestone and Wm. C. McHarris, unpublished.
[24]B. Reehal, private communication.
[25]L. S. Kisslinger and R. A. Sorensen, Rev. Mod. Phys. 35, 853 (1963).