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High-Resolution Gamma-Ray Spectroscopic Studies of the Decays of 2.6-h Nd^{141g} and 60-sec Nd^{141m}

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γ rays emitted in the decays of 2.6-h Nd^{141g} and 60-sec Nd^{141m} have been investigated with Ge(Li) and NaI(Tl) detectors. Following the decay of Nd^{141g}, γ rays with the following energies (and relative intensities) have been observed: 145.4 (30.0), 981.3 (3.0), 1126.8 ($\equiv$100), 1147.1 (38.2), 1292.8 (61.2), 1298.7 (16.3), 1434.6 (3.0), 1579.9 (0.74), 1607.9 (2.3), and 1657.2 keV (0.12). On the basis of coincidence and anticoincidence experiments, energy sums, and relative intensities, states were placed in Pr^{141} at 0, 145.4, 1126.8, 1292.5, 1298.4, 1580.0, 1607.9, and 1657.2 keV. An upper limit of 0.1% of the intensity of the Nd^{141m} 756.5-keV isomeric-transition γ ray was placed on the intensity of any other γ ray between 130 and 2600 keV following direct transitions from the $\frac{11}{2}-$ Nd^{141m} to high-spin states of Pr^{141}. Limits are placed on the spins of Pr^{141} states on the basis of $\log ft$ values and relative photon intensities, and the structures of the states are discussed in terms of current nuclear models.

I. INTRODUCTION

SINCE the first production of Nd^{141} in 1937 by Pool and Quill,[1] who used fast neutrons to induce the $\mathrm{Nd}^{142}(n,2n)\mathrm{Nd}^{141}$ reaction, this nuclide has been produced by a number of reactions involving the use of protons, deuterons, α particles, and photons as projectiles.[2] Similarly, there have been various more or less successful studies of its decay scheme.[2] Among the more complete γ-ray spectroscopic studies that utilized only NaI(Tl) detectors,[3–6] however, there exist some serious discrepancies. Also, in none of these studies are more than three Pr^{141} excited states reported, whereas, as a result of the study of inelastically scattered deuterons on Pr^{141}, Cohen and Price[7] have reported levels at 140, 1140, 1300, 1500, and 1630 keV, with additional levels at 1800 keV and higher energies. Some studies on inelastically scattered neutrons[8] and N^{14}-induced Coulomb excitation,[9] although with poorer resolution, have also indicated the existence of a number of levels starting in the vicinity of 1 MeV. In the only previous published work of Nd^{141} decay utilizing Ge(Li) detectors, Koehler and Grissom,[10] using a very small detector, report only four γ rays, depopulating the first three of the excited states reported by Cohen and Price.

Since the energy for Nd^{141} electron-capture decay is 1800 keV,[5,11] one might expect some of the other higher-lying Pr^{141} levels also to be populated from its decay. For this reason and because of the discrepancies among the earlier studies, we felt that a reinvestigation of Nd^{141} decay was in order. We have produced Nd^{141} by the relatively clean $\mathrm{Pr}^{141}(p,n)\mathrm{Nd}^{141}$ reaction and have used Ge(Li) and NaI(Tl) detectors in singles, coincidence, and anticoincidence configurations to study its γ rays. Additionally, as no specific rare-earth chemical separations had been performed on the targets in any of the previous work, we separated Nd chemically from the other rare earths in order to insure that the activities we were observing came from a Nd isotope. As a result of our studies we have found six new γ rays, and these can be fitted into a decay scheme that includes the population of three additional excited states in Pr^{141}. We also investigated the decay of the short-lived isomer Nd^{141m},[12,13] to see if it might decay directly to high-spin states in Pr^{141}; our results allow us to place an upper limit of 0.1% on any direct population of such levels.

II. SOURCE PREPARATION

The Nd^{141} sources were prepared by bombarding 99.97% pure $\mathrm{Pr_2O_3}$ with protons from the Michigan State University sector-focused cyclotron; these protons were degraded from higher energies to 9 MeV by the use of Al absorbers. Typically, $\approx$100-mg targets

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[*] At present on leave at the Lawrence Radiation Laboratory, Berkeley, Calif.

[†] Supported in part by the National Science Foundation.

[1] M. L. Pool and L. L. Quill, Phys. Rev. **53**, 437 (1938).

[2] *Nuclear Data Sheets*, compiled by K. Way *et al.* (U. S. Government Printing Office, National Academy of Sciences—National Research Council, Washington, D. C.); C. M. Lederer, J. M. Hollander, and I. Perlman, *Table of Isotopes* (John Wiley & Sons, Inc., New York, 1966), 6th ed.

[3] H. L. Polak, W. Schoo, B. L. Schram, R. K. Girgis, and R. van Lieshout, Nucl. Phys. **5**, 271 (1958).

[4] E. W. Cybulska and L. Marquez, Nucl. Phys. **14**, 117 (1959).

[5] E. I. Biryukov and N. S. Shimanskaya, Izv. Akad. Nauk SSSR, Ser. Fiz. **27**, 1402 (1963).

[6] W. L. Alford, D. R. Koehler, and R. G. Polk, Nucl. Phys. **44**, 439 (1963).

[7] B. L. Cohen and R. E. Price, Phys. Rev. **123**, 283 (1961).

[8] V. A. Bukarev and V. I. Popov, Yadern. Fiz. **1**, 443 (1965) [English transl.: Soviet J. Nucl. Phys. **1**, 316 (1965)].

[9] D. G. Alkhazov, K. I. Erokhina, and I. Kh. Lemberg, Izv. Akad. Nauk SSSR, Ser. Fiz. **29**, 139 (1965).

[10] D. R. Koehler and J. T. Grissom, Nucl. Phys. **84**, 235 (1966).

[11] G. Wilkinson and H. G. Hicks, Phys. Rev. **75**, 1687 (1949).

[12] R. A. James and C. D. Bingham, Phys. Rev. **117**, 810 (1960).

[13] K. Kotajima and H. Morinaga, Nucl. Phys. **16**, 231 (1960).

were bombarded with a ≈ 1-μA beam for 1 h. Sources were normally allowed to decay for at least 1 h to let any short-lived contaminants decay away, and then they were counted for two to four half-lives, more source being added with the passage of time in order to retain a relatively constant counting rate. It was found that no competing γ rays with different half-lives were observed for approximately four half-lives of the Nd^{141}. Most of the coincidence experiments, which required several days' counting time, were performed with multiple bombardments.

To insure that we were observing radiations only from Nd, we confirmed the singles γ-ray spectrum with a chemically separated source. In this source the Nd was separated from the Pr target and any other contaminating rare earths by eluting it from a Dowex-50 cation-exchange column with α-hydroxy-isobutyrate.[14]

The Nd^{141m} sources were produced by bombarding similar $\mathrm{Pr_2O_3}$ targets for ≈ 10 sec. No chemical separations were performed on these sources.

III. Nd^{141g} γ-RAY SPECTRA

A. Singles Spectra

A 7-cm^3 five-sided coaxial Ge(Li) detector was used to determine the energies and intensities of the Nd^{141} γ rays. It was mounted in a dip-stick cryostat. The wall thickness of the evacuated Al can covering the detector was 0.16 cm. Typical resolution obtained with this detector was ≈ 4.3 keV full width at half-maximum (FWHM) for the 661.6-keV γ ray of Cs^{137}, using a room-temperature FET preamplifier, a low-noise *RC* linear amplifier with pole-zero compensation, and a 1024-channel analyzer. A 3-cm^3 planar Ge(Li) detector mounted in a similar fashion was used to confirm the energy values and intensity ratios of the γ rays observed. Both of these detectors were manufactured in this laboratory.

TABLE I. γ rays used as energy standards.

Nuclide	γ-ray energy (keV)	Reference
Co^{57}	121.97 ± 0.05	a
Co^{57}	136.33 ± 0.04	a
Ce^{139}	165.84 ± 0.03	b
Cs^{134}	644.744 ± 0.027	c
Cs^{137}	661.595 ± 0.076	d
Cs^{134}	795.806 ± 0.050	c
Mn^{54}	834.84 ± 0.07	e
Y^{88}	898.01 ± 0.07	e
Sc^{46}	1120.50 ± 0.07	e
Co^{60}	1173.226 ± 0.040	f
Co^{60}	1332.483 ± 0.046	f
Na^{24}	1368.526 ± 0.044	f
Tl^{208} (D.E.)	1592.46 ± 0.10	f
Na^{24} (D.E.)	1731.91 ± 0.012	f
Y^{88}	1836.08 ± 0.07	e

[a] J. B. Marion, University of Maryland Technical Report No. 653, 1957 (unpublished).

[b] Reference 20.

[c] D. E. Raeside, J. J. Reidy, and M. L. Wiedenbeck, Nucl. Phys. **A98**, 54 (1967).

[d] J. S. Geiger, R. L. Graham, and F. Brown, Can. J. Phys. **40**, 1258 (1962).

[e] W. W. Black and R. L. Heath, Nucl. Phys. **A90**, 650 (1967).

[f] G. Murray, R. L. Graham, and J. S. Geiger, Nucl. Phys. **63**, 353 (1965).

The energies of the γ rays were measured by counting the Nd^{141} sources simultaneously with a number of well-known calibration sources, which are listed in Table I. In order that activities decaying with different half-lives could be identified, spectra were recorded periodically as the sources aged. A background correction was made for each peak by fitting a cubic equation to several channels above and below the peak and then subtracting. The centroid of each calibration peak was then determined and a least-squares fit made to a quadratic calibration curve. The centroids of unknown peaks were similarly determined and the corresponding energies calculated from the calibration curve. The energies of weak Nd^{141} γ rays, which would be obscured by the calibration standards, were determined by using the now-well-determined stronger γ rays as internal standards. A γ-ray spectrum taken with the 7-cm^3 detector is shown in Fig. 1.

A list of γ-ray energies and relative intensities is given in Table II. The energies assigned are mean values taken from a number of different measurements recorded at different times, different system gains, and with each of the two Ge(Li) detectors. The corresponding uncertainties in energies are based on the reproducibilities both of the standard energies and the Nd^{141} energies from the calibration curves, the sizes of the Nd^{141} photopeaks above the background, and the quoted errors of the standard energies listed in Table I.

The relative peak areas obtained are also averages from a number of runs, and the associated statistical uncertainties include estimated uncertainties in the backgrounds. Relative photopeak efficiency curves for the Ge(Li) detectors were obtained in two ways: First, a set of standard γ-ray sources whose relative intensities had been measured with NaI(Tl) detectors was used. Second, a set of points was obtained from sources emitting several γ rays whose relative intensities were known from well-established decay schemes. The efficiency curves resulting from the separate methods were in very good agreement.

The *K* x-ray intensity was obtained by comparing the low-energy portion of the spectrum directly with the γ-ray spectrum of Ce^{141}; the comparison was made using the 3-cm^3 detector. Ce^{141} also decays to Pr^{141}, with 70% of its decay populating the 145.4-keV state. Its ratio of *K* x rays to 145.4-keV γ's has been measured to be[15] 0.341 ± 0.010, and, using this value, we found the corresponding ratio for Nd^{141} decay to be 264 ± 71.

B. Coincidence Spectra

From the Nd^{141} disintegration energy[5,11] of 1800 keV and the measured γ-ray energies listed in Table II,

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[14] G. R. Choppin, B. G. Harvey, and S. G. Thompson, J. Inorg. Nucl. Chem. **2**, 66 (1956).

[15] L. Nemet, Izv. Akad. Nauk SSSR, Ser. Fiz. **25**, 681 (1961).

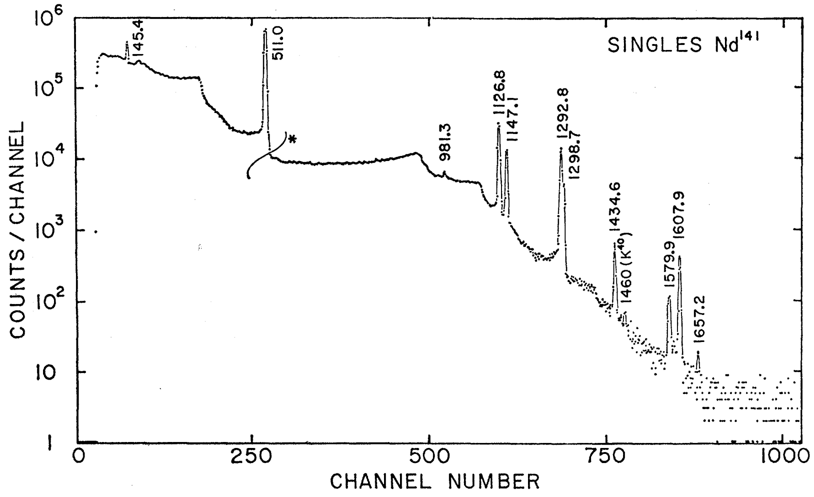

FIG. 1. Singles γ-ray spectrum from the decay of Nd^{141} taken with a 7-cm^3 Ge(Li) detector. Because of analyzer spillover, the portion of the spectrum to the left of the asterisk was recorded for a shorter period of time and then normalized to the remainder of the spectrum.

it is evident that only coincidences involving the 145.4-keV γ ray are energetically allowed. Thus, we gated a 3×3-in. NaI(Tl) detector on the 145.4-keV photopeak and displayed the resultant coincidence spectrum seen by the 7-cm^3 Ge(Li) detector; the resolving time of the system was ≈50 nsec. Figure 2 shows this coincidence spectrum. The relative intensities from this experiment are also included in Table II; these have been corrected for chance coincidences. Comparison of the relative intensities of the 145.4-keV γ-γ coincidence spectrum with those of the singles spectra clearly indicate that the 981.3-, 1147.1-, and 1434.6-keV γ's are in coincidence with the 145.4-keV γ, whereas the 1126.8-, 1292.8-, and 1298.7-keV γ's are not.

In order to search for additional weak γ rays that might have passed unobserved in the other measurements, an experiment was also performed in which the NaI(Tl) gate was set to accept all transitions greater than 130 keV in energy. This "integral" γ-γ coincidence spectrum is shown in Fig. 3, and the relative intensities from it are listed in Table II. They verify the results of the 145.4-keV γ-γ coincidence experiment, but no new, weak γ rays are indicated.

To complement these experiments and confirm which γ rays appeared in cascades and which came from directly-fed ground-state transitions, we then employed an 8×8-in. NaI(Tl) split annulus detector[16] in an anticoincidence experiment with the 7-cm^3 Ge(Li) detector. The single-channel analyzer on the annulus gate was set so that the gate would be active for all γ rays above 80 keV. The Nd^{141} sources were placed inside the annulus tunnel and on top of the Ge(Li) detector. An additional 3×3-in. NaI(Tl) anticoincidence detector was placed in the tunnel above the sources and the

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

Measured γ-ray energy (keV)		Relative intensity		
	Singles spectra[a]	145.4-keV γ-γ coincidence spectrum[b]	Integral γ-γ coincidence spectrum[b]	Anticoincidence spectrum
K x rays	(8.0 ± 2.0)×10^3	...	...	...
145.4±0.3	30.3 ± 3.0	46± 5(16±6)	81± 10(51±11)	11.1 ±1.1
511.006 (annih.)	832 ±83[c]	955±300	1340±150	60 ±6
981.3±0.6	3.0 ± 0.3	147± 30(144±30)	90± 25(87±25)	1.1 ±0.3
1126.8±0.4	≡100	≡100(0)	≡100(0)	≡100
1147.1±0.4	38.2 ± 3.8	1810±200(1770±200)	720± 70(680±70)	14.3 ±1.4
1292.8±0.6	61.2 ± 6.1 }	67± 12(0)	87± 12(0)	{ 58.7 ±5.9
1298.7±0.7	16.3 ± 2.0 }			{ 15.5 ±2.0
1434.6±0.5	3.0 ± 0.3	107± 40(104±40)	27± 9(24±9)	1.6 ±0.2
1579.9±1.0	0.74± 0.12	...	...	0.83±0.15[d]
1607.9±0.6	2.3 ± 0.2	...	...	2.2 ±0.2
1657.2±1.0	0.12± 0.04	...	...	0.15±0.05

[a] J. S. Geiger *et al.* (Ref. 20) report $\alpha = 0.46$ for the 145.4-keV transition; this indicates a total transition intensity of 44.2±4.4 on the above scale. Although all the intensities in the table are photon intensities, the conversion coefficients for the higher-energy transitions should be small enough such that the photon and transition intensities should be nearly the same.

[b] The intensities given in parentheses are those corrected for chance coincidences.

[c] Two 0.32-cm Cu absorbers forming a sandwich around the Nd^{141} source were used for the determination of the intensity of 511-keV photons in total annihilation.

[d] After subtraction of the 1575-keV Pr^{142} contaminant peak produced by a $Pr^{141}(n,\gamma)Pr^{142}$ reaction, where the neutrons were produced predominantly in the degrading foils.

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[16] R. L. Auble, D. B. Beery, G. Berzins, L. M. Beyer, R. C. Etherton, W. H. Kelly, and Wm. C. McHarris, Nucl. Instr. Methods 51, 61 (1967).

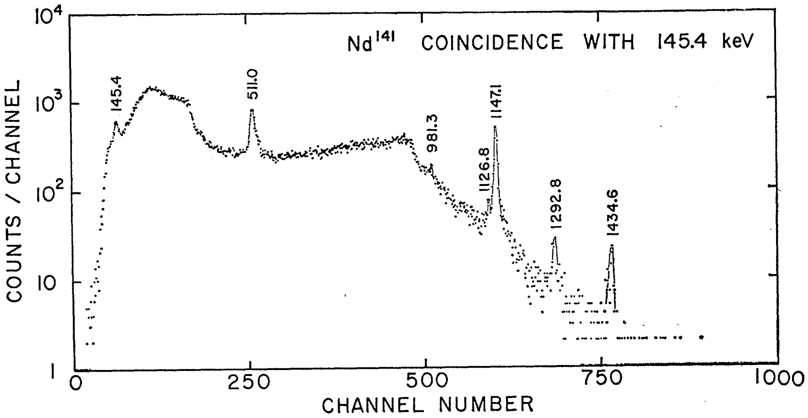

Fig. 2. Spectrum of γ rays in coincidence with the 145.4-keV γ. The gate detector was a 3×3-in. NaI(Tl) scintillator, while the signal detector was the 7-cm^3 Ge(Li) crystal.

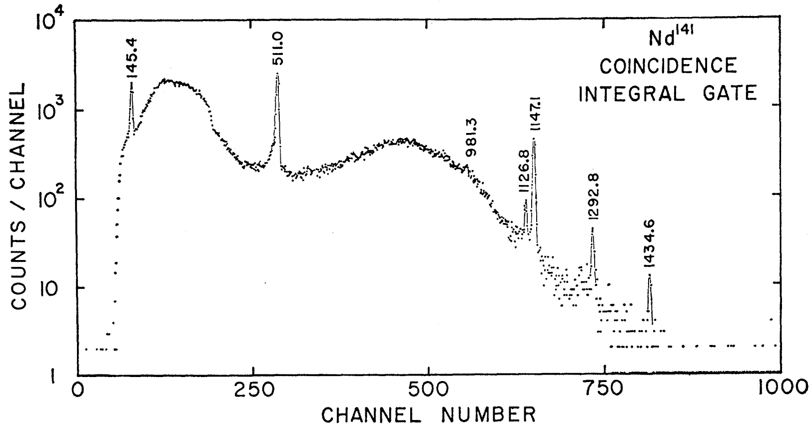

Fig. 3. Integral γ-ray coincidence spectrum. This spectrum was recorded by the 7-cm^3 Ge(Li) detector in coincidence with a 3×3-in. NaI(Tl) scintillator that was set to accept all γ rays above 120 keV.

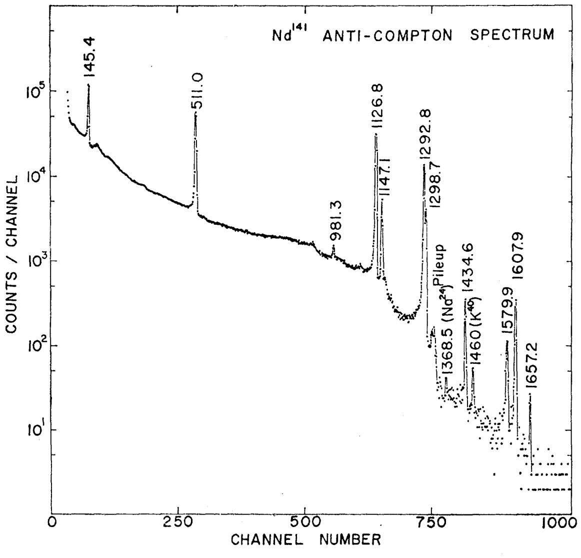

Fig. 4. Anticoincidence spectrum recorded by the 7-cm^3 Ge(Li) detector when placed inside the tunnel of an 8×8-in. NaI(Tl) split annulus with a 3×3-in. NaI(Tl) detector at the other end of the tunnel. For details, see the text or Ref. 16.

Ge(Li) detector to reduce further the sharp Compton edges formed by backscattering in the Ge(Li) detector. The resulting anticoincidence spectrum is shown in Fig. 4. The intensities of all ten of the Nd^{141} γ rays, which were seen in this spectrum, are included in Table II. Only four of these γ rays, the same four indicated by the other coincidence experiments, appear to be in coincidence with another γ ray because of the large reductions in their intensities as compared with the intensities from the singles spectra.

IV. Nd^{141m} γ-RAY SPECTRA

We measured the energy of the 60-sec Nd^{141m} isomeric transition to the ground state to be 756.5±0.3, in excellent agreement with the recent work of Geiger and Graham,[17] who obtained 756.8±1.3 keV. We have also conducted a search for γ rays resulting from direct electron-capture transitions from Nd^{141m} to states of Pr^{141} and/or from alternate transitions depopulating Nd^{141m} to Nd^{141g}. Approximately 1 min after a 10-sec bombardment of Pr_2O_3 with the 9-MeV protons, a

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[17] J. S. Geiger and R. L. Graham, Can. J. Phys. 45, 2281 (1967).

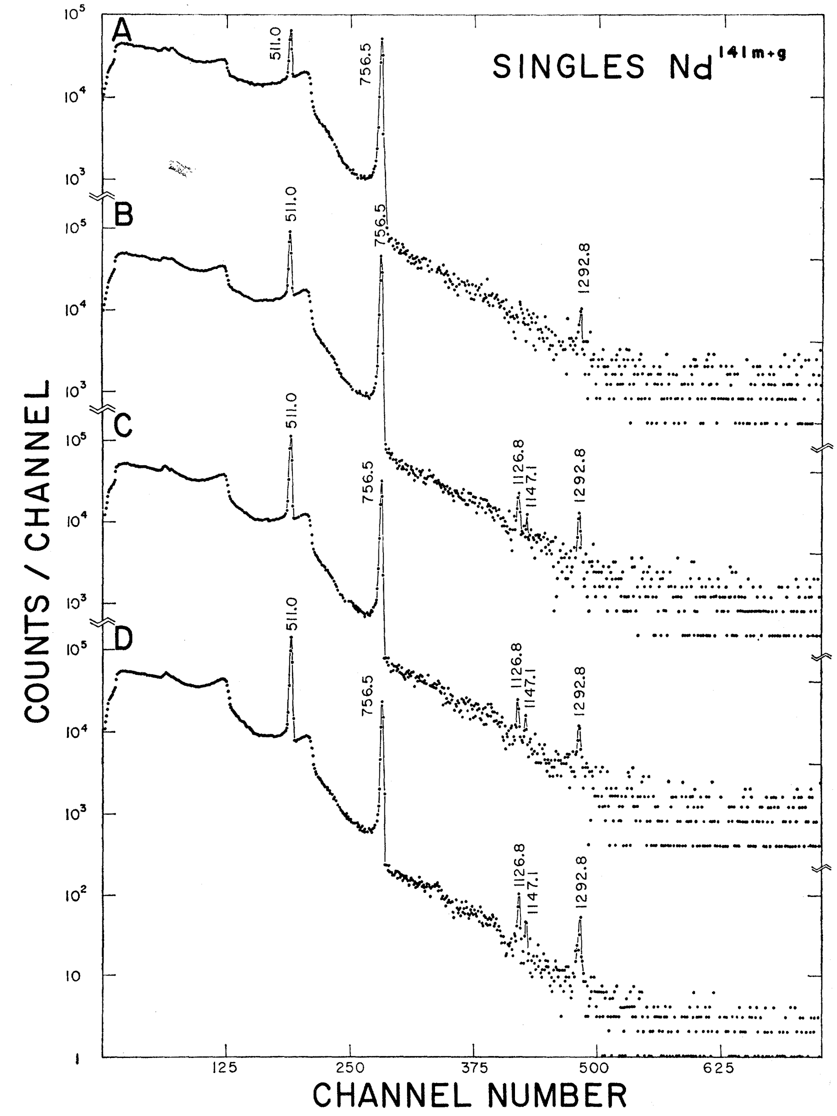

FIG. 5. Singles γ-ray spectra of $Nd^{141m}+Nd^{141g}$. A: The spectrum from the sum of 60 runs, each started ≈1 min after a 10-sec activation and lasting 59 sec. B: Same, except started 60 sec later. C: 120 sec later. D: 180 sec later.

59-sec count of the $Nd^{141m}(+Nd^{141g})$ spectrum was stored in the first quadrant of an analyzer having 4096 channels of memory. The $Nd^{141m}(+Nd^{141g})$ source was gradually moved toward the Ge(Li) detector during this time in order to maintain the analyzer dead time at approximately a constant 12%; this procedure allowed us to collect data more rapidly than with a fixed source position. Following intervals of ≈1 sec for switching analyzer quadrants, 59-sec counts were stored successively in the three remaining quadrants. The entire process was performed 60 times to reduce statistical errors and to search carefully for weak γ rays.

The resulting four spectra, each representing 59 min of counting time, are shown in Fig. 5. The 756.5-keV γ is clearly the only observable γ ray that decays with a 60-sec half-life. The other γ rays in Fig. 5 are the three most intense Nd^{141g} decay transitions. These spectra allow us to place an upper limit of 0.1% of the 756.5-keV γ intensity on any γ ray with an energy between 130 and 2600 keV following direct electron-capture transitions from $\frac{11}{2}-Nd^{141m}$ to high-spin states in Pr^{141}; the same limit applies to alternate transitions to lower-lying states in Nd^{141}.

V. DECAY SCHEME AND DISCUSSION

The decay scheme that we were able to deduce from the foregoing measurements is shown in Fig. 6. Transition energies and excited-state energies are given in keV, the β^+ energy coming from the work of Biryukov and Shimanskaya.[5] The β^+/ϵ ratio for decay to the Pr^{141} ground state (also the limits placed for decay to the 145.4-keV state) is a calculated value, using the method of Zweifel.[18] The other transition intensities, both for

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[18] P. F. Zweifel, Phys. Rev. **107**, 329 (1957).

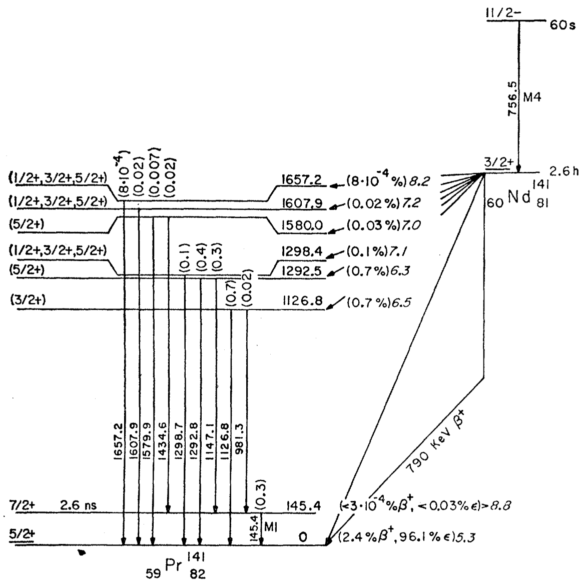

FIG. 6. Decay scheme of Nd^{141g+m}. Excited-state and γ-ray energies are given in keV. The intensities of all transitions are total transition intensities and are given in percent of the total Nd^{141g} disintegrations. Log*ft* values are based on a 2.6-h half-life. The spin and parity assignments to the upper six states in Pr^{141} are tentative; see text.

electron capture and for the (total) electromagnetic transitions, are adjusted to this value and read in percent of the total Nd^{141} disintegrations. Using our own measured value of 9.6 for the ratio of *K* x rays to 511-keV γ's, which is in good agreement with that measured by Biryukov and Shimanskaya,[5] and making reasonable assumptions about the *K* fluorescence yield and the ratio of *K* capture to capture from higher shells (see, e.g., Ref. 19), we arrived at values of 4.3%β^+ and 94.3%ϵ. However, since this is quite clearly an allowed transition, we feel there is at least as much uncertainty in our number as in the theoretical value; we have chosen the theoretical value since any needed future adjustments could be made more easily with respect to it. The log*ft* values were calculated on the basis of a 2.6-h half-life[5] for Nd^{141}.

The 981.3-, 1298.7-, 1434.6-, 1579.9-, 1607.9-, and 1657.2-keV γ's have not been previously reported in decay schemes. The energy of the 145.4-keV state in Pr^{141} has been well calibrated from Ce^{141} decay,[20] the photon energy being given as 145.43 keV. Our evidence for the 1126.8- and 1292.5-keV states, as well as the new state at 1580.0 keV, is based both on the coincidence results with the 145.4-keV γ and the enhancement of the 1126.8-, 1292.8-, and 1579.9-keV γ's in the anticoincidence experiment, indicating that they are ground-state transitions. The energies of these states were chosen on the basis of the best-defined γ rays depopulating them, although it can be seen that the cascade energy sum gives excellent agreement with the crossover energy in each case. The placement of states at 1298.4, 1607.9, and 1657.2 keV is based on the enhancement of the respective γ rays in the anticoincidence experiment and the fact that these γ rays were suppressed in both coincidence experiments. We saw no evidence for the state at 880 keV reported by Cybulska and Marquez.[4]

The ground-state spins of both Nd^{141} and Pr^{141} have been measured by atomic-beam methods, that of the former[21] being $\frac{3}{2}$ and the latter[22] $\frac{5}{2}$. In shell-model terms, Nd^{141} is predicted to be a $(d_{3/2})^{-1}$ neutron state, while the ground state of Pr^{141} should be a $d_{5/2}$ proton state outside a closed $g_{7/2}$ proton subshell. Thus, 98.5% of the Nd^{141} disintegrations consist of its $\frac{3}{2}+$ ground state populating the Pr^{141} $\frac{5}{2}+$ ground state directly, and the log*ft* value of 5.3 is about what one would expect for an allowed transition between such similar states.

Now, the 145.4-keV transition in Pr^{141} has been well characterized[20] from Ce^{141} decay as an *l*-forbidden *M*1 with an *E*2 admixture of 0.4±0.3%, having a mean life of 2.63±0.10 nsec. The state itself is presumed to have a $(g_{7/2})^{-1}(d_{5/2})^2$ configuration. This configuration forms the ground state of Pr^{143}, the $\frac{5}{2}+$ state in this nucleus[23,24] being at 57 keV, so the $\frac{5}{2}+$ and $\frac{7}{2}+$ states cross over between Pr^{143} and Pr^{141}. One would not expect the $\frac{7}{2}+$ 145.4-keV state in Pr^{141} to receive observable direct population from Nd^{141}, again in accord with our measurements.

Considering that Pr^{141} is a single-closed-shell nucleus, one encounters unexpected difficulties in characterizing its higher-lying states. Basically, the problem is as follows: Pr^{141} can be considered to be a single proton outside a Ce^{140} even-even core, so one is tempted to use the core-coupling model in describing the Pr^{141} higher-lying states. Ce^{140}, with a closed neutron shell and a closed $g_{7/2}$ proton subshell, is expected to be rather rigid and not subject to low-lying vibrations. This appears to be true, for its first excited state is a 2+ state at 1.596 MeV that decays via a nonenhanced *E*2 transition.[25] Currie,[26] in trying to account for the retardation of the *E*2 transition from a 4+ level at 2.083 MeV to this level, invoked a quasiparticle representation for both states, but his best numerical results implied a $[(g_{7/2})(d_{5/2})]_2$ configuration instead of the anticipated (and probably more likely) $[(g_{7/2})^2]_2$ or perhaps $[(d_{5/2})^2]_2$. This means that, although the Ce^{140} 2+ state

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[19] A. H. Wapstra, G. J. Nijgh, and R. van Lieshout, *Nuclear Spectroscopy Tables* (North-Holland Publishing Co., Amsterdam, 1959).

[20] J. S. Geiger, R. L. Graham, I. Bergström, and F. Brown, Nucl. Phys. **68**, 352 (1965).

[21] S. S. Alpert, B. Budick, E. Lipworth, and R. Marrus, Bull Am. Phys. Soc. **7**, 239 (1962).

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

[24] D. W. Martin, M. K. Brice, J. M. Cook, and S. B. Burson, Phys. Rev. **101**, 182 (1955).

[25] S. Ofer and A. Schwarzschild, Phys. Rev. **116**, 725 (1959).

[26] W. M. Currie, Nucl. Phys. **48**, 561 (1963).

definitely appears to be a two-quasiparticle state, its exact structure is not clear.

On the other hand, the first excited state of Ce^{142}, having only two additional neutrons, lies at 0.65 MeV and appears to be a $2+$ quadrupole vibrational state.[27] The first few Pr^{143} excited states, which lie much lower than those in Pr^{141}, can probably be explained by a coupling of the $\frac{7}{2}+$ ground state and the $\frac{5}{2}+$ 57-keV state to this Ce^{142} $2+$ collective state.[23,28]

The known Pr^{141} states lie at an intermediate energy, so one cannot *a priori* decide whether they are three-quasiparticle states, one-quasiparticle states coupled to a vibrational core, or perhaps a mixture of the two. Granted that the two neutrons of Ce^{142} are probably more effective in softening the Ce^{140} core than is the single proton (outside only a subshell) of Pr^{141}, one still has to be quite cautious, especially with $E2$ transition probabilities which may or may not be enhanced over the single-particle estimates. In the following, keeping in mind the different kinds of states possible, we make tentative predictions for the spins and parities of the six upper states on the basis of β- and γ-decay systematics. It must be borne in mind, however, that these are only tentative, and for quite definite assignments one needs more information about the levels. High-resolution scattering reactions of various kinds that populate these states would be particularly valuable.

The log*ft* values are all more or less in the range expected for allowed transitions. One cannot exclude first-forbidden decay, especially to the highest-lying states, on the basis of the log*ft* values, but then the only negative-parity states would be those resulting from the $h_{11/2}$ shell-model state or from octupole vibrations. The $d_{3/2}$ ground state of Nd^{141} should not populate the former, although the $h_{11/2}Nd^{141m}$ might. The latter have not been reported near this excitation in any of the neighboring even-even nuclei. Thus, one can reasonably say that all six states are probably $\frac{1}{2}+$, $\frac{3}{2}+$, or $\frac{5}{2}+$. This set is consistent with either interpretation of the states—by coupling the $\frac{5}{2}+$ or $\frac{7}{2}+$ single-quasiparticle states to a $2+$ vibrational core, one can get $\frac{1}{2}+$ through $\frac{11}{2}+$, with two sets of $\frac{3}{2}+$ through $\frac{9}{2}+$ states, and on the basis of three quasiparticles, the range is even broader.

Assignments for the three states that exhibit γ-ray branching can be narrowed down from the above limits. The intensity ratio of the 1126.8-keV γ to the 981.3-keV γ from the 1126.8-keV state is 35. The mere existence of the 981.3-keV γ rules out a $\frac{1}{2}+$ assignment, for such would force the 981.3-keV transition to be $M3$. For a $\frac{5}{2}+$ assignment, the single-particle estimate[19] yields a ratio (both $M1$'s) of less than 2, while for a $\frac{3}{2}+$ it predicts a ratio ($M1/E2$) of about 200. Even a slight $E2$ enhancement or $M1$ retardation would thus favor a $\frac{3}{2}+$ assignment.

For the 1292.5- and 1580.0-keV states, which have ground-state–to–cascade ratios of 1.33 and 0.35, respectively, we can similarly eliminate the $\frac{1}{2}+$ assignment. And, unless there is some quite gross $M1$ retardation or $E2$ enhancement, we can also eliminate the $\frac{3}{2}+$, so we favor a $\frac{5}{2}+$ assignment.

The 756.5-keV excited state of Nd^{141} has been shown to have a half-life of 60.3±1.0 sec.[17] It is one of the series of $h_{11/2}$ isomers found just below the $N=82$ shell. Since the $\frac{11}{2}-$ (presumably single-quasiparticle $h_{11/2}$) state lies[29] at 822 keV in Pr^{139}, it is quite conceivable that the same state lies in the 1-MeV vicinity in Pr^{141} and there could be some direct population of it from Nd^{141m}. From the data displayed in Fig. 5, however, it can be deduced that such population must be less than 0.1% of the intensity of the 756.5-keV isomeric γ ray. Depending on the exact location of the $h_{11/2}$ state in Pr^{141}, this upper limit means merely that the log*ft* for electron capture has to be greater than approximately 6.0. We can place the same upper limit on any branching γ decay to lower states in Nd^{141} itself, provided that at least one γ ray having an energy greater than 130 keV is involved.

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