Unfavored allowed beta decay of the $11/2^-$ isomer of ^{141}Nd

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The β decay of the $\frac{11}{2}{}_1^-$ isomer of ^{141}Nd to the odd parity states in ^{141}Pr has been investigated by measurement of the γ rays of ^{141}Pr in the radioactive decay of ^{141}Nd^m and the reaction ^{139}La(α,$2n\gamma$)^{141}Pr. The half-life of the $\frac{11}{2}{}_1^-$ isomer of ^{141}Nd is determined to be 60.9±1.0 s. An upper limit of 0.010% for the β feeding to the 1117.6 keV ($\frac{11}{2}^-$) state of ^{141}Pr is deduced, in disagreement with earlier reports. No detectable β feeding to the 2000.8 keV ($\frac{9}{2}^-$) and 2382.8 keV ($\frac{11}{2}^-$) states of ^{141}Pr is observed, and upper limits of 0.020% and 0.012%, respectively, are determined. The ratio of occupancies of protons in the $1h_{11/2}$ and $2d_{5/2}$ proton orbitals in ^{141}Nd deduced from the β-decay data is compared with that from the spectroscopic factors for pickup and stripping reactions, and the results are discussed.

Study of β decay from the $\frac{11}{2}^-$ isomers of the odd mass $N=81$ nuclei, namely, ^{145}Gd, ^{143}Sm, and ^{141}Nd, to the low-lying $\frac{11}{2}^-$ single-proton states in the neighboring $N=82$ nuclei is of great interest because it yields information regarding the proton occupation probability in the $h_{11/2}$ proton orbitals in the parent nuclei. The $\frac{11}{2}^-$ isomers in the $N=81$ nuclei[1] are known to decay predominantly by $M4$ γ-ray transitions to the $\frac{3}{2}^+$ states in the respective nuclei. Weak β branchings from these isomers have been reported to the first $\frac{11}{2}^-$ states in the neighboring $N=82$ nuclei, viz., ^{145}Eu, ^{143}Pm, and ^{141}Pr,[1] from measurements of the γ rays of the daughter nuclei. In recent years, considerable new information has become available regarding the levels and γ-ray transitions in ^{141}Pr, especially about the high-spin states in this nucleus,[2] necessitating a reinvestigation of the β decay of the $\frac{11}{2}^-$ isomer of ^{141}Nd. The Q value for the electron capture decay of the ground state of ^{141}Nd being 1814 keV (Ref. 2), the electron capture from the 756 keV $\frac{11}{2}^-$ isomer of ^{141}Nd is energetically possible to the levels in ^{141}Pr with excitation energy below 2570 keV. A weak 971 keV γ ray has been reported by Abulaffio *et al.*[3] in the decay of $\frac{11}{2}^-$ isomer of ^{141}Nd and assigned as a transition between a 1116 keV ($\frac{11}{2}^-$) and the 145.4 keV ($\frac{7}{2}^+$) states of ^{141}Pr on the basis of the level energy difference. The authors[3] did not observe the weaker $\frac{11}{2}^- \rightarrow \frac{5}{2}^+$ crossover transition and hence deduced the intensity of β feeding to the $\frac{11}{2}^-$ state of ^{141}Pr, neglecting the branching for crossover transition. In recent experimental studies on the structure of ^{141}Pr, however, the excitation energy of the first $\frac{11}{2}^-$ state in this nucleus has been reported to be 1117.5 (Ref. 4), 1117.7 (Refs. 5 and 6), and 1120 (Refs. 7 and 8) keV. Besides, many negative-parity states in ^{141}Pr, including levels with $J^\pi=\frac{9}{2}^-$ and $\frac{11}{2}^-$ at 2000.8 and 2382.8 keV, respectively, have been reported.[2] In the present work, the decay of the 61 s isomer of ^{141}Nd has been studied to reinvestigate the β deay to the first $\frac{11}{2}^-$ state and to determine β feeding, if any, to the higher-lying odd-parity states in ^{141}Pr, by looking for the weak γ transitions of ^{141}Pr using a high efficiency Ge(Li) detector with massive shielding for reduction of background. In view of the wide variation in the reported values of the excitation energy of the first $\frac{11}{2}^-$ state of ^{141}Pr with respect to the value used in Ref. 3, and a consequent ambiguity regarding the energies of the depopulating γ transitions, an auxiliary experiment has been carried out to ascertain these energies by in-beam γ-ray measurements in the reaction ^{139}La(α,$2n\gamma$)^{141}Pr.

The 61 s activitiy of ^{141}Nd was produced by the reaction ^{142}Nd(n,$2n$)^{141}Nd at $E_n=14$ MeV, using 2 g natural neodymium oxide targets of spectroscopic grade purity. The in-beam γ-ray measurements on ^{141}Pr were carried out in the reaction ^{139}La(α,$2n\gamma$)^{141}Pr at $E_\alpha=30$ MeV at the Variable Energy Cyclotron Centre (VECC), Calcutta. The target thickness used in the in-beam experiments was about 10 mg/cm^2 and α-particle beam current typically in the range 1–3 nA.

The measurements on the γ rays following the radioactive decay of the 61 s ^{141}Nd were carried out with a 111 cm^3 Ge(Li) detector of 25% efficiency, surrounded by a massive lead shield which reduced the total background by about 98%. The in-beam γ-ray measurements in the α-particle-induced reaction were carried out using two n-type HpGe gamma-X detectors of 25% and 19% efficiency, placed at 90° and 125° to the beam direction, respectively. The data were acquired on a Nuclear Data Series 620 analyzer coupled to a Pertec magnetic tape unit.

Typical energy resolution of the detectors used in the experiments was 1.8–2.0 keV at 1332 keV. Standard sources of ^{152}Eu, ^{133}Ba, ^{60}Co, and ^{57}Co were used for relative efficiency and energy calibration of the detectors. In the radioactivity measurements, the well-established γ rays arising in the decay of the 2.49 h ^{141}Nd^g and 1.72 h ^{149}Nd served as internal reference.

For the study of the 61 s ^{141}Nd^m decay, about 200 cycles of irradiations and data acquisition were carried out to improve the counting statistics. Each cycle consisted of a 60 s irradiation of a 2 g target, followed by a cooling time of 20 s and data acquisition in four consecutive time intervals of 60, 60, 120, and 120 s. The 20 s cooling time was sufficient to considerably reduce the unwanted Compton continuum background due to the high-energy γ rays (6.1 and 7.1 MeV) arising from the decay of the 7 s ^{16}N produced by the (n,p) reaction on ^{16}O. Three targets of neodymium oxide, each weighing 2 g, were used successively by rotation to reduce the buildup of unwanted long-lived activities. Also, after every 20 cycles of runs, there was a cooling period of 12 h during which the irradiation-data acquisition cycles were discontinued to allow the long-lived activities, especially the 2.49 h ground state of ^{141}Nd, to decay. The relevant parts of the four consecutive γ-ray spectra observed in the 61 s ^{141}Nd decay are shown in Figs. 1(a)–(d). The insets in Figs. 1(a)–(c) show expanded regions around 972 keV. The spectra of these three insets are added to improve the statistical accuracy of measurements on the weak γ rays in this region and the resulting spectrum is shown as an inset in Fig. 1(d). Figure 1(e) shows a part of the γ-ray spectrum observed in the reaction ^{139}La$(\alpha,2n\gamma)^{141}$Pr at $\theta_\gamma = 90°$. Prominent γ rays belonging to ^{141}Pr are labeled in Fig. 1(e). Figure 2 shows the relevant parts of the decay scheme of ^{141}Nd^{m,g} and the levels of ^{141}Pr.

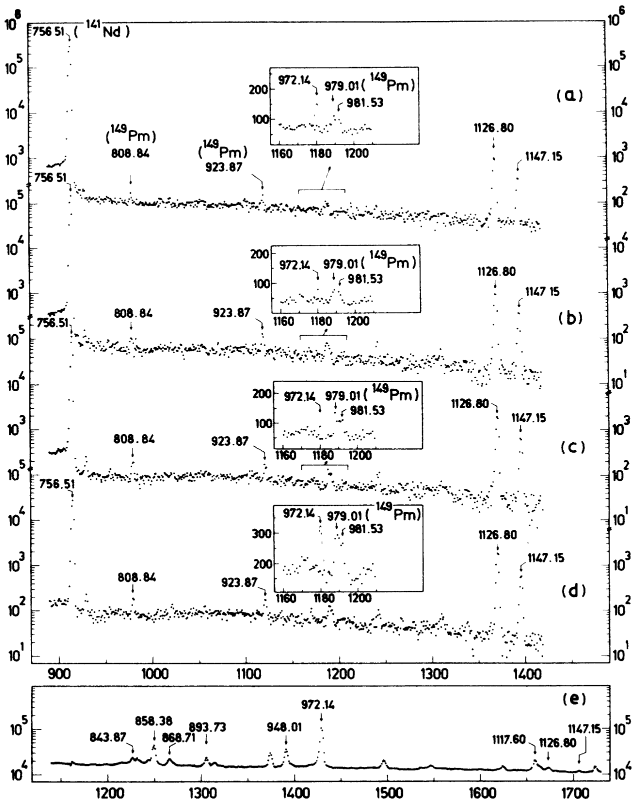

FIG. 1. Gamma-ray spectra of irradiated natural neodymium target acquired in four consecutive time intervals (a) 60 s, (b) 60 s, (c) 120 s, and (d) 120 s. The insets in the spectra (a), (b), and (c) show expanded regions of these spectra around 972 keV. The added spectrum of these insets, corresponding to the acquisition interval of 240 s is shown as an inset in (d). The peaks shown with broken lines in the insets indicate the expected position and intensity of the 972.14 keV γ ray for 0.032% β feeding to the 1117.60 keV state of ^{141}Pr. Spectrum (e) shows some of the prominent γ rays of ^{141}Pr observed in the reaction ^{139}La$(\alpha,2n\gamma)^{141}$Pr at $\theta_\gamma = 90°$.

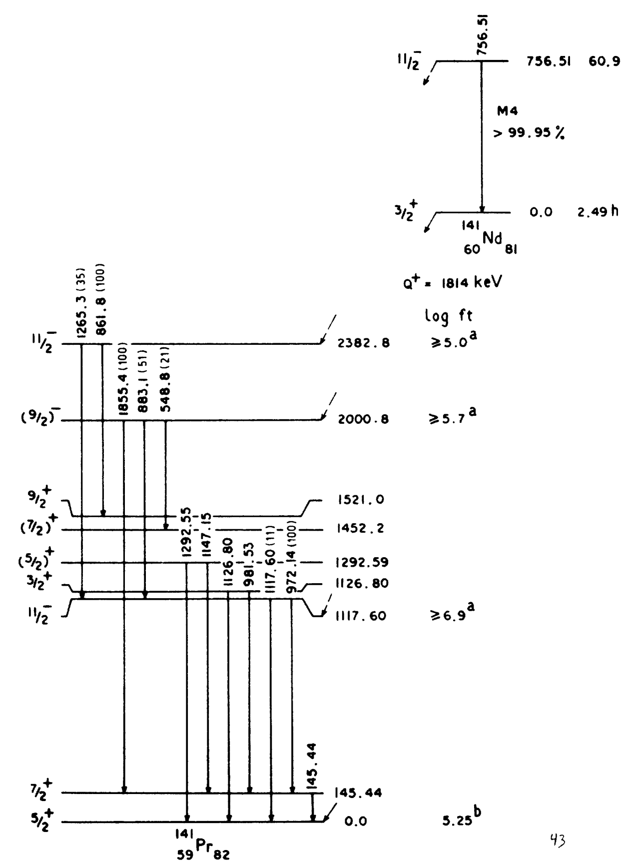

FIG. 2. Partial level schemes of ^{141}Pr and ^{141}Nd. The gamma-ray transitions and branching ratios from the 1117.60 keV state of ^{141}Pr are from the present work and those from the 2000.8 and 2382.8 keV states from Ref. 6. The logft values marked with superscripts a and b refer to the β decays from the metastable and ground states of ^{141}Nd, respectively.

The first $\frac{11}{2}^-$ state of ^{141}Pr is strongly populated in the $(\alpha,2n\gamma)$ reaction and the energies of the two γ-ray transitions depopulating this state are measured to be 972.14 ± 0.10 and 1117.60 ± 0.10 keV, with intensity ratio

$$I_\gamma(972\ \text{keV}/I_\gamma(1117\ \text{keV}) = (100\pm5)/(11\pm1)\ .$$

These results are in good agreement with the reported values in Ref. 5. The measured energy 145.44 ± 0.05 keV for the well-established $\frac{7}{2}^+ \rightarrow \frac{5}{2}^+$ transition in ^{141}Pr, both from the 2.49 h ^{141}Nd^g decay and the in-beam measurements in this work, agrees with its earlier adopted value.[2] The 2000.8 and 2382.8 keV states of ^{141}Pr are not well populated in the $(\alpha,2n\gamma)$ reaction. The energies and branching ratios for the γ rays depopulating these levels shown in Fig. 2 are taken from Ref. 6.

The spectra of Figs. 1(a)–(d) show the prominent 756.51 ± 0.05 keV γ ray, due to the $\frac{11}{2}^- \rightarrow \frac{3}{2}^+$ $M4$ transition in ^{141}Nd, decaying with 60.9 ± 1.0 s half-life. The expected position of the 972.14 keV γ ray of ^{141}Pr in the spectra shown, is marked in the insets. No evidence is obtained for the presence of this γ ray and its intensity is estimated to lie within the limits of experimental error. The curves with broken lines in the insets of Figs. 1(a)–(d) show the peak shape and intensity expected for the 972.14 keV γ ray, considering a 0.032% β branch from the 61 s isomer of ^{141}Nd to the first $\frac{11}{2}^-$ state of ^{141}Pr as reported in Ref. 3, taking the measured intensity of 756.51 keV and the intensity ratio for the 972.14 and 1117.60 keV γ rays from the present work, and the total internal conversion coefficients for these γ rays from Ref. 2. It is evident from Fig. 1 that the reported intensity of the $\frac{11}{2}^- \rightarrow \frac{7}{2}^+$ transition and hence the β branch to the first $\frac{11}{2}^-$ level of ^{141}Pr are overestimated in Ref. 3. The present work gives an intensity limit of 0.009 for the 972.14 keV γ ray relative to 100 for the total transition intensity of 756.51 keV isomeric transition. This result, together with the measured branching ratio for the 972.14 and 1117.60 keV transitions in this work, gives the limit of intensity of β branch, if any, to the first $\frac{11}{2}^-$ state of ^{141}Pr,

$$I_\beta(\tfrac{11}{2}{}^-_1, {}^{141}\mathrm{Nd} \rightarrow \tfrac{11}{2}{}^-_1, {}^{141}\mathrm{Pr}) < 0.010\% \ .$$

A search for γ rays depopulating the 2382.8 keV ($\frac{11}{2}^-$) and 2000.8 keV ($\frac{9}{2}^-$) states of ^{141}Pr similarly, gave no indication of any β feeding to these states and yielded the limits of β intensities to be $<0.012\%$ and $<0.020\%$, respectively.

The upper limit of β intensity to the $(\frac{11}{2}^-)_1$ state of ^{141}Pr obtained in the present work is about three times less than its value reported in Ref. 3. The lower limits of log*ft* values for this and other β transitions investigated in the present work are given in Table I, along with the previous result. Large log*ft* values indicate the "unfavored" nature of these β transitions.

The odd-parity states in ^{141}Pr have been described by configurations involving proton excitation to the $h_{11/2}$ orbital. In particular, the lowest $\frac{11}{2}^-$ state has been shown to be almost a pure shell-model state with one proton in the $h_{11/2}$ orbital coupled to the 0^+ ground state of the corresponding $A=140$ even-even core. Large log*ft* values for the β transitions to these states in ^{141}Pr imply low occupation probabilities of proton pairs in the $h_{11/2}$ proton orbital in ^{141}Nd. The limit of log*ft* value for the $^{141}\mathrm{Nd}(\frac{11}{2}^-)_1 \rightarrow {}^{141}\mathrm{Pr}(\frac{11}{2}^-)_1$ β transition obtained in the present work, together with the known[2] $\log ft = 5.25$ for the $^{141}\mathrm{Nd}(\frac{3}{2}^+)_{\mathrm{g.s.}} \rightarrow {}^{141}\mathrm{Pr}(\frac{5}{2}^+)_{\mathrm{g.s.}}$ β transition, gives information about the proton part of the wave function of ^{141}Nd. Assuming the low-lying states of ^{141}Nd and ^{141}Pr to be pure isospin states with $T=T_z$, we can consider these β transitions to be pure Gamow-Teller (GT) in nature. We consider a simple model with the wave functions for the ground and isomeric states of ^{141}Nd as follows:

$$\psi^{3/2^+}[{}^{141}\mathrm{Nd}]_g = (d_{3/2})_n^{-1}[a(g_{7/2})_0^6(d_{5/2})_0^2(h_{11/2})_0^2 + b(g_{7/2})_0^6(d_{5/2})_0^4]_p \ , \tag{1}$$

$$\psi^{11/2^-}[{}^{141}\mathrm{Nd}]_m = (h_{11/2})_n^{-1}[a(g_{7/2})_0^6(d_{5/2})_0^2(h_{11/2})_0^2 + b(g_{7/2})_0^6(d_{5/2})_0^4]_p \ . \tag{2}$$

The wave functions given in (1) and (2) above are based on a plausible assumption that the proton part of the wave function is independent of the neutron hole configuration.[3,9] The wave functions for the $(\frac{5}{2}^+)_1$ and $(\frac{11}{2}^-)_1$ states of ^{141}Pr are simply taken as

$$[(g_{7/2})_0^6(d_{5/2})^3]_p$$

and

$$[(g_{7/2})_0^6(d_{5/2})_0^2(h_{11/2})^1]_p \ ,$$

since recent shell-model calculations[5] suggest that the dominant configurations for ^{141}Pr have six protons in the $g_{7/2}$ orbital. The $\frac{3}{2}^+ \rightarrow \frac{5}{2}^+$ GT decay is due to the $d_{5/2} \rightarrow d_{3/2}$ transition and the $\frac{11}{2}^- \rightarrow \frac{11}{2}^-$ decay due to the $h_{11/2} \rightarrow h_{11/2}$ transition. Using the log*ft*'s for these β transitions, and calculating the GT strength in the framework of lowest seniority,[11] we find $a^2/b^2 \leq 0.22$. The ratio of the occupancies of the $1h_{11/2}$ and $2d_{5/2}$ proton orbitals is given by $a^2/(a^2+2b^2)$ and has the value ≤ 0.1. The corresponding value for this ratio for ^{142}Nd as deduced from spectroscopic factors for pickup and stripping reactions is reported to be 0.29 (Ref. 8) and 0.50.[10] Assuming that the addition of a neutron does not drastically change the proton occupancies, one expects this ratio to have comparable values for ^{141}Nd and ^{142}Nd.

An analogous situation is also seen for the decay of the ground state and the isomeric state of ^{143}Sm (with log*ft*'s 4.9 and 6.4, respectively),[12] where a similar calculation gives a lower value for the ratio of the occupancies of

TABLE I. The intensities and log*ft* values for β transitions from the 61 s $\frac{11}{2}^-$ isomer of ^{141}Nd to the odd-parity levels in ^{141}Pr with $\Delta J = 0, \pm 1$.

Final state (^{141}Pr)		I_β (%)		log*ft*	
J^π	E_x (keV)	present	previous	present	previous
$\frac{11}{2}^-$	1117.60	≤ 0.010	0.032 ± 0.008[a]	≥ 6.9	6.6[b], 6.4[c]
$(\frac{9}{2})^-$	2000.8	≤ 0.020		≥ 5.7	
$\frac{11}{2}^-$	2382.8	≤ 0.012		≥ 5.0	

[a]References 2 and 3.
[b]Reference 3.
[c]Reference 2.

$1h_{11/2}$ to $2d_{5/2}$ proton orbitals compared to that observed for the ground state of ^{144}Sm from analysis of pickup and stripping reactions.[10]

We finally observe that the low $1h_{11/2}$ occupancy derived in the present work may be explained by the following: (i) the ground state and the $\frac{11}{2}^-$ state in both ^{141}Nd and ^{141}Pr may not be adequately described by the lowest seniority states, (ii) the states in ^{141}Pr should really be of mixed configuration instead of pure ones as assumed here, and (iii) the proton parts of the wave function for ^{141}Nd are not independent of the neutron-hole configuration. A detailed shell-model study of these wave functions, including excitations of particles to the $1h_{11/2}$ orbital both for the positive- and negative-parity states in this region, is needed to get a definite answer to this anomaly.

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