^{144}Nd levels fed in β decay of ^{144}Pr isomers

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The decay of radiochemically separated ^{144}Ce source in equilibrium with ^{144}Pr isomers has been reinvestigated with HPGe detectors. The energies and intensities of 19 γ rays were measured, of which three are new. A ^{144}Nd level scheme allows the incorporation of most of the transitions between 13 excited states. Levels at 2072.8 (2^+), 2368.3 (2^+), 2581.8 (3^+), and 2742.8 (0^+) keV, observed earlier in nuclear reactions, are found to be fed in these decays. A 2675.3 keV ($J^\pi=0^+$) level seems to be a component of the 2.663 MeV multiplet observed in the (p,t) reaction.

Because of the nearness of the $N=82$ closed shell, the knowledge of the excited levels in $^{144}_{60}Nd_{84}$ is of great interest as regards nuclear models. Excited states of this nucleus have been investigated in past years by single and two particle transfer reactions: (d,p) and (p,t) (Ref. 1) or (t,p) (Ref. 2). More recently, Al-Janaby *et al.*[3] used ^{144}Nd(n,n'γ) inelastic scattering, and Snelling and Hamilton[4] carried out a neutron capture experiment to investigate ^{144}Nd nuclear levels up to 3.8 MeV.

Concerning the radioactive decay of ^{144}Pr, the study of Behar *et al.*,[5] adopted in the Nuclear Data Sheets,[6] leads to a relatively simple ^{144}Nd level scheme with six excited levels. A preliminary study by Pravikoff *et al.*[7] added five more levels to this known decay scheme. A more recent reinvestigation of ^{144}Pr decay by Krane *et al.*,[8] carried out to confirm the $J^\pi=0^+$ character of the 2084.5 keV level, did not mention these additional levels. Because $J^\pi=0^-$ and 3^-, respectively, for ^{144}Pr(g.s.) and ^{144}Pr^m, it seemed to us that other $J^\pi=0^+-4^\pm$ levels in ^{144}Nd found in nuclear reaction studies[1-4] in the range of 2–3 MeV could be fed in the decays of ^{144}Pr isomers. We decided to carefully reinvestigate these decays by means of single γ-ray and γ-γ coincidence measurements in order to verify our preliminary results.

The ^{144}Ce mother source, provided by the Laboratoire de Métrologie des Radiations Ionisantes (LMRI), had a standard activity of 7.40 MBq g^{-1}. This source was weakly contaminated by long-lived fission products such as ^{137}Cs and ^{154}Eu, as well as by ^{60}Co and ^{22}Na. A radiochemical separation was performed as described in Ref. 7; briefly, we extracted Ce^{4+} in a 0.15 F HDEHP [Di- (2-ethylhexyl) phosphoric acid] organic phase (*n*-heptane) from the 11 *M* nitric solution and we back-extracted the Ce^{3+} by means of a reducing (10 *M* HNO_3, 1 *M* H_2O_2) aqueous solution.

The γ-ray spectra were measured with two different size detectors. The first one was a 75-cm^3 HPGe detector (EG&G Ortec) having a relative detection efficiency of 17% and a peak to Compton ratio of 53:1. Its energy resolution (FWHM) measured at 1.33 MeV was 1.75 keV. Low-energy measurements were performed with a planar HPGe detector of 2 cm^3 active volume with an energy resolution (FWHM) of 180 eV for the Fe K_α line. The γ-ray spectra were analyzed using a 4096 channel Norland 5400 analyzer coupled with a 350 Professional (DEC) computer. γ-γ coincidence experiments were realized using the 17% HPGe detector and an 8% Ge(Li) detector viewing the source in a 90° geometry. The resolving time of the conventional fast-slow coincidence unit was $2\tau=50$ ns.

The ^{144}Ce-^{144}Pr equilibrium source was mainly counted with a coaxial HPGe detector inside a 10 cm thick lead castle in order to minimize background contribution. A 2 mm thick lead, 1 mm thick Cu absorber was interposed between source and detector to exclude the intense 133.5 keV γ ray belonging to ^{144}Ce decay. The spectrometer was calibrated in energy and relative efficiency, as has been described elsewhere.[9] Precise energy values of ^{144}Pr main photopeaks were obtained by simultaneous calibration with ^{207}Bi, ^{182}Ta, ^{152}Eu, and ^{137}Cs as standard. We also used internal calibration with precise energy values from ^{144}Ce and ^{144}Pr decays.[10,11] Several counting runs of duration between 30 and 120 h, and energy dispersion ranging from 0.4 to 0.9 keV/channel, were carried out with a pileup rejection system. Figure 1 shows a typical γ-ray spectrum measured with the coaxial HPGe detector. Table I summarizes the energy and intensity values of the γ rays attributed to ^{144}Pr isomer decay, and compares them with earlier studies of Pravikoff *et al.*[7] and Behar *et al.*[5] Good agreement can be noted between these three measurements concerning most of the γ rays. However, a 2842.9 keV γ ray, observed earlier with a larger detector,[7] could not be found in this work. A 1631.36 keV line was misinterpreted earlier[7] as the double escape peak of the 2654.9 keV γ ray. Two additional lines were observed at 1182.0 and 1885.3 keV. γ-γ coincidence experiments were performed with the system described above, using a 696.5±5 keV gate in the Ge(Li) detector. Due to the weakness of γ rays, the γ-γ experiment was counted for about 120 h. Table II gives the list of γ rays coincident with this gate. A ^{144}Nd level scheme was built using the γ data of Table I assuming that the 696.5 keV photon accounts for 1.34% of the ^{144}Pr^{m+g} decays.[12] Excluding the possible β feeding to the 1314.3 keV ($J^\pi=4^+$) level (see the discussion below), it seems possible that four ^{144}Nd levels can be fed by the ^{144}Pr^m isomer ($J^\pi=3^-$), i.e., 696.5 keV (2^+), 1510.6 keV (3^-), 2581.8 keV (3^+), and 2945.6 keV. Since the 696.5 keV level β feeding from ^{144}Pr^m

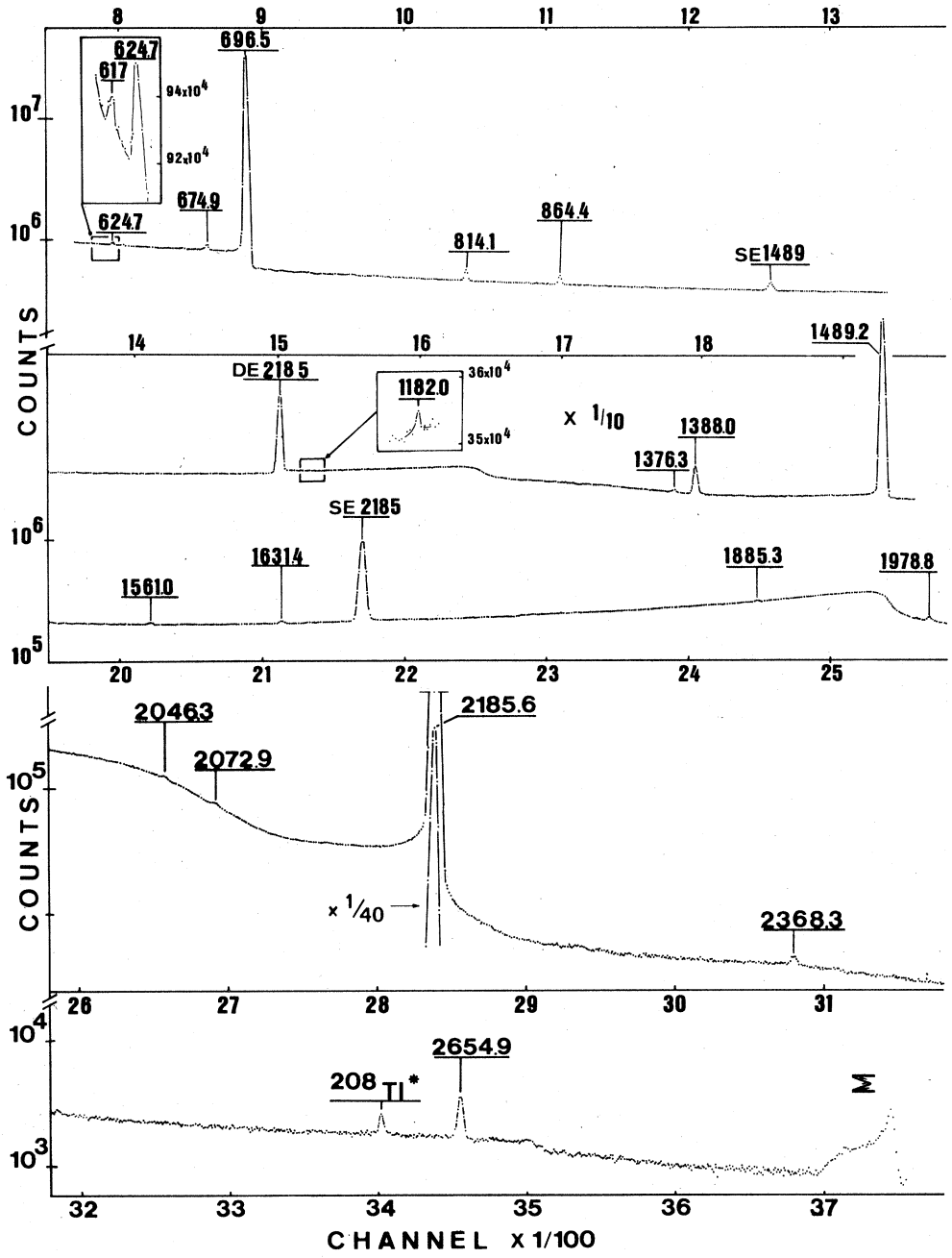

FIG. 1. γ-ray spectrum of $^{144}Pr^{m+g}$ isomers in equilibrium with ^{144}Ce, measured with a 17% HPGe detector. Energies are in keV; the energy dispersion is 0.76 keV/channel. SE and DE stand for single and double escape peaks, respectively. An asterisk denotes a γ ray from the background; $\sum$ indicates summing a peak from 2185.6 and 696.5 keV γ rays.

could not be determined, the intensity balance was calculated only for the last three levels and normalized to 100 β decays of $^{144}Pr^{g}$, giving a total β feeding of 0.000 87%; assuming that $^{144}Pr^{m}$ is fed in 1.51% of the ^{144}Ce β decay,[6] we could deduce the value 0.055% for the β branching ratio of $^{144}Pr^{m}$. Comparative half-lives for β decay were calculated using $T_{1/2}=17.3$ min and 7.2 min, respectively, for ^{144}Pr(g.s.) and $^{144}Pr^{m}$; $E_{\beta_{max}}=2996\pm3$ keV; and the matrix elements f^0 given by Gove and Martin.[13] Because $J^{\pi}=0^-$ for ^{144}Pr(g.s.), $\log f_1 t$ values were calculated for unique first-forbidden transitions to 2^+ states in ^{144}Nd. As it appears from Fig. 2, the 1314.3 keV ($J^{\pi}=4^+$) level was found to be indirectly fed by a γ transition from a tentative 2945.6 keV level; otherwise, we must assume a β feeding from the $^{144}Pr^{m}$ isomer with a high $\log ft$ value (9.1). For the 1560.96 keV ($J^{\pi}=2^+$) level, using the measured 36% $E2$ mixing ratio of the 864.4 keV transition,[8] we can deduce the experimental reduced probability ratio

TABLE I. Energy and intensity of γ rays from $^{144}Pr^{m+g}$ decays. Uncertainties on energy and intensity values (in brackets) are given on last digits.

Present work		Pravikoff *et al.* (Ref. 7)		Behar *et al.* (Ref. 5)	
E_γ (keV)	I_γ	E_γ (keV)	I_γ	E_γ (keV)	I_γ
617.8(2)	0.16(7)	618.2(5)	0.15(7)		
624.7(1)	0.84(2)	624.89(20)	0.92(9)	624.66(20)	0.85(15)
674.95(10)	2.2(2)	675.02(10)	1.95(20)	675.02(20)	2.07(15)
696.50(5)	1000	696.50(2)	1000	696.49(20)	1000
814.10(10)	2.4(2)	814.03(10)	2.31(25)	814.15(15)	2.45(13)
864.45(10)	1.8(2)	864.44(10)	1.97(20)	864.53(15)	1.93(12)
1182.0(3)	0.04				
1376.27(10)	0.29(3)	1376.31(30)	0.29(3)		
1388.02(10)	5.01(4)	1388.20(10)	5.06(20)	1388.00(15)	4.45(16)
1489.17(5)	220(12)	1489.16(5)	218(9)	1489.15(5)	203(7)
1560.97(10)	0.15(2)	1561.0(2)	0.16(5)	1562(2)	0.17
1631.36(10)	0.30(3)				
1885.3(2)	0.10(3)				
1978.82(10)	0.65(6)	1978.67(10)	0.71(7)		
2046.3(2)	0.20(4)	2046.5(5)	0.21(4)		
2072.9(2)	0.17(2)	2072.7(7)	0.16(4)		
2185.65(5)	561(25)	2185.60(5)	557(22)	2185.70(6)	522(20)
2368.3(3)	0.04(1)	2368.4(10)	0.031(10)		
2654.9(2)	0.11(2)	2654.1(5)	0.16(2)	2654.6(7)	0.14(2)
		2842.9(10)	0.08(2)		

$$B(E2;2_2^+\rightarrow 0_1^+)/B(E2;2_2^+\rightarrow 2_1^+)=0.012\pm 0.002$$

which is about twice the theoretical interacting boson approximation (IBA) calculation of Krane *et al.*[8] The population of the 2072.8 keV level, observed as $J^\pi=2^+$ in the ^{142}Nd(t,p) reaction,[2] ^{144}Nd(n,n',γ),[3] and neutron capture[4] experiments, has been suggested in ^{144}Pr decay.[7] Assuming a pure $E2$ multipolarity for the 1376.3 keV transition, the experimental reduced branching ratio

$$B(E2;2_3^+\rightarrow 0_1^+)/B(E2;2_3^+\rightarrow 2_1^+)=0.19\pm 0.04$$

rules out the interpretation of this level as a component of a three phonon multiplet. It seems more reasonable to emphasize that this level is the band head of a $K^\pi=2^+$ quasi-γ band. The energy of this level is well predicted by unified model calculations,[15] but it should rise above 3 MeV in IBA calculations.

A 2368.3 keV level, previously reported in ^{144}Pr decay,[7] was also observed in (d,p) and (p,t) experiments[1] as well as in (n,n'γ) (Ref. 3) and (n,γ) (Ref. 4) reactions. The spin and parity $J^\pi=2^+$, proposed by Rabenstein *et al.*,[16] is confirmed here owing to the logf_1t value (10.2) consistent with unique first forbidden transitions.[14] The 1671.8 keV γ ray, which should deexcite this level to the 2^+ state, could not be resolved in our spectra because it overlapped the strong 2185.6 keV single escape (SE) peak in the γ-ray spectrum.

A 2581.8 keV level is proposed on the basis of a 1885.3 keV γ ray feeding the 2^+ level as it was interpreted in (n,n'γ) (Ref. 3) and (n,γ) (Ref. 4) experiments. The absence of the crossover transition suggests $J=0$ or 3. The value $J^\pi=3^+$ deduced by Al-Janaby *et al.*[3] implies that this level is fed from $^{144}Pr^m$.

A 2675.3 keV state is proposed to account for the

TABLE II. Energy of γ rays observed in γ-γ coincidence with a 17% HPGe detector (696.5±5 keV gate).

E_γ (keV)
511.0 (annihilation line), 675.0, 814.1, 864.5, 978.4(SE1489), 1489.2, 1630.9, 1671.8,[a] 1978.3, 2045.6

[a]Not resolved in single γ-ray spectra from the single-escape peak of the 2185.6 keV γ ray.

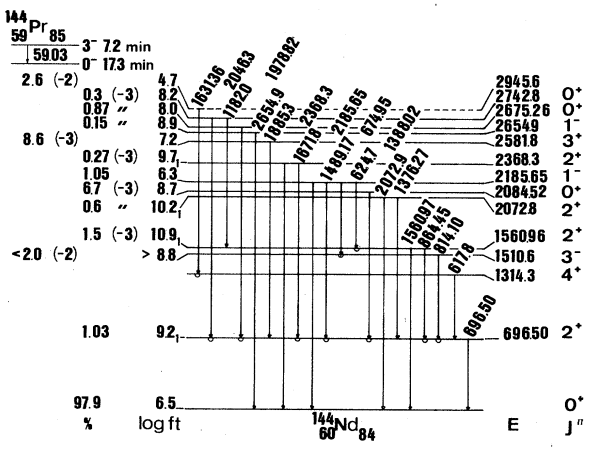

FIG. 2. $^{144}Pr^m$ ($J^\pi=3^-$) and $^{144}Pr^g$ ($J^\pi=0^-$) decay schemes. Energies are in keV. The left and right column give the percent of β feeding from $^{144}Pr^m$ and ^{144}Pr(g.s.), respectively. [(−3) means 10^{-3}.] For $\Delta J=2$, $\Delta\pi=+\beta$ transitions, logf_1t values are given (lower subscript 1). The intensity of the 1671.8 keV γ ray was deduced from the branching ratio measured in Ref. 3. The semicircle with a bar symbol means that the indicated coincidence was observed with a 696 keV gate.

1978.8 keV γ ray which was found in coincidence with the 696 keV gate. This state could be identified as the $J^\pi=0^+$ member of the 2663 keV multiplet found in the (p,t) reaction.[1]

The existence of a 2742.8 keV state had been proposed earlier on the basis of a 2046.3 keV transition to the 2^+ level. The new 1182.0 keV γ line (Table I) is interpreted as deexciting this level to the 2_2^+ state. Assuming $E2$ multipolarity for both aforementioned transitions, the reduced probability ratio

$$B(E2;0_n^+\rightarrow 2_1^+)/B(E2;0_n^+\rightarrow 2_2^+)=0.32\pm 0.15$$

suggests a two-quasiparticle character to be assigned to this $J^\pi=0^+$ state.

The tentative level at 2945.6 keV allows the incorporation of the 1631.4 keV γ ray observed here in singles spectra and in γ-γ coincidence with the 696 keV gate, or else, this transition should deexcite a 2328 keV level which was never observed until now; however, this transition was found earlier in the (n,γ) (Ref. 16) and (n,n'γ) (Ref. 3) reactions but unplaced in the ^{144}Nd level scheme. Taking account of the β feeding of this excited state from the ^{144}Pr^m isomer, it is more likely that the assignment is $J^\pi=(3-5)^\pm$. Moreover, a 2945.6 keV level was deduced from the occurrence of a 727.6 keV γ ray in coincidence measurements,[4] populating the 2218.1 keV level ($J^\pi=5^+,6^+$). Indeed, no strong argument appears to substantiate the idea that the two 2945.6 keV levels are different.

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