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The ^{130}Nd $\rightarrow$ ^{130}Pr $\rightarrow$ ^{130}Ce decay chain revisited

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Abstract. An investigation of low-lying energy levels of ^{130}Pr and ^{130}Ce has been made via β-decay. The radioactive parent nuclei were produced via ^{94,96}Mo + ^{40}Ca reactions at 6.8 MeV/nucleon and transported by a He-jet system. Gamma-γ-t, γ-X-t, γ-e$^-$-t coincidence measurements were performed. Internal conversion coefficients have been measured with a magnetic spectrometer. The new β-decay half-life of ^{130}Nd has been determined to be 21(3) s. A partial level scheme of ^{130}Pr at low-spin has been constructed. The β-decay of ^{130}Pr to ^{130}Ce suggests the existence of three β-instable isomeric states in ^{130}Pr, while only one half-life $T_{1/2}$ = 40(4) s has been measured. Based on the present work and low-lying excited states in neighbouring odd-mass nuclei, the spins and parities of isomeric states in ^{130}Pr are proposed to be 2^+, $(4,5)^+$ and $(7,8^{\mp})$. The ground state in ^{130}Pr is still undetermined.

PACS. 23.20.Lv Gamma transitions and level energies – 23.20.Nx Internal conversion and extranuclear effects – 27.60.+j $90 \leq A \leq 149$

1 Introduction

During the last decade, the isotope ^{130}Pr has been the subject of several detailed in-beam γ-ray spectroscopic studies with heavy-ion fusion-evaporation reactions [1–6]. A well-established positive-parity yrast cascade is seen by all the authors and associated by systematics to a $\pi h_{11/2} \otimes \nu h_{11/2}$ coupling. However, the situation is very complex for the other collective structures which are proposed with different parity and configuration assignments by different authors.

The decay paths from these bands to one (or more) low-lying low-spin isomeric state(s) are not established. From on-line experiments, made using the POLYTESSA array facility at Daresbury, the existence of an additional $T_{1/2} \approx 400$ ns isomeric state decaying by a 80 keV γ-ray is known [7]. The authors have also observed that a collective band proposed with negative parity and based on a strong 81 keV line (band 1 of refs. [2] and [4]) feeds this isomeric level.

Recently, S. Xu *et al.* [8] have reported on the (EC + β^+) decay of ^{130}Nd (0^+) to ^{130}Pr. They have measured a new half-life $T_{1/2} = 13 \pm 3$ s in disagreement with the previous one, $T_{1/2} = 28 \pm 3$ s, observed long ago by Bogdanov *et al.* [9,10]. A deduced partial ^{130}Pr level scheme based on an assumed (4^+) ground state is proposed on the basis of γ-singles measurements and γ-γ coincidence relationships. All the γ-ray multipolarities indicated in this level scheme have also been assumed, without any experimental argument.

Results of two series of new measurements are reported in the present work. The first experiment concerns the β-decay of ^{130}Nd (0^+) to ^{130}Pr and the second one the β-decay(s) of ^{130}Pr to ^{130}Ce.

2 Experimental procedures

The experiments have been carried out with heavy-ion beams provided by the first cyclotron of the SARA facility. The largest production of isotopes of the $A = 130$ decay chain was reached by the bombardment of ^{40}Ca beams on thin (1 or 2 mg/cm^2) isotopically enriched metallic targets of ^{94}Mo (97.6% enrichment) or ^{96}Mo (96.6% enrichment). The ^{40}Ca beam energies were approximately 6.8 MeV/nucleon with 200 to 800 nAe (11^+ ions) intensities. The He-jet technique was used to transport the recoiling products on aluminized Mylar tape from the target to a low-background counting site equipped with an automatic tape driver system. The detection site was designed for different purposes. Gamma and X-ray singles, γ-ray

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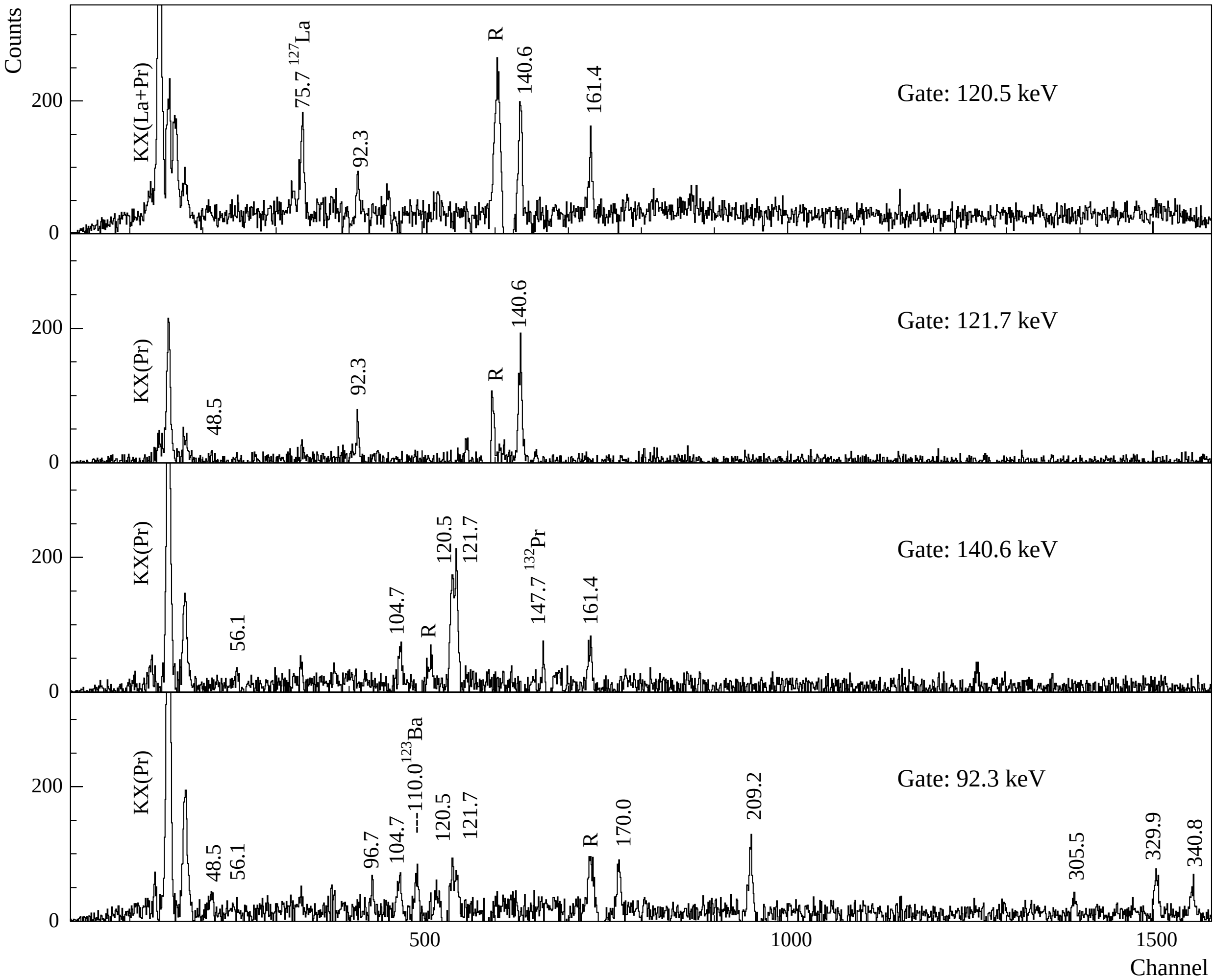

Fig. 1. Examples of prompt γ-γ coincidence spectra observed with the ^{94}Mo + ^{40}Ca reaction and $\Delta t_{\rm coll} = 6$ s (R: backscattered radiation).

multianalysis, γ-γ-t or γ-X-t coincidences have been performed with two Ge detectors (45% and 60% efficiencies) and one X-ray detector. Conversion electrons were measured with a Si(Li) detector placed at the focal plane of an electron magnetic spectrometer [11]. Coincidences e$^-$-γ-t have been recorded simultaneously.

3 Experimental results

3.1 The β-decay of ^{130}Nd to low-lying low-spin states of ^{130}Pr and half-life of ^{130}Nd

The measurement of energies and intensities of the γ-rays as well as of γ-γ-t or γ-X-t coincidences have been performed with the ^{96}Mo + ^{40}Ca reaction and 13 s collection time ($\Delta t_{\rm coll}$) or with the ^{94}Mo + ^{40}Ca reaction and $\Delta t_{\rm coll} = 6$ s. Conversion electrons have been recorded with two different $\Delta t_{\rm coll}$ of 10 s and 60 s. As the radioactive samples helium collected by the jet technique contain a mixture of recoil products, several collection times with various multiscaling analyses (generally eight time groups per spectrum) have been performed to deduce half-lives as follows: for the ^{94}Mo target: $\Delta t_{\rm coll} = 9\,{\rm s}$–$8 \times 1\,{\rm s}$; for the ^{96}Mo target: $\Delta t_{\rm coll} = 10\,{\rm s}$–$8 \times 1\,{\rm s}$; $\Delta t_{\rm coll} = 42\,{\rm s}$–$8 \times 5\,{\rm s}$; $\Delta t_{\rm coll} = 82\,{\rm s}$–$8 \times 10\,{\rm s}$.

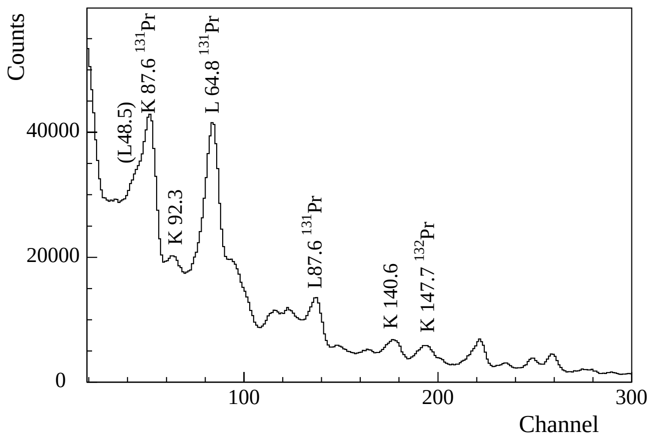

Fig. 2. Electron singles spectrum observed with the ^{96}Mo + ^{40}Ca reaction ($\Delta t_{\rm coll} = 60$ s).

Table 1. Energies, relative intensities, coincidence relationships and placements of γ-transitions observed in the β-decay of ^{130}Nd with the ^{94}Mo + ^{40}Ca reaction ($\Delta t_{\mathrm{coll}} = 6$ s) and the ^{96}Mo + ^{40}Ca reaction ($\Delta t_{\mathrm{coll}} = 13$ s). The placements are given by indicating the initial and final levels (E_{i}, E_{f}).

E_γ(keV)	$I_\gamma(\Delta I_\gamma)$	Coincidence relationships	E_{i}(keV)	E_{f}(keV)
48.5(3)	10(2)	(56.1), 92.3, (104.7), 120.5, 121.7, (161.4)	140.6	92.3
56.1(1)	7(2)	48.5, 92.3, 140.6	196.7	140.6
92.3(2)	100(9)	KX(Pr), 48.5, (56.1), 96.7, 104.7, 120.5, 121.7, 161.4 170.0, 209.2, 305.5, 329.9, 340.8	92.3	0
96.7(2)	7(2)	KX(Pr), 92.3	188.8	92.3
104.7(3)	8(3)	KX(Pr), 56.1, 92.3, 104.7, 140.6, 196.7	196.7	92.3
104.7(3)	12(3)	KX(Pr), 56.1, 92.3, 104.7, 140.6, 196.7	301.4	196.7
120.5(2)	33(5)	KX(Pr), (48.5), 92.3, 140.6, 161.4	261.1	140.6
121.7(2)	36(5)	KX(Pr), 48.5, 92.3, 140.6	262.3	140.6
140.6(2)	100(9)	KX(Pr), 56.1, 104.7, 120.5, 121.7, 161.4	140.6	0
161.4(3)	18(3)	KX(Pr), 92.3, 120.5, 140.6, (261.2)	422.3	261.1
170.0(3)	18(4)	KX(Pr), 92.3	262.3	92.3
188.7(3)	6(2)	KX(Pr)	188.8	0
196.7(3)	9(2)	KX(Pr), 104.7	196.7	0
209.2(3)	23(3)	KX(Pr), 92.3	301.4	92.3
261.2(3)	6(2)	KX(Pr)	261.1	0
305.5(3)	10(3)	KX(Pr), 92.3	397.9	92.3
329.9(3)	23(5)	KX(Pr), 92.3	422.3	92.3
340.8(3)	20(5)	KX(Pr), 92.3	433.1	92.3
398.0(3)	10(3)	–	397.9	0
422.3(3)	15(5)	–	422.3	0

Examples of prompt γ-γ coincidence spectra are presented in fig. 1. The singles spectrum for electrons shown in fig. 2 has been recorded simultaneously in the e$^-$-γ coincidence experiment. The list of γ-rays associated to the β-decay of ^{130}Nd with their energies, intensities and γ-γ coincidence relations is reported in table 1. The partial level scheme of ^{130}Pr, deduced in the present work from the β-decay of ^{130}Nd (0^+), is given in fig. 3.

This new ^{130}Pr level scheme severely disagrees with the one proposed recently by S. Xu *et al.* [8]. Comparing table 1 in the present work to table 1 in ref. [8], one observes differences for a few energies and global intensities. The $I_\gamma(92.2)/I_\gamma(140.6)$ ratio equals 1 in the present work compared to 2.1 in ref. [8]. An important difference appears concerning the 104.7 keV γ-ray which was placed directly above the excited state at 140.6 keV in ref. [8] and found to be a doublet in the present work, as shown in fig. 1 and table 1. Consequently, the excited state at 245.5 keV given in ref. [8] is not confirmed by our data. The placement of a 196.6 keV γ-ray between excited states at 442.1 and 245.5 keV is also ruled out by the present γ-γ coincidence relationships (see table 1 and fig. 1). The main disagreements concern the multipolarities of the γ-rays which were not measured in the previous work [8] but only assumed. From our data we deduced the following: i) For the 140.6 keV transition, we measured $\alpha_K = 0.37 \pm 0.10$ and $K/L = 8 \pm 3$. The α_K value could agree with $M1$ or $E2$ multipolarities but the K/L ratio supports only $M1$ (7.29 for $M1$ and 2.72 for $E2$ [12]). ii) As shown in fig. 2, our conversion electron spectra are strongly contaminated by $^{131\mathrm{m}}$Pr

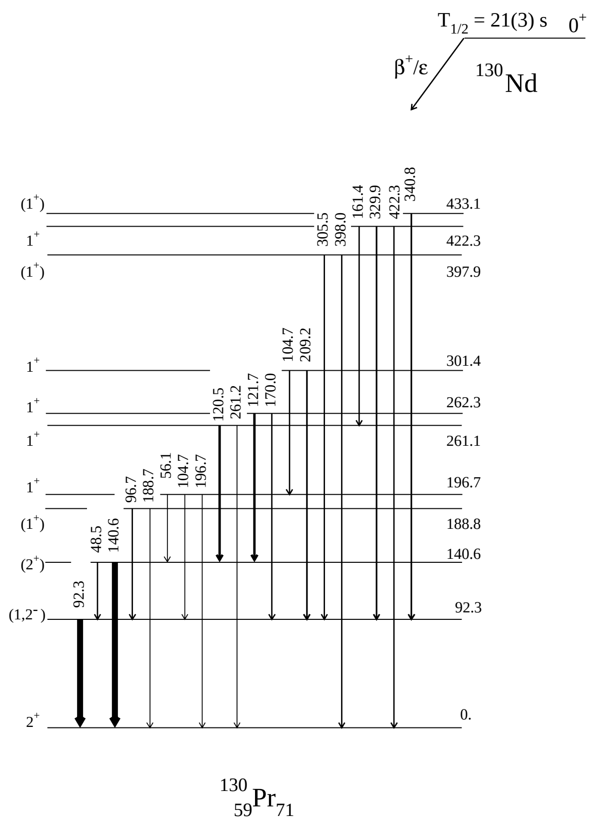

Fig. 3. Level scheme of ^{130}Pr deduced from the present work.

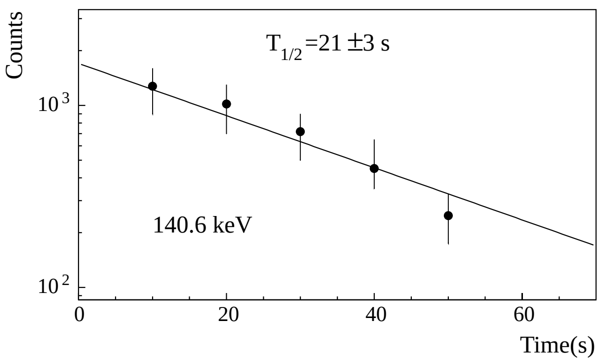

Fig. 4. Time decay curve measured for the strong 140.6 keV γ-line with the ^{96}Mo + ^{40}Ca reaction and $\Delta t_{\mathrm{coll}} = 82$ s.

Table 2. Apparent β-decay feedings and log*ft*-values of levels in ^{130}Pr.

E_{level} (keV)	I^π	Feeding (%)	log*ft*
92.3	$(1,2^-)$	≈ 0	> 7.5
140.6	(2^+)	0.1	7.2
188.8	(1^+)	4.8	5.5
196.7	1^+	15	5.0
261.1	1^+	12	5.1
262.3	1^+	24	4.8
301.4	1^+	14.5	5.0
397.9	(1^+)	5.9	5.3
422.3	1^+	18.3	4.8
433.1	(1^+)	5.9	5.3

($T_{1/2} = 5.7$ s) which decays via the cascade of two γ-rays 64.8 keV ($E3$) and 87.6 keV($M1$). In fig. 2 the lines $L48.5$ at 41.7 keV and $K92.3$ at 50.3 keV, assigned to ^{130}Pr, are visible on each side of the strong $K87.6$ line of $^{131\mathrm{m}}$Pr. A complete separation of the three lines was not possible in our experiment. However it is very easy to exclude the $M1$ multipolarities proposed by S. Xu *et al.* in ref. [8] for both the 92.3 and 48.5 keV transitions in ^{130}Pr, comparing their conversion lines with the $K140.6$ line (also seen in fig. 2) and taking into account their relative γ intensities (see table 1). The theoretical values are $\alpha_L(48.5) = 0.24$ for $E1$ and 1.27 for $M1$ while $\alpha_K(92.3) = 0.27$ for $E1$ and 1.4 for $M1$. With $I_\gamma(92.3)/I_\gamma(140.6) = 1$ (table 1) an $M1$ multipolarity for the 92.3 keV γ-ray can be ruled out by comparing the $K92.3$ and $K140.6$ lines (fig. 2). If the 92.3 keV γ-ray were $M1$, its K conversion electron line would be at least four times larger. The evaluation is more difficult for the 48.5 keV transition but the intensity of its $L48.5$ lines is also too weak for an $M1$ transition. For all the other transitions, the presence of contaminated lines does not allow precise estimations for conversion coefficients but the observation of several K lines is in favour of $M1$ or $M1+E2$ transitions as for example for the doublet at 120.5–121.7 keV.

From multianalysis measurements, the time decay curves have been analysed for the strongest lines and in particular for that at 140.6 and 92.3 keV. An average value of $T_{1/2} = 21(3)$ s for the half-life of ^{130}Nd has been deduced (see fig. 4). This value is in between those previously reported $T_{1/2} = 13(3)$ s [8] and $T_{1/2} = 28(3)$ s [9].

The low-spin partial level scheme of ^{130}Pr fed from ^{130}Nd (0^+) is proposed as based on a $I^\pi = 2^+$ assignment for the lowest-lying state in ^{130}Pr as shown in fig. 3. It has many similarities with the ^{132}Pr level scheme established in the β-decay of ^{132}Nd (0^+) and based on a $I^\pi = 2^+$ ground state [13]. Since the ground state of ^{130}Nd has spin and parity 0^+, levels with $I^\pi = 1^+$ are preferentially populated by allowed β/EC decay. From γ-ray intensities and internal conversion coefficients for the three lowest transitions, we have determined the apparent β-feedings of the ^{130}Pr levels and calculated the log*ft*-values listed in table 2. The Q_β-value of 5.03 MeV given in ref. [14] has been used. The log*ft*-values have been calculated under the assumption that the lowest state of ^{130}Pr, shown in fig. 3 (possibly its ground state as discussed in sect. 4) is not directly fed by the β-decay.

3.2 The β-decay of ^{130}Pr to ^{130}Ce

Following a first half-life measurement of 28(6) s for ^{130}Pr reported by Bogdanov [9], the β-decay of ^{130}Pr to levels in ^{130}Ce has been the subject of several studies [15–19]. Though radioactive samples have been produced via different nuclear reactions induced by ^{28}Si, ^{46}Ti [16], or ^{40}Ca [15], and collected during various collection times, only one half-life of 40(4) s has been observed. However, as underlined by some of the authors [15,16], the partial level scheme of ^{130}Ce fed by β-decay shows that the ^{130}Pr radioactive samples contain a mixture of low-spin and high-spin isomers. For the high-spin part, $I^\pi = (5^+)$ [16] or $I = (6,7)$ [15] have been independently proposed. In the present study, the ^{96}Mo + ^{40}Ca fusion-evaporation reaction at 273 MeV beam energy has been used. For γ-γ or γ-X and e^--γ coincidence measurements, $\Delta t_{\mathrm{coll}} = 82$ s and 50 s have been selected, respectively. Energies and relative intensities of the γ-rays placed in ^{130}Ce are summarized in table 3. The multipolarities deduced for the main transitions are also reported in the table. The normalization of the conversion electron coefficients was based on the $E2$, $2^+ \to 0^+$ transition at 253.7 keV in ^{130}Ce. The estimated α_K coefficients correspond to $E2$, $M1$ or $E2+M1$ multipolarities, except for the 631.3 and 632.5 keV γ-rays for which a mean value $\alpha_K = 2.2(8) \times 10^{-3}$ is associated with an electric dipole transition (theoretical values are 1.84×10^{-3} for $E1$, 4.94×10^{-3} for $E2$, 7.8×10^{-3} for $M1$, respectively). As already reported earlier [18, 19], a second 0^+ state at 1025 keV has been observed by the detection of conversion electrons of a weak $E0$ transition ($0^+_2 \to 0^+_{\mathrm{gs}}$) [18]. In the present study this state is confirmed by an anormally converted 771 keV transition having $\alpha_K = 7(2) \times 10^{-3}$ (for a pure $M1$ transition $\alpha_K = 4.7 \times 10^{-3}$). Based on a 280–771 keV γ-γ coincidence, a 2^+_3 state was already proposed at 1305 keV [18]. Recently, Asai *et al.* [19] gave an excitation energy of 1356 keV for this 2^+_3 state but we have no indication of such a state from the present study.

Table 3. Energies, relative intensities, multipolarities and placements of γ-transitions observed in the ^{130}Ce level scheme with the ^{96}Mo + ^{40}Ca reaction (Δt_{coll} = 82 s). The $[E2]^{\star}$ multipolarity is associated to the $2^+ \to 0^+$ transition in ^{130}Ce. The placements are given by indicating the initial and final levels (E_{i}, E_{f}).

E_γ(keV)	$I_\gamma(\Delta I_\gamma)$	Multipolarity	E_{i}(keV)	E_{f} (keV)	E_γ(keV)	$I_\gamma(\Delta I_\gamma)$	Multipolarity	E_{i}(keV)	E_{f}(keV)
189(1)	2.1(4)		2643	2454	631.3(5)	2.0(3)	$E1$	1955	1324.2
253.7(1)	[100]	$[E2]^{\star}$	253.7	0	632.5(5)	1.0(2)	$E1$	1955	1323.1
260(1)	≈ 0.1		2313	2053	708(1)	≈ 0.1		2033	1324.2
263(1)	1.7(8)		2644	2381	729(1)	0.2(1)		2053	1324.2
280(1)	≈ 0.1		1305	1025	771(1)	2.8(4)	$M1(+E0)$	1025	253.7
283(2)	≈ 0.1		1955	1671.7	792(1)	≈ 0.1		2115	1323.1
331(1)	0.2(1)		2644	2313	834.7(2)	10.1(6)	$E2$	834.7	0
343.0(4)	0.7(3)		1177.1	834.7	837.2(2)	4.4(4)	$E2$,$M1$	1671.7	834.7
348.6(3)	0.6(3)		1671.7	1323.1	923.4(2)	13.6(7)	$E2$,$M1$	1177.1	253.7
358(1)	≈ 0.1		2313	1955	938.2(3)	4.0(2)	$M1$,$E2$	2115	1177.1
401(1)	≈ 0.1		2454	2053	951.9(3)	3.5(2)	$M1$,$E2$	2623.6	1671.7
416(1)	≈ 0.2		2313	1898	961.4(3)	2.0(4)		1671.7	710.2
426(1)	1.5(5)		2381	1955	975(1)	≈ 0.1		2299	1324.2
456.5(2)	42(3)	$E2$	710.2	253.7	1045(1)	0.9(3)		1755	710.2
466.9(3)	1.7(1)	$M1$,$E2$	1177.1	710.2	1051(1)	≈ 0.1		1305	253.7
483.0(5)	1.6(5)		2381	1898	1057(1)	0.2(1)		2381	1324.2
488.4(3)	4.4(4)		1323.1	834.7	1069.4(5)	1.7(3)	$M1$,$E2$	1323.1	253.7
494.4(2)	5.5(3)	$M1$	1671.7	1177.1	1130(1)	0.5(2)		2454	1324.2
499.4(2)	0.5(2)		2454	1955	1244(1)	0.4(2)		1955	710.2
556(1)	0.6(3)		2454	1898	1282.0(6)	1.7(4)	$M1$,$E2$	2115	834.7
574.0(5)	0.5(2)		1898	1324.2	1322(1)	1.5(5)		2033	710.2
575.0(5)	0.7(3)		1898	1323.1	1331(1)	≈ 0.2		2655	1324.2
578.5(4)	1.5(5)		1755	1177.1	1348.0(8)	3.0(6)	$M1$,$E2$	2058	710.2
580.9(3)	8.9(4)	$M1$	834.7	253.7	1405(1)	0.5(3)	2115	710.2	
588(1)	0.5(2)		2703	2115	1589(1)	5.0(8)		2299	710.2
591(1)	weak		2644	2053	1779(1)	3.5(5)		2033	253.7
596(1)	0.3(1)		1305	710.2	1861(1)	3.9(5)		2115	253.7
613(1)	0.6(3)		1323.1	710.2	1945(1)	3.0(7)		2655	710.2
614.0(4)	6.0(5)	$E2(M1)$	1324.2	710.2					

Figure 5 shows the partial level scheme of ^{130}Ce built with the present data from the β-decay of ^{130}Pr. As several rotational band structures have been identified by Todd *et al.* [20] via in-beam γ-ray spectroscopy, one can easily identify many excited states of ^{130}Ce. In fig. 5 the ground-state band is observed up to the 8^+ at 2053 keV. The levels at 834.7 keV ($I^\pi = 2^+$), 1177.1 keV ($I^\pi = 3^+$), 1323.1 keV ($I^\pi = 4^+$), 1755 keV ($I^\pi = 5^+$) and 1898 keV ($I^\pi = 6^+$) are the members of the quasi-γ band. The excited states at 1955, 2313, 2381 and 2644 keV have been assigned $I^\pi = 5^-$, 7^-, 6^- or 8^-, respectively, and considered as members of the two signatures of a $\pi d_{3/2}1/2^+[420] \otimes \pi h_{11/2}3/2^-[541]$ configuration [20]. Two other levels at 2454 keV ($I^\pi = 7^-$) and 2643 keV ($I^\pi = 8^-$) are fed by this β-decay. Todd *et al.* [20] have proposed a $\nu h_{11/2}7/2^-[523] \otimes \nu g_{7/2}7/2^+[404]$ configuration for these two states. It is interesting to note that all the links observed by in-beam spectroscopy and by β-decay between these negative-parity states and other bands are similar.

As reported previously [15,16,18], several other excited states in ^{130}Ce are also strongly fed by β-decay (fig. 5). This is in particular the case for states at 1671.7 keV ($I^\pi = (3,4)^+$), 2115 keV ($I^\pi = (4)^+$), 2623.6 keV ($I^\pi = (4,5)^+$) and 2703 keV ($I^\pi = (6^+)$) which decay mainly to the members of the quasi-γ band and have been previously compared with calculations performed in the framework of the IBM-2 model [18]. The four other states at 2033, 2058, 2299 and 2655 keV decay only to the members of the ground-state band and are also well fed by β-decay. Even if no firm I^π assignment can be deduced from the present data, these states have very likely $I^\pi = 4^+$. From the γ-ray intensities and internal conversion coefficients we have determined the apparent β-feedings of the ^{130}Ce levels. The values listed in table 4 are calculated under the assumption that the 0^+ ground state of ^{130}Ce is not directly fed by the β-decay. This may be justified by the possible low-lying 2^+ level proposed for ^{130}Pr in subsect. 3.1 and also by the weak β-feeding deduced for the 0_2^+ state at 1025 keV.

4 Discussion

In the present work, only one half-life has been observed for the ^{130}Pr decay but the β-feedings (see table 4) clearly establish the existence of three β-unstable isomeric states in ^{130}Pr: i) A first one, fed in the β-decay of ^{130}Nd (0^+), has been proposed with $I^\pi = 2^+$ in subsect. 3.1. This

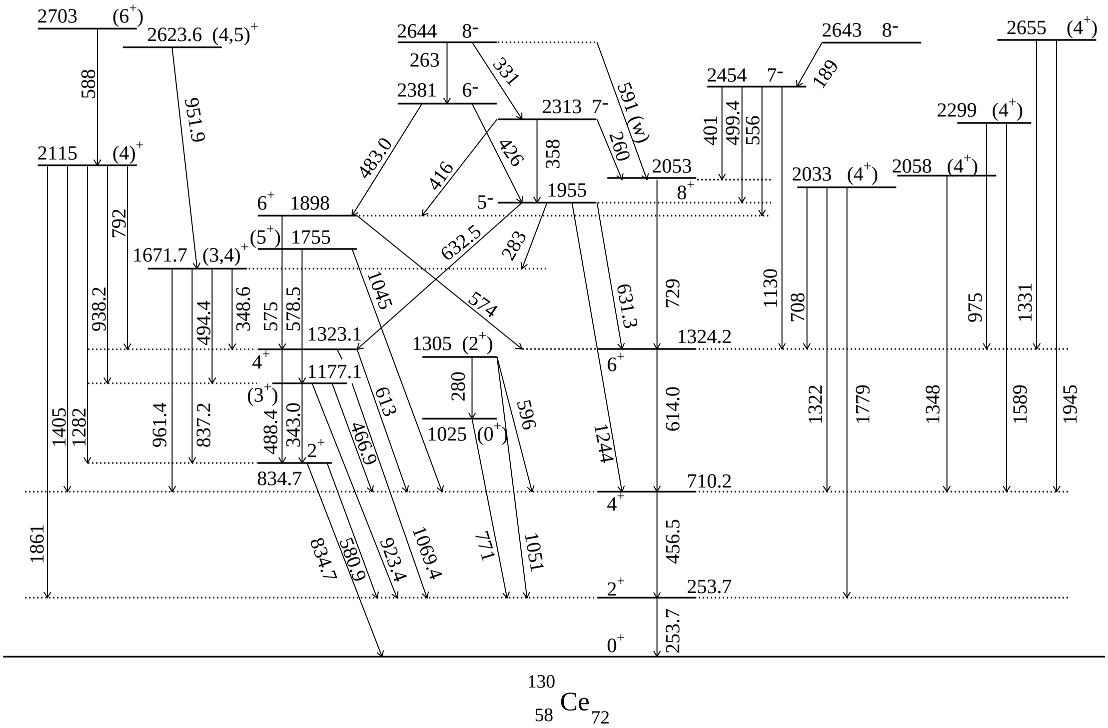

Fig. 5. Partial level scheme of ^{130}Ce deduced from the present work.

Table 4. Apparent β-decay feedings of levels in ^{130}Ce.

E_{level}(keV)	I^π	Feeding (%)
253.7	2^+	21
710.2	4^+	15
834.7	2^+	7.0
1025	(0^+)	2.4
1177.1	3^+	4.5
1305	(2^+)	0.5
1323.1	4^+	3.7
1324.2	6^+	2.1
1671.7	$(3,4)^+$	7.9
1755	5^+	2.1
1898	6^+	0
1955	5^-	1.2
2033	(4^+)	4.5
2053	8^+	0
2059	$(4)^+$	2.7
2115	$(4)^+$	8.7
2299	(4^+)	4.5
2313	7^-	0.2
2381	6^-	1.4
2454	7^-	0
2623.6	$(4,5)^+$	3.1
2643	8^-	1.9
2644	8^-	1.7
2655	(4^+)	2.9
2703	(6^+)	0.5

low-spin state explains the large feedings observed in the β-decay of ^{130}Pr to ^{130}Ce for the first 2^+ state and the 2^+ and 3^+ states of the γ-band. ii) Approximately 61% of the β-feedings (see table 4) populate states with 3^+, 4^+ and 5^+ in ^{130}Ce and require the existence of a β-unstable ^{130}Pr state with $I^\pi = (4,5)^+$. Apparently the same precursor state feeds also weakly (1.2%) the $I^\pi = 5^-$ state at 1955 keV in ^{130}Ce. iii) The remaining part of the ^{130}Pr β-decay preferentially populates the $I^\pi = 8^-$ states at 2643 and 2644 keV and slightly the 6^+ at 1324 keV, the 6^- at 2381 keV, the (6^+) at 2703 keV and the 7^- at 2313 keV. On the contrary, the states 6^+ at 1898 keV, 8^+ at 2053 keV or 7^- at 2454 keV are not directly fed by β-decay. Thus, a third isomeric β-unstable state with likely $I^\pi = (7, 8^\mp)$ is needed in ^{130}Pr to explain the data.

To assign tentative π, ν configurations to these isomeric states observed in ^{130}Pr, we have looked at the situation in the neigbouring odd-A Pr and Ce isotopes. In this region, the nuclei have a nearly symmetric prolate shape with a deformation $\beta_2 = 0.20$ to 0.24. Figure 6 shows the low-lying states in ^{129,131,133}Pr below 400 keV [21–25] and in ^{129,131}Ce [26]. In addition, a $I^\pi = 9/2^+$ excited state at 975.4 keV in ^{131}Pr, which is fed in the β-decay of ^{131}Nd [22], has also been identified by on-line spectroscopy as the basis of a highly deformed collective band. A $\pi g_{9/2} 9/2^+[404]$ assignment has been deduced from quadrupole moment measurement [27,28]. A $\pi 9/2^+[404]$ isomeric state ($T_{1/2} = 60$ ns) identified at 497 keV in ^{129}Pr [29,21] is also the base state of a deformed collective band [5].

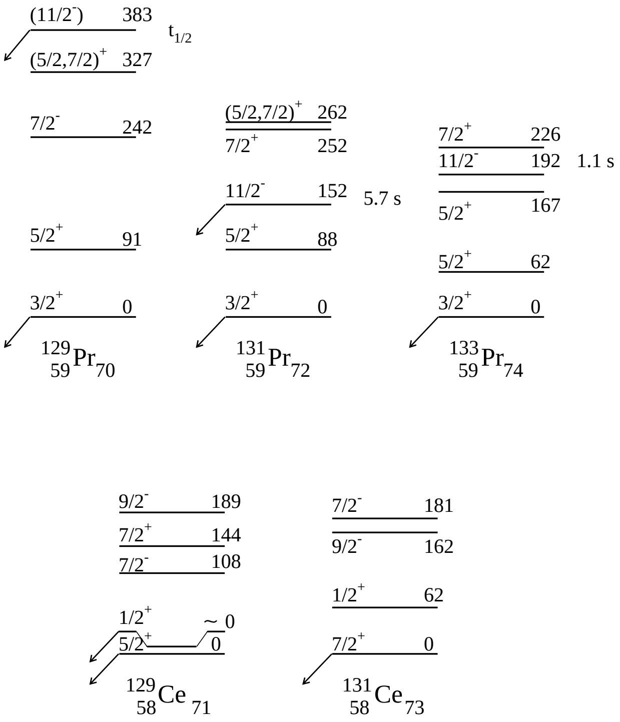

Fig. 6. Low-lying states in odd-A Pr and Ce isotopes. The data are taken from refs. [21–25] and [26], respectively. Observed β-unstable states are indicated by full arrows, $t_{1/2}$ indicated for ^{129}Pr has not been measured.

One observes that for all the odd-A Pr nuclei the ground state has a $I^\pi = 3/2^+$ configuration and that excitation energies of the first $I^\pi = 5/2^+$ and $I^\pi = 7/2^+$ states appear to be very stable. From calculations performed in the frame of IBFM-2 model, large mixings of $\pi d_{5/2}$ and $\pi g_{7/2}$ orbitals have been deduced at low-excitation energies [22]. For example, the $3/2^+$ ground states have a structure dominated by the $d_{5/2}$ orbital (approximatively 78% $d_{5/2}$ + 14% $g_{7/2}$ in ^{131}Pr) while the first $5/2^+$ excited states have a structure dominated by the $g_{7/2}$ orbital (approximatively 69% $g_{7/2}$ and 24% $d_{5/2}$ in ^{131}Pr). The $I^\pi = 3/2^+$ ground states of these Pr isotopes could be considered as a mixture of $\pi 3/2^+[411]$ and $\pi 3/2^+[422]$ Nilsson states. The β-unstable $I^\pi = 11/2^-$ high-spin isomeric states identified in ^{129,131}Pr originate from the $\pi h_{11/2}$ spherical orbital. From in-beam spectroscopy $\pi 3/2^-[541]$ or $\pi 1/2^-[550]$ Nilsson orbitals have been assigned to these isomers [21,30].

The spin parity assignments for the ground states and the low-lying excited states in ^{129,131}Ce have also been investigated and compared to IBFM calculations [26]. The complex situation is shown in fig. 6. The $I^\pi = 1/2^+$ states correspond very likely to the $\nu 1/2^+[411]$ Nilsson states as in ^{127,129,131}Ba [31] but an admixture with a $\nu 1/2^+[400]$ intrinsic state cannot be excluded. The lowest $5/2^+$ and $7/2^+$ excited states are dominated by the $\nu 5/2^+[402]$ and the $\nu 7/2^+[404]$ intrinsic states, respectively. To reproduce the experimental structures built on these positive-parity states, mixed $\nu d_{5/2} + \nu g_{7/2}$ configurations have been extracted from the calculations.

The low-lying negative-parity states $I^\pi = 7/2^-$ and $9/2^-$ identified in ^{129,131}Ce originate from the $\nu h_{11/2}$ shell model orbital and correspond to the $\nu 7/2^-[523]$ and $\nu 9/2^-[514]$ configurations, respectively. For $N = 71$ neutrons, the $7/2^-$ state is below the $9/2^-$ state in ^{129}Ce but the situation is opposite in ^{131}Ce (see fig. 6).

Based on the experimental situation for odd-A nuclei of this region (see fig. 6) and according to the Gallagher-Moskovski rules [32] both the configurations $\pi 3/2^+[411] \uparrow \otimes \nu 7/2^+[404] \downarrow$ and $\pi 3/2^+[422] \downarrow \otimes \nu 1/2^+[411] \downarrow$ are the most probable candidates to form the $I^\pi = 2^+$ low-spin isomeric state in ^{130}Pr. From Kondev *et al.* [6] the first one, with antiparallel intrinsic spins, is calculated at 342 keV, while it is considered as ground state in ^{132}Pr.

The situation is rather complicated for the medium-spin isomer proposed with a tentative $I^\pi = (4,5)^+$ assignment because, in absence of log*ft*-values we cannot use β-decay selection rules. From excitation energies calculated by Kondev *et al.* [6] for two quasiparticle structures in ^{132}Pr and ^{130}Pr, two couplings give rise to $I^\pi = 4^+$ levels at low energy. The $\pi 3/2^+[411] \uparrow \otimes \nu 5/2^+[402] \uparrow$ coupling, with parallel intrinsic spins, gives a $I^\pi = 4^+$ state proposed as ground state in ^{130}Pr. The other $I^\pi = 4^+$ is based on the coupling $\pi 1/2^-[550] \uparrow \otimes \nu 7/2^-[523] \uparrow$ and expected at 233 keV in ^{130}Pr. For a $I^\pi = 5^+$ assignment, the proton-neutron configurations $\pi 3/2^+[422] \downarrow \otimes \nu 7/2^+[404] \downarrow$, $\pi 3/2^-[541] \uparrow \otimes \nu 7/2^-[523] \uparrow$, or $\pi 1/2^-[550] \uparrow \otimes \nu 9/2^-[514] \uparrow$ are possible. Though the $\pi 3/2^-[541]$ or $\pi 1/2^-[550]$ $h_{11/2}$ single-particle energies are not experimentally known, predicted excitation energies for the two-quasiparticle states in odd-odd ^{130}Pr and ^{132}Pr are less than 300 keV [6].

The $\pi g_{9/2}$ orbital has to be used to explain the third β-unstable isomeric state identified in the present work with a spin $I^\pi = (7, 8^\mp)$. The $\pi 9/2^+[404] \uparrow \otimes \nu 7/2^-[523] \uparrow$ coupling could appear as a probable candidate to form a $I^\pi = 8^-$ isomer at low-excitation energy in ^{130}Pr which is able to feed the 8^- states at 2643 and 2644 keV in ^{130}Ce (fig. 5 and table 4). In this case the $I^\pi = 8^-$ isomeric state could be the base state of the highly deformed band identified in ^{130}Pr by on-line experiments [3,5,28].

In conclusion, the half-life of the (EC+β^+) decay of ^{130}Nd has been determined to be 21 ± 3 s. A partial level scheme of ^{130}Pr, based on a $I^\pi = 2^+$ state has been established. To explain the (EC+β^+) decay of ^{130}Pr to ^{130}Ce, it has been found that at least three β-unstable isomeric states in ^{130}Pr are required. As only one half-life of 40 ± 4 s has been observed in this study, in addition to the low-spin $I^\pi = 2^+$ state, only tentative $I^\pi = (4,5)^+$ and $I^\pi = (7, 8^\mp)$ assignments can be proposed for the two other isomers. In particular, the identification of the ground state in ^{130}Pr is still an open question and efficient measurements with on-line mass separation would yield to clear up the situation.

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