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Short Note

Pseudo-spin band in the odd-odd nucleus ^{172}Lu

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Abstract. High-spin states in the odd-odd nucleus ^{172}Lu have been populated in a ^{170}Er(^{7}Li, 5n) reaction and the emitted γ-radiation was detected with the GASP array. Two sequences of a new identical band have been observed with the transition energies in the favoured and unfavoured sequences being identical within ≈ 3 keV at low spins and ≈ 1 keV at high spins over the whole observed spin range. An interpretation as a pseudo-spin singlet band of $\pi 1/2^-[541] \otimes \nu 1/2^-[\widetilde{420}]$ configuration is proposed. It represents the best example of a pseudo-spin singlet band in normal deformed nuclei known until now.

PACS. 21.10.-k Properties of nuclei; nuclear energy levels – 21.10.Re Collective levels – 23.20.Lv γ transitions and level energies – 27.70.+q $150 \leq A \leq 189$

1 Introduction

The phenomenon of identical bands was first discovered in two superdeformed bands in ^{151}Tb and ^{152}Dy which show nearly identical γ-ray energies [1]. Subsequently, identical bands were also observed in nuclei of normal deformations. A review of this new phenomenon can be found in [2]. Identical bands have been defined as bands having identical dynamic moments of inertia resulting from the fact that they have identical γ-ray energies [2].

Examples of identical bands in doubly odd nuclei are pseudo-spin [3–5] bands in which an aligned neutron pseudo-spin of the singlet type ($\widetilde{\Lambda} = 0$) is coupled to an aligned proton [6]. To the best studied examples lying in the upper rare-earth region (Lu-Ta-Re-Ir) [7–17] the $\pi h_{9/2} \otimes \nu 1/2^-[521]$ configuration has been assigned. The $h_{9/2}$ proton orbital with a rather pure j (= 9/2) and an $\Omega = 1/2$ component ($1/2^-[541]$), which is mainly contributing here, has a large positive decoupling parameter. The neutron orbital has a decoupling parameter very close to unity and the neutron is of pseudo-spin singlet $\nu 1/2^-[\widetilde{420}]$ nature being aligned parallel or antiparallel to the rotation axis, respectively. The orbital with the Nilsson quantum numbers $1/2^-[521]$ corresponds to that with the pseudo oscillator quantum numbers $1/2^-[\widetilde{420}]$. The favoured sequence consisting of odd-spin members ($I = 3, 5, 7, \ldots$) connected by strong stretched $E2$ transitions and the unfavoured ones ($I = 2, 4, 6, \ldots$), shifted up in energy away from the yrast line with considerably less feeding, have been observed in the odd-odd nuclei ^{170}Lu [7], ^{172}Ta [11], ^{174}Ta [9], ^{176}Re [10,12] and ^{186}Ir [17]. The $M1$ transitions de-exciting the unfavoured into the favoured levels are hindered because the neutron is flipped from being aligned along the rotational axis to the opposite direction. In the isotonic $N = 101$ chain with known pseudo-spin flip-decoupled structures the nuclei ^{176}Re [10, 12], with differences in γ-ray energies of $\Delta E_\gamma \approx 10$ keV, and ^{174}Ta [9], with energy differences of $\Delta E_\gamma < 6$ keV, are known. The next candidate with lower Z is the odd-odd isotope ^{172}Lu.

We report here about new results for the strongest populated band observed in the odd-odd nucleus ^{172}Lu

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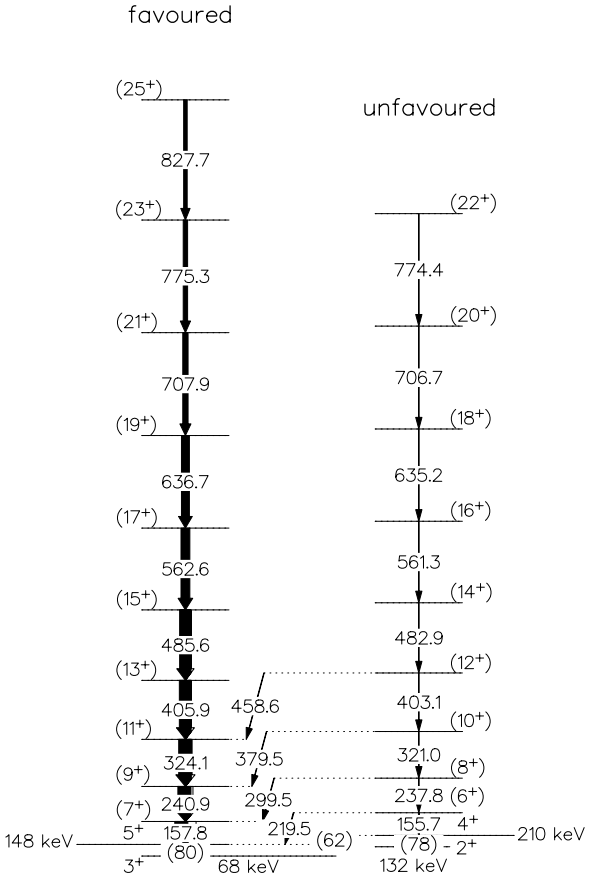

Fig. 1. Partial level scheme of ^{172}Lu. Uncertain spin-parity assignments are given in brackets. The widths of the arrows represent the intensities of the transitions. The energies of the 4^+ and 5^+ levels are taken from the literature (cf. text).

showing identical energies within 3 keV —maybe the best example of a pseudo-spin singlet band in normal deformed nuclei known until now.

2 Experimental methods and results

The high-spin states in the doubly odd nucleus ^{172}Lu have been populated through the ^{170}Er(^{7}Li, 5n) reaction at a bombarding energy of 51 MeV. The beam was provided by the Tandem XTU accelerator of the Legnaro National Laboratory, Italy, and γ-rays emitted by the reaction residues were detected using the GASP array [18] which consisted of 40 Compton-suppressed large-volume Ge detectors, an inner BGO ball and the charged-particle array ISIS [19]. The ^{170}Er target (enrichment 99.2%) was a self-supporting metallic foil with a thickness of 3.05 mg/cm^2. Events were recorded when ≥ 2 escape suppressed Ge detectors and ≥ 3 BGO scintillators detected γ-rays in coincidence. In total $4 \cdot 10^9$ events have been collected and they were sorted into cubes and matrices using the program Ana [20].

Prior to this work only information on low-spin structures known from decay, (α, t), (^{3}He, d) and (p, 3nγ) studies was available [21]. We assigned six new rotational

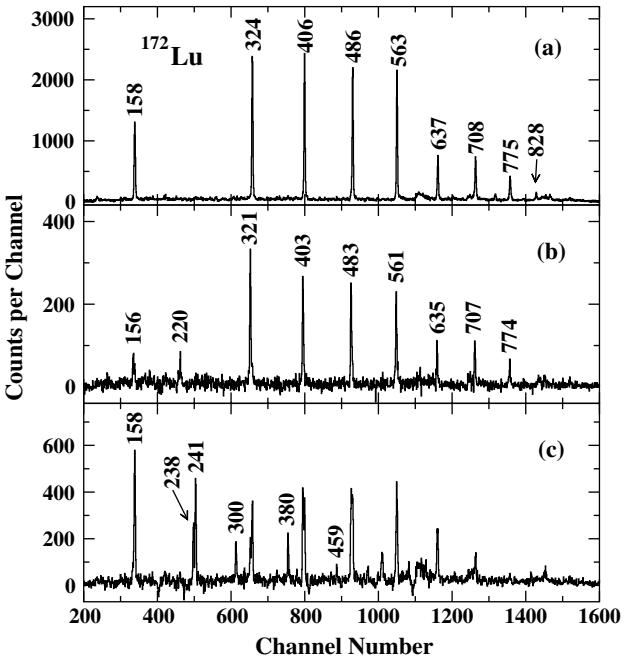

Fig. 2. Doubly gated summed concidence spectra for the identical band in ^{172}Lu. The energies are given in keV. The gating conditions are (a) 241 – (637 + 708 + 775), (b) 238 – (635 + 707 + 774), (c) (158 – 321) + (241 – 403) + (324 – 483).

bands consisting of two signature sequences each [22] to ^{172}Lu taking into account i) the relative population with respect to ^{171}Lu [23] and ^{173}Lu [24,25], populated in the same experiment, ii) the level systematics in comparison to the neighbouring odd-A Lu, Yb and Hf nuclei [26–28], iii) the similarity in the population pattern for various band structures in the odd-odd nuclei ^{170,172}Lu [7,29], iv) the connections to known structures in ^{172}Lu [21] and v) coincidences with X-rays.

The strongest populated band structure being reported here has the two sequences shown in fig. 1. The favoured cascade consists of ten stretched $E2$ transitions, while the unfavoured one, being shifted up in energy away from the yrast line, consists of nine stretched $E2$ transitions. The transition intensities of the unfavoured sequence are of the order of 14% of those of the favoured sequence. In fig. 2(a) and (b) very clearly the two sequences gated on transitions belonging to the favoured and unfavoured sequences, respectively, are shown. The linking $M1$ transitions of 219.5, 299.5, 379.5 and 458.6 keV have $<$ 18% intensity of the transitions in the unfavoured sequence de-exciting the same respective levels. The 219.5 keV transition can be seen in fig. 2(b) and the other ones in a spectrum gated on members of the favoured and unfavoured sequences as shown in fig. 2(c). In this spectrum, transitions from the favoured and unfavoured bands appear as doublets, the 238 and 241 keV lines being marked.

The 1^+–5^+ members of the $\pi 1/2^-[541] \otimes \nu 1/2^-[521]$ band have been assigned from a comparison of experimental and calculated cross-sections in the proton transfer

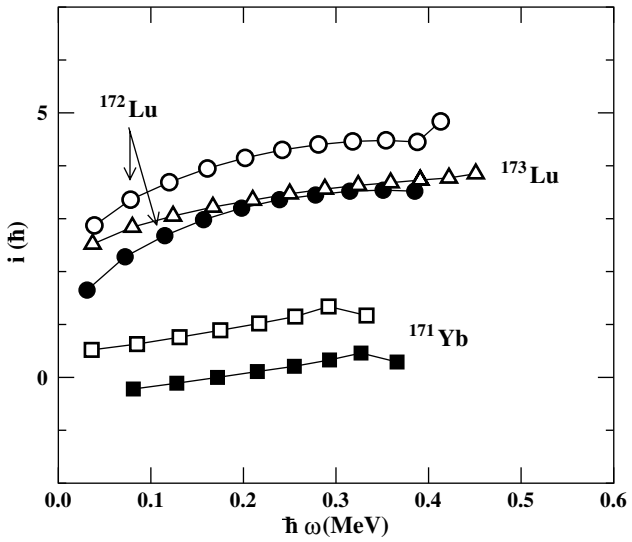

Fig. 3. Aligned angular momenta for the band in ^{172}Lu, the $\pi h_{9/2}$ band in ^{173}Lu and the $\nu 1/2^-[521]$ band in ^{171}Yb. The parameters of the Harris expansion used in the calculations are $\Theta_0 = 39\,\hbar^2/\mathrm{MeV}$ and $\Theta_1 = 50\,\hbar^4/\mathrm{MeV}^3$.

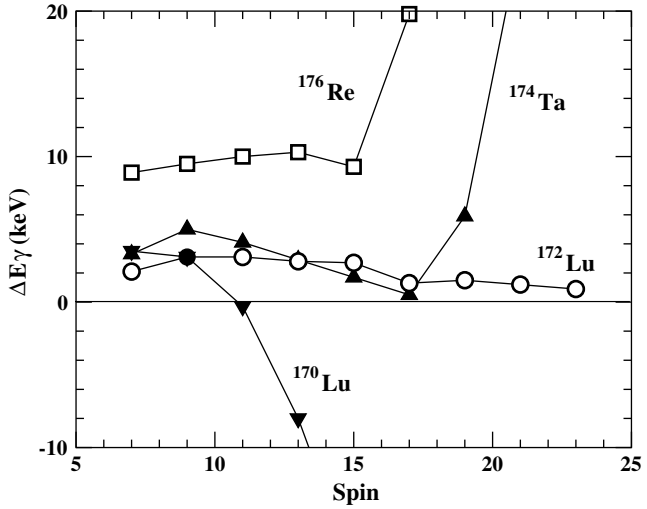

Fig. 4. Comparison of the energy differences of the identical band in ^{172}Lu with those in ^{170}Lu, ^{174}Ta and ^{176}Re.

reactions (α, t) and $(^3\mathrm{He}, \mathrm{d})$ [21]. The transitions between these levels have not been observed in the present experiment. The favoured sequence of the band in ^{172}Lu is considered to start with the strong 158 keV $E2$ transition assigned as $(7^+ \rightarrow 5^+)$ transition, feeding the 5^+ level at 148 keV. In our data the excitation energy of the 4^+ level is calculated to be 212 keV using the sum relations of the 220 and 156 keV transitions, starting from the 5^+ level at 148 keV. This is in good agreement with the energy of 210 keV given in ref. [21].

3 Discussion

Supporting evidence for the configuration assignment to the band of ^{172}Lu shown in fig. 1 comes from the alignment plot of fig. 3. Here, the aligned angular momenta are plotted as a function of the rotational frequency for the favoured and unfavoured sequences in ^{172}Lu in comparison to those of the $\nu 1/2^-[521]$ band in ^{171}Yb [27] and the favoured sequence of the $\pi h_{9/2}$ band in ^{173}Lu [25].

At a rotational frequency of $\hbar\omega = 0.2$ MeV the favoured sequence of the $\pi h_{9/2}$ band in ^{173}Lu has an aligned angular momentum of $i \approx 3.2\hbar$ and those of the $\nu 1/2^-[521]$ band in ^{171}Yb and the band in ^{172}Lu ($\alpha^{\mathrm{f}} = 1$) are $i \approx 1.0$ and $4.2\hbar$, respectively. For the unfavoured sequences of the $\nu 1/2^-[521]$ band in ^{171}Yb and the band in ^{172}Lu ($\alpha^{\mathrm{uf}} = 0$) the aligned angular momenta are $i \approx 0$ and $3.2\hbar$, respectively. For both sequences the additivity rule of aligned angular momenta [30] is very well fulfilled. This result supports the spin-parity and the $\pi 1/2^-[541] \otimes \nu 1/2^-[521]$ configuration assignments for the band in ^{172}Lu.

The differences in transition energies $\Delta E_\gamma = E_{\mathrm{f}}(I \rightarrow I-2) - E_{\mathrm{uf}}(I-1 \rightarrow I-3)$ for the favoured and unfavoured sequences of the $\pi 1/2^-[541] \otimes \nu 1/2^-[521]$ band in ^{172}Lu are shown in fig. 4 in comparison with the corresponding results for ^{176}Re [10,12], ^{174}Ta [9] and ^{170}Lu [7]. The energy differences for ^{172}Lu start at low spin with values of ≈ 3 keV and decrease to ≈ 1 keV for the highest observed spin values. For ^{170}Lu and ^{174}Ta, shown in fig. 4, the energy differences are similar at low spins but deviate significantly at higher spins. For ^{170}Lu, ΔE_γ first decreases but above $I = 17$ increases again and assumes large positive values for the highest spins (not shown in fig. 4). For ^{174}Ta the energy differences increase strongly at higher spins. For ^{176}Re the differences are at low spins ≈ 10 keV and increase strongly at higher spins as well. Hence, the $\pi 1/2^-[541] \otimes \nu 1/2^-[521]$ band in ^{172}Lu may be considered as a very well developed example of an identical band in normal deformed nuclei. Furthermore, it is noteworthy that the difference in the aligned angular momentum is practically constant for the whole spin range, the average value being $\Delta i = 0.97$.

An alignment difference of $\Delta i = 1$ is expected for identical bands and can be explained in the limit of pseudo-spin symmetry [2,31]. The aligned angular momentum of a quasiproton-quasineutron band in an odd-odd nucleus is $i_{\mathrm{np}} = i_{\mathrm{n}} + i_{\mathrm{p}}$. For a $\Omega = 1/2$ orbital the aligned angular momentum is $i = a/2$, a being the decoupling parameter. In the pseudo-spin limit the decoupling parameter is $a = 1$. Hence, for a pseudo-spin singlet configuration the alignment is $i = 1/2$ for the sequence for which the contribution to the signature is $\alpha = 1/2$ and $i = -1/2$ for the sequence involving the $\alpha = -1/2$ component, since the particle is coupled parallel or antiparallel to the rotation axis, respectively. Here, the $1/2^-[521]$ neutron has such features. Considering that the transition energies are almost identical and that $\Delta i \approx 1$ for the band in ^{172}Lu we propose an interpretation as a pseudo-spin singlet band of $\pi 1/2^-[541] \otimes \nu 1/2^-[\widetilde{420}]$ configuration.

The $\nu\ 1/2^-[521]$ ($\nu 1/2^-[\widetilde{420}]$) bands in the odd-$N$ isotones ^{171}Yb [27] and ^{173}Hf [28] have also almost identical energies in the favoured and unfavoured sequences. The differences in transition energies for the two nuclei are 7 and 8 keV, respectively, at low spins and decrease to 0 keV at $I^\pi = 25/2^-$ of the favoured sequences. For higher spins the deviations become larger and in ^{173}Hf a band crossing occurs indicating a configuration change. For the low-spin range the difference in the aligned angular momentum is on average $\Delta i = 0.89$ for both nuclei. This probably means that the pseudo-spin nature is not fully developed in these bands. Probably, the $h_{9/2}$ proton, being aligned along the rotation axis as well, is needed to stabilize the pseudo-spin mechanism in ^{172}Lu.

4 Summary

The two sequences of a new identical band have been observed in ^{172}Lu. The nucleus has been populated in a ^{170}Er(^{7}Li, 5n) reaction and the emitted γ-radiation was detected with the GASP array. The transition energies of the corresponding transitions in the favoured and unfavoured sequences of the band are identical within ≈ 3 keV at low spins and ≈ 1 keV at high spins over the whole observed spin range. The difference in aligned angular momenta of the favoured and unfavoured sequences is $\Delta i \approx 1$. Therefore, we propose for the band in ^{172}Lu an interpretation as a pseudo-spin singlet band of $\pi 1/2^-[541] \otimes \nu 1/2^-[\widetilde{420}]$ configuration. It represents the best example of a pseudo-spin singlet band in normal deformed nuclei known until now.

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