Eur. Phys. J. A **18**, 577–581 (2003)
DOI 10.1140/epja/i2003-10068-4

THE EUROPEAN PHYSICAL JOURNAL A

Short Note

Delayed crossing in the $\pi h_{9/2}$ $1/2^-[541]$ band of ^{173}Lu

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Received: 19 May 2003 /
Published online: 11 November 2003 –
Communicated by D. Schwalm

Abstract. High-spin states in the odd-proton nucleus ^{173}Lu have been populated in a ^{170}Er(^{7}Li,4n) reaction and the emitted γ-radiation was detected with the GASP array. The favoured and unfavoured sequences of the $\pi 1/2^-[541]$ band have been considerably extended. The favoured sequence does not show any indication of a band crossing up to a rotational frequency of ≈ 0.45 MeV. This is the largest crossing frequency ever observed for $1/2^-[541]$ bands of odd-proton nuclei with $67 \le Z \le 77$ and $90 \le N \le 106$. Previous Cranked Shell Model (CSM) calculations underestimate the crossing frequency by 100 keV.

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 $150 \le A \le 189$

1 Introduction

The phenomenon of delayed alignment of $i_{13/2}$ neutrons in the $h_{9/2}$ bands of odd-proton nuclei in the rare-earth region is well established in many Ho to Ir nuclei with neutron numbers $90 \le N \le 106$ [1–11]. The band crossings occur in these $1/2^-[541]$ $h_{9/2}$ proton bands at considerably larger frequencies than those in their even-even neighbours and they are systematically delayed as compared to the alignment in the other bands of the same odd-proton nuclei. This phenomenon was first noticed in studies of band crossings [12–15] and has been investigated in systematic studies of delayed crossings in odd-Z Ho-Ir isotopes [2,3,8,16]. A complete list of experimental crossing frequencies and alignments for these nuclei is given in the work of Jensen *et al.* [3]. The interpretation of this anomalous band crossing behaviour of the $1/2^-[541]$ bands is a longstanding problem. It has initially been assumed that deformation changes would cause these shifts in the crossing frequencies [15], but when deformations predicted from Potential Energy Surface (PES) calculations were used to evaluate the shifts with the Cranked Shell Model (CSM) [17] an underestimate was obtained [3]. It has, therefore, been proposed that proton-neutron interactions play an important role for the shifts of the crossing frequencies [18]. From empirical estimates of the shifts due to proton-neutron interactions it has been concluded that a combination of deformation changes and residual interactions can qualitatively account for the observed shifts [19]. Another approach to the problem of the delayed crossings in the $1/2^-[541]$ bands are Projected Shell Model (PSM) [20–22] calculations which are able to give a possible explanation for the observed shifts in the crossing frequencies [21].

We report here about new results for the $1/2^-[541]$ band observed in the odd-proton nucleus ^{173}Lu showing no band crossing up to a rotational frequency of 0.45 MeV.

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2 Experimental methods and results

High-spin states in the odd-Z nucleus ^{173}Lu were populated through the ^{170}Er(^{7}Li,4n) reaction at a bombarding energy of 51 MeV. The beam was provided by the Tandem XTU accelerator of the Legnaro National Laboratory,

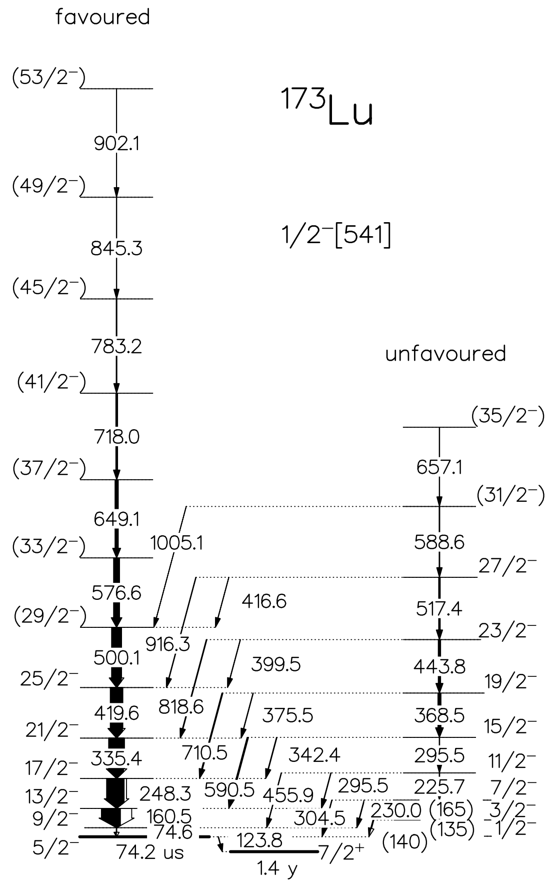

Fig. 1. Partial level scheme of ^{173}Lu. Uncertain spin-parity assignments are given in brackets. The widths of the arrows represent the intensities of the transitions. Transitions in brackets have been taken from [23,24].

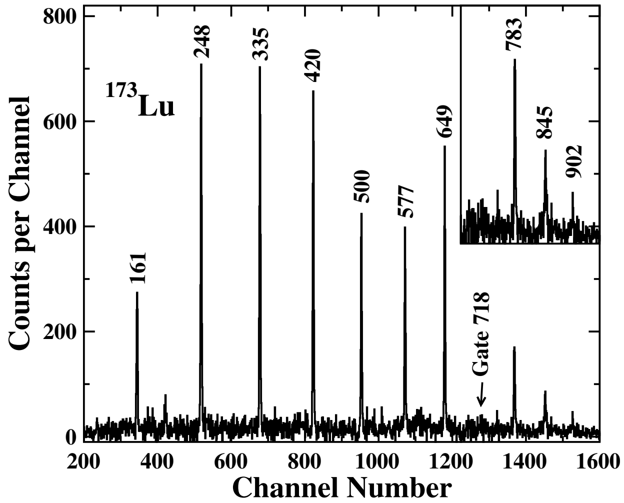

Fig. 2. Doubly gated summed concidence spectrum for the $1/2^-[541]$ band in ^{173}Lu. On one axis the gate has been placed on the new 718 keV transition, as indicated, and on the other axis on the 161, 500, 577 keV lines. In the inset the high-energy part of the spectrum is shown in an enlarged scale. The energies are given in keV.

Italy and γ-rays emitted by the reaction residues were detected using the GASP array [25] which consisted of 40 Compton-suppressed large-volume Ge detectors, an inner BGO ball and the charged-particle array ISIS [26]. The ^{170}Er target (enrichment of 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 were sorted in cubes and matrices using the program Ana [27].

In a prior work on this nucleus [23,24] five rotational bands have been identified. They are based on the $7/2^+[404]$, $1/2^-[541]$, $9/2^-[514]$, $1/2^+[411]$ and $5/2^+[402]$ quasiproton excitations and were previously observed up to $I^\pi = 23/2^+$, $25/2^-$, $23/2^-$, $17/2^+$ and $19/2^+$, respectively. We extended the ^{173}Lu level scheme to much higher spins and established three new three-quasiparticle bands [28] similar to the bands in ^{171}Lu [10].

Here we report about the behaviour of the favoured and unfavoured sequences of the $1/2^-[541]$ band. The favoured sequence forms the yrast states. A partial level scheme of ^{173}Lu is shown in fig. 1. A coincidence spectrum showing the favoured sequence of the $1/2^-[541]$ band is displayed in fig. 2. This sequence has been extended up to $I^\pi = (53/2^-)$ assuming that the new transitions are of stretched $E2$ character. Their order is based on transition intensities. The unfavoured sequence, from previous work known up to the $19/2^-$ level [23,24], is ≈ 6 times more weakly populated than the favoured one and has been extended to $I^\pi = (35/2^-)$. It de-excites by $\Delta I = +1$ and $\Delta I = -1$ transitions into the favoured sequence.

3 Discussion

Plots of the aligned angular momentum as a function of the rotational frequency are shown in fig. 3a for the favoured sequences ($\alpha = +1/2$) of the $1/2^-[541]$ bands in the nuclei ^{165,167,169,171,173}Lu [7–10]. The alignment of the first $i_{13/2}$ quasineutron pair occurs for ^{165,167,169,171}Lu at a rotational frequency of ≈ 0.33 MeV, whereas in ^{173}Lu no band crossing can be seen until ≈ 0.45 MeV. In fig. 3b the alignment behaviour of the $1/2^-[541]$ ($\alpha = +1/2$) sequence of ^{173}Lu is compared to those of the neighbouring odd-mass nuclei ^{175,177}Ta [5,6] and that of the yrast band in the even-mass nucleus ^{174}Hf [29] which is the isotone of ^{173}Lu and ^{175}Ta. In the case of ^{175}Ta [6] the $\nu i^2_{13/2}$ band crossing occurs at $\hbar\omega = 0.38$ MeV, which is significantly delayed with respect to that of the yrast band of ^{174}Hf [29] for which the crossing frequency is $\hbar\omega = 0.31$ MeV. The alignment plot for ^{177}Ta shows a smooth behaviour up to $\hbar\omega = 0.44$ MeV. From a detailed investigation of this alignment behaviour Archer *et al.* [5] concluded that the band in ^{177}Ta shows a band crossing at $\hbar\omega \approx 0.39$ MeV but that, in contrast to the other bands, it involves a much larger interaction strength.

In fig. 3b the alignment behaviour of the $1/2^-[541]$ ($\alpha = +1/2$) sequences of ^{173}Lu and ^{177}Ta looks similar.

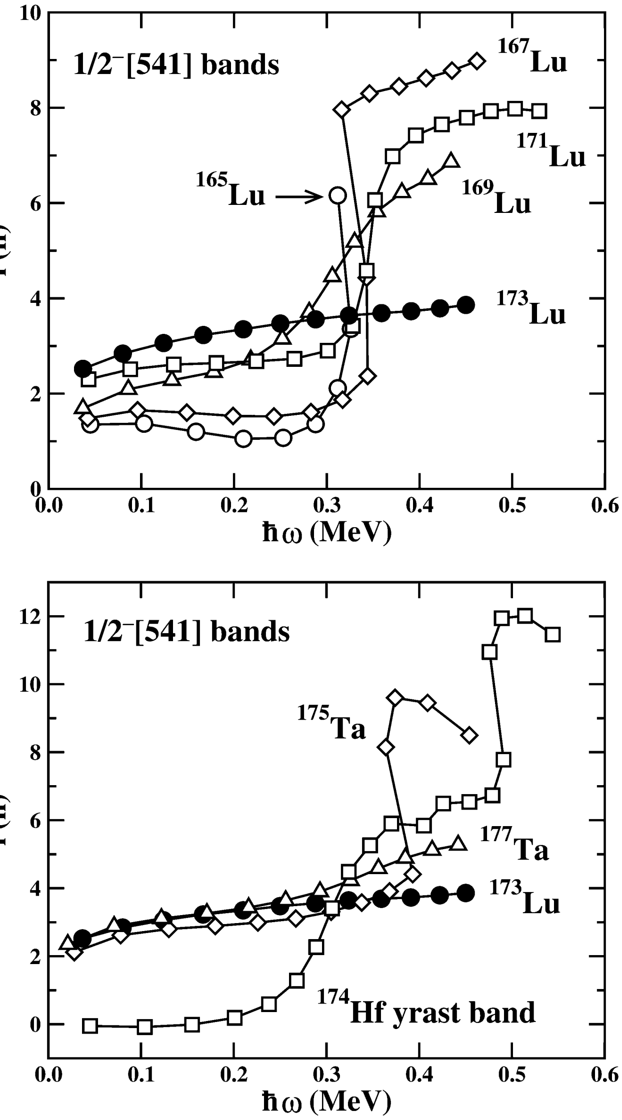

Fig. 3. (a) Aligned angular momentum *vs.* rotational frequency for the favoured sequences ($\alpha = +1/2$) of the $1/2^-[541]$ bands in the odd-mass nuclei $^{165-173}$Lu. (b) Same but for the $1/2^-[541]$ bands in the odd-mass nuclei ^{173}Lu and ^{175,177}Ta as well as for the yrast band of the neighbouring even-mass nucleus ^{174}Hf. The parameters of the Harris expansion used in the calculations are $\Theta_0 = 39\ \hbar^2$/MeV and $\Theta_1 = 50\ \hbar^4/\mathrm{MeV}^3$ for ^{173}Lu, $\Theta_0 = 36\ \hbar^2$/MeV and $\Theta_1 = 54\ \hbar^4/\mathrm{MeV}^3$ for ^{175,177}Ta and $\Theta_0 = 34\ \hbar^2$/MeV and $\Theta_1 = 59\ \hbar^4/\mathrm{MeV}^3$ for ^{174}Hf.

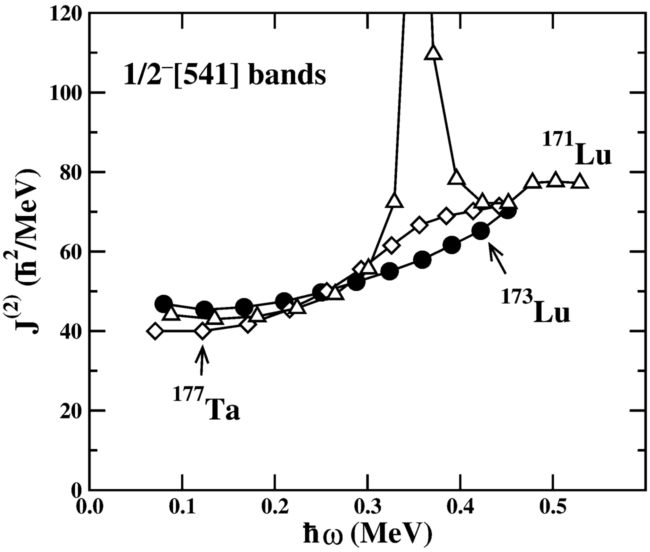

Fig. 4. Dynamic moment of inertia *vs.* rotational frequency for the favoured sequences of the $1/2^-[541]$ bands in the odd-mass nuclei ^{171,173}Lu and ^{177}Ta.

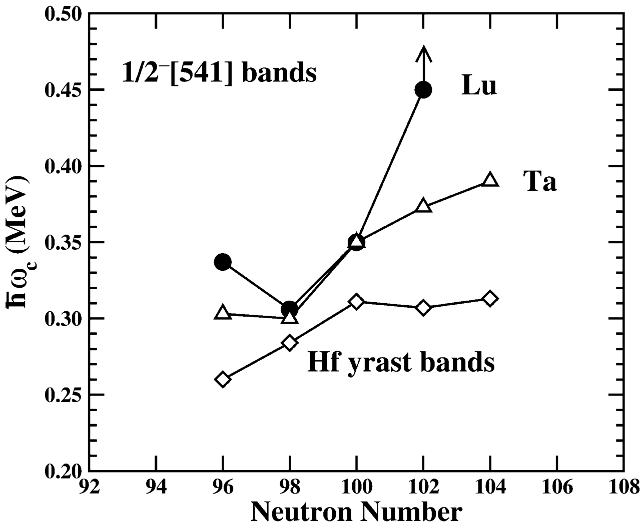

Fig. 5. Crossing frequency for the alignment of the first $i_{13/2}$ quasineutron pair *vs.* neutron number for the favoured sequences of the $1/2^-[541]$ bands in odd-mass Lu and Ta nuclei and for the yrast bands in even-mass Hf nuclei.

However, if one inspects the more sensitive plot of the dynamic moment of inertia *vs.* rotational frequency for these two bands, shown in fig. 4, then one can see a different behaviour. For comparison also the $1/2^-[541]$ ($\alpha = +1/2$) sequence of ^{171}Lu is included in the diagram. This band shows a strong increase of the dynamic moment of inertia at the band crossing, typical for a sudden increase of the aligned angular momentum. For ^{177}Ta a small but clear increase of the dynamic moment of inertia can be seen at the band crossing supporting the interpretation of Archer*et al.* [5]. For ^{173}Lu the behaviour is clearly different. No change in curvature can be seen up to the highest observed frequencies. Therefore, it has been concluded that no band crossing occurs for the $1/2^-[541]$ band of ^{173}Lu up to a rotational frequency of 0.45 MeV. This is the largest crossing frequency ever observed in $1/2^-[541]$ bands of odd-proton nuclei with $67 \le Z \le 77$ and $90 \le N \le 106$.

In fig. 5 the crossing frequencies $\hbar\omega_c$ for the favoured sequences of the $1/2^-[541]$ bands in odd-mass Lu and Ta nuclei and for the yrast bands in even-mass Hf nuclei are plotted as a function of the neutron number. It can be seen that the alignment of the $i_{13/2}$ quasineutron pair is delayed for the $1/2^-[541]$ bands in the Lu and Ta nuclei as compared to that of the yrast bands in the Hf nuclei. The delay is on average 45 keV, similar to that of all $1/2^-[541]$ bands in the odd-mass Ho to Ir nuclei [3]. For ^{173}Lu the delay is considerably larger, *viz* > 140 keV.

Several approaches have been used to calculate the crossing frequencies in order to understand the origin of the delayed crossings observed for intruder configurations, *e.g.*, the $1/2^-[541]$ configuration. In the thorough investigation of Jensen *et al.* [3] CSM calculations of crossing frequencies have been carried out. The predicted crossing frequencies for the yrast bands in even-mass Er to W nuclei lying in the considered region of neutron numbers underestimate already the observed values by around 45 keV and overestimate the alignment gains. The reason for the discrepancies is not understood but may be related to pairing. The predicted crossing frequencies for the $1/2^-[541]$ bands are between ≈ 45 and 100 keV too small and the predicted alignment gains are $1 - 3\hbar$ too large. Taking into account that the deformation of the odd-mass nuclei increases by $\approx 10\%$ if the $1/2^-[541]$ band is excited, as found in lifetime measurements, the predicted crossing frequencies are shifted only to ≈ 20 keV higher frequencies so that the discrepancies remain [3].

Since the CSM fails to describe the band crossing also after varying deformation and pairing parameters within an acceptable range, it has been proposed to consider the influence of residual interactions between the $h_{9/2}$ proton and $i_{13/2}$ neutrons on the crossing frequency [18]. They lead to an additional configuration mixing in the band crossing region where the spin alignment takes place and cause a shift of the crossing frequency. A shift of 17 to 40 keV was empirically estimated for bands in ^{173,174}Ta and ^{173}Hf involving the $1/2^-[541]$ configuration and it was concluded that a combination of deformation change and residual interaction can qualitatively account for the entire shift in many cases [19].

For the $1/2^-[541]$ band in ^{173}Lu the CSM calculations predict $\hbar\omega_c = 0.35$ MeV [3] which is 100 keV smaller than the observed lower limit. Even if an additional shift of 20 keV due to a deformation change and of 40 keV due to residual proton-neutron interactions is taken into account, the observed crossing frequency cannot be explained.

Projected Shell Model (PSM) calculations have recently been used to reproduce the delayed crossings of $1/2^-[541]$ bands in odd-mass Lu to Ir nuclei [21]. For PSM calculations the shell model basis is built by selecting configurations from deformed single-particle states and performing the angular-momentum projection exactly. It allows to treat heavy nuclei in a shell model framework so that important nuclear correlations are taken into account [22]. Particular attention was given to the $1/2^-[541]$ band in ^{175}Ta (isotone of ^{173}Lu) and to the yrast bands of the neighbouring even-mass nuclei ^{174}Hf and ^{176}W, since their crossings frequencies should be described in a consistent manner [6,20,21]. The crossing frequency for the $1/2^-[541]$ band in ^{175}Ta can be described very well by varying the quadrupole pairing strength. The predicted alignment gain is $\approx 2\hbar$ smaller than the observed one. It was concluded from the PSM calculations that the quadrupole pairing force plays an important role in the delay of the band crossing. The quadrupole pairing interaction prevents the alignment from occuring too soon [6, 20,21]. In case of the neighbouring even-mass nuclei the crossing frequencies can be reproduced as well, however the quadrupole pairing strength is somewhat smaller than for ^{175}Ta [6,20,21]. For the $1/2^-[541]$ bands in the odd-mass Ta isotopes the interaction strength of the crossing bands $|V_{\text{int}}|$ has been determined in PSM calculations [5] showing the typical oscillatory behaviour as a function of the neutron number with a maximum for ^{171}Ta and a very large one for ^{177}Ta. For the latter nucleus the calculated crossing frequency is $\hbar\omega_c = 0.36$ MeV as compared to the experimental value of 0.39 MeV. The observed variation of the "sharpness" of the band crossings for the $1/2^-[541]$ bands in $^{169-177}$Ta is reproduced by the PSM calculations. PSM calculations for the $1/2^-[541]$ band in ^{173}Lu are desirable to see whether the unusually large value of the crossing frequency can be explained.

4 Summary

The favoured and unfavoured sequences of the $1/2^-[541]$ band in the odd-proton nucleus ^{173}Lu have been extended from $25/2^-$ to $53/2^-$ and from $19/2^-$ to $35/2^-$, respectively. The nucleus has been populated in a ^{170}Er(^{7}Li,4n) reaction and the emitted γ-radiation was detected with the GASP array. The favoured sequence does not show any indication of a band crossing up to a rotational frequency of 0.45 MeV. This is the largest crossing frequency ever observed in $1/2^-[541]$ bands of odd-proton nuclei with $67 \leq Z \leq 77$ and $90 \leq N \leq 106$. Previous Cranked Shell Model (CSM) calculations give a crossing frequency of 0.35 MeV. Even if an additional shift of 20 keV due to a deformation change and of 40 keV due to residual proton-neutron interactions is taken into account, the observed crossing frequency cannot be explained. Projected Shell Model (PSM) calculations for the $1/2^-[541]$ band of the isotone ^{175}Ta allowed to reproduce its crossing frequency. Hence, PSM calculations for ^{173}Lu are desirable to see whether the unusually large value of the crossing frequency for the $1/2^-[541]$ band can be explained as well.

We are grateful to D.J. Hartley for communicating information on the level scheme of ^{174}Hf to us prior to publication. The GASP experiment was performed at Legnaro and was financially supported under the EU contracts ERB-FMGECT-980110 and HPRI-CT-1999-00083. Financial support from the Deutsche Forschungsgemeinschaft (DFG) by the grant 436 BUL 17/7/02 for the stay of Ts.V. in Jülich is gratefully acknowledged.

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