Journal of Physics: Conference Series

PAPER • **OPEN ACCESS**

Triaxiality-related nuclear phenomena in the $A \approx 100$ mass region

To cite this article: J. Timár *et al* 2020 *J. Phys.: Conf. Ser.* **1555** 012025

Triaxiality-related nuclear phenomena in the $A \approx 100$ mass region

J. Timár[1], **B. Kruzsicz**[1], **I. Kuti**[1], **D. Sohler**[1], **J. Molnár**[1], **B.M. Nyakó**[1], **Q.B. Chen**[2], **S.Q. Zhang**[3], **J. Meng**[3], **P. Joshi**[4], **R. Wadsworth**[4], **K. Starosta**[5], **T. Koike**[6]

[1] Institute for Nuclear Research, Hungarian Academy of Sciences, H-4026 Debrecen, Hungary
[2] Physik-Department, Technische Universität München, D-85747 Garching, Germany
[3] State Key Laboratory of Physics and Technology, School of Physics, Peking University, Beijing 100871, China
[4] Department of Physics, University of York, York, YO10 5DD, United Kingdom
[5] Department of Chemistry, Simon Fraser University, Burnaby, British Columbia V5A 1S6, Canada
[6] Graduate School of Science, Tohoku University, Sendai, 980-8578, Japan

E-mail: timar@atomki.hu

Abstract. Solid experimental evidence for triaxial nuclear shape is difficult to obtain and is quite rare. Such evidence can be provided by the phenomena of chiral rotation and wobbling motion, as these can occur only in triaxially deformed nuclei. Although nuclear chirality is well documented in different mass regions, experimental evidence for multiple chiral bands as well as for wobbling motion has been reported so far only in a few nuclei. Pd and Rh nuclei in the $A \approx 100$ mass region have been recently studied, and transverse wobbling motion as well as multiple chiral band structures were identified for the first time in this region. These observations provide experimental evidence for the predicted triaxial shape in this mass region, and new data which enable a better understanding of the studied phenomena.

1. Introduction

Observed rotational spectra in nuclei show us that many nuclides have deformed shape. Among them there are nuclides with non axially symmetric, triaxial shapes, which allow exotic types of rotation. Such exotic rotation types are the wobbling motion and the chiral rotation. The special rotational band structure corresponding to one of these exotic rotations can provide a key evidence for stable triaxial shape of the nucleus at medium to high angular momentum.

In the case of wobbling motion the nucleus rotates around the principal axis having the largest moment of inertia and this axis executes harmonic oscillations about the space-fixed angular momentum vector. Its analog in classical mechanics is the motion of a free asymmetric top, while in quantal systems it is due to the rotation of molecules having different moments of inertia for the three principal axes. The expected energy spectra related to this motion are characterized by a series of rotational E2 bands corresponding to the different oscillation quanta (n). The signature quantum number of the consecutive bands is different, thus the yrast and yrare bands (corresponding to n=0 and n=1, respectively), look like signature partner bands with large signature splitting. The yrare band decays by ΔI=1 M1+E2 transitions to the yrast band; however, contrary to the case of signature partners, the mixing ratio is very large and the transition has predominant E2 character. The possibility of nuclear wobbling motion was first discussed by Bohr and Mottelson [1] for the case of even-even nuclei. However, all the observed cases so far belong to odd-mass nuclei. Moreover, in spite of its importance and the fact that this phenomenon has been predicted long time ago, experimental evidence for it could be gained only in a handful of nuclei. Experimentally this type of rotation was identified first in the triaxial strongly-deformed ^{163}Lu nucleus [2], followed soon by other neighboring odd-A Lu nuclei and ^{167}Ta where wobbling was observed in the same one-proton configuration as in ^{163}Lu. The first and only observation of the phenomenon in a normal-deformed nucleus before our studies was in ^{135}Pr [3]. Wobbling of odd-mass nuclei was classified as longitudinal and transverse wobbling by Frauendorf and Dönau [4]. For the latter they have shown that the wobbling frequency is expected to decrease with increasing rotational frequency in agreement with the experimental results.

Nuclear chirality was predicted by Frauendorf and Meng about two decades ago [5]. They have shown that at certain configurations of the active valence nucleons in a rotating triaxial nucleus the total angular momentum vector can lie outside the three principal planes in the intrinsic frame. This is called chiral geometry. Thus, the components of the angular momentum vector along the principal axes can be arranged in two different ways which are chiral partners of each other. In the laboratory frame the chiral symmetry is restored, which manifests itself as a nearly degenerate $\Delta I = 1$ band pair with the same parity. Such chiral band pairs were first identified in four $N = 75$ isotones [6]. To date, many chiral candidate doublet bands have been reported in nuclei belonging to different mass regions. A recent overview of them is given in Ref. [7]. A most recent aspect of nuclear chirality is the appearance of multiple chiral bands in nuclei. It was predicted by Meng et al. [8] that two or more chiral band pairs can be formed in a single nucleus. The first experimental evidence for the predicted phenomenon has been reported in ^{133}Ce [9].

Recently we have studied the possible occurrence of both of these phenomena in the $A \approx 100$ mass region in the Pd and Rh nuclei. We have found experimental evidence for the existence of both phenomena in that mass region in good agreement with the predicted triaxial shape of these nuclei.

2. Transverse wobbling in ^{105}Pd

No nuclear wobbling motion has been reported in the $A \approx 100$ mass region before our present investigation, in spite of the fact that strong deviation from the axially symmetric shape had been predicted for these nuclei close to the ground state [10]. Furthermore, all the (odd mass) nuclei in which wobbling have been observed until now are characterized by odd proton number and even neutron number. Therefore, ^{105}Pd looked a good choice to look for wobbling motion in a new mass region and corresponding to a new type of configuration.

High-spin excited states of ^{105}Pd have been populated using the ^{96}Zr(^{13}C,4n) fusion-evaporation reaction at IReS, Strasbourg. The ^{13}C beam, which was provided by the Vivitron accelerator at energies of 51 MeV and 58 MeV impinged upon a stack of two self supporting metallic foil targets being enriched to 86% in ^{96}Zr, and each having a thickness of 558 μg/cm^2. The emitted γ-rays were detected by the EUROBALL IV spectrometer equipped with 15 Cluster detectors at backward angles and 24 Clover detectors at 90° relative to the beam direction. The highly efficient DIAMANT charged-particle detector array consisting of 88 CsI detectors has been used as an off-line veto to suppress the contaminants from the charged-particle reaction channels. A total of $\sim 2 \times 10^9$ triple- and higher-fold coincidence events were obtained and stored onto magnetic tapes. The majority of these events belonged to the ^{105}Pd channel.

The level scheme of ^{105}Pd has been constructed using the Radware analysis package [11] on the basis of the triple-coincidence relations taking into account the energy and intensity balances of the observed γ-rays, too. Many new rotational bands have been observed in the studied nucleus. Among them there are several negative-parity quadrupole bands with probable neutron $h_{11/2}$ high-j configuration. Two of these bands have opposite signature than the previously known, yrast neutron $h_{11/2}$ band. Fig. 1 shows the yrast neutron $h_{11/2}$ band (band A) up to spin $43/2\ \hbar$, the two newly identified bands with different signature (bands B and C), and another new band (band D) with the same signature than that of the yrast band. A few coincidence spectra proving the placements of the gamma-ray transitions in the bands B and C are presented in Fig. 2.

The arrangement of the clover and cluster detectors in the EUROBALL IV spectrometer enabled us to measure linear polarizations and directional correlation from oriented states (DCO) ratios [12, 13] for the transitions of sufficient intensity. Using these data we have determined the multipolarities of the strong inband and interband transitions. The inband transitions are proved to have the expected E2 characters. For the 991 keV, 1034 keV and 994 keV interband transitions from band B to band A M1+E2 character has been derived with large multipole mixing ratios. The obtained δ multipole mixing ratios for them are 1.8(5), 2.3(3) and 2.7(6), respectively. These mixing ratios correspond to around 80% E2 content (calculated as $\delta^2/(1+\delta^2)$), which is expected for the wobbling band, but not expected for the signature partner band.

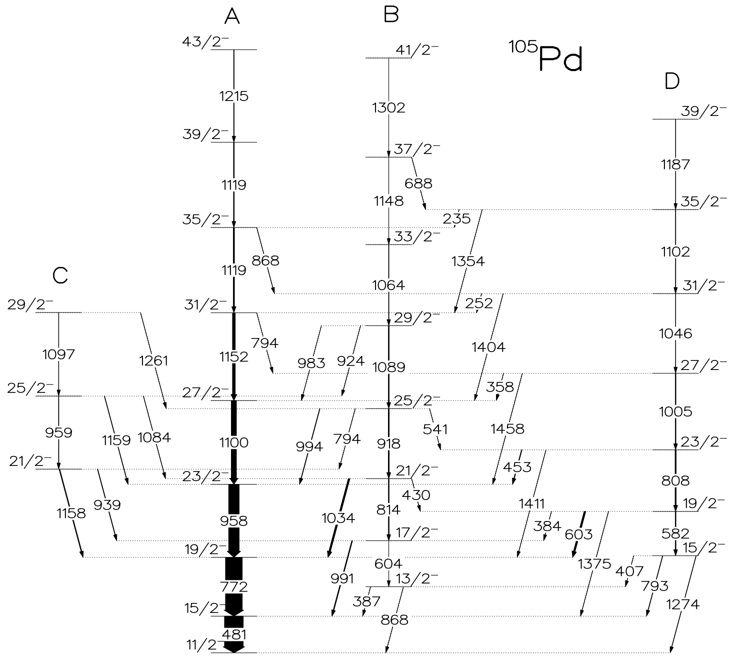

Figure 1. Partial level scheme of ^{105}Pd showing the yrast (A) and the newly observed bands (B, C, D).

The parity of band B and the spins of the levels in it are deduced from the measured multipolarities of the 991 keV, 1034 keV and 994 keV interband transitions. Together with the E2 characters of the inband transitions, they provide consistently the $17/2^-$, $21/2^-$ and $25/2^-$ spin-parity values for the levels decaying by the 991, 1034 and 994 keV transitions, respectively. Although the decay-out transitions from band C were not intense enough for DCO and linear polarization measurements, the parity of this band and the spins of its levels are fixed by the E2 gamma transition pairs feeding the band C levels from band B and going from these levels back to the band B levels. Such transitions are the 794 keV - 939 keV and the 924 keV - 1084 keV pairs. They both carry altogether 4 units of angular momenta. Taking into account that emission of M2, E3 or higher multipolarity transitions competing with the inband E2 transitions is very unprobable, these transitions must have E2 multipolarities, which fixes unambiguously the spins and parities in band C. The parity of band D and the spins of its levels can be determined similarly based on the 794 keV - 1458 keV and the 868 keV - 1404 keV transition pairs between bands D and A.

The observed three bands of A, B and C show the features of a pair of transverse wobbling bands with oscillation quanta zero and one (bands A and B, respectively) and the signature partner band of band A (band C).

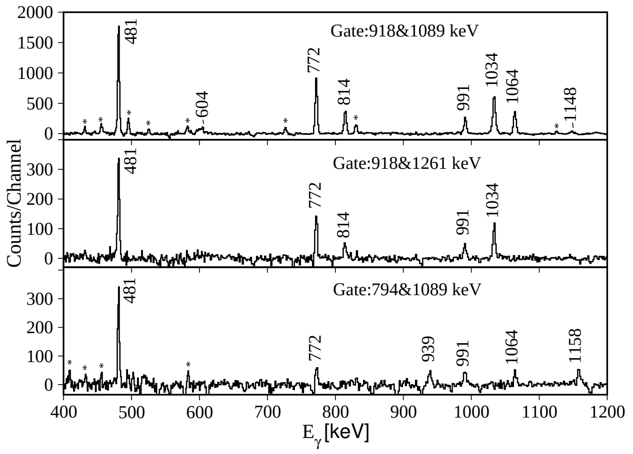

Figure 2. γ-γ-γ coincidence spectra confirming the placements of bands B and C. Stars denote transitions belonging to ^{105}Pd, but placed at higher energy.

The wobbling frequency derived from the level energies of bands B and A (as shown by the length of arrow in Fig. 3) shows a decreasing pattern up to spin 33/2 $\hbar$, thus the observed wobbling in ^{105}Pd is transverse wobbling.

In order to explore the nature of the observed rotational band structures in ^{105}Pd, they have been studied by the constrained triaxial covariant density functional theory (CDFT) [8] as well as the quantum particle rotor model (PRM) [14, 4, 15]. The calculated energy spectra as functions of spin I for bands A (solid line), B (short dash line), and C (short dash-dot line), in comparison with those of the experimental data, are shown in Fig. 3. It is seen that the PRM with $h_{11/2}$ configuration calculations can reproduce the data of bands A and B well up to the angular momentum of about 35/2 $\hbar$. At higher spins both in bands A and B the configuration changes due to the gradual alignment of a pair of $h_{11/2}$ neutrons and of $g_{9/2}$ protons, respectively. The wobbling frequency calculated from the level energies shows an increasing pattern in this spin region. However, this pattern is attributed to the alignments and not to longitudinal wobbling. For band C, the energies are overestimated by about 500 keV. A similar deviation between the theoretical and experimental data is also seen in Ref. [3] for ^{135}Pr. The calculations reproduce well the electromagnetic properties of the transitions in the wobbling bands.

These results prove the occurrence of transverse wobbling motion in ^{105}Pd, which is the first observation of wobbling in this mass region and in a nucleus with odd neutron number [16]. According to these results band B corresponds to the n=1 wobbling band. It is straightforward now to search for the n=2 band, too. Indeed, very recently the n=2 band has been observed in ^{135}Pr [17]. Band D could in principle correspond to the n=2 wobbling band taking into account its parity and the spin values of the levels. Unfortunately the 407 keV and 384 keV M1+E2 transitions from the first and second levels of band D to band B are quite weak. We could not get DCO and polarization values for them. Thus the mixing ratios could not be deduced for them.

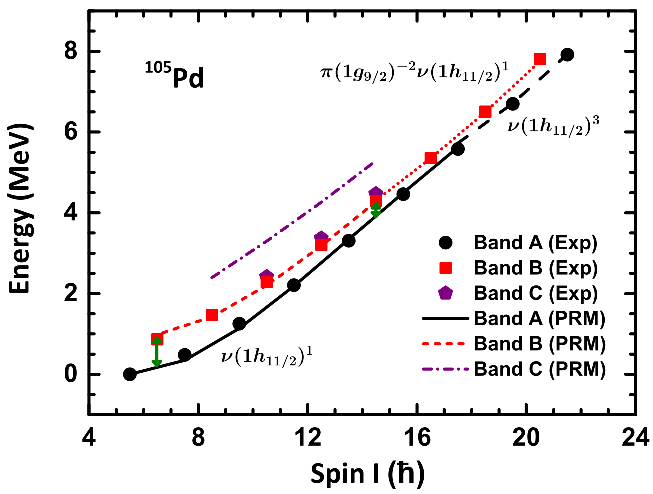

Figure 3. Experimental and PRM energy spectra of bands A, B and C.

3. Multiple chiral doublet bands in ^{103}Rh and ^{104}Rh

In order to search for multiple chiral doublet bands in the $A \approx 100$ mass region, we have studied the medium- and high-spin band structures of ^{103}Rh based on the high-statistics data set measured with the Gammasphere spectrometer at LBNL using the ^{96}Zr(^{11}B,4n) fusion-evaporation reaction at a beam energy of 40 MeV. For the experimental details see Ref. [18]. A more complete level scheme of ^{103}Rh has been constructed containing several new negative- and positive-parity bands. Four negative-parity bands could be grouped into two band pairs showing the characteristics of chiral band pairs.

To understand the nature of the observed band structure, adiabatic and configuration-fixed constrained CDFT calculations [8], as well as tilted axis cranking CDFT (TAC-CDFT) calculations [19] were performed together with quantum particle rotor model calculations [14, 5], and the results were compared with the experimental data. These comparisons revealed that the observed four negative-parity bands can be described as the first four bands corresponding to the $\pi(g_{9/2})\otimes\nu(h_{11/2})(g_{7/2}, d_{5/2})$ configuration. Moreover, they form two chiral band pairs. Thus, besides the known positive-parity chiral band pair, there are two additional chiral band pairs in ^{103}Rh. The observed multiple chiral doublet bands in the negative-parity bands of ^{103}Rh are built from the first and second doublets of the same configuration [20]. This is a different case from that of predicted in Ref. [8] and experimentally reported in ^{133}Ce [9]. Observation of such type of multiple chiral doublet bands shows that the chiral geometry in nuclei can be robust against the increase of the intrinsic excitation energy. These results were published in Ref. [18].

Using the data provided by the same experiment, we have conducted a search for multiple chiral doublet bands also in ^{104}Rh. The medium-spin positive-parity band structure of this nucleus was less known before our present investigation. Based on this work we have observed five new positive-parity medium-spin bands in ^{104}Rh. These bands are close to each other in energy, and their quasiparticle alignment values are also close to each other. In Fig. 4 the quasiparticle alignments of the five new bands are compared with that of the $\pi(g_{9/2})\otimes\nu(h_{11/2})$ configuration band. It can be seen that the alignment values of bands 1 and 3, as well as bands 2 and 4 are especially close to each other in a certain region. According to the large, $\sim 12\hbar$, alignment values of the new bands, and on their positive parities, their configurations are very probably $\pi(g_{9/2})\otimes\nu(h_{11/2})^2(g_{7/2}, d_{5/2})$. This is the configuration for which chirality has been predicted among the positive-parity configurations [21]. Based on these preliminary results, it is possible that the observed five bands contain one or two chiral band pairs. Thus, besides the two negative-parity chiral band pairs, possibly one or two positive-parity chiral band pairs also exist in

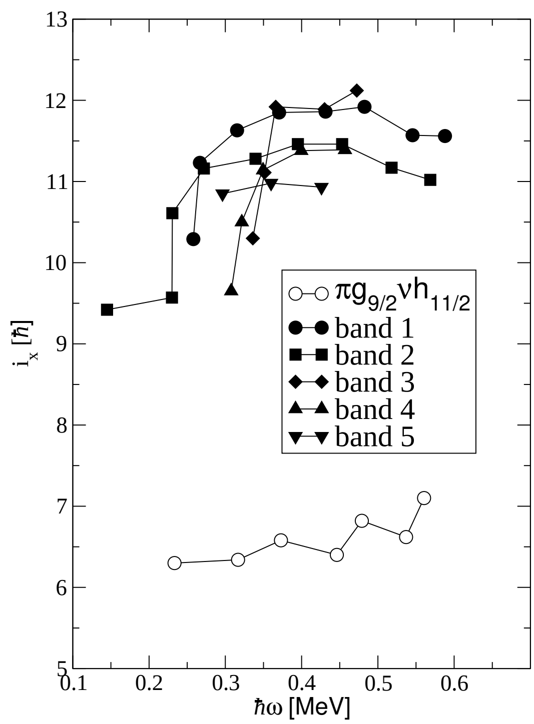

Figure 4. Quasiparticle alignments of the new positive-parity bands in ^{104}Rh compared with that of the $\pi(g_{9/2})\otimes\nu(h_{11/2})$ band.

^{104}Rh, which would show that multiple chiral doublet bands exist not only in odd-A, but also in odd-odd nuclei in this region.

4. Conclusion

Medium- and high-spin band structures of ^{103}Rh, ^{104}Rh and ^{105}Pd have been studied in two experiments. The properties of the observed band structures were compared with constrained covariant density functional theory and particle rotor model calculations. Experimental properties of one of the observed negative-parity bands in ^{105}Pd are characteristic of transverse wobbling motion. The transverse wobbling scenario is confirmed by the results of the calculations. Thus, this is the first wobbling case observed in the $A \approx 100$ mass region and in a nucleus with odd neutron number. Multiple chiral doublet bands have been found in ^{103}Rh, which is the first observation of this phenomenon with bands built on the same configuration. Preliminary results show possible multiple chiral doublet bands in ^{104}Rh, too. These results confirm the expected triaxial shape of nuclei in this mass region.

Acknowledgements

This work was supported by the National Research, Development and Innovation Fund of Hungary, financed under the K18 funding scheme with project no. K128947. This work was also supported by the European Regional Development Fund (Contract No. GINOP-2.3.3-15-2016-00034), as well as by Deutsche Forschungsgemeinschaft (DFG) and National Natural Science Foundation of China (NSFC) through funds provided to the Sino-German CRC 110 "Symmetries and the Emergence of Structure in QCD", the National Key R&D Program of China (Contract No. 2018YFA0404400 and No. 2017YFE0116700), the NSFC under Grants No. 11935003, No. 11875075, and No. 11621131001, the UK STFC under grant no. ST/P003885/1. I.K. was supported by National Research, Development and Innovation Office NKFIH, contract number PD 124717.

References

[1] Bohr A and Mottelson B R 1975 *Nuclear Structure, Vol. II (Benjamin, New York)*
[2] Ødegard S W et al. 2001 *Phys. Rev. Lett.* **86** 5866
[3] Matta J T et al. 2015 *Phys. Rev. Lett.* **114** 082501
[4] Frauendorf S and Dönau F 2014 *Phys. Rev.* C f89 014322
[5] Frauendorf S and Meng J 1997 *Nucl. Phys.* A **617** 131
[6] Starosta K et al. 2001 *Phys. Rev. Lett.* **86** 971
[7] Xiong B W and Wang Y Y 2019 *Atomic Data and Nuclear Data Tables* **125** 193
[8] Meng J et al. 2006 *Phys. Rev.* C **73** 037303
[9] Ayangeakaa A D et al. 2013 *Phys. Rev. Lett.* **110** 172504
[10] Möller P et al. 2008 *At. Data. Nucl. Data Tables* **94** 758
[11] Radford D C 1995 *Nucl. Instrum. Meth.* **A 361** 297
[12] Jones P M et al. 1995 *Nucl. Instrum. Methods* **A 362** 556
[13] Krane K S et al. 1973 *Nucl. Data Tables* **A 11** 351
[14] Frauendorf S and Meng J 1996 *Z. Phys.* A **356** 263
[15] Streck E et al. 2018 *Phys. Rev.* C **98** 044314
[16] Timár J et al. 2019 *Phys. Rev. Lett.* **122** 062501
[17] Sensharma N et al. 2019 *Phys. Lett.* B. **792** 170
[18] Kuti I et al. 2014 *Phys. Rev. Lett.* **113** 032501
[19] Zhao P W et al. 2011 *Phys. Lett.* B **699** 181
[20] Chen Q B et al. 2010 *Phys. Rev.* C **82** 067302
[21] Peng J et al. 2008 *Phys. Rev.* C **77** 024309