MULTIPLE CHIRAL DOUBLET BANDS AND POSSIBLE TRANSVERSE WOBBLING NEAR ^{104}Rh*

J. Timár, I. Kuti, B. Kruzsicz, D. Sohler, B.M. Nyakó

Institute for Nuclear Research, Hungarian Academy of Sciences
Pf. 51, 4001 Debrecen, Hungary

Q.B. Chen, S.Q. Zhang, J. Meng

State Key Laboratory of Physics and Technology, School of Physics
Peking University, Beijing 100871, China

K. Starosta

Department of Chemistry, Simon Fraser University
Burnaby, British Columbia V5A 1S6, Canada

T. Koike

Graduate School of Science, Tohoku University, Sendai, 980-8578, Japan

C. Vaman

Department of Physics and Astronomy, State University of New York
Stony Brook, New York 11794-3800, USA

P. Joshi, R. Wadsworth

Department of Physics, University of York, York YO10 5DD, UK

(Received December 8, 2017)

The medium- and high-spin band structure of ^{103}Rh, ^{104}Rh and ^{105}Pd has been studied in order to search for new multiple chiral doublet bands and bands corresponding to the recently predicted transverse wobbling motion. Several new band structures have been identified and their properties compared with constrained covariant density functional theory and particle

* Presented at the XXIV Nuclear Physics Workshop "Marie and Pierre Curie", Kazimierz Dolny, Poland, September 20–24, 2017.

rotor model calculations. Based on this comparison, three chiral band pairs were identified in ^{103}Rh, of which two belong to the same configuration. Several new positive- and negative-parity bands in ^{104}Rh can form chiral band pairs according to their experimental properties and to the preliminary calculations, thus the existence of multiple chiral doublet bands in this nucleus is possible. Experimental properties of one of the observed negative-parity bands in ^{105}Pd are characteristic of transverse wobbling motion, predicted also by calculations in this nucleus.

DOI:10.5506/APhysPolBSupp.11.179

1. Introduction

Phenomena related to triaxial deformation of nuclei at medium-spin states have attracted great interest in the past years. Such phenomena are nuclear chirality and wobbling motion of rotating triaxial nuclei. Nuclear chirality was predicted by Frauendorf and Meng twenty years ago [1]. They have shown that in the intrinsic frame of a rotating triaxial nucleus, the total angular momentum vector can lie outside the three principal planes in certain cases, called chiral geometry. Thus, its components 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 pair of $\Delta I = 1$ bands with the same parity. Such chiral band pairs were first identified in four $N = 75$ isotones [2]. So far, many chiral candidate doublet bands have been reported in nuclei of the $A \sim 80$, 100, 130, and 190 mass regions. A recent overview of them is given in Ref. [3].

Recent adiabatic and configuration-fixed constrained triaxial covariant density functional theory (CDFT) calculations by Meng *et al.* [4] predicted that multiple pairs of chiral doublet bands can be formed in a single nucleus, and the acronym MχD was introduced for this phenomenon. Although the first prediction was made for ^{106}Rh, the first experimental evidence for the predicted MχD has been reported in ^{133}Ce [5].

Wobbling is a special type of rotation which occurs in triaxially deformed nuclei and is characterized by the oscillation of the principal axes relative to the angular momentum vector. It was first discussed in nuclei by Bohr and Mottelson [6] for the case of even–even nuclei. The experimental signature of this motion is the existence of a rotational band decaying to the yrast band through $\Delta I = 1$, M1+E2 transitions with dominating E2 component. The wobbling frequency in the even–even case is expected to increase with increasing rotational frequency. Experimentally, this type of rotation was first identified in the triaxial strongly-deformed ^{163}Lu nucleus [7]. Since then, wobbling has been identified in other strongly-deformed Lu isotopes and in ^{167}Ta. Recently, the first normal-deformed wobbling case was identified in ^{135}Pr [8]. All of these known cases belong to odd-mass nuclei, and the experimental wobbling frequencies were found to decrease with increasing rotational frequency. Wobbling of odd-mass nuclei was discussed by Frauendorf and Dönau [9]. They classified the wobbling in odd-mass nuclei as "longitudinal" and "transverse" wobbling, and for the latter, they have shown that the wobbling frequency is expected to decrease with increasing rotational frequency in agreement with the experimental results.

2. Multiple chiral doublet bands in the $A \sim 100$ region

Although MχD was experimentally identified first in the $A \sim 130$ mass region, it was first predicted in the $A \sim 100$ mass region and also the first hints for its existence came from this region. Indeed, two groups studied the medium-spin band structure of ^{105}Rh recently, and published the observation of chiral doublet bands corresponding to the $\pi(g_{9/2})\otimes\nu(h_{11/2})^2$ configuration [10] and possible chiral doublet bands corresponding to the $\pi(g_{9/2})\otimes\nu(h_{11/2})(g_{7/2}, d_{5/2})$ configuration [11]. Adiabatic and configuration-fixed constrained triaxial relativistic mean-field calculations confirmed later that MχD based on these two configurations is highly expected in ^{105}Rh [12]. Motivated by the theoretical predictions and the experimentally observed possible MχD in ^{105}Rh, we studied the medium-spin band structure of ^{103}Rh and ^{104}Rh to search for multiple chiral doublet bands in these nuclei.

2.1. MχD in ^{103}Rh

A chiral band pair based on the positive-parity $\pi(g_{9/2})\otimes\nu(h_{11/2})^2$ configuration has been previously published in this nucleus [13]. Our aim was to search for a new chiral band pair based on the $\pi(g_{9/2})\otimes\nu(h_{11/2})(g_{7/2}, d_{5/2})$ negative-parity configuration.

Medium- and high-spin band structures of ^{103}Rh were extended using the high-statistics data set measured at LBNL using the ^{96}Zr(^{11}B,4n) reaction at a beam energy of 40 MeV and the Gammasphere spectrometer. For details, see Ref. [14]. A more complete level scheme of ^{103}Rh was 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. A partial level scheme of ^{103}Rh showing these band pairs is plotted in Fig. 1.

In order to understand the nature of the observed band structure, adiabatic and configuration-fixed constrained CDFT calculations [4], as well as tilted axis cranking CDFT (TAC-CDFT) calculations [15] were performed together with quantum particle rotor model (PRM) calculations [16], and

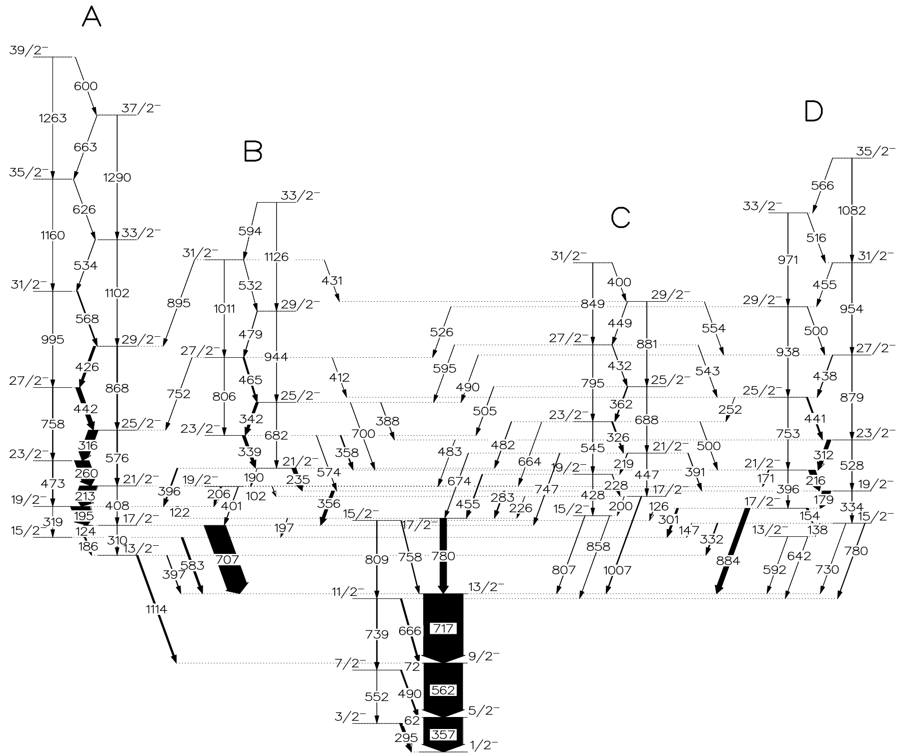

Fig. 1. Negative-parity chiral band pairs observed in ^{103}Rh.

the results were compared with the experimental data. Based on these comparisons, it turned out that bands A, B, C and D in Fig. 1 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. Furthermore, they form two chiral band pairs. Thus, together with the known positive-parity chiral band pair, there are three chiral band pairs in ^{103}Rh. In contrast with the multiple chiral doublets predicted in Ref. [4] and experimentally reported in ^{133}Ce [5], the observed MχD in the negative-parity bands of ^{103}Rh is built from the first and second doublets of the same configuration. Observation of such a type of MχD shows that the chiral geometry in nuclei can be robust against the increase of the intrinsic excitation energy. These results were published in Ref. [14].

2.2. Multiple chiral doublet bands in ^{104}Rh

^{104}Rh was the first nucleus in the $A\sim 100$ mass region in which nuclear chirality has been observed [17]. Therefore, it is sensible to search for MχD in this nucleus. It is especially interesting to search for the second chiral band pair corresponding to the negative-parity $\pi(g_{9/2})\otimes\nu(h_{11/2})$ configuration, for which chirality has been shown in Ref. [17]. MχD based on the same such a simple configuration, containing only high-j orbitals, has not been observed yet, although it was predicted theoretically for both the $A \sim 100$ and the $A \sim 130$ mass regions [18–20]. Searching for chiral band pairs among the positive-parity bands was also our aim, as chirality based on the $\pi(g_{9/2})\otimes\nu(h_{11/2})^2(g_{7/2}, d_{5/2})$ configuration was predicted in this nucleus [21].

We have studied the medium- and high-spin band structure of ^{104}Rh using the same data set which was measured for the ^{103}Rh band structure. In the performed experiment, ^{104}Rh was the second strongest reaction channel, which enabled us to observe new bands in this nucleus. As a result of our study, we could identify several new negative- and positive-parity bands.

A preliminary partial negative-parity level scheme of ^{104}Rh is shown in Fig. 2. Bands A and B are the known chiral partner bands [17], while bands C and D are newly observed. These latter two bands are linked by many transitions to the known chiral pair. They are probably of negative-parity and seem to form a chiral band pair, too. However, the energy separation between the first and the second pairs is only a few hundred keV, while according to Hamamoto's calculations [18], the energy separation between the first and second chiral pair of the $\pi(g_{9/2})\otimes\nu(h_{11/2})$ configuration is expected to be around 1.5 MeV. Thus, the band pair of C and D most likely do not correspond to the above configuration.

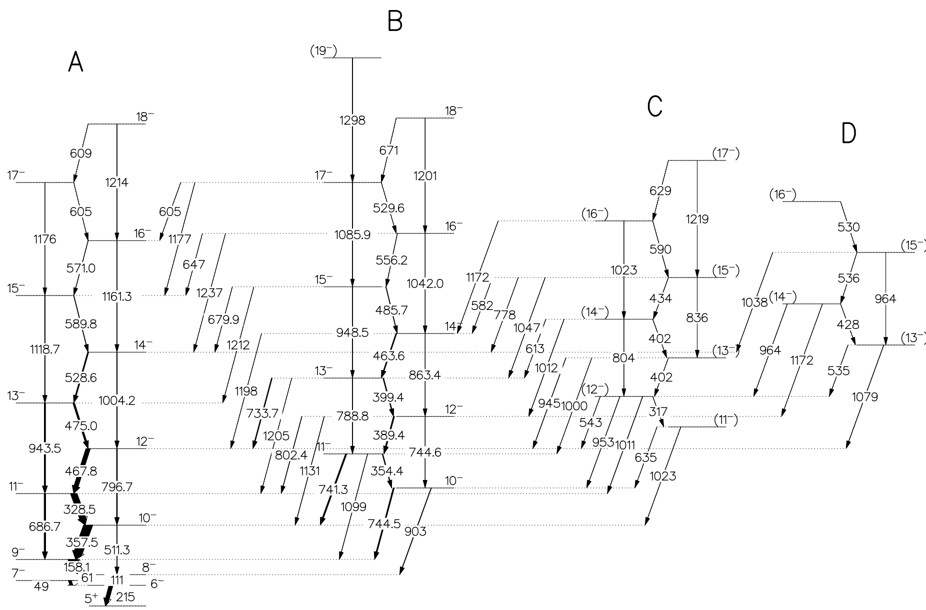

Fig. 2. Partial negative-parity level scheme of ^{104}Rh.

Adiabatic and configuration-fixed constrained CDFT calculations [4], as well as tilted axis cranking CDFT (TAC-CDFT) calculations [15] were performed together with quantum particle rotor model [16] calculations to understand the nature of the observed new bands. These calculations predict chirality for the $\pi(g_{9/2})\otimes\nu(h_{11/2})(g_{7/2},d_{5/2})^2$ configuration. Comparison of the preliminary theoretical results with the observed properties of the band structure indicates that band A has $\pi(g_{9/2})\otimes\nu(h_{11/2})$ configuration, while band C corresponds to the $\pi(g_{9/2})\otimes\nu(h_{11/2})(g_{7/2},d_{5/2})^2$ configuration. Very probably the lower-spin part of bands B, up to spin 14, is the chiral partner of band A, while states above this spin correspond to the medium-spin chiral partner of band C. Thus, probably two negative-parity chiral partner band pairs exist in ^{104}Rh, however with different configurations.

We have also observed five new positive-parity medium-spin bands in ^{104}Rh. In Fig. 3, 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. Based on 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

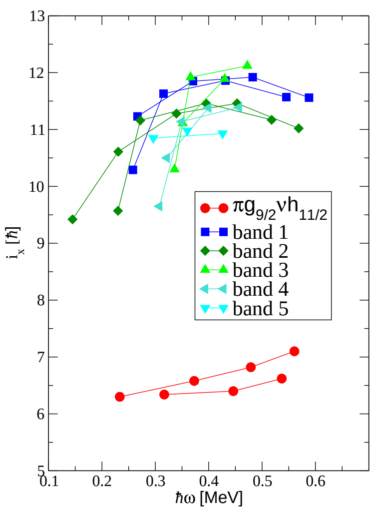

Fig. 3. Alignments of the new positive-parity bands and the $\pi(g_{9/2})\otimes\nu(h_{11/2})$ band in ^{104}Rh.

positive-parity configurations [21]. Figure 4 shows that these bands are very close to each other in energy. Indeed, the energy spacings between bands 3, 4 and 5 are only around 100 keV. It is, therefore, possible that two of them form a chiral band pair. Thus, besides the two negative-parity chiral band pairs, probably one or two positive-parity chiral band pairs also exist in ^{104}Rh.

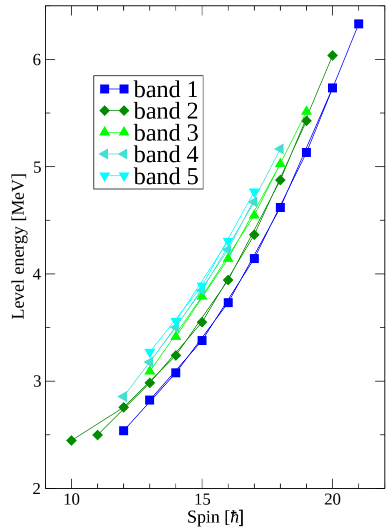

Fig. 4. Level energies of the new positive-parity bands in ^{104}Rh as a function of the spin.

3. Possible transverse wobbling in ^{105}Pd

The medium- and high-spin band structure of ^{105}Pd has been studied using the ^{96}Zr(^{13}C,4n) reaction. The emitted γ rays were detected by the EUROBALL IV spectrometer. For the detailed description of the experiment, see Ref. [10]. The spectrometer contained 15 Cluster and 24 Clover detectors at backward angles and around 90°, respectively, relative to the beam direction. The detector arrangement allowed us to perform both DCO and linear polarization analysis for the observed gamma transitions. As a result of the study, several new negative- and positive-parity bands have been assigned to ^{105}Pd. One of the negative-parity bands, band B in Fig. 5, shows the characteristics of the expected transverse wobbling band. The previously known yrast negative-parity band A, based on the $\nu(h_{11/2})$ configuration, and the new band B with wobbling characteristics are plotted in Fig. 5. Band B is linked to band A by the strong 991, 1034 and 994 keV transitions. The results of preliminary DCO and linear polarization analysis of these M1+E2 transitions enabled us to determine the E2 content of them, which proved to be larger than 80%. This fact, together with the observed decreasing wobbling frequency, which is shown in Fig. 6, suggests that band B is a transverse wobbling band. Preliminary CDFT and PRM calculations support this assumption. If this band is a wobbling band, then this is the first one observed in the $A \sim 100$ mass region.

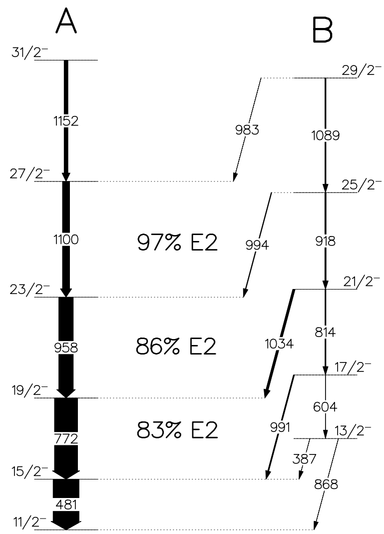

Fig. 5. Partial negative-parity level scheme of ^{105}Pd.

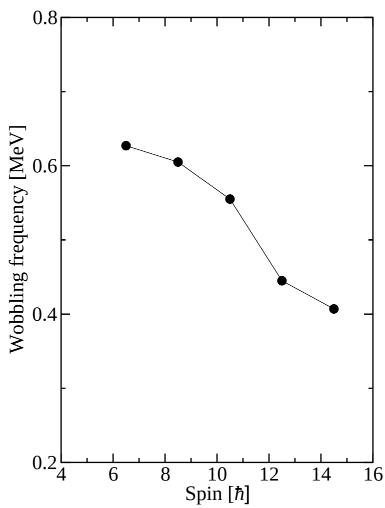

Fig. 6. Wobbling frequency for band B in ^{105}Pd.

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. MχD has been found in ^{103}Rh, which is the first observation of MχD built on the same configuration. Possible MχD has also been found in ^{104}Rh. Experimental properties of one of the observed negative-parity bands in ^{105}Pd are characteristic of transverse wobbling motion. This could be the first transverse wobbling case observed in the $A \sim 100$ mass region.

This work was supported in part by GINOP-2.3.3-15-2016-00034. I.K. was supported by the National Research, Development and Innovation Office — NKFIH, contract number PD 124717.

REFERENCES

[1] S. Frauendorf, J. Meng, *Nucl. Phys. A* **617**, 131 (1997).
[2] K. Starosta *et al.*, *Phys. Rev. Lett.* **86**, 971 (2001).
[3] K. Starosta, T. Koike, *Phys. Scr.* **92**, 093002 (2017).
[4] J. Meng, J. Peng, S.Q. Zhang, S.-G. Zhou, *Phys. Rev. C* **73**, 037303 (2006).
[5] A.D. Ayangeakaa *et al.*, *Phys. Rev. Lett.* **110**, 172504 (2013).
[6] A. Bohr, B. Mottelson, *Nuclear Structure, Volume II*, W.A. Benjamin, New York 1975.
[7] S.W. Odegard *et al.*, *Phys. Rev. Lett.* **86**, 5866 (2001).
[8] J.T. Matta *et al.*, *Phys. Rev. Lett.* **114**, 082501 (2015).
[9] S. Frauendorf, F. Dönau, *Phys. Rev. C* **89**, 014322 (2014).
[10] J. Timár *et al.*, *Phys. Lett. B* **598**, 178 (2004).
[11] J.A. Alcántara-Núñez *et al.*, *Phys. Rev. C* **69**, 024317 (2004).
[12] J. Li, S.Q. Zhang, J. Meng, *Phys. Rev. C* **83**, 037301 (2011).
[13] J. Timár *et al.*, *Phys. Rev. C* **73**, 011301(R) (2006).
[14] I. Kuti *et al.*, *Phys. Rev. Lett.* **113**, 032501 (2014).
[15] P.W. Zhao *et al.*, *Phys. Lett. B* **699**, 181 (2011).
[16] B. Qi *et al.*, *Phys. Lett. B* **675**, 175 (2009).
[17] C. Vaman *et al.*, *Phys. Rev. Lett.* **92**, 032501 (2004).
[18] I. Hamamoto, *Phys. Rev. C* **88**, 024327 (2013).
[19] Ch. Droste *et al.*, *Eur. Phys. J. A* **42**, 79 (2009).
[20] Q.B. Chen *et al.*, *Phys. Rev. C* **82**, 067302 (2010).
[21] J. Peng *et al.*, *Phys. Rev. C* **77**, 024309 (2008).