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Dynamic chirality in mass regions $A=105$ and $A=130$

M.S. Yavahchova¹, D. Tonev¹, G. de Angelis², P. Petkov^{1,3}, N. Goutev¹, R.K. Bhowmik⁴, R. P. Singh⁴, S. Muralithar⁴, N. Madhavan⁵, R. Kumar⁶, M. Kumar Raju⁸, J. Kaur⁹, G. Mohanto¹⁰, A. Singh¹¹, N. Kaur¹², R. Garg^{5,7}, A. Shukla¹³, R. Mateva¹, E. Geleva¹, B. Slavchev¹, and S. Brant^{14,†}

¹ Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, 1784 Sofia, Bulgaria

² INFN, Laboratori Nazionali di Legnaro, I-35020 Legnaro, Italy

³ Horia Hulubei NIPNE, R-76900, Bucharest-Magurele, Romania

⁴ Inter University Accelerator Centre, New Delhi-110067, India

⁵ Inter University Accelerator Centre, Aruna Asaf Ali Marg, New Delhi 110067, India

⁶ Department of Physics, Indian Institute of Technology Bombay, Powai, Mumbai 400076, India

⁷ Department of Physics and Astrophysics, University of Delhi, Delhi 110007, India

⁸ Nuclear Physics Department, Andhra University, Visakhapatnam 530003, India

⁹ Department of Physics, Guru Nanak Dev University, Amritsar, Punjab 143005, India

¹⁰ Nuclear Physics Division, Bhabha Atomic Research Centre, Mumbai 400085, India

¹¹ Indian Institute of Technology, Kharagpur 721302, India

¹² Department of Physics, Panjab University, Chandigarh, India

¹³ Department of Physics, Banaras Hindu University, Varanasi, India

¹⁴ Department of Physics, Faculty of Science, Zagreb University, Zagreb, Croatia

Corresponding author's e-mail address: m.yavahchova@gmail.com

Abstract. Chiral symmetry is dichotomic and its spontaneous breaking by the axial angular momentum vector leads to a pair of degenerate $\Delta I = 1$ rotational bands, called chiral doublet bands. In many cases the energy degeneracy of the chiral candidate bands has almost been observed but the transition probabilities of the analogue states have been found to be different. In the angular momentum region where chirality sets in the $B(E2)$ values of the electromagnetic transitions deexciting analogue states of the chiral twin bands should be almost equal. Correspondingly the $B(M1)$ values should exhibit staggering. Experimental data for two nuclei from different mass regions are compared with theoretical predictions. Excited states in ^{134}Pr were populated in the fusion-evaporation reaction $^{119}\text{Sn}(^{19}\text{F}, 4n)^{134}\text{Pr}$, while excited states in ^{102}Rh were populated in the fusion-evaporation reaction $^{94}\text{Zr}(^{11}\text{B}, 3n)^{102}\text{Rh}$. Our lifetime measurements and level-scheme investigations show that there are similarities in both chiral candidates nuclei related to dynamic chirality.

1. Introduction

Chirality is recognized as an interesting phenomenon in different branches of science. Some of the most popular cases, which are easy to understand, are identified in chemistry. The chiral molecule is non-superimposable on its mirror image. The mirror images of a chiral molecule are called enantiomers and they could be right- and left-handed. The terminology emphasizes the analogy to the human hands, for which one hand can be superimposed onto the mirror image of the other. The term “chirality” originates from the Greek word for hand and is a synonym to “handedness”.

In the last decades chirality in nuclei is among the most studied phenomena. A spontaneous breaking of chiral symmetry can take place for configurations where the angular momenta of the valence proton, the valence neutron, and the core are mutually perpendicular [1]. Under such conditions, the angular momenta of the valence particles are aligned along the short and long axes of the triaxial core, while the angular momentum of the rotational core is aligned along the intermediate axis. The resulting aplanar



total angular momentum can be arranged into a right- or a left-handed systems, which differs by intrinsic chirality [2]. Because the chiral symmetry is dichotomic, its spontaneous breaking by the axial angular momentum vector leads to doublets of closely lying rotational bands of the same parity [1,2,3].

Due to the underlying symmetry, the pairs of chiral twin bands should exhibit systematic properties [4, 5, 6, 7]. The first property is the existence of a couple of yrast and side bands, which are nearly degenerate. In the angular momentum region where chirality sets in, the $B(E2)$ values of the electromagnetic transitions deexciting analogue states of the chiral twin bands should be almost equal. Correspondingly the $B(M1)$ values should exhibit odd-even staggering, being much bigger for transitions deexciting states with odd spins than for transitions deexciting states with even spin [6]. The $B(M1)$ values for $\Delta I=1$ transitions connecting the side to the yrast band should have odd-even staggering which is out of phase with respect to the $B(M1)$ staggering for transitions deexciting states in the yrast band and the side band. This is a fingerprint of the ideal static chirality as discussed in [6,8,9]. To investigate the presence of chirality in a certain nucleus, it is crucial to determine the $B(E2)$ and $B(M1)$ values.

In many cases, the energy degeneracy of the chiral candidate bands is nearly observed but the corresponding transition probabilities are different, as in the cases of ^{134}Pr [7,10] and ^{102}Rh [11]. We will study in the present paper the similarities in these two nuclei and investigate the existence of dynamic chirality in real nuclei.

2. Experiments

We have performed three experiments to determine reduced transition probabilities in ^{134}Pr and ^{102}Rh . The goal of the present work is to investigate similarities in the level-schemes and transition probabilities in the chiral twin bands in these two nuclei from the mass region $A=130$ and $A=105$.

3. The case of ^{134}Pr

The two chiral candidate bands are displayed in Fig.1. Excited states in ^{134}Pr were populated using the fusion-evaporation reaction $^{119}\text{Sn}(^{19}\text{F}, 4n)$ at a beam energy of 87 MeV for the recoil distance Doppler-shift (RDDS) measurement. The beam was delivered by the Vivitron accelerator at IReS in Strasbourg. The target consisted of 0.5 mg/cm² ^{119}Sn foil enriched to 89.9%. It was evaporated on a 1.8 mg/cm² ^{181}Ta foil facing the beam. A 6.0 mg/cm² gold foil was used to stop the recoils that were leaving the target with a mean velocity of 0.98(2)% of the velocity of light, c . The γ rays de-exciting the recoiling ^{134}Pr nuclei were detected using the EUROBALL IV [12] detector array composed of 26 clover and 15 cluster Ge detectors and an inner BGO (bismuth germanate) ball. The cluster and clover detectors of EUROBALL were grouped into 10 rings corresponding to approximately the same polar angle with respect to the beam axis.

In order to measure the lifetimes in the femtosecond region the Doppler-shift attenuation method (DSAM) was utilized. For the DSAM experiment, a beam energy of 83 MeV was used. The target consisted of 0.7 mg/cm² ^{119}Sn evaporated on a 9.5 mg/cm² ^{181}Ta backing used to stop the recoils.

Detailed description of the experiments performed to investigate the structure of ^{134}Pr is presented in work [7].

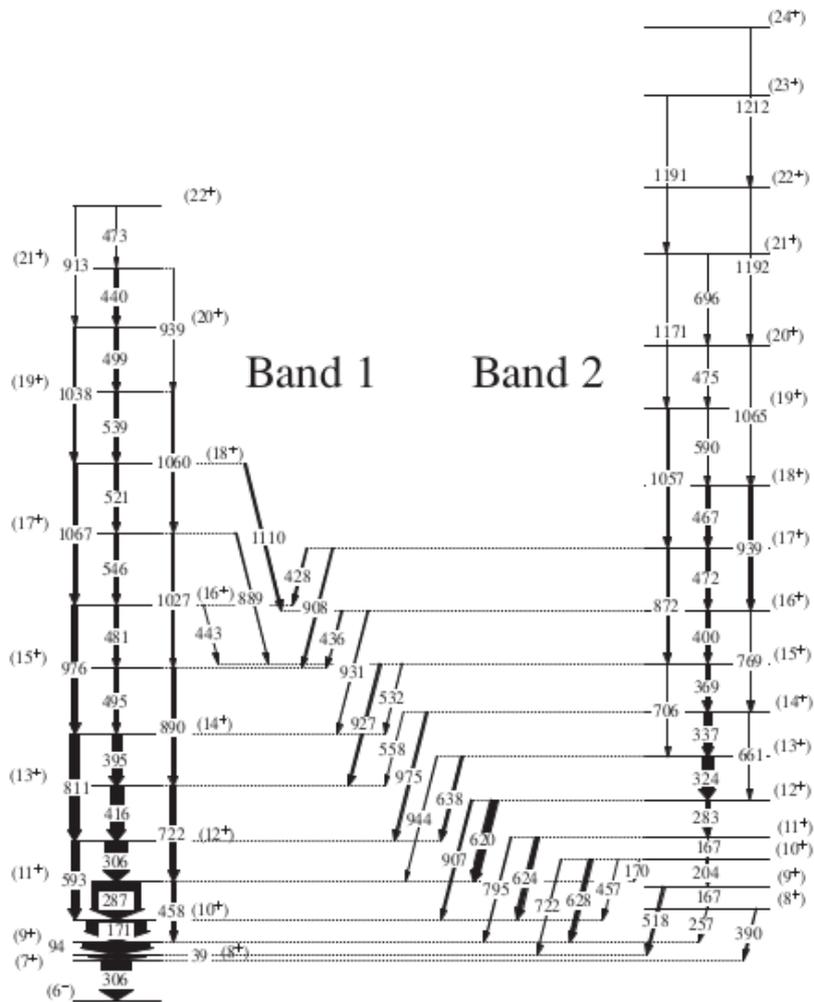


Figure 1. Partial level scheme of ^{134}Pr from Ref. [7].

4. The case of ^{102}Rh

The partial level scheme of ^{102}Rh is displayed in Fig. 2. Excited states in ^{102}Rh were populated using the reaction $^{94}\text{Zr}(^{11}\text{B}, 3n)^{102}\text{Rh}$ at a beam energy of 36 MeV. The beam was delivered by the 15-UD Pelletron accelerator at the Inter University Accelerator Center (IUAC) in New Delhi. The target consisted of 0.9 mg/cm^2 ^{94}Zr , enriched to 96.5%, evaporated onto a 8 mg/cm^2 gold backing. The recoils were leaving the target with the mean velocity v of about 0.9% of the velocity of light, c . The deexciting γ rays were registered by the Indian National Gamma Array (INGA), whose 15 clover detectors are accommodated in a 4π geometry [13]. The detectors of INGA were grouped into rings with approximately the same position with respect to the beam axis. For more information see [11].

New accelerator centers like the National cyclotron center in Sofia [14] will open new opportunities for nuclear structure investigations.

level-scheme was extended by a new $\Delta I=1$ band with negative parity and new eight lifetimes were determined for the first time, six in the yrast and two in the side band [11].

8. Discussion

Dynamic chirality in nuclear physics is introduced in the work [7]. The term *dynamical chirality*, refers to the possibility that the angular momenta of the proton, neutron, and core in the odd-odd nucleus, find themselves in the favorable geometry, as if they would in the equivalent triaxially deformed rotor. The IBFFM calculations in [7] show that such a possibility is present, but it is far from being dominant. The condition for the appearance of twin bands with wave functions realistic enough to reproduce the electromagnetic decay of the bands is that the core is a γ -unstable rotor whose effective γ is in the range of triaxial values.

In the article [20], for shortness, the structure in which a pair of twin bands is close in excitation energy, but the electromagnetic decay properties do not show the chiral pattern, is denoted as *case A*. The structure where the pair of twin bands is close in excitation energy and the electromagnetic decay properties display the chiral pattern, is denoted as *case B*. We will use the same types of chiral description in the present work. Odd-odd nuclei in the $A \sim 130$ mass region can be classified as *case A* or *case B* nuclei. In all these nuclei the cores are γ -soft, their odd-proton odd-mass neighbors have also a similar structure and their odd-neutron odd-mass neighbors have a similar structure, too. Therefore, there is *a priori* no evident reason why should they be different in structure, some of them being chiral (*case B*) and some being not chiral (*case A*). Either the structure of all these nuclei is not chiral, or there is a mechanism that dynamically induces chirality, in such a way that in *case B* it is far more pronounced than in *case A*. For the first time we will investigate the possibility to have a nucleus from mass region $A \sim 105$ with the same characteristics like ^{134}Pr . The level-schemes of both nuclei as well as their electromagnetic properties will be compared with the theoretical expectations.

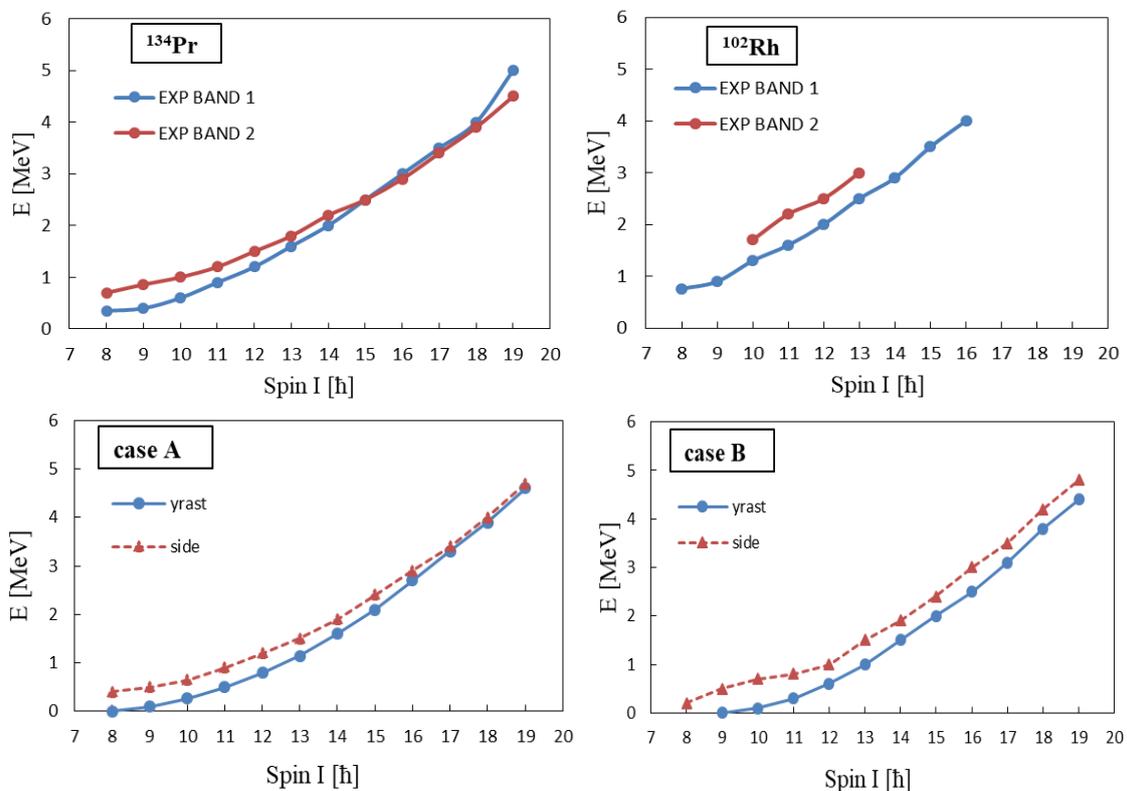


Figure 3. In the upper panels the excitation energies of levels in the yrast and side band of ^{134}Pr (left) and ^{102}Rh (right) are presented. In the second row of panels sister bands calculated in the IBFFM for *case A* (left) and *case B* (right) are shown.

In Figure 3 are presented the excitation energies of levels of the twin chiral bands in ^{134}Pr and ^{102}Rh as well as the predictions obtained from IBFFM for *case A* and *case B* [20]. The level energies for the yrast and side bands are becoming closer with increasing spin and cross at high spins, while in *case B* they are equidistant from the spin region where chirality sets up. In all cases, experiment and theory, the level energies of the side band are higher than these of the yrast band for low and middle spin regions. For the nucleus of ^{134}Pr the behavior of the level energies is following *case A*. For ^{102}Rh excitation energies are similar to both *cases A* and *B*. Due to the limited statistics we have identified only states up to 13 \hbar for the side band of ^{102}Rh . Obviously an extension to higher spins for the second band will answer the question whether the twin bands cross in excitation energies of the states. We need to note that two bands could be called degenerate at least when the energy difference for analogue states is no more than 500 keV.

The predictions for *case A* are close to the two real nuclei in mass regions $A\sim 105$ and $A\sim 130$. From the point of view of the comparison of the level-schemes we could note that the two bands are almost degenerate and similarities for the nucleus of ^{102}Rh with *cases A* and *B* are good for the low spins. For the nucleus of ^{134}Pr we observe the behavior like in *case A*. Obviously we need more experimental data for band 2 in ^{102}Rh .

In order to make conclusions about the existence of chirality in nuclei it is crucial to perform lifetime measurements.

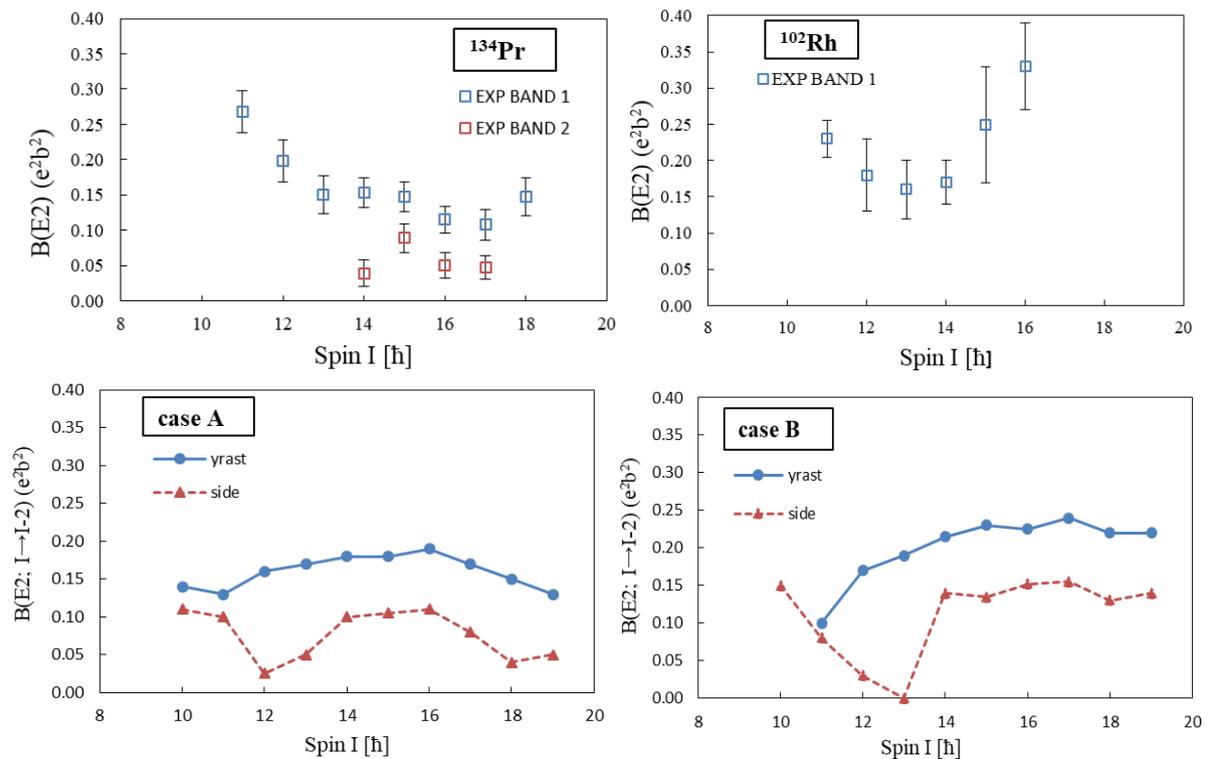


Figure 4. In the upper panels experimentally determined $B(E2)$ values for ^{134}Pr (left) and ^{102}Rh (right) are shown. In the second row of panels $B(E2)$ values for twin bands calculated in the IBFFM for *case A* (left) and *case B* (right) are shown.

In Figure 4 are compared $B(E2)$ values obtained for ^{102}Rh and ^{134}Pr with the predictions from the work [20]. For the nucleus of ^{134}Pr determined $B(E2)$ values in the chiral candidate bands are different and in addition they have different behavior. This fact clearly shows that static chirality is not present in this nucleus.

For the nucleus of ^{102}Rh we have determined only $B(E2)$ values in Band 1. These $B(E2)$ values show a similar behavior like in the yrast band of ^{134}Pr . Concerning Band 2 of ^{134}Pr the $B(E2)$ values show similarities like in *case A*.

In order to conclude about the presence of chirality we need to check for existence of staggering of $B(M1)$ values determined in both nuclei. This test is may be the strongest one for existence of static chirality. Figure 5 shows experimentally determined $B(M1)$ values for ^{134}Pr and ^{102}Rh . Chiral interpretation in IBFFM also like in the case of two quasiparticle plus triaxial rotor model (TQPTR) predicts the existence of staggering for $B(M1)$. There is a pronounce similarity for $B(M1)$ in Band 1 and Band 2 of ^{134}Pr , but the staggering is not seen. The same is the case with the nucleus of ^{102}Rh , where $B(M1)$ staggering - the fingerprint for static chirality, is not present. The $B(M1)$ staggering predicted for static chirality is not present in both nuclei, which means that we observe dynamic chirality only.

Even-even nuclei in the $A\sim 130$ mass region are well described by the $O(6)$ symmetry in IBM, that corresponds to γ -unstable rotor [21], and the accepted interpretation is that they are γ -soft. The potential energy surface is flat in the γ direction and rather broad in β direction for γ -unstable nuclei in the $O(6)$ limit or close to it. The wave functions are not (β, γ) dependent, but an *effective* γ_{eff} can be calculated [22] and for $O(6)$ is 30° . γ_{eff} is not the static geometrical deformation and the fluctuations of γ are very large [23]. In this context the term dynamical chirality refers to the possibility that the angular momenta of the proton, neutron, and core in the odd-odd nucleus, find themselves in the favorable geometry [7]. This means that the core is a γ -unstable rotor whose effective γ is in range of triaxial values.

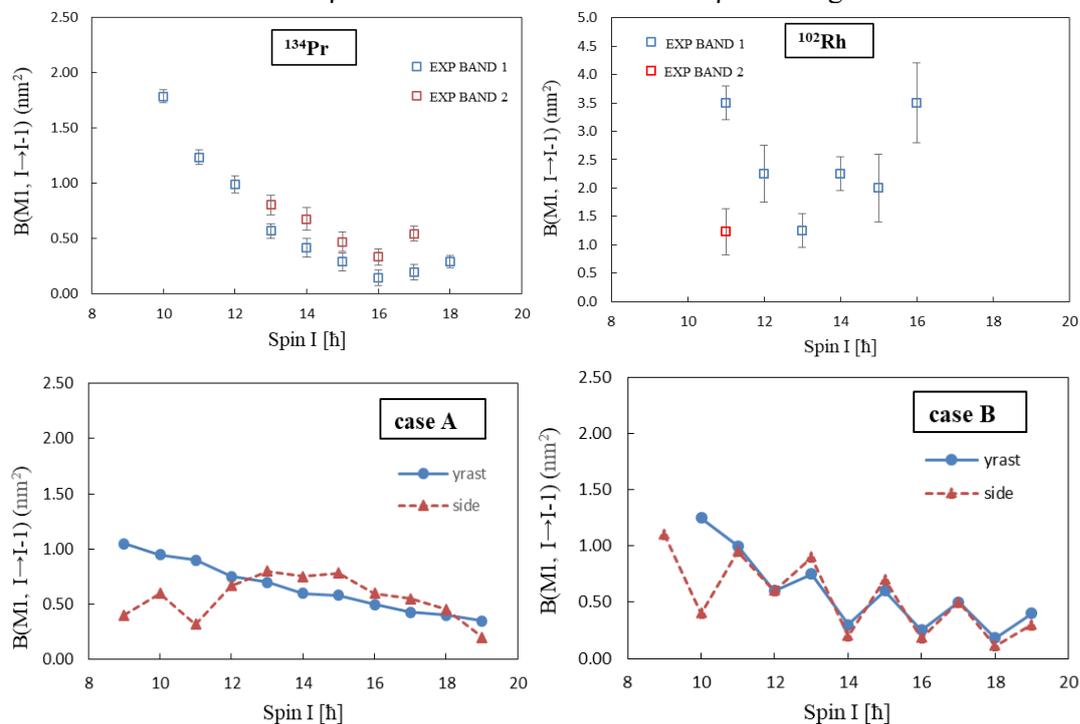


Figure 5. In the upper panels experimentally determined $B(M1)$ values for ^{134}Pr (left) and ^{102}Rh (right) are shown. In the second row of panels $B(M1)$ values for twin bands calculated in the IBFFM for *case A* (left) and *case B* (right) are shown.

For the nucleus of ^{134}Pr the absence of the staggering in the IBFFM is due to fluctuations of the shape with contributions from near axial shapes that wash out the staggering at high spin. Therefore, the

experimental difference between the $B(E2)$ values in Bands 1 and 2 and the absence of the pronounced staggering of the $B(M1)$ values, indicate that the coupling due to shape fluctuations plays a central role in the structure of the twin bands in ^{134}Pr [7].

The similar absence of an appreciable staggering of the data in Band 1 of ^{102}Rh indicates that the expectations for the observation of a static chirality in ^{102}Rh are not realized [11]. Also, the TQPTR calculations reveal that the optimum value of the triaxiality parameter $\gamma=20^\circ$ differs from the value of 30° characterizing the static chiral case. The differences in the core contributions to the yrast and yrare negative-parity bands mentioned above point that dynamic effects as coupling of the quasiparticles to fluctuations of the shape of the core may lead to differences in the properties of these two bands.

The same mechanisms are supposed to determine the structures of the twin bands in ^{134}Pr and ^{102}Rh , revealing dynamic character of chirality.

9. Conclusions

All models applied to describe chirality in nuclei, like the tilted axis cranking model [2], two quasiparticle+triaxial rotor model [10], core-particle-hole coupling model [1,3] suppose a rigid triaxial core. On the contrary all odd-odd nuclei in which twin bands have been observed are in regions of masses where even-even nuclei are γ -soft, effectively triaxial but not rigid. Their potential energy surface is rather flat in the γ -direction and the coupling with other core structures, not only the ground state band, are significant. It is evident that odd-odd nuclei in these mass regions could not reach the full requirements needed for the existence of chirality, but they can approach them. Our theoretical and experimental investigations clearly show that nuclei of ^{134}Pr and ^{102}Rh support the presence of dynamic chirality. In the cases of nuclei ^{128}Cs [24], ^{135}Nd [25] and ^{194}Tl [26] next to the existence of degenerate bands, B(M1) and B(E2) are similar and could be that conditions for static chirality are fulfilled. More theoretical and experimental efforts are needed to investigate chirality in nuclear physics [27].

10. Acknowledgments

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