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Role of the core in degeneracy of chiral candidate band doubling: ^{103}Rh

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Chiral partner candidate bands have been found in ^{103}Rh. As a result of this observation, a special quartet of neighboring chiral candidate nuclei can be investigated for the first time. With this quartet identified, a comparison between the behavior of the nearly degenerate doublet bands belonging to the same core but to different valence quasiparticle configurations, as well as belonging to different cores but to the same valence quasiparticle configuration, becomes possible. The comparison shows that the energy separation of these doublet band structures depends mainly on the core properties and to a lesser extent on the valence quasiparticle coupling. This observation sets up new criteria for the explanations of the band doublings, restricting the possible scenarios and providing new information on the characteristics of the underlying mechanism; it is in qualitative agreement with the chiral scenario.

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Nearly degenerate $\Delta I = 1$ rotational bands have been observed recently in several odd-odd nuclei in the $A \approx 130$ and $A \approx 105$ mass regions (see, e.g., Refs. [1–10] and [11–14], respectively), and most recently in ^{188}Ir [15]. The properties of these doublet bands have been found to agree with the scenario of spontaneous formation of chirality [16,17] and disagree with other possible scenarios. However, the most recent results obtained from lifetime experiments for ^{128}Cs [18], ^{132}La [19], and ^{134}Pr [20] seem to contradict the chiral interpretation of the doublet bands in these nuclei based on the observed differences in the absolute electromagnetic transition rates; the transition rates expected for chiral doublets are predicted to be very similar [21].

In the above mentioned ^{128}Cs, ^{132}La, and ^{134}Pr nuclei, it was already known even before the lifetime experiments that the inband $B(M1)/B(E2)$ ratios were different for the two bands, so either the $B(M1)$ or the $B(E2)$ values could have been expected to be different. In the $A \approx 105$ mass region, however, though no experimental lifetime data are available yet, the $B(M1)/B(E2)$ ratios are rather similar for the two bands [22]. Thus, it would not be a surprise to find the absolute $B(E2)$ and $B(M1)$ values similar as well. In this case, a new type of experimental data may provide further possibilities to distinguish between alternative interpretations and may uncover new properties of the mechanism responsible for the band doubling in these nuclei.

Such a new experimental founding presented in this work comes from the comparison of the degeneracy pattern of the doublet bands in the neighboring odd-odd and odd-A nuclei. Nearly degenerate band structures were reported recently in odd-A ^{135}Nd [23], ^{105}Rh [24], and ^{135}Ce [25], and interpreted as chiral rotation based on the Tilled Axis Cranking (TAC) calculations in the first two cases. In the present Rapid Communication, we discuss a candidate chiral band structure found in ^{103}Rh and compare the observed degeneracies in the four nuclei of ^{102,103,104,105}Rh. This presents a comparison between the degeneracies of the observed band structures belonging to the same core but to different valence quasiparticle configurations, as well as belonging to different cores but the same valence quasiparticle configuration. Thus it enables us to investigate in a model-independent way if the degeneracy is determined predominantly by the properties of the core or by the valence quasiparticle coupling. This comparison reflects, therefore, an important property of the underlying mechanism for the doubling of states despite the adopted interpretation.

High-spin states in ^{103}Rh were populated using the ^{96}Zr(^{11}B,4n) reaction at 40 MeV beam energy. The beam, provided by the 88-in. cyclotron of the Lawrence Berkeley National Laboratory (LBNL), impinged upon a self-supporting target foil of 500 μg/cm^2 thickness, and also on a 2 mg/cm^2 thick target backed with natural Pb. The emitted γ-rays were detected by the GAMMASPHERE spectrometer. A total of $\sim 9 \times 10^8$ quadruple- and higher-fold events were accumulated using the thin target, and sorted off-line into 2-d, 3-d, and 4-d histograms in the Radware format [26].

Partial level scheme for ^{103}Rh derived from the present experiment and typical γ-ray coincidence spectra are shown in Figs. 1 and 2, respectively. The level scheme was constructed based on the triple- and quadruple-coincidence relationships, as well as energy and intensity balances extracted for the observed γ-rays with the use of the Radware analysis package. For the sake of clarity, band 2 is plotted only up to spin 21/2 in Fig. 1. The 786 keV transition used as a gate in the bottom panel of Fig. 2 feeds this 21/2$^+$ level.

Directional correlation of oriented nuclei (DCO) ratios [27] were derived for the transitions of sufficient intensity in order to determine their multipolarities using the five detector rings around 90° against the three most forward and three most backward rings. For this geometry, we can expect $R_{\rm DCO} \approx 0.6$

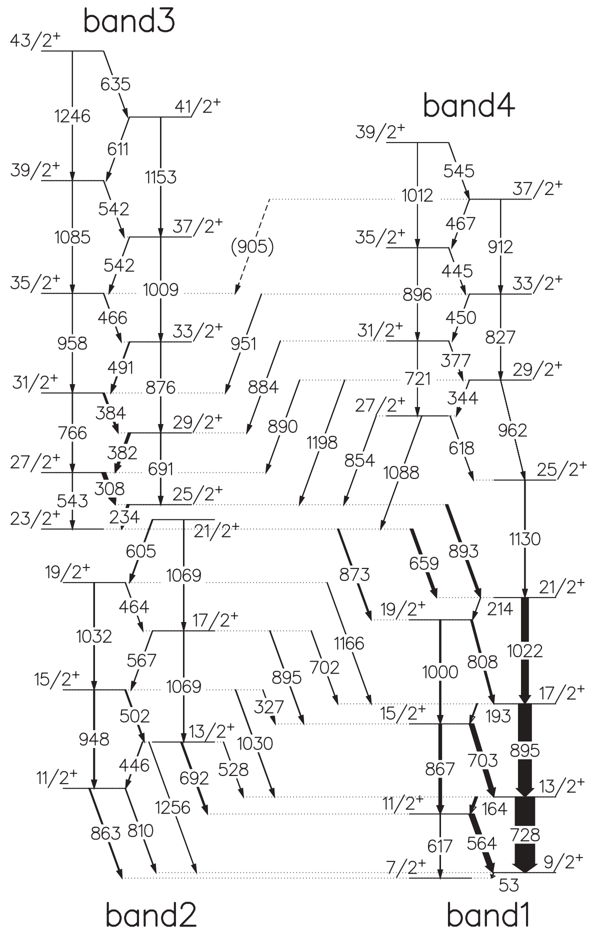

FIG. 1. Partial level scheme of ^{103}Rh obtained in the present work.

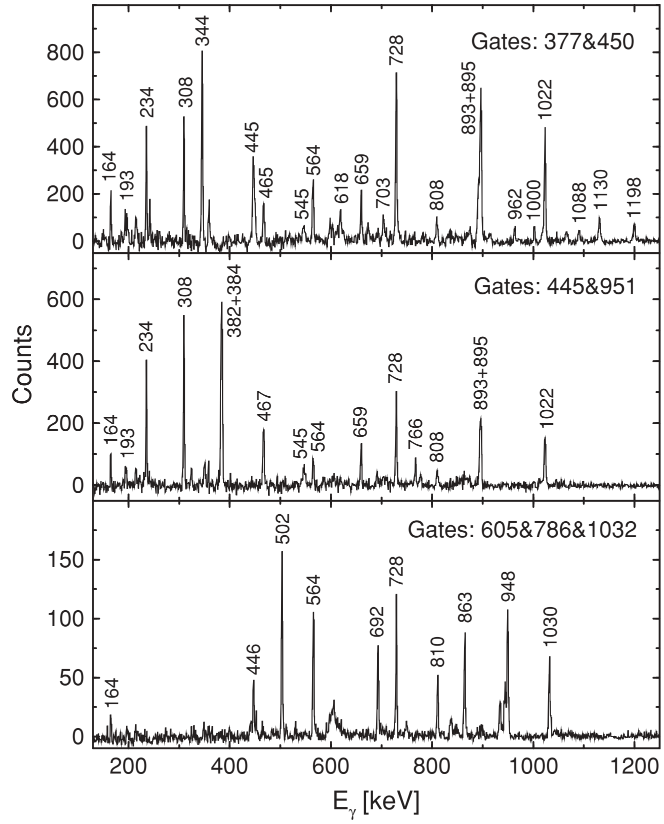

FIG. 2. Typical γ-γ-γ coincidence spectra (upper two panels) showing the placement of band 4, and γ-γ-γ-γ coincidence spectrum (lowest panel) showing the placement of band 2. Double and triple gates are indicated on the panels.

for a stretched dipole and $R_{\mathrm{DCO}} \approx 1$ for a stretched quadrupole transition when gating on a stretched quadrupole transition. Setting the gate on a stretched dipole transition, the expected R_{DCO} values are 1 and $\approx$1.5, respectively. The derived R_{DCO} important in establishing the spins and parities of the new bands are given in Table I.

Band 1 and the bottom part of band 3 were previously reported in Ref. [28] with the $\pi g_{9/2}$ and $\pi g_{9/2}\nu(h_{11/2})^2$ configurations assigned, respectively. Bands 2 and 4 are observed in the present experiment for the first time. In the level scheme shown in Fig. 1, the spins and parities from Ref. [28] are accepted for band 1. The spins and parities for the other bands are established from the deduced multipolarities of γ-ray transitions linking to states in band 1. The multipolarities established from the present work for band 3 agree well with that of Ref. [28].

The lowest energy state of band 2 decays by a stretched dipole transition to the 9/2$^+$ and by a stretched quadrupole transition to the 7/2$^+$ state of band 1 (see Table I). This suggests an 11/2 spin value for the lowest state of band 2. If the parity of this state is positive, then the dipole transition and the quadrupole transitions are $M1$ and $E2$; if the parity is negative, then the $E1$ and $M2$ multipolarities should be observed, respectively. The relative intensities of the 863 and 810 keV transitions depopulating this state are approximately equal. This fact is in good agreement with the $M1$ and $E2$, but in disagreement with the $E1$ and $M2$ multipolarity assignments because of the fact that about six orders of magnitude difference is expected between the strengths of an $E1$ and an $M2$ transition for the observed γ-ray energies. This argument suggests positive parity for the lowest level of band 2. When reiterated for the stretched dipole transitions between the successive levels and the stretched quadrupole cross-over transitions in band 2, the argument leads to spin and parity assignments for states in band 2 as shown in Fig. 1.

TABLE I. Energies, DCO ratios, and suggested multipolarities of transitions deexciting the lowest levels of bands 2 and 4. The *d* and *q* labels denote stretched dipole and quadrupole gates, respectively.

Band 2			Band 4		
E_γ (keV)	R_{DCO}	Mult.	E_γ (keV)	R_{DCO}	Mult.
446	1.12(7)^d	D	344	0.65(11)^q	D
502	0.91(5)^d	D	377	0.53(9)^q	D
567	1.11(18)^d	D	445	0.97(11)^d	D
692	1.11(6)^d	D	450	1.01(12)^d	D
810	0.95(12)^d	D	962	0.95(12)^q	Q
863	1.46(14)^d	Q	1088	1.49(26)^d	Q
948	0.96(8)^q	Q			

The 13/2 spin value of the second level in band 2 is further supported by the stretched dipole character of the 692 keV transition to the $11/2^+$ state of band 1.

A band similar to band 2 has been reported in ^{105}Rh [24,29] and assigned as γ-band coupled to the $\pi g_{9/2}$ configuration on the basis of comparison with core-quasiparticle coupling model calculations [24]. The close similarity between that band in ^{105}Rh and band 2 in ^{103}Rh, as well as the observed strong $\Delta I = 1$ and $\Delta I = 0$ transitions between bands 2 and 1 suggest that band 2 in ^{103}Rh is a γ band coupled to the valence $g_{9/2}$ proton.

The lowest energy level in band 4 decays to the $23/2^+$ state of band 3 by the stretched quadrupole 1088 keV transition and to the $25/2^+$ state of band 1 by the weaker 618 keV transition for which multipolarity cannot be determined. Similarly, the second level of band 4 decays to the $25/2^+$ state of band 1 by the 962 keV stretched quadrupole transition and to the first level of band 4 by the 344 keV stretched dipole transition. The same argument that was used for spin assignments in band 2 suggests positive parity and 27/2 and 29/2 spin values for the first and second levels in band 4, respectively.

There is a close similarity between relative energies of levels and decay properties for the band 3- band 4 doublet structure in ^{103}Rh and the published chiral partner band structure in ^{105}Rh, except for the fact that the energy separation between the two bands is larger in ^{103}Rh than in ^{105}Rh.

Most of the experimental observables, based on which the partner structure in ^{105}Rh was interpreted as chiral doublet band, are also present in the doublet structure of ^{103}Rh.

(i) Although the degeneracy of levels is never reached, the separation energy between states of the same spin in bands 3 and 4 decreases gradually with increasing spin (and rotational frequency). This decreasing separation is in contradiction to the cranked shell model predictions for the lowest quasiparticle excitation.
(ii) The energy separation between the observed γ band (band 2) and the $\pi g_{9/2}$ band (band 1) is on average increasing slightly as a function of spin in contrast to the trend observed for bands 3 and 4 (see Fig. 3); this observation rules out a possibility that band 4 arises from a γ phonon coupled to band 3.
(iii) The energy level staggering as a function of spin measured by the $S(I) = [E(I) - E(I-1)]/2I$ function is small for bands 3 and 4. The small values of $S(I)$ are consistent with a minimal impact of the Coriolis interactions following from the orthogonal coupling of angular momentum vectors.
(iv) Intense $M1$ and $E2$ linking transitions between levels of bands 3 and 4 are observed as expected for the same underlying single-particle configuration.
(v) The $B(M1)/B(E2)$ ratios for the two bands are close to each other and show odd-even staggering as a function of spin (see Fig. 4).

Based on the above observations, the nearly degenerate band structure in ^{103}Rh is a good candidate for being a chiral partner band. On the other hand, the observed close similarity between the positive-parity level schemes of ^{103}Rh and ^{105}Rh implies similar underlying mechanisms for the band doublings in the two nuclei, despite the adopted interpretation.

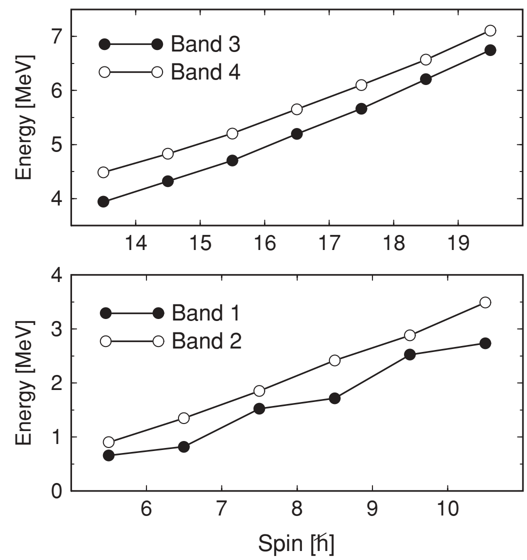

FIG. 3. Excitation energy vs spin plots for the ^{103}Rh bands shown in Fig. 1.

Chiral partner bands reported in ^{104}Rh [11] and ^{105}Rh [24] correspond to the same ^{102}Ru core but to the different $\pi g_{9/2}\nu h_{11/2}$ and $\pi g_{9/2}\nu(h_{11/2})^2$ valence particle configurations, respectively. Most recently, nearly degenerate bands with the characteristics of the reported chiral bands in ^{104}Rh [11] and ^{106}Rh [12] were identified in ^{102}Rh [14].

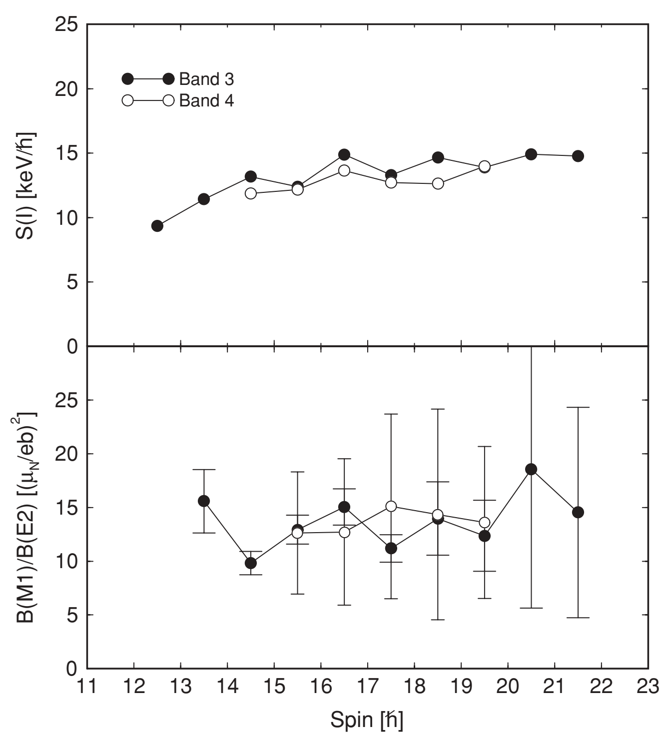

FIG. 4. $S(I) = [E(I) - E(I-1)]/2I$ values (upper panel) and inband $B(M1)/B(E2)$ ratios of the bands 3 and 4 in ^{103}Rh.

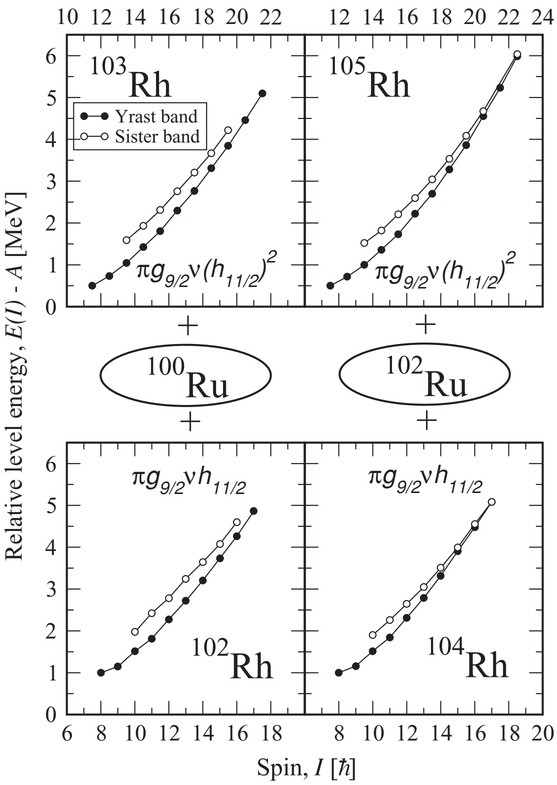

FIG. 5. Comparison of the relative energy vs spin plots of the chiral candidate bands in the neighboring ^{102,103,104,105}Rh nuclei. The energy of the yrast bandhead is shifted to 1 MeV in the odd-odd cases and to 0.5 MeV in the odd-*A* cases.

With the observation of partner bands in ^{103}Rh, a special quartet consisting of ^{102,103,104,105}Rh neighboring nuclei is identified as the one in which the doubling of states occurs. Similar properties of the doublet bands for this quartet strongly suggest that the doubling is caused by the same mechanism.

Below, the band structures belonging to the same core but to different valence quasiparticle configurations, as well as belonging to different cores but the same valence quasiparticle configuration, are compared for this quartet. Figure 5 presents the separation energy between the observed doublet bands in ^{102,103,104,105}Rh nuclei. A similarity between band structures built on the same core but corresponding to different valence quasiparticle configurations should be pointed out. Indeed the two- and three-quasiparticle bands in ^{102}Rh and ^{103}Rh, respectively, show a persisting energy separation between partner bands, which is the expected characteristic of chiral vibrators. On the other hand, the corresponding bands in ^{104}Rh and ^{105}Rh show decreasing energy separation with increasing spin and nearly degenerate states at the top of the bands, which is the expected characteristic of stable chiral rotors. This observation emphasizes the impact of the core properties on the mechanism underlying the doublings of states in these nuclei. The dependence on the particular coupling scheme or on the Fermi level seems relatively less significant since no essential difference is observed between the patterns for the two-quasiparticle and the three-quasiparticle configurations belonging to the same core.

If the underlying mechanism for the doubling of state is related to spontaneous formation of chiral geometry, the observation discussed above emphasizes the impact of the core properties on the stability of the orthogonal angular momentum coupling. It also indicates that the conditions favorable for chiral configurations change vary rapidly with the mass number of the core, while the dependence of the chiral doubling on the Fermi level seems relatively less rapid.

The experimental information extracted for band doublings in the discussed quartet of candidate chiral nuclei awaits theoretical studies. Presently there is no nuclear model capable of addressing chiral band separations in odd-*A* nuclei, thus these experimental results cannot be directly compared with quantitative predictions for chirality. However, they restrict the possible scenarios and give new information on the characteristics of the underlying mechanism for the doubling of states. For example, the scenario of obtaining the yrare band by moving one quasineutron to the next $\nu h_{11/2}$ level is strongly excluded by the current results as the quasiparticle excitation would occur between different orbitals in the odd-odd case than in the odd-*A* case, leading to different degeneracy patterns in the two cases.

In summary, doubling of states in the $\pi g_{9/2}\nu(h_{11/2})^2$ band has been identified in ^{103}Rh with experimental characteristics expected from spontaneous formation of chirality in the intrinsic body-fixed reference frame. Comparison of the doublet structures in ^{102,103,104,105}Rh shows that the band separation energy depends strongly on the core properties and only to a lesser extent on the valence particle configuration and the position of the Fermi level. This observation sets up new criteria for the possible explanations of the observed band doublings, restricting the possible scenarios and providing new information on the characteristics of the underlying mechanism. The lack of a nuclear model capable of addressing chiral band separations in odd-*A* nuclei prevents this observation from being compared quantitatively with expectations for the chiral scenario; however, the large impact of the core properties is in qualitative agreement with it. Clearly, it would be interesting to search for similar sets of nuclei with chiral candidate band doublings in this region to test the robustness of the observed dependence of the degeneracies. It would be even more interesting, however, to check these dependences for the nuclei in which the chiral interpretation became questionable due to the lifetime data, and compare the results with the present observations. The present results also indicate a need for developing a quasiparticle-rotor model capable of handling the chiral doubling in the discussed three-quasiparticle configurations.

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