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Recent progress on the investigation of spontaneous formation of chirality in rotating nuclei

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Abstract

Experimental properties of nearly degenerate $\Delta I = 1$ doublet bands, which are built on the same single-particle configuration, are tested against three criteria for spontaneous formation of chirality in nuclei via the coupling of three mutually perpendicular angular momenta. Four representative nuclei, ^{134}Pr, ^{130}Cs, ^{104}Rh and ^{105}Rh are discussed. The doublet bands in these nuclei exhibit chiral characteristics except for ^{134}Pr, which shows a significant difference in electromagnetic properties between the two candidate chiral structures.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

A pair of nearly degenerate[6] $\Delta I = 1$ rotational bands built on the same single-particle configuration has been identified in several odd–odd as well as in a few odd–A nuclei in the mass $A \sim 130$ and $A \sim 150$ regions. These observations are results of concerted experimental efforts that are ongoing to investigate the occurrence of spontaneous formation of handedness in the body-fixed frame of a nucleus. The phrase *spontaneous formation of handedness* means an existence of degenerate energy eigenstates which are not invariant under the exchange of right- or left-handed geometry or chirality while the total Hamiltonian in the laboratory frame is required to be chiral invariant. The physical origin of this geometry in a nucleus is an energy minimization of the nuclear system via the non-coplanar coupling of three angular momenta; the mutually perpendicular coupling is an idealized case [1]. In odd–odd nuclei, the total angular momentum can be decomposed into a single-particle angular momentum of a valence

[6] I denotes a total angular momentum.

proton and of a valence neutron and the collective rotation of an even–even core. In odd–A nuclei, one of the components comes from the angular momenta associated with a broken pair of quasi-particles at higher spin. Regardless of mechanisms for generating chiral angular momentum coupling, its geometrical nature leads to configuration-independent characteristics of chiral doublet bands. Thus far, three of them are recognized and those are:

- near degenerate levels of the same spin and parity in two $\Delta I = 1$ bands built on the same single-particle configuration;
- smooth variation of $S(I) = [E(I) - E(I-1)]/2I$ within each band as a function of spin;
- within the pair of chiral bands,

$$B(EM; I'+ \to I+) = B(EM; I'- \to I-) \quad \text{and}$$
$$B(EM; I'+ \to I-) = B(EM; I'- \to I+)$$

where EM expresses either $E2$ or $M1$ while $I+$ and $I-$ denote the degenerate states.

It should be noted, however, that this set of criteria is, strictly speaking, applicable to the portion of bands or band members over the spin range where the collective rotation is sufficiently large and assumes that the core is triaxial. Even in the case of an idealized rigid triaxial core, chiral doublet bands are not degenerate at lower spin states near the bandhead due to a planar geometry which is resulted from a coupling of two angular momenta of the high-j particle and hole.

In this paper, candidate chiral doublet bands in ^{134}Pr, ^{130}Cs, ^{104}Rh and ^{105}Rh will be checked against the three criteria above. All these four nuclei have been studied relatively well with the high sensitivity of the Gammasphere and Euroball germanium-detector arrays and are chosen for the present discussion as the representative cases.

2. Configuration-independent characteristics of chiral doublet bands

In principle, the first characteristic is the most essential consequence of the spontaneous formation of chirality. The experimental starting point has been to identify two rotational bands and to show that they are almost degenerate ($\leqslant\sim$300 keV) with their relative spin and parity determined from multipolarities of the inter-band transitions. When only unique parity orbitals comprise the configurations such as $\pi h_{11/2} \otimes \nu h_{11/2}{}^{-1}$ in the $A \sim 130$ region and $\pi g_{9/2}{}^{-1} \otimes \nu h_{11/2}$ in the $A \sim 105$ region, the same parity of the two bands leads to the common single-particle configuration [2]. The energy degeneracy between the doublet bands is often represented in a plot of excitation energies of the two bands as a function of spin. (See the left column in figures 1 and 2.)

The second characteristic has been introduced as a consistency check for the perpendicular coupling of the single-particle angular momenta to the collective core rotation. The smooth variation of $S(I)$ values as a function of spin, in particular no pronounced zig-zag patterns with alternating odd/evenness of spin, reflects a small Coriolis force which is proportional to the scalar product of the angular momenta of a single particle and the collective core. When the Fermi level favours perpendicular angular momentum coupling of a valence proton and neutron, even if only one of the single-particle angular momentum vectors is orthogonal to the collective rotation, the $S(I)$ curves could still be smooth for both bands. However, the degeneracy between the two bands, with the same single-particle configuration, is unique to chiral geometry.

The third characteristic deals with electromagnetic properties expected of chiral geometry and thus serves as the most sensitive probe of the wavefunctions. Experimentally, lifetime measurements of the doublet band members are necessary in comparing absolute reduced

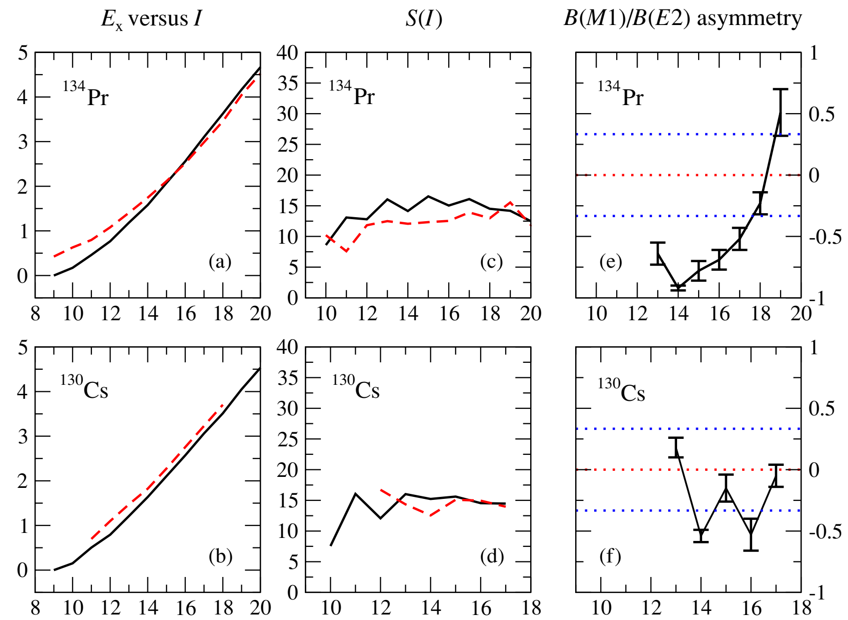

Figure 1. Plots to check for the chiral interpretation of the doublet bands in ^{134}Pr and ^{130}Cs. (a) and (b): excitation energy (in MeV) VS spin, (c) and (d): $S(I) = [E(I) - E(I-1)]/2I$ (keV/$\hbar$), (e) and (f): $B(M1)/B(E2)$ asymmetry where the three horizontal lines indicate $Y = S$ (middle), $S/Y = 0.5$ (top), $Y/S = 0.5$ (bottom). For all graphs, the horizontal axis is spin I in unit of $\hbar$.

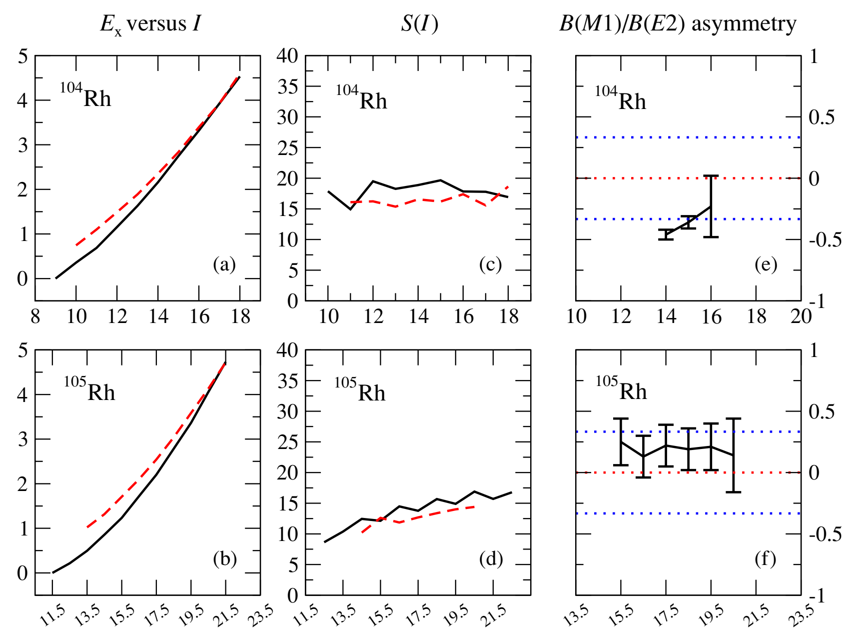

Figure 2. Plots similar to figure 1 for odd–odd ^{104}Rh and odd–A ^{105}Rh.

transition probabilities. As mentioned in the next section, only a few such lifetime measurements have been performed up to date. In lieu of the absolute $B(M1)$ and $B(E2)$ values, $B(M1; I \rightarrow I-1)/B(E2; I \rightarrow I-2)$ ratios, which can be extracted without the lifetime measurements, are compared between the doublet bands. In doing so, asymmetry parameter P is defined as

$$P = \frac{Y - S}{Y + S}, \tag{1}$$

where $Y = [B(M1; I \rightarrow I-1)/B(E2; I \rightarrow I-2)]_Y$ for the energetically lower of the two bands, and S is defined in a similar way for the higher lying band.

3. Consistency check for the chiral geometry in ^{134}Pr, ^{130}Cs, ^{104}Rh and ^{105}Rh

The mass $A \sim 130$ region was the first and most extensively studied region in the search for chiral-like structures. The side band to the yrast $\pi h_{11/2} \otimes \nu h_{11/2}{}^{-1}$ band had been identified in ^{134}Pr [3] before these doublet bands were interpreted as chiral doublet candidates [4]. Later re-studies to obtain further experimental information on these bands [5, 2] have been carried out. As shown in figure 1(a), the two bands achieve degeneracy of ~50 keV at spin $I = 15$ and 16, which is the best observed in this mass region. Although the $S(I)$ curve for the yrast band exhibits a slight zig-zag pattern, that for the side band is almost flat as a function of spin (figure 1(c)). A large asymmetry in the $B(M1)/B(E2)$ values, as shown in figure 1(e), clearly fails to meet the third criterion for these bands to be considered as the chiral twins. This poses a serious inconsistency within the chiral geometry origin of the doublet bands. Recent results of lifetime measurements have revealed that the $B(E2)$ strengths are appreciably different between the two bands [6].

The $\pi h_{11/2} \otimes \nu h_{11/2}{}^{-1}$ doublet band properties of ^{130}Cs [7], an $N = 75$ isotone of ^{134}Pr, are shown in figures 1(b), (d) and (f). The energy degeneracy, shown in figure 1(b), is rather constant around at ~300 keV up to high spin states. The overall $S(I)$ values are close to constant without any clear zig-zag pattern for both bands (figure 1(d)). Compared to ^{134}Pr, the asymmetry of $B(M1)/B(E2)$ is small. A staggering pattern can be observed reflecting that of the yrast band $B(M1)/B(E2)$ values while the side band shows flat $B(M1)/B(E2)$ values as a function of spin. The lifetime measurements of the doublet band members of this nucleus have to be performed. In terms of the consistency with the expected chiral characteristics, ^{130}Cs is a better chiral nucleus than ^{134}Pr.

The mass $A \sim 105$ region has turned out to offer the strongest candidates for chiral nuclei observed until now. The doublet bands have been identified in odd–odd $^{106}_{47}$Ag [8], $^{100,102,104,106}_{45}$Rh [8–11] and $^{100}_{43}$Tc [12] and in odd–A ^{103,105}Rh [13, 14]. In this mass region, for odd–odd nuclei, the valence proton in the $g_{9/2}$ orbital and neutron in the $h_{11/2}$ orbital is hole-like and particle-like, respectively. In odd–A nuclei, quasi-neutrons are also particle-like. Their characters are interchanged relative to the $A \sim 130$ region where the valence proton occupies the lower subshell and the valence neutron occupies the upper subshell of the $h_{11/2}$ orbital. The degeneracy of ~2 keV at spin 17 with the overall degeneracy better than 160 keV is observed in the ^{104}Rh doublet bands of the $\pi g_{9/2}{}^{-1} \otimes \nu h_{11/2}$ configuration. Figures 2(a), (c) and (e) indicate that the doublet bands in this nucleus exhibit chiral properties. The doublet bands identified in ^{105}Rh involving quasi-particle excitation, namely a broken pair of $h_{11/2}$ neutrons in the $\pi g_{9/2}{}^{-1} \otimes \nu(h_{11/2})^2$ configuration, are equally indicative of their chiral aspects. The observation of the doublet bands with common characteristics in odd–odd and odd–A Rh isotopes supports their configuration-independent geometrical origins. Lifetime measurements have so far not been performed on the doublet bands in this mass region and

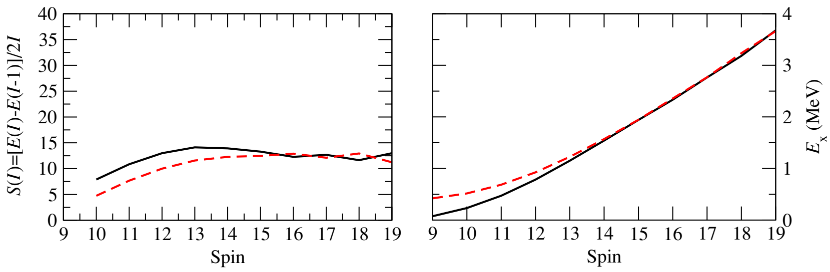

Figure 3. Calculated excitation energy in MeV (left) and $S(I)$ in keV/$\hbar$ (right) as a function of spin in $\hbar$.

are clearly highly desired, while in the $A \sim 130$ region the measurements have recently been made in ^{134}Pr [6], ^{132} La [15] and ^{128}Cs [16].

4. Symmetry of the model Hamiltonian and the selection rules

Independent of interpretation for the systematic observation of the doublet bands, doubling of rotational states has been numerically confirmed in particle rotor model calculations in which a particle and a hole in the same unique parity high-j orbital are coupled to a rigid triaxial rotor with irrotational flow moment of inertia. Figure 3 shows the degeneracy plot and $S(I)$ for the bands obtained from the model calculations [17]. The model assumptions are purposefully chosen so as to achieve mutually perpendicular coupling of the angular momentum vectors of the particle, hole and the core rotation. Nevertheless, this theoretical idealization is relevant to the $\pi \mathrm{i}_{13/2} \otimes \nu \mathrm{i}_{13/2}{}^{-1}$, the $\pi \mathrm{h}_{11/2} \otimes \nu \mathrm{h}_{11/2}{}^{-1}$ and the $\pi \mathrm{g}_{9/2} \otimes \nu \mathrm{g}_{9/2}{}^{-1}$ configurations of odd–odd nuclei in the mass $A \sim 190$, 130 and 80 regions, respectively. The particle has the largest angular momentum projection along the short axis of the triaxial core whilst that of the hole is directed along the long axis. The core rotation has maximum projection along the intermediate axis, since this has the largest moment of inertia for irrotational flow.

The particle rotor model has been previously used in investigating chirality in [4, 18]. However, the latest development came from the recognition of a symmetry in the model Hamiltonian specific for the present model assumptions described above [17]. This symmetry defines an additional good quantum number to spin and parity, and the selection rules have been derived analytically. Therefore, it has been shown that there exists a subgroup of chiral configurations with a higher symmetry. The collective rotation is small for the lower spin states, and thus near the bandhead the chiral geometry is not well developed. However, the derived selection rules are valid, at least in the model, regardless of spin. The experimental evidence for this symmetry, which leads to chiral geometry at higher spin, will provide a solid evidence for a stable triaxial nuclear shape.

5. Summary

Nearly degenerate $\Delta I = 1$ bands have been systematically observed in odd–odd and odd–A nuclei in the mass $A \sim 130$ and 105 regions. The experimental features of the doublet bands in four representative nuclei, ^{134}Pr, ^{130}Cs, ^{104}Rh and ^{105}Rh, are tested against the three mutually consistent characteristics of chiral doublet bands. Similarities of experimental features seen in the doublet band structures of ^{130}Cs, ^{104}Rh and ^{105}Rh, involving different mass regions and single-particle configurations, support their geometrical origins, namely the spontaneous formation of handedness. The significant difference in the reduced transition probabilities between the doublet bands of ^{134}Pr must be explained by further studies.

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