NEAR-DEGENERATE ROTATIONAL BANDS IN THE Tl ISOTOPES*

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Sets of near-degenerate rotational bands built on configurations involving $\pi h_{9/2}$ particle and $\nu i_{13/2}$ holes were observed in the neighbouring ^{193,194}Tl isotopes. Such sets of bands, involving particle and hole configurations and occurring in nuclei with triaxial shape, are caused by chiral symmetry formed in angular momentum space. Each nuclear chiral system is expected to generate a pair of near-degenerate partner bands. However, several sets of three partner bands were observed in these Tl isotopes, raising questions whether one or two chiral systems are formed, and which two bands are partners in the chiral pair. Many-particle-rotor model calculations reproduce well the features of the observed negative-parity bands in ^{193,194}Tl and support the suggested chiral geometry of the angular momenta.

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1. Introduction

Nuclei with triaxial shape produce a variety of interesting phenomena. For instance, even–even triaxial nuclei exhibit γ-bands; odd-mass triaxial nuclei can generate wobbling bands; and odd–odd triaxial nuclei can form chiral symmetry systems in angular momentum space. About 20 years ago, it was realised that calculations with triaxial rotor model for odd–odd nuclei with a $\pi h_{11/2}$ particle and a $\nu h_{11/2}$ hole produce a pair of degenerate

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rotational bands. In a pioneering work of Frauendorf and Meng, this degeneracy was interpreted as resulting from broken chiral symmetry in angular momentum space [1]. Since then, a lot of experiments were carried out to search for chiral partners. An abundance of chiral candidates were found in several nuclei in the $A = 80$, 100, 130 and 190 mass regions. In parallel, many theoretical studies were carried out, aiming at establishing characteristic features of the chiral systems and defining reliable fingerprints for their identification [2–5]. Despite all the efforts, a number of questions remain open. For instance, no experimental technique is yet able to confirm that the experimentally observed near-degenerate bands are caused by broken chiral symmetry in angular momentum space. Further studies, both by theory and experiment, on such near-degenerate bands are needed. Cases that challenge our understanding are particularly interesting.

The Tl isotopes in the 190 mass region have moderate quadrupole deformation of about 0.15. They are also expected to have triaxial shape, indicated *(i)* by the observation of low-energy γ-bands in the neighbouring even–even cores [6]; *(ii)* by the observation of a number of low-spin rotational bands associated with the $\pi h_{9/2}$ orbital in the odd-mass Tl isotopes which were successfully reproduced by a particle coupled to a triaxial rotor, *e.g.* [7]; *(iii)* by theoretical calculations, such as Cranked–Nilsson–Strutinsky, which predict triaxial shape for the Tl isotopes, *e.g.* [8]. In addition, high-j orbitals with both particle ($\pi h_{9/2}$) and hole ($\nu i_{13/2}$) nature lie near the Fermi surface making the Tl isotopes good candidates for nuclear chiral symmetry breaking.

The first near-degenerate pair of bands in a Tl isotope, associated with the $\pi h_{9/2} \otimes \nu i^{-1}_{13/2}$ confguration, was observed in ^{198}Tl [9, 10]. A number of near-degenerate partners built on $\pi h_{9/2} \otimes \nu i^{-n}_{13/2}$ ($n = 1, 3$) configurations were reported later in ^{194}Tl [11]. A striking feature of the latter bands is that three partner bands were identified with the same configuration. However, a chiral pair consists of two partner bands. Is then the observation of three bands an indication that two chiral systems are formed, but one band remains unobserved? Or perhaps only one chiral system is formed, while the third bands has a different, non-chiral nature. Further study of ^{194}Tl through DSAM analysis revealed deeper similarities of the observed bands [12], but could not resolve the open questions on their nature. To understand better the $\pi h_{9/2} \otimes \nu i^{-n}_{13/2}$ bands in this mass region the neighbouring nucleus, ^{193}Tl, was studied.

2. Near-degenerate bands in ^{194}Tl

In ^{194}Tl, a set of three 2-quasiparticle negative-parity $\pi h_{9/2} \otimes \nu i^{-1}_{13/2}$ bands were observed [11]. In Fig. 1, the lowest energy band of this set is labelled 2qpA, the second lowest — 2qpB, the third — 2qpC. At an excitation energy of ∼ 2.5 MeV, these two-quasiparticle bands undergo backbends, associated with an alignment of a neutron $i_{13/2}$ pair, producing three 4-quasiparticle bands. These bands were labelled 4qpA, 4qpB and 4qpC in Fig. 1. The excitation energy of the negative-parity bands in ^{194}Tl is shown in Fig. 1 (a). A characteristic feature of these bands is that they group in two sets of three bands each, associated with $\pi h_{9/2} \otimes \nu i^{-n}_{13/2}$ configurations, where $n = 1, 3$, and each set comprises of one band at lower energy and two excited bands at similar energies.

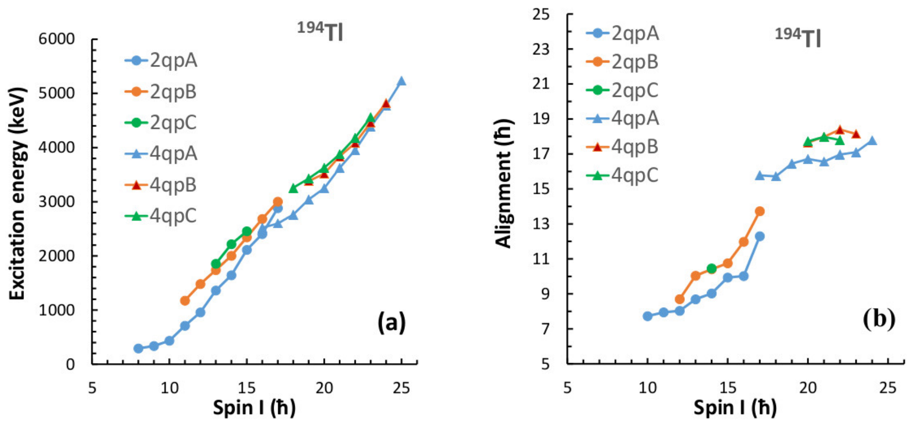

Fig. 1. (a) Excitation energies of the 2- and 4-quasiparticle $\pi h_{9/2} \otimes \nu i^{-n}_{13/2}$, $(n = 1, 3)$ bands in ^{194}Tl. (b) Alignments of these bands, calculated with $J_0 = 8\,\hbar^2/\text{MeV}$ and $J_1 = 40\,\hbar^4/\text{MeV}^3$, and $K = 5$.

The alignments of the three bands that belong to the same set are not necessarily the same. The two excited bands have similar alignments, however the alignment of the lowest energy band is lower by $\sim 2\,\hbar$, see Fig. 1 (b). It is natural to assume that a good chiral pair should have an identical alignments of the two partner bands, therefore bands 4qpB and 4qpC were suggested as chiral partners [8]. The close similarity of these bands was noted and they are probably the chiral pair that exhibits the best chiral near-degeneracy observed to date.

However, the nature of the lowest energy, 4qpA band was questioned [11]. Does this band have a non-chiral nature, for instance, could it correspond to an axially symmetric shape? Or, if the nuclear shape remains the same for these three bands, perhaps a second chiral system is formed? In this case, a fourth band, built on the same configuration, should be present. Could such a band remain unobserved due to, for instance, weak population and low statistics in the experimental data?

In order to study further the sets of three bands, in particular to investigate whether the bands might exhibit differences in their transition probabilities, as expected if the bands were associated with different nuclear shapes, DSAM lifetime measurements were performed [12]. The results on the transition probabilities ascertained further the excellent near-degeneracy of bands 4qpB and 4qpC. They also indicated that the 4qpA band has similar B(M1) and B(E2) reduced transition probabilities to those of 4qpB and 4qpC bands. Therefore, the data did not show any evidence that 4qpA band might have different nature or that it might correspond to a different nuclear shape. Thus, an interpretation assuming the same nuclear shape seems most appropriate.

The 4qp bands were interpreted using the Many-Particle-Rotor model (MPR) [13–15]. The calculations were made for the four lowest energy bands with $\pi h_{9/2} \otimes \nu i_{13/2}^{-3}$ configuration, assuming a triaxial nuclear shape with $\epsilon_2 = 0.15$ and $\gamma = 40°$, as predicted [8] by the Cranked–Nilsson–Strutinsky (CNS) model [13,16]. The MPR calculations successfully predicted the characteristic energy splitting of these bands; one of the calculated bands was found at lower energy, while three excited bands have similar energies, see Fig. 2. In addition, the calculations showed that all four bands correspond to an angular momentum that has large projections on all three nuclear axes, thus indicating chiral geometry for all four bands [12]. Therefore, these calculations highlight a strong possibility that two chiral systems are formed in ^{194}Tl.

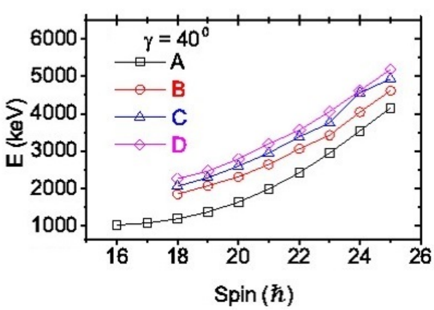

Fig. 2. Excitation energies of the four lowest energy $\pi h_{9/2} \otimes \nu i_{13/2}^{-3}$ bands in ^{194}Tl calculated with the MPR model.

In order to study further these $\pi h_{9/2} \otimes \nu i_{13/2}^{-n}$ bands, in particular to try to discover a fourth partner bands, we studied the neighbouring nucleus, ^{193}Tl.

3. Near-degenerate bands in ^{193}Tl

Recent experimental data taken at iThemba LABS with the AFRODITE array led to a revision and an extension of the previous level scheme of ^{193}Tl [17]. In particular, several sets of rotational bands, built on $\pi h_{9/2} \otimes \nu i_{13/2}^{-n}$ configurations with $n = 2$, 4 were identified [18, 19]. The bands are labelled according to the number of quasiparticles involved and according to their relative excitation energy at low spins, in a similar way as in ^{194}Tl.

The excitation energies and the alignments of the near-degenerate bands in ^{193}Tl are shown in Fig. 3. Three bands are observed for the 3-quasiparticle $\pi h_{9/2} \otimes \nu i_{13/2}^{-2}$ configuration and two bands for the 5-quasiparticle $\pi h_{9/2} \otimes \nu i_{13/2}^{-4}$ configuration. Comparing Figs. 1 and 3, one observes a striking similarity for the bands, for instance: *(i)* in the spin region near the band heads, one of the bands lies at lower energy, while the excited bands have similar excitation energies; *(ii)* in the spin region well above the band heads, the excitation energies of the three bands become similar; *(iii)* the lowest energy bands in all cases have an alignment that is about $\sim 2\,\hbar$ lower than the alignments of the corresponding excited bands.

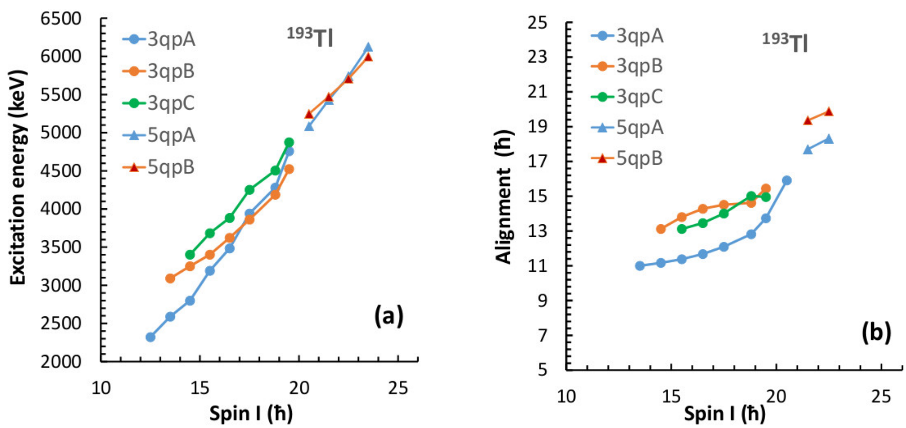

Fig. 3. (a) Excitation energies of the 3- and 5-quasiparticle $\pi h_{9/2} \otimes \nu i_{13/2}^{-n}$, ($n = 2, 4$) bands in ^{193}Tl. (b) Alignments for these bands, calculated with $J_0 = 8\,\hbar^2/\text{MeV}$ and $J_1 = 40\,\hbar^4/\text{MeV}^3$, and $K = 4.5$.

While the near-degenerate bands in the two neighbouring isotopes show large similarities, they also exhibit one interesting difference, *i.e.* in ^{193}Tl the second lowest bands, B, cross the lowest energy bands, A, and become yrast at high spins, see Fig. 3 (a), while in ^{194}Tl no such crossings are observed. This new behaviour in ^{193}Tl opens additional questions, such as: *(i)* how can two bands with the same parity and very similar nature cross each other without an apparent interaction? *(ii)* is there a specific symmetry that forbids such an interaction, and could this be the chiral symmetry? *(iii)* could it be that bands A and B in ^{193}Tl have very different nature, so different that despite having the same parity their interaction in the crossing region is negligible? In this case, bands A and B cannot be chiral partners, instead bands A and C could be considered as a chiral pair. This is an interesting possibility, these bands indeed show a decreasing relative excitation energy as a function of spin, which is a typical behaviour of chiral partner bands. In addition, the difference in their alignments decreases as a function of spin. MPR calculations were performed for the bands in ^{193}Tl. While they reproduce the characteristic energy splitting into one lower energy band and three excited bands, there is no clear indication on which bands to couple into chiral pairs. Therefore, a number of interesting questions on the nature of the negative-parity bands in the Tl isotopes remain open. To understand these bands larger experimental data sets are needed.

4. Summary

Sets of near-degenerate bands corresponding to $\pi h_{9/2} \otimes \nu i_{13/2}^{-n}$ with $n = 1$, 2, 3, 4 were found in the neighbouring ^{193,194}Tl nuclei. The most likely interpretation involves chiral symmetry in angular momentum space. However, three near-degenerate bands were observed in most cases, while a chiral system generates only two partner bands. The odd number of observed bands raises several questions, *e.g.* is it possible that a second chiral system is formed, but the fourth band remains still unobserved; or alternatively, can two of the bands, and which ones, form a chiral system, while the third band has a different, non-chiral nature. These questions remain open.

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