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DSAM lifetime measurements for the chiral bands in ^{194}Tl

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Abstract. When a left-handed and a right-handed nuclear system form in angular momentum space, a pair of nearly degenerate rotational bands is observed. To identify chiral symmetry most important is to establish near-degeneracy not only in excitation energies of the partner bands, but also in their intra-band and inter-band B(M1) and B(E2) transition probabilities. This needs dedicated lifetime measurements. Such measurements were performed for four bands of ^{194}Tl. Two of these have very close near-degeneracy and form a prime candidate for best chiral pair. The lifetime measurements confirm the excellent near-degeneracy in this chiral pair.

1. Chiral symmetry in nuclei.

Chiral symmetry in nuclei forms in angular momentum space [1]. It occurs when a system, which is made of angular momenta, shows well defined handedness, i.e. the mirror image of the system does not coincide with the original. A simple chiral system is made of three mutually orthogonal angular momenta, which can be arranged either in a left-handed or in a right-handed system. A nucleus with ideal chiral symmetry shows a pair of degenerate rotational bands. In real nuclei, however, the partner bands may show considerable divergence from degeneracy [2,3]. Many chiral partners were observed to date in the mass regions of 80, 100, 150, and 190. A review of the experimental data can be found in Ref. [4]. More recent results are published in Refs. [5-14]. The observed chiral bands show certain similarities, but not true degeneracy in all their properties. It is, however, expected that pairs with closer near-degeneracy should correspond to purer chiral symmetry. Thus, search for chiral pairs with good near-degeneracy is being carried out in many laboratories all over the world for the last couple of decades.

2. Chiral pair with excellent near-degeneracy in ^{194}Tl.

At iThemba LABS in South Africa the heavier Tl isotopes were investigated searching for chirality. In particular a pair of rotational bands with very good near-degeneracy was discovered in ^{194}Tl [8]. This experiment used a thin ^{181}Ta target, ^{18}O beam at 91 and 93 MeV, and the AFRODITE array, comprising of 8 Compton suppressed clover detectors [15,16]. The data analysis yielded more than a 100 new transitions, placed in several new bands [9].

The pair of negative parity bands, shown in Fig.1, was proposed as a chiral pair [8]. The two bands are assigned a $\pi h_{9/2} \times \nu i_{13/2}^{-1}$ configuration at low spins. The proton lies at the bottom of the $h_{9/2}$ shell and has particle nature, thus its angular momentum tends to align along the short nuclear axis. The neutron occupies an orbital at the upper part of the $i_{13/2}$ shell, it has hole nature and its angular momentum aligns along the long nuclear axis.

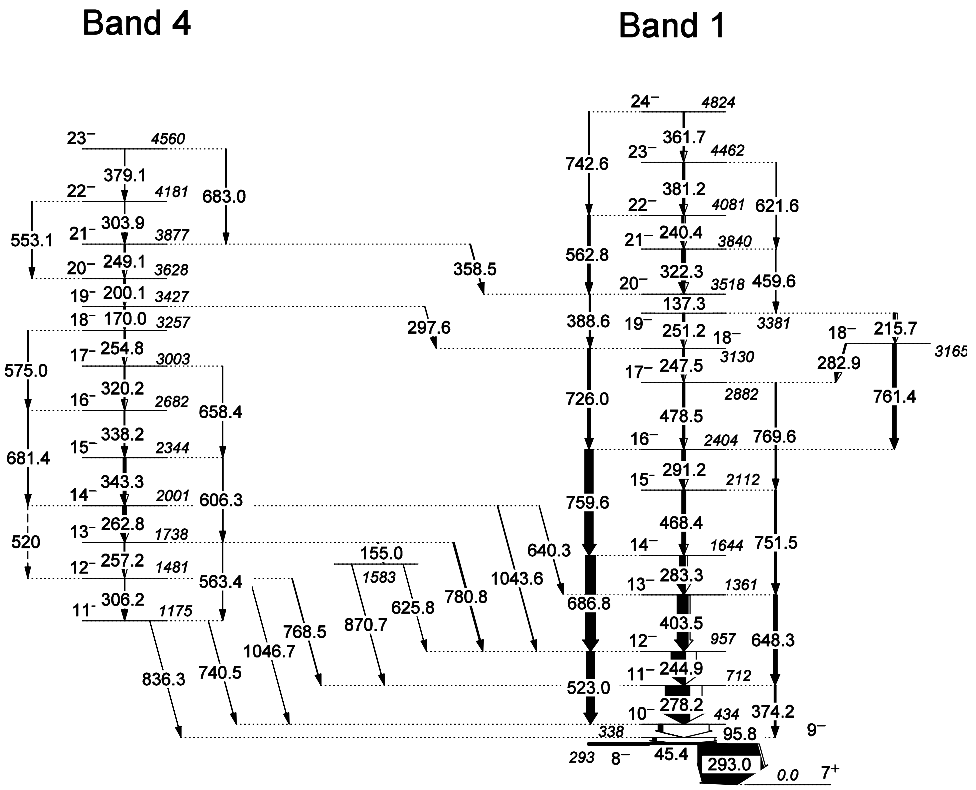

Figure 1. The pair of negative parity bands in ^{194}Tl, proposed as chiral partners. From Ref. [8].

In addition, the calculations performed with the Cranked Nilsson Strutinsky code suggest that ^{194}Tl has a triaxial shape, with a rotational angular momentum that is oriented along the intermediate axis [8]. Therefore the three angular momenta, those of the odd proton, the odd neutron and the rotation are oriented predominantly along the three nuclear axes, and should thus form a chiral system. The pair of observed rotational bands, see Fig. 1, shows some similarity at low spins. For instance the difference in the excitation energies of the two partners decreases from $\Delta E \sim 463$ keV at I = 11 to $\Delta E \sim 127$ keV at I = 18. The near-degeneracy, however, improves further at high spins.

In the spin range of 16 - 19 ħ a backbend occurs. A pair of $i_{13/2}$ neutrons is broken and their angular momenta are aligned along the long nuclear axis. Thus, above I ~ 19 ħ the partner bands are associated with a $\pi h_{9/2} \times \nu i_{13/2}^{-3}$ configuration [8]. This is the first 4-quasiparticle chiral pair observed to date. It is also the only case in which the chiral symmetry persists through a backbend. Still more remarkable is the excellent near-degeneracy observed for this pair at high spins. A comparison with other excellent chiral pairs is shown in Fig. 2. It is obvious that the pair in ^{194}Tl exhibits particularly close near-degeneracy in all properties, such as excitation energies, alignments, and ratios of B(M1)/B(E2) transition probabilities. It is, thus, a prime candidate for best chiral pair found to date.

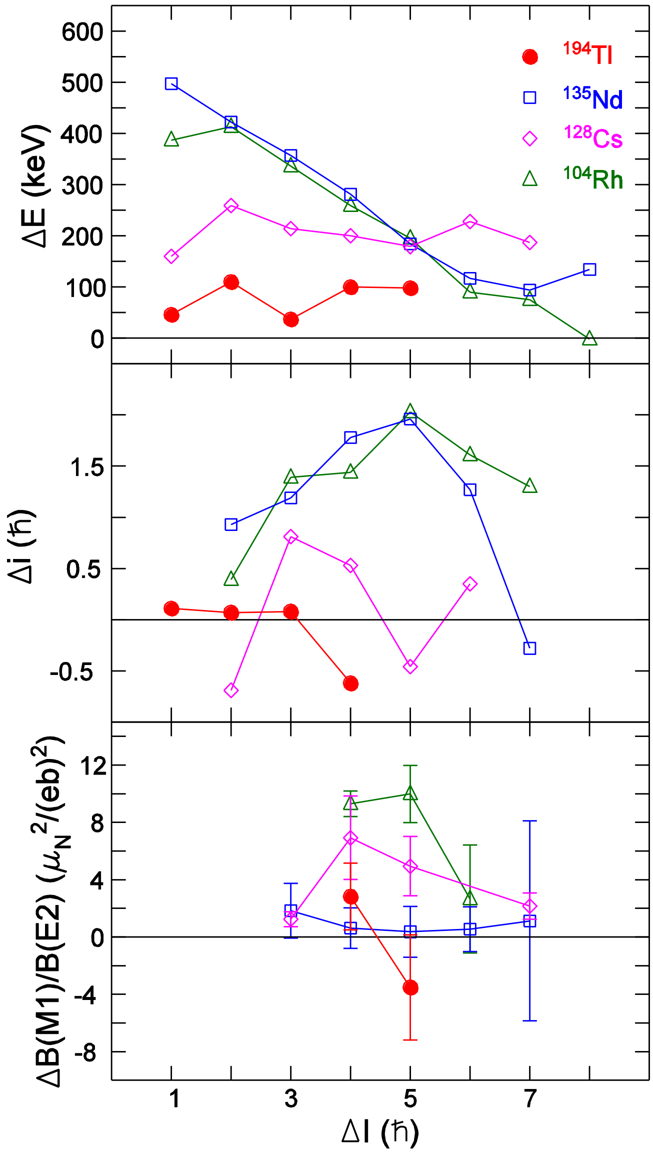

Figure 2. The difference in the excitation energies ΔE, alignments Δi, and ratios of the reduced transition probabilities ΔB(M1)/B(E2) as a function of the spin I with respect to the band head spin for the chiral pairs in ^{194}Tl (the 4-quasiparticle pair), ^{135}Nd, ^{128}Cs and ^{104}Rh. From Ref. [8].

To test whether this pair exhibits good near-degeneracy for the B(M1) and B(E2) reduced transition probabilities, we have performed lifetime measurements in ^{194}Tl using the Doppler Shift Attenuation Method (DSAM). Such measurements are crucial, since as previously shown [17], good energy near-degeneracy alone does not confirm unambiguously that a pair of bands represents a good chiral system.

3. DSAM lifetime measurements in ^{194}Tl.

The experiment was performed at iThemba LABS, South Africa. The high spin states in ^{194}Tl were populated in the ^{181}Ta(^{18}O,5n) reaction at a beam energy of 91 MeV. The target was a 1 mg/cm^2 foil of

^{181}Ta on which a thick layer of Bi was evaporated. The emitted γ rays were detected with the AFRODITE array, consisting of 9 Compton suppressed clover detectors and 6 LEPS detectors. Four clovers were arranged at 45° and four clovers were placed at 135° with respect to the beam direction. The remaining detectors were mounted at 90°. The γ rays were emitted while the ^{194}Tl nuclei were slowing down in the Bi backing. Thus, the γ-ray peaks detected at 45° and 135° showed Doppler broadening, which was then analyzed to extract the lifetime of the nuclear states.

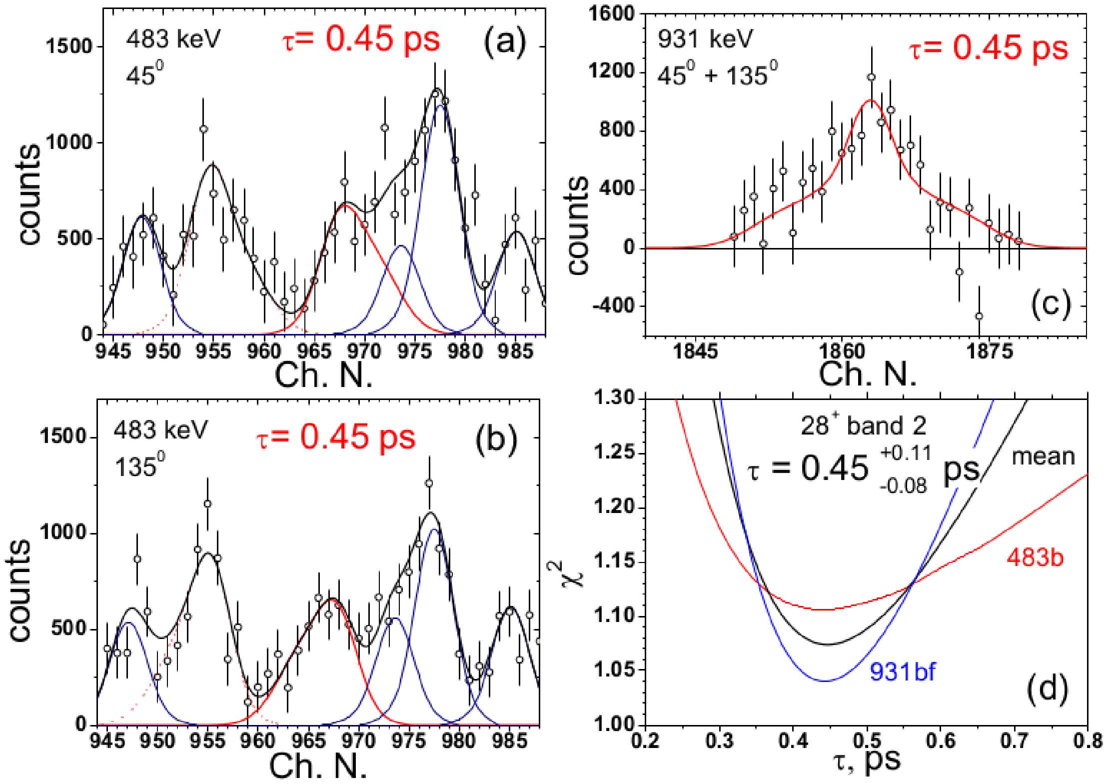

Figure 3. Analysis of the Doppler broadening to extract the lifetime of the 28$^+$ level in ^{194}Tl. Gated spectra at forward, (a), and backward, (b), angles are shown illustrating the Doppler broadening of the 483 keV peak, shown in red. The spectrum in (c) shows the sum of the forward and backward angles spectra for the 931 keV transition. In panel (d) the χ^2 functions from the analysis of the spectra in panels (b) and (c) are shown.

Data were sorted into background subtracted gated spectra at forward (45°) and backward (135°) angles. The DSAM analysis was performed using the programs COMPA, GAMMA, and SHAPE [18-22], which have been previously applied with the AFRODITE array [11,23]. Monte-Carlo methods were employed to simulate the entry state and the side feeding cascades to the level of interest. Lifetimes were determined step by step starting from the highest-energy level of a band. An example of DSAM analysis is shown in Fig. 3 for the 28$^+$ level, which decays by a 483 and a 931 keV transitions. One can notice the difference in the broadening of the low-energy part of the medium-energy 483 keV peak, shown in red in panels (a) and (b). The Doppler broadening is much larger for the higher-energy 931 keV peak, which appears symmetric in the summed spectrum of forward and backward angles, see panel (c) of Fig. 3. The analysis of the χ^2 functions for the spectra in panels (b) and (c) is shown in panel (d) and illustrates the extraction of the lifetime of the 28$^+$ level. Lifetimes were measured for several levels in four rotational bands in ^{194}Tl.

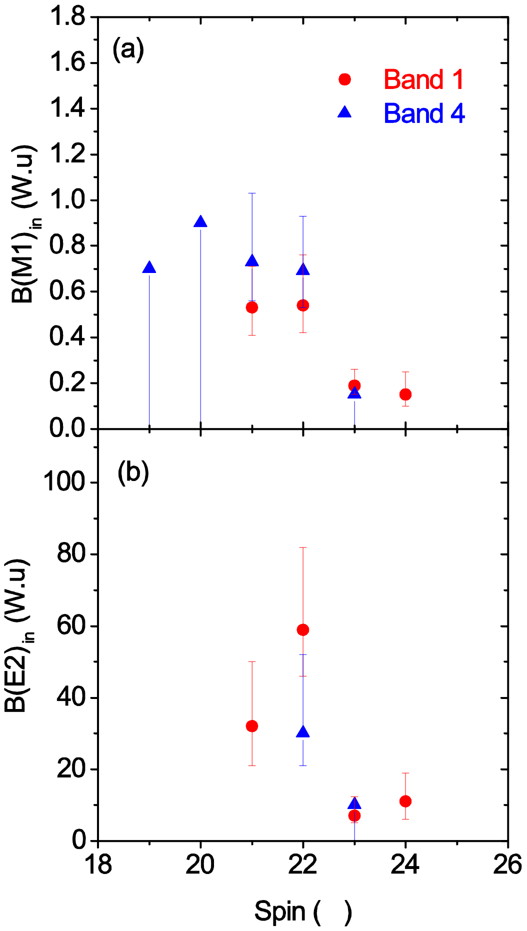

Figure 4. The measured B(M1) and B(E2) in-band transition rates in the yrast (Band 1) and side (Band 4) bands of the chiral pair in ^{194}Tl.

The extracted B(M1) and B(E2) reduced transition probabilities for the states of the chiral pair are shown in Fig. 4. Both bands exhibit very similar values for the in-band transition probabilities. This confirms that the pair shows excellent near-degeneracy, including in the B(M1) and B(E2) rates. It indicates that the bands in ^{194}Tl are (among) the best known chiral symmetry partners.

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