^{194}Tl as the first example revealing chiral symmetry breaking in a pair of four-quasiparticle bands

P.L. Masiteng[1,2,3,*], E.A. Lawrie[1], T.M. Ramashidzha[1,2], R.A. Bark[1], B.G. Carlsson[4], J.J. Lawrie[1], R. Lindsay[2], F. Komati[1,5], J. Kau[1,5], P. Maine[1,2], S.M. Maliage[1,2], I. Matamba[6], S.M. Mullins[1], S.H.T. Murray[1], K.P. Mutshena[1,6], A.A. Pasternak[7], I. Ragnarsson[4], D.G. Roux[2], J.F. Sharpey-Schafer[1,2], O. Shirinda[1,2], P.A. Vymers[1,2]

[1] iThemba LABS, National Research Foundation, P.O. Box 722, 7129 Somerset West, South Africa
[2] University of the Western Cape, Private Bag X17, 7535 Bellville, South Africa
[3] University of Johannesburg, P.O. Box 524, 2006 Auckland Park, South Africa
[4] Division of Mathematical Physics, LTH, Lund University, SE-221 00 Lund, Sweden
[5] University of North West, Private Bag X2046, 2735 Mmabatho, South Africa
[6] University of Venda for Science and Technology, Thohoyandou, South Africa
[7] A.F. Ioffe Physical-Technical Institute, 194021 St.-Petersburg, Russia

E-mail: *plmasiteng@uj.ac.za

Abstract. A study of ^{194}Tl has revealed the presence of two strongly coupled negative-parity rotational bands up to the 24^- and 23^- states, respectively. These two bands are associated with a two-quasiparticle configuration at lower spins and the four-quasiparticle configuration at higher spins. The two 4-quasiparticle bands show exceptionally close near-degeneracy in the excitation energies. The relative excitation energies of these 4-quasiparticle bands were compared to the relative excitation energies of the best known chiral candidates with close near-degeneracy. This is one of the best cases of near degeneracy in partner bands observed to date, probably resulting from a chiral geometry in the angular momentum space. It is also the first pair of 4-quasiparticle bands associated with chiral symmetry.

1. Introduction

The manifestation of chirality in atomic nuclei, originally suggested in Ref. [1] and vigorously investigated over the past few years from both the experimental and theoretical standpoint, continues to be the subject of intense discussion. Subsequent to the observation of chiral doublet bands in $N = 75$ isotones [2], candidate chiral bands have been reported in more than 21 nuclei in $A \sim$80, 100, 130, 190 mass regions.

Nuclear chirality depends on a delicate balance between the collective core with a triaxial mass distribution and a single particle degree of freedom associated with the valence proton and neutron. An energy minimizing mechanism among the core and the valence nucleons results in a mutually perpendicular coupling of their respective angular momenta forming either a left- or a right-handed system in the nuclear body-fixed frame. The intrinsic chirality then is seen in

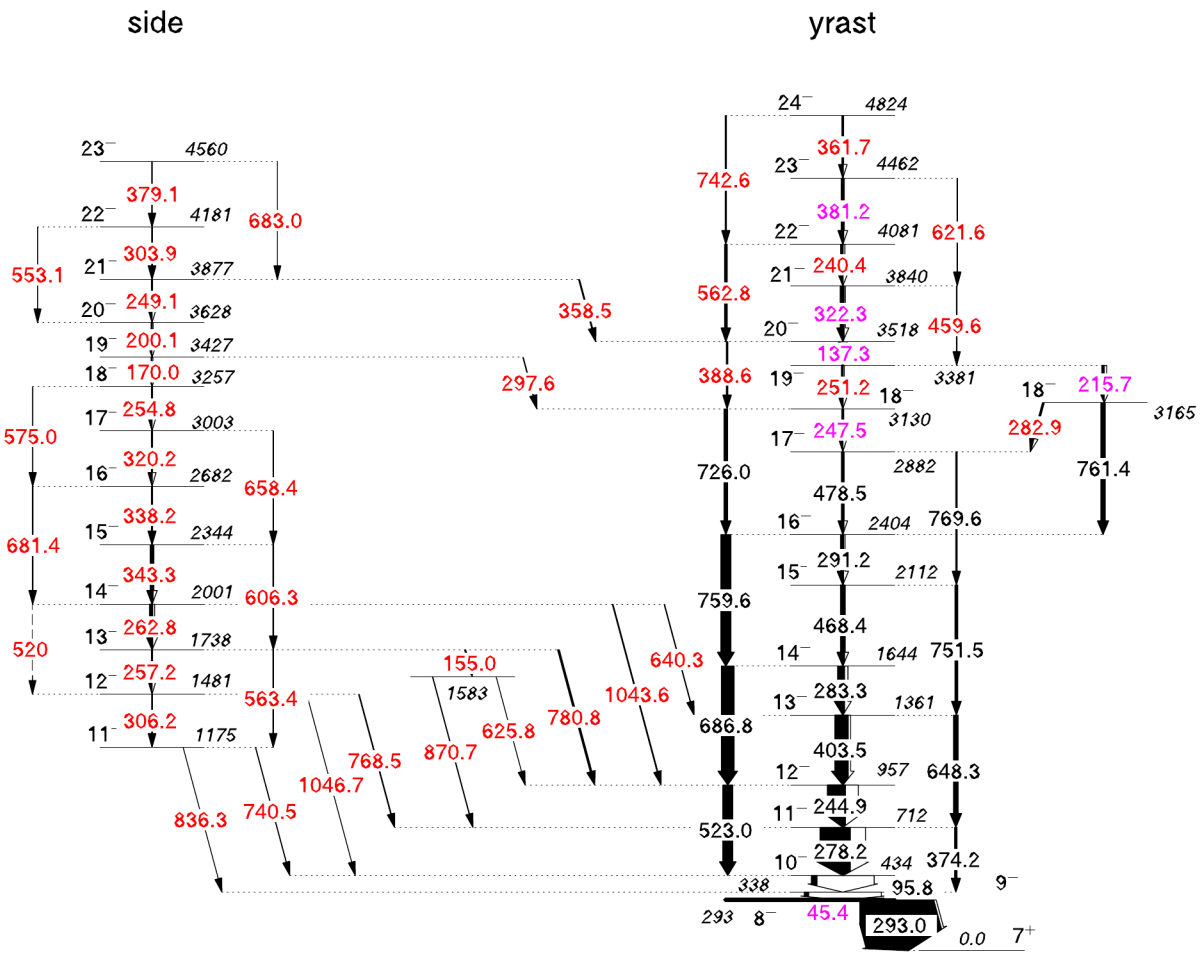

Figure 1. Partial level scheme showing the near-degenerate pair of rotational bands in ^{194}Tl. The uncertainties in the measured γ-ray energies are typically about 0.3 keV for most transitions, but increase to 0.5 keV for weak and doublet transitions.

the laboratory frame, which is free of handedness, as a doubling of energy levels with the same spin and parity.

Despite many discoveries reporting possible chiral partner bands, degenerate band structures are yet to be observed. The currently known chiral candidates show similar properties rather than degeneracy. The best known nearly degenerate band structures were reported in odd-A ^{135}Nd [3], ^{126,128}Cs [4, 5], ^{104}Rh [6] and recently we found such structure in ^{194}Tl [7]. In the present report we discuss the candidate chiral band structure found in ^{194}Tl and compare the observed degeneracies in the ^{135}Nd , ^{128}Cs, ^{104}Rh and ^{194}Tl.

2. Experimental method and data analysis

High-spin states in ^{194}Tl were populated using the ^{18}O(^{181}Ta, 5n) reaction at 93 and 91 MeV beam energies. The beam, provided by the separator sector cyclotron (SSC) of the iThemba LABS, impinged upon a self-supporting stack of two (and three) 0.5 mg/cm^2 target foils. The emitted γ rays were detected by the AFRODITE γ-ray spectrometer [8, 9], which comprised of 8 Compton-suppressed clover detectors and 6 LEPS detectors with the trigger logic set to accept events when at least two γ rays were detected in coincidence in the clover detectors. The data

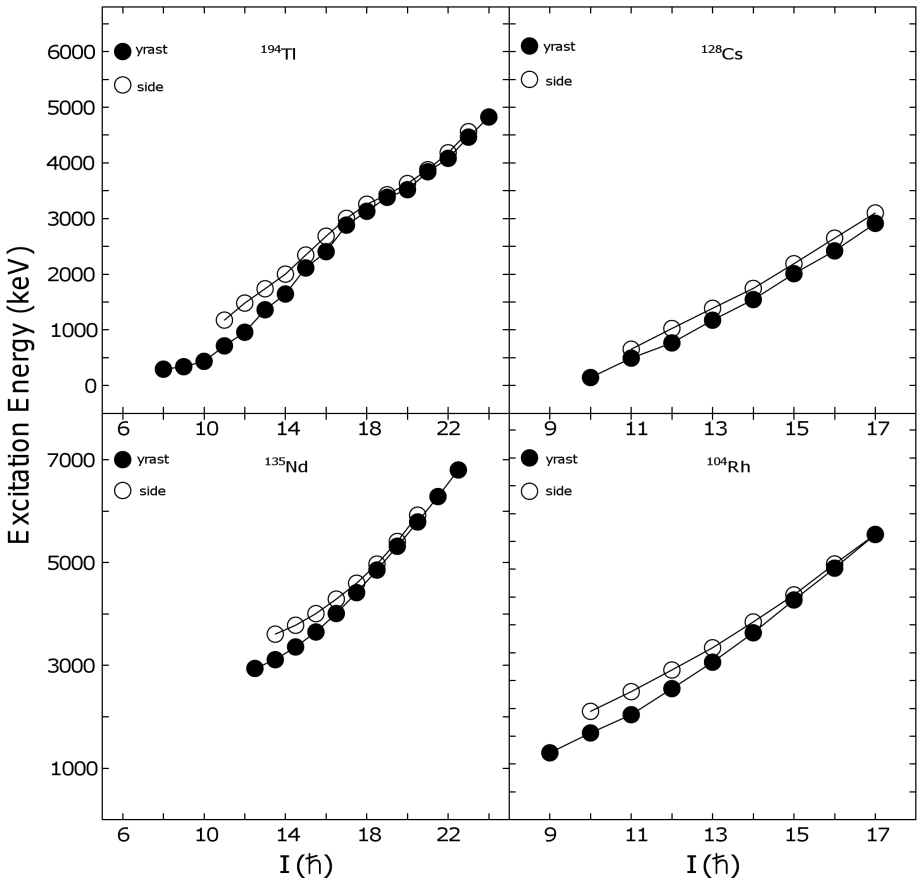

Figure 2. Comparison of the excitation energy vs spin plots of the best known close near-degenerate chiral candidate bands in ^{194}Tl, ^{128}Cs, ^{135}Nd and ^{104}Rh.

were sorted into matrices and spectra, and RadWare software package [10] was employed for analyses. In order to determine the spins and parities of the new transitions angular distribution ratios, R_{AD}, and linear polarization anisotropies were measured, respectively. The previously known level schemes of ^{194}Tl [11, 12] were revised and considerably extended. More than 130 new transitions were observed and placed in five rotational bands, three of which are observed for the first time. In this report we show the two bands which exhibit close-near-degeneracy, see Figure 1. Detailed experimental method and data analysis procedure for this experiment can be found in [7].

3. Results and discussion

The properties of the partner bands in ^{194}Tl were evaluated with respect to the suggested fingerprints of chiral doublet bands such as: degeneracy in the excitation energies, moments of inertia, ratios of the $B(M1)$ and $B(E2)$ reduced transition probabilities, and showed strong similarities [7]. The remarkable feature of these two 4-quasiparticle $\pi \mathrm{h}_{9/2} \otimes \nu \mathrm{i}_{13/2}^{-3}$ bands is the exceptionally good near-degeneracy observed in a long spin range.

Figure 2 presents the excitation energies as a function of spin for the partner bands in ^{194}Tl and in the previously known examples of partner bands with best near degeneracy, the two-quasiparticle $\pi \mathrm{h}_{11/2} \otimes \nu \mathrm{h}_{11/2}^{-1}$ bands in ^{126,128}Cs (the near-degeneracy in ^{126}Cs is very similar to

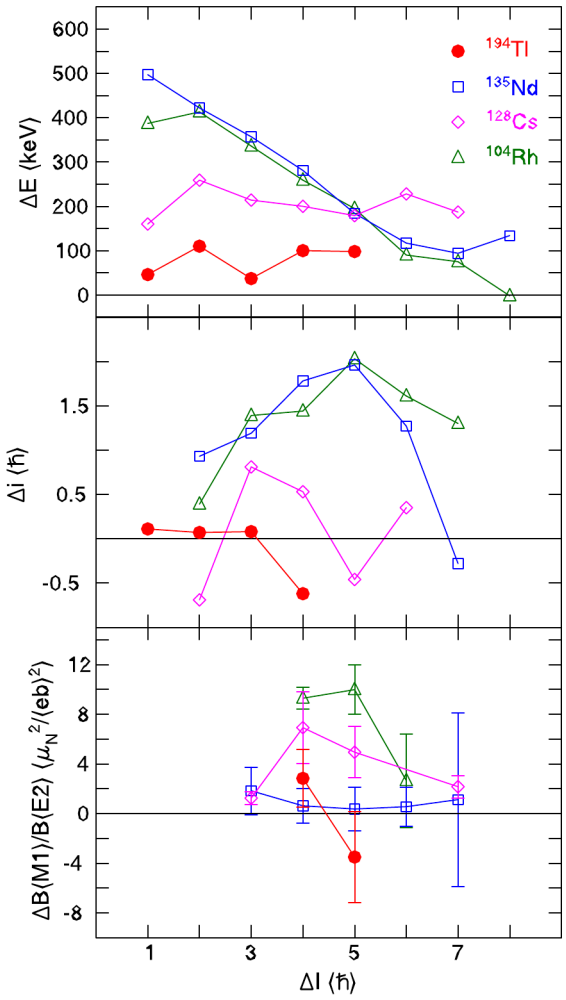

Figure 3. The difference in the excitation energies ΔE, alignments Δi, and ratios of the reduced transition probabilities $\Delta B(M1)/B(E2)$, as a function of spin ΔI with respect to the band head spin, for the 4-quasiparticle bands in ^{194}Tl, 3-quasiparticle bands in ^{135}Nd, and 2-quasiparticle bands in ^{128}Cs. The alignments are calculated with reference parameters of $J_0 = 8\ \hbar^2$/MeV and $J_1 = 40\ \hbar^4$/MeV^3 for ^{135}Nd, and $J_0 = 16\ \hbar^2$/MeV and $J_1 = 33\ \hbar^4$/MeV^3 for ^{128}Cs. Experimental data for ^{135}Nd and ^{128}Cs are taken from [3, 13] and [5], respectively.

that in ^{128}Cs), the $\pi g_{9/2}^{-1} \otimes \nu h_{11/2}$ bands in ^{104}Rh, and the three-quasiparticle $\pi h_{11/2}^{2} \otimes \nu h_{11/2}^{-1}$ bands in ^{135}Nd. The ^{194}Tl pair of four-quasiparticle bands maintains a relative energy separation of less than 110 keV within the whole observed spin range of I = 19-23 and reaches a value as small as 37 keV at I = 21. The relative excitation energies of the levels in the ^{126,128}Cs partner bands remain approximately constant at $\Delta E \sim 200$ keV over the whole observed spin ranges of I = 11-22 and I = 11-17, respectively while the relative excitation energy in the close near-degenerate bands of ^{135}Nd is not constant but decreases from ΔE = 497 keV at I = 27/2 and reaches a value of ΔE = 94 keV at I = 39/2 and a subsequent increasing trend is then observed. In the case of ^{104}Rh these partner bands also show a decreasing trend of the relative excitation energy from ΔE = 413 keV at I = 11, to an almost completely vanishing value of ΔE = -1 keV at I = 17.

The exceptional near-degeneracy of this pair of bands in ^{194}Tl is further illustrated in Figure 3 in which the differences in the excitation energies ΔE=E_{side}-E_{yrast}, alignments Δi=i_{side} − i_{yrast}, and ratios of reduced transition probabilities $\Delta B(M1)/B(E2)$=$B(M1)/B(E2)_{side}$ − $B(M1)/B(E2)_{yrast}$ for the four-quasiparticle bands in ^{194}Tl and the partner bands in ^{104}Rh, ^{135}Nd, ^{128}Cs are shown. The spin ΔI=$I - I_0$ is with respect to the band head spin I_0 of 9, 10, 25/2, and 18 are adopted for ^{104}Rh, ^{128}Cs, ^{135}Nd and ^{194}Tl, respectively.

In summary, a new chiral candidate is found in ^{194}Tl. Furthermore the relative excitation energy of this pair of negative-parity bands is compared to the relative excitation energies of the four best chiral candidates known to date. This comparison shows that the near-degeneracy in the 4-quasipartcle bands in ^{194}Tl is possibly the best found to date.

Acknowledgments

We would like to thank the crew of the iThemba LABS separated sector cyclotron for the delivery of the oxygen beam. This work is based upon research supported by the National Research Foundation, South Africa with grants GUN 65581 and 76632, and by a South Africa - Russian Federation bilateral agreement with a grant GUN 75248.

[1] Frauendorf S and Jie Meng 1997 *Nucl. Phys.* **A617** 131.
[2] Starosta K *et al.* 2001 *Phys. Rev. Lett.* **86** 971.
[3] Zhu S *et al.* 2003 *Phys. Rev. Lett.* **91** 132501.
[4] Wang S, Liu Y, Komatsubara T, Ma T Y, Zhang Y, 2006 Phys. Rev. C **74** 017302.
[5] Koike T, Starosta K, Chiara C J, Fossan D B, LaFosse D R, 2003 Phys. Rev. C **67** 044319.
[6] Vaman C, Fossan D B, Koike T, Starosta K, Lee I Y, Macchiavelli 2004 *Phys. Rev. Lett.* **92** 032501.
[7] Masiteng P L *et al.* 2013 Phys. Lett. B **719** 83-88.
[8] Newman R T*et al.* 1998 Balkan Phys. Lett. **Special Issue** 182.
[9] Sharpey-Schafer J F 2004 Nucl. Phys. News **12** 5.
[10] Radford D C 1995 Nucl. Instrum. Methods Phys. Res. A **361** 297.
[11] Kreiner A J 1979 Phys. Rev. C **20** 2205.
[12] Pai H *et al.* 2012 Phys. Rev. C **85** 064313.
[13] S. Mukhopadhyay *et al.* 2007 Phys. Rev. Lett. **99** 172501.