

## Predicted isomers in neutron-rich $^{162,164}\text{Tb}$

N. Susshma, B. Aadarsh Kumar, S. Deepa, K. Vijay Sai, and R. Gowrishankar\*

Department of Physics, Sri Sathya Sai Institute of Higher Learning, Prasanthi Nilayam-515134, INDIA.

### Introduction

In an experimental investigation of spin-trap isomers in deformed odd-odd nuclei, Orford et al. [1] used the Penning trap mass spectrometer to study the isotopes of Pm, Eu and Tb with neutron number around  $N \sim 98$ . From the measured masses, the work reported the discovery of new isomers in  $^{160}\text{Pm}$ ,  $^{162}\text{Tb}$  and  $^{164}\text{Tb}$ . Multi-quasiparticle blocking calculations using a deformed Woods-Saxon potential and the Lipkin-Nogami prescription of pairing correlations interpreted these isomers as ‘spin-traps’ and proposed their tentative structures. These isomers have not been characterized any further and are tentatively mentioned in the datasheets [2]. In a recently published comment on Orford et al. [1], Stryjczyk et al. [3], based on their study of the neutron separation energies, suggested that the isomer reported in  $^{162}\text{Tb}$  may have been due to a contaminant in the former experiment.

Considering the short half-life and low experimental cross section of these neutron-rich nuclei, a model-based empirical approach can be an effective tool to independently investigate these proposed isomers. In the present study we have used the well-tested empirical Two Quasiparticle Rotor Model (TQRM) [4,5] to construct the low-lying level structures of  $^{162}\text{Tb}$  and  $^{164}\text{Tb}$  and explore the possible existence of isomers. The study could not be carried out for  $^{160}\text{Pm}$  due to lack of available experimental data in its neighbouring mass region.

The empirical TQRM calculations were carried out using the three standard steps. Firstly, the lowest lying 1qp proton and neutron orbital energy trends from the neighbouring isotopes and isotones of  $^{162}\text{Tb}$  and  $^{164}\text{Tb}$  were plotted to identify their systematics around the nuclei of interest. Fig.1 is the energy systematics plot of 1qp orbitals in odd-mass nuclei lying close to

$^{162}\text{Tb}$ . Following this the spin-parities of the 2qp bandheads formed by the coupling of these 1qp orbitals were calculated. The energies of the 2qp states thus formed were calculated from the empirical formula [4, 5]

$$E(p_i, n_j) = E_0 + E_p + E_n + E_{\text{rot}} + \langle V_{np} \rangle \quad \dots(1)$$

where, the n-p interaction residue potential  $V_{pn}$  and rotational energy  $E_{\text{rot}}$  are defined as

$$\langle V_{np} \rangle = - \left[ \frac{1}{2} - \delta_{\Sigma,0} \right] E_{GM} + (-)^I E_N \delta_{K,0}$$

$$E_{\text{rot}} = \frac{\hbar^2}{2I} [K - (\Omega_p + \Omega_n)] = \frac{\hbar^2}{2I} (\Omega_{\Sigma}) \delta_{K,K'}$$

Here,  $E_p$  and  $E_n$  are experimental single particle excitation energies for proton and neutron orbitals respectively.

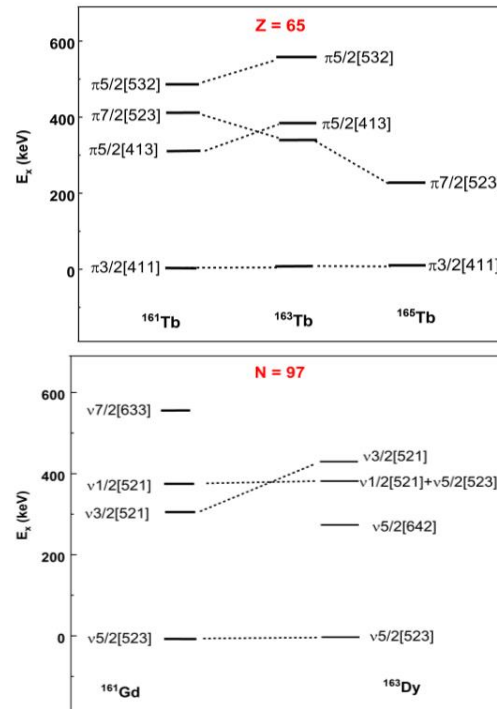


Fig. 1 Single particle orbital energy systematics of  $Z=65$  proton orbitals and  $N=97$  neutron orbitals in isotopes and isotones neighbouring  $^{162}\text{Tb}$  [2].

\*Electronic address: rgowrishankar@sssihl.edu.in

### Results and Discussions

The TQRM calculations on  $^{162}\text{Tb}$  and  $^{164}\text{Tb}$  yielded valuable results identifying possible isomers in both isotopes.

**$^{162}\text{Tb}$ :** As it can be seen in Fig.1, the energy difference between the lowest 1qp orbitals ( $p_0, n_0$ ) and other orbitals are very high. The energies of other 2qp bandheads thus formed are greater than 250 keV. The singlet  $p_0 n_0: 4^- \{ \pi 3/2^+ [411 \uparrow] \otimes \nu 5/2^- [523 \downarrow] \}$  is estimated to be the level closest to the  $J^\pi = 1^-$  gs with  $E_x = 114$  keV. This level can possibly be the isomeric state in  $^{162}\text{Tb}$  as there are no other low-lying levels with a large spin difference causing a spin-trap isomer. Orford et al. [1] also proposed this state as the predicted isomer from their survey of orbital systematics close to the Fermi surface. Our calculations thereby present evidence confirming this proposal with added understanding of the other physically admissible bandheads at low energies. Our observations supporting the existence of an isomer in  $^{162}\text{Tb}$  thereby are incompatible with the proposal of Stryjczyk et al. [3].

**Table 1:** Physically admissible 2qp Gallagher-Moszkowski doublet bands ( $K_T, K_S$ ) in  $^{164}\text{Tb}$ .

$n_i \downarrow \backslash p_i \rightarrow$	$p_0:$ $3/2^+ [411 \uparrow]$ 0 keV	$p_1:$ $7/2^- [523 \uparrow]$ 273 keV
$n_0:$ $7/2^+ [633 \uparrow]$ 0 keV	$5^+, 2^+$	$0^-, 7^-$
$n_1:$ $1/2^- [521 \downarrow]$ 108 keV	$1^-, 2^-$	$3^+, 4^+$
$n_2:$ $5/2^- [512 \uparrow]$ 184 keV	$1^-, 4^-$	$6^+, 1^+$

**$^{164}\text{Tb}$ :** Due to lack of available data in the (A-1) neighbouring isotone  $^{163}\text{Gd}$ , 1qp neutron orbital energies for N=99 was taken only from  $^{165}\text{Dy}$  to calculate the low energy spectra of  $^{164}\text{Tb}$ . Table 1 lists the physically admissible 2qp bandheads deduced from the coupling of low-lying ( $E_p + E_n < 500$  keV) 1qp orbitals. The ground state of  $^{164}\text{Tb}$ , listed tentatively in the latest data sheets [1] is found to be in concordance with our

calculations viz.  $J^\pi = 5^+ \{ 3/2^+ [411 \uparrow] \otimes 7/2^+ [633 \uparrow] \}$ . In their study, Orford et al. [1] had proposed the 2qp gs singlet level  $J^\pi = 2^+$  as the possible isomeric state in this case as well. While our calculations estimate the energy of this singlet state to be  $E_x = 168$  keV, the  $p_0 n_1: 1^- \{ \pi 3/2^+ [411 \uparrow] \otimes \nu 1/2^- [521 \downarrow] \}$  bandhead is predicted at an energy  $E_x = 108$  keV, lower than the gs singlet partner. With only  $5^+$  gs below it, this  $1^-$  could well be the predicted isomeric state in  $^{164}\text{Tb}$ , but in disagreement with the assignment of Orford et al [1].

### Conclusion

The presence of spin-trap isomers in neutron-rich isotopes  $^{162,164}\text{Tb}$  predicted previously by experimental studies were explored through a different method using the empirical TQRM calculations. Following the three-step technique we propose the following 2qp bandheads as the predicted isomers:

$$^{162m}\text{Tb}: 4^- \{ \pi 3/2^+ [411 \uparrow] \otimes \nu 5/2^- [523 \downarrow] \}$$

$$E_x = 114 \text{ keV}$$

$$^{164m}\text{Tb}: 1^- \{ \pi 3/2^+ [411 \uparrow] \otimes \nu 1/2^- [521 \downarrow] \}$$

$$E_x = 108 \text{ keV}$$

The existence of these isomers requires further experimental validation and characterization. Based on the previous studies of both the isotopes [6], neutron-induced reactions and heavy-ion reactions can yield good cross sections to carry out their spectroscopic and life time studies. The results of the present work can be effective location guides for experimental and theoretical studies on  $^{162,164}\text{Tb}$ .

### References

- [1] Orford *et al.*, Phys. Rev. C **102**, 011303(R) (2020) 1-5.
- [2] ENSDF data files (August 2024 version) from NNDC, Brookhaven, USA).
- [3] Stryjczyk *et al.*, Phys. Rev. C **111**, 049801 (2025) 1-2.
- [4] A. K. Jain *et al.*, Rev. Mod. Phys. **70** (1998) 843.
- [5] D. M Headly *et al.*, At. Data Nucl. Data Tables, **69** (1998) 239.
- [6] Nuclear Science References (NSR NNDC), NIM **A 640**, 213 (2011).