# Yrast and non-yrast spectroscopy of $^{199}$Tl using $\alpha$-induced reactions

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The excited states of the $^{199}$Tl nucleus have been studied by using the light ion induced fusion evaporation reaction $^{197}$Au$(\alpha, 2n)^{199}$Tl at 30 MeV of beam energy by $\gamma$-ray spectroscopic methods. VECC Array for NUclear Spectroscopy (VENUS) has been used to detect the prompt $\gamma$ rays. Level scheme of $^{199}$Tl has been significantly improved and extended with the placement of 53 new transitions. The yrast $\pi h_{9/2}$ band has been extended in this nucleus beyond the band crossing. Several new near- and non-yrast band structures have also been identified. It has been observed that in case of the three-quasiparticle structures, a different configuration involving negative parity neutron orbitals becomes yrast for heavier Tl isotopes with $N \geqslant 118$ in contrast to the involvement of the neutron $i_{13/2}$ orbital for lighter Tl isotopes. It was possible to identify both the yrast and the non-yrast states corresponding to these configurations in the present work. The observed band structures have been interpreted in light of the systematics of the neighboring odd mass Thallium nuclei. Total Routhian surface calculations have been performed to study the deformation and shape changes as a function of rotational frequency in this nucleus.

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## I. INTRODUCTION

Thallium isotopes, with only one proton below the $Z = 82$ shell closure, are the most appropriate candidates to extend our knowledge on the polarizing effect of the high-$j$ proton intruder orbitals (e.g., $\pi h_{9/2}, \pi i_{13/2}$) or high-$j$ neutron orbitals (e.g., $\nu i_{13/2}$) on the shape of a nucleus, which are otherwise near-spherical at their ground state. Several interesting and exotic phenomena, like magnetic rotational bands [1] and chiral bands [2–4] have been reported in the thallium isotopes around the $A \sim 200$ mass region. It is, therefore, interesting to investigate the interplay of the single particle structures (involving high-$j$ orbitals) and the collectiveness of the underlying core that generates the above exotic phenomena, below the $Z = 82$ shell closure region [5–7]. It is known that the high-$j$ orbitals, specially, $\pi h_{9/2}$ and $\nu i_{13/2}$, induce oblate shape in the nuclei in this region [8]. In the case of the odd-$A$ Tl nuclei, a wide diversity of shapes and structures have been observed from superdeformed structures in neutron deficient $^{191,193,195}$Tl [9–11] to weakly deformed oblate band structures in $^{191,193,195,197,201}$Tl [12–15], depending on the neutron Fermi level and the excitation energy. In the heavier isotope $^{205}$Tl, which is close to the doubly magic $^{208}$Pb nucleus, excited states corresponding to the octupole core excitation was also observed [16]. Although deformed shapes based on the $\pi i_{13/2}$ intruder orbital have been observed for the lighter Tl isotopes, no such band structure has been reported in heavier odd-mass thallium isotopes. A survey of the excitation energies of these states in the heavier isotopes indicates that it becomes more and more non-yrast with the increase in neutron number [17]. In the neighboring isotope $^{197}$Tl, an excited state corresponding to the $\pi i_{13/2}$ orbital has been reported but no band structure was observed on top of this state [18].

It is interesting to note that the shape polarizing effect of the $\pi h_{9/2}$ orbital continues to generate deformed band structures for the isotopes $^{200,201}$Tl, as reported in our previous work [15,19]. However, the three-quasiparticle configuration, observed after the band crossing of the $\pi h_{9/2}$ oblate band, in the $N = 120$ isotope $^{201}$Tl was observed to be different with smaller gain in aligned angular momentum compared to the other lighter isotopes. This is possibly because of the fact that the neutron Fermi level moves up and away from the $\nu i_{13/2}$ orbital with the increase in neutron number. For spherical shape, the neutron Fermi level is expected to be situated around the $3p_{3/2}$ orbital above the $i_{13/2}$ orbital for $N \geqslant 114$. However, for oblate deformation, as it is the case for the Tl isotopes, it would move up to lie close to the $2f_{5/2}$ orbital for $N \geqslant 118$. Therefore, it is important to study the band crossing behavior of $^{199}$Tl to understand the relative position of the $\nu i_{13/2}$ orbital.

The available information on the excited states in $^{199}$Tl is very scarce and limited to a few low-lying states which precludes one to get any idea about the $\nu i_{13/2}$ alignment. One of the first measurements of the excited states in $^{199}$Tl was performed way back in 1970 by Newton *et al.* [20], with a few Ge(Li) detectors. Although only a few states could be identified in that work, but importantly, the deformed nature

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