Tops-on-top model for triaxial, strongly deformed bands in $^{164}\text{Lu}$

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Abstract. The triaxial, strongly deformed rotational bands in odd-odd nucleus $^{164}\text{Lu}$ are analyzed based on the “tops-on-top model”, which is an extension of the “top-on-top model” to include two valence nucleons in each single-$j$ orbital. It is demonstrated that energy levels of experimentally known TSD bands of positive and negative parities are well reproduced. The location of negative parity yrare band is predicted, and also $B(E2)$ and $B(M1)$ values for in-band and out-of-band transitions among the yrast and yrare TSD bands are estimated. It is confirmed that one unit difference in the “wobbling quantum number” corresponds to the same difference in the alignment of rotor angular momentum. Coriolis interaction is effective to fully align single-particle spins both in the yrast and yrare bands.

1. Introduction

In the present paper we attempt to analyze triaxial, strongly deformed (TSD) rotational bands in the odd-odd nucleus $^{164}\text{Lu}$ $^{[1, 2]}$ by extending the top-on-top model to “tops-on-top model” in order to include one more valence nucleon. In a series of papers $^{[3, 4, 5]}$, usefulness of the top-on-top model has been demonstrated in describing TSD bands in odd-$A$ isotopes $^{163}\text{Lu}^{[6, 7, 8, 9]}$, $^{165}\text{Lu}^{[10]}$, $^{167}\text{Lu}^{[11]}$ and $^{167}\text{Ta}^{[12, 13]}$. In this model, one nucleon in a single-$j$ orbital is coupled to a triaxially deformed rotating core, whose rigid-body moments of inertia change with increasing angular momentum $I$ in order to simulate evolution of intrinsic structure mainly due to collapse of the pairing correlation. We have developed an algebraic treatment of this model and gained two quantum numbers $(n_\alpha, n_\beta)$ to classify the precessions of rotor spin $\vec{R}(\equiv \vec{I} - \vec{j})$ and single-particle spin $\vec{j}$ under the influence of Coriolis force and deformed single-particle field. We have also carried out exact diagonalization to confirm perfect correspondence between the algebraic states characterized by these quantum numbers and the exact solutions. We remark importance of rigid-body moments of inertia whose period in $\gamma$-space coincides with that of Nilsson harmonic oscillator in order to describe TSD bands in odd-$A$ nuclei.

2. Formalism

Our purpose in this paper is to reproduce energy level schemes of the TSD bands and electromagnetic transition rates among these levels in the odd-odd nucleus $^{164}\text{Lu}$ based on a model as simple as possible, and to foresee some further physical properties. We start from the Hamiltonian with a proton in a $j_1$ orbital and a neutron in a $j_2$ orbital, both coupled to a
triaxially deformed core:

\[ H = H_{\text{rot}} + H_{\text{sp}}(\bar{j}_1) + H_{\text{sp}}(\bar{j}_2); \quad H_{\text{rot}} = \sum_{k=x,y,z} A_k(I_k - j_{1k} - j_{2k})^2, \]

\[ H_{\text{sp}}(\bar{j}) = \frac{V_j}{j(j+1)} \left[ \cos \gamma (3j^2_x - j^2_y) - \sqrt{3} \sin \gamma (j^2_x - j^2_y) \right], \quad (1) \]

where \( A_k = 1/(2\mathcal{J}_k) \), and \( \bar{j} \) stands for either \( \bar{j}_1 \) or \( \bar{j}_2 \). Similar to the odd-\( A \) case, we introduce the angular-momentum dependence of rigid-body moments of inertia as

\[ \mathcal{J}_k = \frac{\mathcal{J}(I)}{1 + (\frac{60}{164})^{1/2} \beta_2} \left[ 1 - \left( \frac{5}{4\pi} \right)^{1/2} \beta_2 \cos \left( \gamma + \frac{2}{3} \pi k \right) \right]; \quad \mathcal{J}(I) = \mathcal{J}_0 \frac{I - c_1}{I + c_2}, \quad (2) \]

where \( k = 1, 2 \) and 3 correspond to \( x, y \) and \( z \), and \( \beta_2 \) and \( \gamma \) are the deformation parameters. The relation of \( \mathcal{J}_x \geq \mathcal{J}_y \geq \mathcal{J}_z \) holds within a range of \( 0^\circ \leq \gamma \leq 60^\circ \). Single-particle Hamiltonian \( H_{\text{sp}}(\bar{j}) \) in Eq. (1) is obtained from Nilsson Hamiltonian by applying Wigner-Eckart theorem for single-\( j \) case. In Nilsson Hamiltonian, the oscillator strength satisfies the relation of \( \omega^2_x \geq \omega^2_y \geq \omega^2_z \) within this range of \( \gamma \). This relation is also consistent with the radii of the oscillator satisfying \( R_x \leq R_y \leq R_z \). We get \( \mathcal{J}_x = \mathcal{J}_y = \omega^2_x = \omega^2_y \) and \( R_x = R_y \) at \( \gamma = 0^\circ \), and \( \mathcal{J}_y = \mathcal{J}_z = \omega^2_z \) and \( R_y = R_z \) at \( \gamma = 60^\circ \). If we adopt hydrodynamical moments of inertia, the period of their \( \gamma \)-dependence does not agree with that of Nilsson Hamiltonian, even when we change the sign of \( \gamma \).

The complete set of the physical space is spanned by \((2I+1)(2j_1+1)(2j_2+1)/4\) independent bases, i.e.,

\[ \left\{ \sqrt{\frac{2I+1}{16\pi^2}} \left[ D^I_{M,K}(\theta_1)\phi_{\Omega_1}^{j_1} \phi_{\Omega_2}^{j_2} + (-1)^{I-j_1-j_2} D^I_{-M,-K}(\theta_1)\phi_{-\Omega_1}^{j_1} \phi_{-\Omega_2}^{j_2} \right]; \quad K - \Omega_1 - \Omega_2 = \text{even}, \Omega_1 > 0 \right\}, \quad (3) \]

where \( K, \Omega_1 \) and \( \Omega_2 \) denote eigenvalues of \( I_x, j_{1x} \) and \( j_{2x} \), respectively. The wave functions \( \phi_{\Omega_1}^{j_1} \) and \( \phi_{\Omega_2}^{j_2} \) stand for spherical bases of the single-particle states, and \( D^I_{M,K}(\theta_1) \) is Wigner D-function. We have carried out exact diagonalization of the Hamiltonian to calculate eigenvalues for a given \( I \), and E2 and M1 transition rates from the eigenfunctions.

Before we display the results of analysis, we show that an application of the Holstein-Primakoff (HP) transformations for three angular momenta \( \bar{I}, \bar{j}_1 \) and \( \bar{j}_2 \). We derive an approximate formula for the energy eigenvalue of the rotor Hamiltonian, i.e., \( H_{\text{rot}} \), which is expressed in terms of three precession quantum numbers \((n_\alpha, n_\beta, n_\gamma)\) as

\[ E_{\text{rot}}(I, n_\alpha, n_\beta, n_\gamma) = A_x R(R+1) - \frac{p+q}{2} n_\alpha^2 + \left( 2R\sqrt{pq} + \sqrt{pq} - \frac{p+q}{2} \right) (n_\alpha + \frac{1}{2}), \quad (4) \]

where \( R = I - j_1 - j_2 + n_\beta + n_\gamma, \) and \( p \equiv A_y - A_x, q \equiv A_z - A_x \). Derivation of this formula follows an extensive application of the method for the case of the triaxial rotor with one nucleon outside \[3\]. We remark that not only the formula takes into account both the Coriolis effect and recoil terms as particle-particle correlation, but also the effect of the next-to-leading order in the HP boson expansion.

## 3. Numerical analysis

We perform the exact diagonalization of \( H \) in Eq. (1) by using Lanczos method. Two TSD bands with positive parity (TSD3 and TSD2) and one negative parity TSD band (TSD1) are identified for \(^{164}\)Lu \[2\]. In the beginning TSD2 was assumed to be of negative parity \[1\] after which its
naming comes, but later was confirmed to be of positive parity [2]. The proton single-particle orbital is \( i_{13/2} \) the same as in the other odd-\( A \) Lu isotopes, but the neutron single-particle orbital is not definite. It is suggested in Ref. [1] neutron orbital is also \( i_{13/2} \) for TSD3 band as the band starts from \( 13^+ \) state, and \( h_{9/2} \) orbital for TSD1 band though TSD1 starts from \( 14^- \) state. The neutron orbital for TSD1 is suggested to be \( j_{15/2} \) by Ref. [2]. We adopt the same deformation of \( \gamma = 17^\circ \) and \( \beta = 0.38 \) as in the neighboring \(^{163}\)Lu. We want to use the same set of parameters both for positive and negative parity bands [5]. Thus, we compare two cases, i.e., Case 1 where we assume \( \nu i_{13/2} \) orbital for TSD3 and \( \nu j_{15/2} \) for TSD1 bands, and Case 2 where \( \nu g_{9/2} \) for TSD3 and \( \nu h_{9/2} \) for TSD1.

The parameter set differs from that in odd-\( A \) nucleus, as we need new extra parameters \( V_k \) for \( k = \pi \) (or 1) and \( \nu \) (or 2). In analyzing the zigzag bands in odd-neutron nuclei based on the particle-rotor model, the attenuation factor should be introduced on the Coriolis interaction [14, 15]. Based on the renormalization group method, we have shown that the effect of truncating the basic Fock space must be compensated by scaling the coupling constant, and the attenuation factor on the Coriolis interaction is such a typical example [16]. We adopt attenuation factor of 0.55 for the Case 1 and 0.65 for the Case 2 in Coriolis term of \(- \sum_{k=x,y,z} I_k(j_{1k} + j_{2k})/J_k \). This attenuation factor compensates the effect of reducing the single-particle space only to single-\( j \) orbital. There is another problem in Case 1, as both proton and neutron orbitals are the same \( i_{13/2} \). Then, the interaction between the proton and neutron becomes important, while our model Hamiltonian has no such correlation as an additional interaction. We introduce another attenuation factor 0.55 as the proton-neutron interaction in the recoil term \( \sum_{k=x,y,z} j_{1k} j_{2k}/J_k \). Finally, the parameter set of Case 1 is given

![Figure 1](image1.png)  
**Figure 1.** Comparison between the experimental and the theoretical energy levels \( E^* - aI(I + 1) \) as functions of angular momentum \( I \) for TSD3 and TSD2 bands in \(^{164}\)Lu. The vertical axis is in unit of MeV. Theoretical values are shown as filled squares connected by solid lines, while experimental values as open triangles connected by solid lines. The proton orbital is \( i_{13/2} \) and the neutron orbital \( i_{13/2} \). The parameter set is Case 1 (see the text). The experimental data are from Ref. [2].

![Figure 2](image2.png)  
**Figure 2.** Comparison between the experimental and the theoretical energy levels \( E^* - aI(I + 1) \) as functions of angular momentum \( I \) for TSD1 and X2 bands, together with the predicted partner band TSD1-2 band in \(^{164}\)Lu. The proton orbital is \( i_{13/2} \) and the neutron orbital is \( j_{15/2} \). The parameter set is Case 1. The meanings of the curves are as defined in Fig. 1. The experimental data are from Ref. [2].
by $V_1 = V_2 = 2.3\text{MeV}$, $J_0 = 82\text{MeV}^{-1}$, $c_1 = -8$, and $c_2 = 41$ together with the attenuation factor of 0.55 both in $- \sum_{k=x,y,z} I_k (j_{1k} + j_{2k}) / J_k$ and $\sum_{k=x,y,z} I_k j_{1k} j_{2k} / J_k$. The parameter set in Case 2 is given by $J_0 = 87.7\text{MeV}^{-1}$, $c_1 = -8.5$, and $c_2 = 47.3$ with the attenuation factor of 0.65 only in $- \sum_{k=x,y,z} I_k (j_{1k} + j_{2k}) / J_k$. Employing parameter set of Case 1, we calculate energy eigenvalue $E^*$ for a given $I$ and show $E^* - a I (I + 1)$ with $a = 0.0075$ for TSD3 and TSD2 in Fig. 1, and for TSD1 in Fig. 2. Only the band head energy of TSD3 is adjusted to experimental value. While $E^* - a I (I + 1)$ at $I$ around the ending of TSD2 band is not in good agreement with experimental data, theoretical values reproduce both TSD3 band with $(n_\alpha=0,n_\beta=0,n_\gamma=0)$ and TSD2 band with (1,0,0) quite well over all region. The $20^+$ level in TSD2 decays to four $18^+$ levels [2]. According to Ref. [2], we choose $18^+$ level 0.566 MeV down from $20^+$ level in Fig. 1. However, if we take $18^+$ level 0.536 MeV down from $20^+$, which is originally chosen as a member of TSD2 band by Ref. [1], the experimental band head energy in Fig. 1 goes up by 0.029 MeV in better agreement with the theoretical band head energy of TSD2. With the same parameter set of Case 1, we show theoretical results for the negative parity band of TSD1 with (0,0,0) and its partner band TSD1-2 with (1,0,0) in Fig. 2. There is no experimental data for TSD1-2 band levels with odd $I$ and negative parity. Instead, Ref. [2] identifies the other sequence of levels along the band X2 which forks from TSD1 at 42$^-$. The theoretical level scheme follows this yраст band X2 rather than the extension of the experimental TSD1. Agreement of theoretical levels for TSD3 and TSD2 with the experimental data seems to be very good except for the starting and the ending of the band in both parameter sets. However, if we adopt Case 2 parameter set, the band with odd spin sequence 19, 21, · · · (TSD1-2) appears lower than the one with even spin sequence 16, 18, · · · (TSD1). As $I - j_1 - j_2 = I - 11$, odd spin sequence of TSD1-2 has precession quantum numbers (0,0,0) and even spin sequence of TSD1 has (1,0,0) because of

**Figure 3.** The alignments of $I_x$, $R_x$ and $j_{1x}$ for two positive parity TSD bands as functions of $I$. Solid lines correspond to TSD3, while dashed lines to TSD2. The alignment of $j_{1x}$ comes from $\pi i_{13/2}$ orbital. As for $j_{2x}$, see the text.

**Figure 4.** The alignments of $I_x$, $R_x$, $j_{1x}$ and $j_{2x}$ for two negative parity TSD bands as functions of $I$. Solid lines correspond to TSD1, while dashed lines to TSD1-2. The alignment of $j_{2x}$ comes from $\nu j_{15/2}$ orbital, and $j_{1x}$ from $\pi i_{13/2}$ orbital.
Table 1. Comparison of theoretical $B(E2)_{\text{out}}$, $B(E2)_{\text{in}}$ and $B(M1)_{\text{out}}$ for $^{163}\text{Lu}$ with the experimental data [17]. The first column gives the initial angular momentum $I$, the second column $B(E2)_{\text{out}}$, the third column $B(E2)_{\text{in}}$ and the fourth column $B(M1)_{\text{out}}$. From the second to the fourth column are theoretical values, while from the fifth to seventh column experimental values. The fifth column gives $B(E2)_{\text{out}}$, the sixth $B(E2)_{\text{in}}$ and the seventh $B(M1)_{\text{out}}$.

| $I$  | $B(E2)_{\text{out}}$ (theory) | $B(E2)_{\text{out}}$ (exp.) | $B(E2)_{\text{in}}$ (theory) | $B(E2)_{\text{in}}$ (exp.) | $B(M1)_{\text{out}}$ (theory) | $B(M1)_{\text{out}}$ (exp.) |
|-----|----------------|----------------|----------------|----------------|----------------|----------------|
| 23.5| 0.528 $^{+0.13}_{-0.11}$ | 5.15 $^{+0.24}_{-0.21}$ | 0.024 | 0.017 $^{+0.000}_{-0.000}$ | 0.017 $^{+0.000}_{-0.000}$ | 0.017 $^{+0.000}_{-0.000}$ |
| 25.5| 0.489 $^{+0.06}_{-0.02}$ | 2.39 $^{+0.08}_{-0.09}$ | 0.022 | 0.017 $^{+0.008}_{-0.005}$ | 0.017 $^{+0.008}_{-0.005}$ | 0.017 $^{+0.008}_{-0.005}$ |
| 27.5| 0.455 $^{+0.04}_{-0.02}$ | 2.18 $^{+0.03}_{-0.04}$ | 0.019 | 0.024 $^{+0.007}_{-0.007}$ | 0.024 $^{+0.007}_{-0.007}$ | 0.024 $^{+0.007}_{-0.007}$ |
| 29.5| 0.425 $^{+0.03}_{-0.02}$ | 2.43 $^{+0.04}_{-0.03}$ | 0.017 | 0.023 $^{+0.013}_{-0.013}$ | 0.023 $^{+0.013}_{-0.013}$ | 0.023 $^{+0.013}_{-0.013}$ |
| 31.5| 0.399 $^{+0.02}_{-0.02}$ | 2.44 $^{+0.02}_{-0.02}$ | 0.016 | 0.024 $^{+0.012}_{-0.010}$ | 0.024 $^{+0.012}_{-0.010}$ | 0.024 $^{+0.012}_{-0.010}$ |

the $D_2$-symmetry. If we proceed the calculation for the configuration $\pi i_{13/2} \otimes \nu j_{15/2}$ with the parameter set of Case 2, the gradient of $E^* - aI(1 + 1)$ turns out to be much steeper than the experimental curve. Since no lower band like TSD1-2 is observed experimentally, and as far as we want to explain both positive and negative parity bands with a common set of parameters, $\nu h_9/2$ is not a good candidate for TSD1 band. From now on we concentrate on the theoretical results based on Case 1.

We investigate the alignment of spins in TSD bands. In Fig. 3 (positive parity TSD2 and TSD3 bands) and Fig. 4 (negative parity TSD1 and TSD1-2 bands), we show the alignment of $\langle \bar{I}_2 \rangle_{1/2}$, $\langle R_2^z \rangle_{1/2}$, and $\langle j_{2x}^z \rangle_{1/2}$ for $k = 1(\pi), 2(\nu)$. In Fig. 3, as both proton and neutron occupy the same $i_{13/2}$ orbital, so that $\langle j_{2x}^z \rangle_{1/2} = \langle j_{2x}^z \rangle_{1/2}$, and we show only $\langle j_{2x}^z \rangle_{1/2}$. Here the state $\langle \rangle$ stands for the eigenstate of $H$ belonging to the eigenvalue $E^*$. Comparing solid lines (TSD3) with dashed lines (TSD2) for $\langle I_2^z \rangle_{1/2}$ and $\langle R_2^z \rangle_{1/2}$, we recognize almost one unit difference between TSD3 and TSD2 independent of $I$. It confirms the one unit difference in $n_\beta$ between the yrare and yrast TSD bands. As seen in Fig. 3, the fact that $\langle j_{2x}^z \rangle_{1/2} = \langle j_{2x}^z \rangle_{1/2} \sim 13/2$ both for TSD3 and TSD2 bands demonstrates that full alignment of $\bar{j}_1$ and $\bar{j}_2$ to $x$-direction, indicating $n_\beta = n_\gamma = 0$ for both yrast and yrare TSD bands. Similarly, in Fig. 4, it is also seen almost one unit difference alignment of TSD1 and TSD1-2 in $\langle I_2^z \rangle_{1/2}$ and $\langle R_2^z \rangle_{1/2}$. The difference between $\langle j_{2x}^z \rangle_{1/2} \sim 15/2$ and $\langle j_{2x}^z \rangle_{1/2} \sim 13/2$ is one unit due to the difference between $\nu j_{15/2}$ and $\pi i_{13/2}$. Both Figs. 3 and 4 demonstrate that yrast TSD (TSD3 and TSD1) band has quantum number $(0, 0, 0)$ and the yrare TSD (TSD2 and TSD1-2) band $(1, 0, 0)$.

Next, we discuss the electromagnetic transitions. We adopt bare values of g-factors, i.e., $g_{\ell_1} = 1$, $g_{\ell_2} = 0$, $g_s = 3.906$, $g_{s_2} = -2.678$, and $g_R = Z/A$. As for $Q_0$ we adopt $7b$ [2]. At first, in Table 1, we compare theoretical values of $B(E2)_{\text{out}}$, $B(E2)_{\text{in}}$ and $B(M1)_{\text{out}}$ for $^{163}\text{Lu}$ [3] with experimental values [17]. In Tables 1 and 2, $B(E2)_{\text{out}}$ and $B(E2)_{\text{in}}$ values are given in unit of $(e\beta)^2$, and $B(M1)_{\text{out}}$ in unit of $(\mu_N)^2$ with $\mu_N = e\hbar/(2Mc)$. It is seen that the theoretical transition rates agree with experimental ones for $^{163}\text{Lu}$ within the error bars. We temporarily consider the range of $I$ from 23.5 to 31.5 in $^{163}\text{Lu}$ corresponding to the range from 24 to 32 in $^{164}\text{Lu}$. In Table 2, we show theoretical values for $^{164}\text{Lu}$, and compare with $^{163}\text{Lu}$ in Table 1. As seen in Tables 1 and 2, $B(M1)_{\text{out}}$ in $^{164}\text{Lu}$ is much reduced in comparison with $^{163}\text{Lu}$ because of the cancellation due to opposite sign of $g_s$ between proton and neutron. As for $B(E2)_{\text{out}}$ and $B(E2)_{\text{in}}$, the values in $^{164}\text{Lu}$ are reduced nearly by 1/2 compared with those in $^{163}\text{Lu}$ as we adopted $Q_0 = 10b$ in $^{163}\text{Lu}$ [3], while $7b$ in $^{164}\text{Lu}$ [2]. There is no difference in the ratio $B(E2)_{\text{out}}/B(E2)_{\text{in}}$. However, the linking transition from TSD2 to TSD3 are not yet observed. Case 2 parameter set also produces similar results for $B(E2)_{\text{out}}$, $B(E2)_{\text{in}}$ and $B(M1)_{\text{out}}$.
Table 2. Theoretical $B(E2)_{\text{out}}$, $B(E2)_{\text{in}}$ and $B(M1)_{\text{out}}$ values for $^{164}\text{Lu}$. The first column gives the initial angular momentum $I$, the second column $B(E2)_{\text{out}}$, the third column $B(E2)_{\text{in}}$ and the fourth column $B(M1)_{\text{out}}$ for $^{164}\text{Lu}$.

| $I$ | $B(E2)_{\text{out}}$ | $B(E2)_{\text{in}}$ | $B(M1)_{\text{out}}$ |
|-----|----------------------|----------------------|----------------------|
| 24  | 0.254                | 1.141                | 0.0051               |
| 26  | 0.235                | 1.150                | 0.0046               |
| 28  | 0.219                | 1.159                | 0.0041               |
| 30  | 0.205                | 1.159                | 0.0038               |
| 32  | 0.192                | 1.171                | 0.0032               |

4. Conclusion

Calculations are carried out for an odd-odd nucleus $^{164}\text{Lu}$ based on the “tops-on-top” model, which is essentially the particle-rotor model with valence proton and neutron each in a definite single-$j$ orbital coupled to the rotor with angular-momentum dependent rigid-body moments of inertia. The angular-momentum dependence simulates the collapse of pairing correlation in the rotating core. In order to explain both energy level schemes for positive and negative parity TSD bands [2], we choose Case 1 parameter set. As for the positive parity bands, an assumption that a valence neutron occupies $i_{13/2}$ orbital is favorable, while for the negative parity bands $j_{15/2}$ orbital seems to be favorable in $^{164}\text{Lu}$.

We have confirmed that the calculated alignments $\langle I_x^2 \rangle^{1/2}$ and $\langle R_x^2 \rangle^{1/2}$ give stable difference by one unit between two TSD bands characterized by the precession (or wobbling) quantum number $n_\alpha=1$ and 0. The degeneracy of the calculated alignments $\langle j_{1x}^2 \rangle^{1/2}$ and $\langle j_{2x}^2 \rangle^{1/2}$ between yrare and yrast TSD bands indicates precession quantum numbers $n_\beta = n_\gamma = 0$ for both TSD bands. Electromagnetic transition rates are calculated for in-band and out-of-band $E2$ and $M1$ transitions. The $B(M1)_{\text{out}}$ is much reduced due to cancellation by the different signs of proton and neutron gyromagnetic factors, while $B(E2)_{\text{out}}$ and $B(E2)_{\text{in}}$ depend on $Q_0$ and its ratio is in the same order.

Acknowledgments

The authors express their sincere thanks to Professor Naotaka Yoshinaga for his kind help in numerical analysis and valuable discussion.

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