Lifetime measurements in the yrast band of ^{167}Lu

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Lifetime measurements of the lower excited states in the yrast band of ^{167}Lu have been measured using the recoil distance Doppler shift method. The excited nuclear states in ^{167}Lu were populated via ^{159}Tb (^{12}C, 4n) fusion-evaporation reaction at a beam energy of 74 MeV. In the experiment, the lifetime of states from $13/2^{-}\hbar$ to $29/2^{-}\hbar$ spins were obtained. From extracted lifetimes, the reduced transition probabilities [$B(E2)$] and transition quadrupole moments (Q_t) values have been deduced. The large (Q_t) values obtained in the experiment indicate high deformation for ^{167}Lu near ground state, a typical characteristic of the mass region. The almost constant values of experimental $B(E2)$ reflects the stability of deformed structure of ^{167}Lu nucleus in the yrast configuration. The experimental results are compared with the results of the cranked Hartree-Fock-Bogoliubov model based total Routhian surface (TRS) calculations. The experimental values are in better agreement with the TRS calculations at low frequencies than at high frequencies.

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I. INTRODUCTION

The neutron-deficient Lu nuclei with mass $A \approx 165$ have been investigated theoretically and experimentally for a variety of nuclear structure issues [1–7]. Being in the rare-earth region, these nuclei are expected to be highly prolate deformed in or near ground state. The available experimental data [1,4,8–11] suggest that the Lu nuclei ($A = 161$–167) present normal deformed prolate shape [12] near ground state but assume strongly deformed triaxial shapes (TSD) [13] of with or without wobbling character [9] at $I \approx 25\ \hbar$. In Lu nuclei with $A \geqslant 167$, highly deformation driving $1/2^{-}[541]$ orbital forms the yrast band. These nuclei are expected to be the most rigid among all Lu isotopes with respect to changes in triaxiality. Interestingly, apart from ^{167}Lu [5], no other higher mass Lu nuclei has shown any TSD band or wobbling band at high excitation. Though in almost all the Lu nuclei, the TSD/wobbling excitation are found to be based on the low-Ω $\pi i_{13/2}$ band but deformation studies of lower excited states in the yrast band of ^{167}Lu are important to see if the likely high deformation of the $\pi h_{9/2}$ band is large enough to create the neutron shell gap at $\gamma \approx 20^{\circ}$, as done by the $\pi i_{13/2}$ band (see Ref. [13]). Experimentally, information about triaxiality in the nucleus can either be obtained by observing decoupled bands and evaluating their signature splitting, as has been done for the yrast $9/2^{-}$ band in ^{163,165}Lu [11,14,15], or by measuring the quadrupole moment of the band, as has been done in ^{165}Lu in Ref. [11]. The quadrupole moment depends upon deformation parameter (β_2) and triaxiality parameter (γ) and therefore a test of axial asymmetry of a nucleus can be done by measuring its quadrupole moment [14,17,18]. For this reason, in the present work we decided to measure the quadrupole deformation of the yrast band in ^{167}Lu through RDM lifetime measurement. Also, to investigate the issue of origin of triaxiality, a comparison of the results with the total Routhian surface (TRS) calculations has been done.

II. EXPERIMENTAL DETAILS

The experiment was done at the Pelletron accelerator facility available at the Inter University Accelerator Center (IUAC), New Delhi. High spin states in ^{167}Lu were populated via ^{159}Tb(^{12}C, 4n) reaction. For this purpose a good quality ^{12}C beam at $E_{\rm lab} = 74$ MeV, was delivered by the Pelletron accelerator. The statistical model calculations (with code PACE4) and brief excitation function measurements were employed to determine the optimum beam energy for the reaction. The target was a self-supporting ^{159}Tb foil of thickness $\approx$1.2 mg/cm^2 and the stopper, a thick self-supporting gold foil of thickness $\approx$8 mg/cm^2. The target and the stopper foils were mounted and stretched on identical metal (aluminum) cones placed opposite to each other in the RDM plunger setup [19] available at IUAC, with the target facing the beam. The data were collected for target-to-stopper distances ranging from the closest attainable distance (corresponding to electrical contact) of 10 μm to a maximum distance of $\approx$2000 μm in 15 unequal steps. The minimum distance (D_0) of 10 μm between the target and the stopper foils in the plunger setup was found with capacitance method [20]. Since for large distances the capacitance method is not reliable as due to the stray capacitance the overall behavior of capacitance with distance become nonlinear, the distances beyond $D_{T-S} \approx 50\ \mu$m were measured with a digital-readout meter. The γ rays were detected with the Gamma Detector Array (GDA) setup available at IUAC, Delhi [19]. The GDA consists

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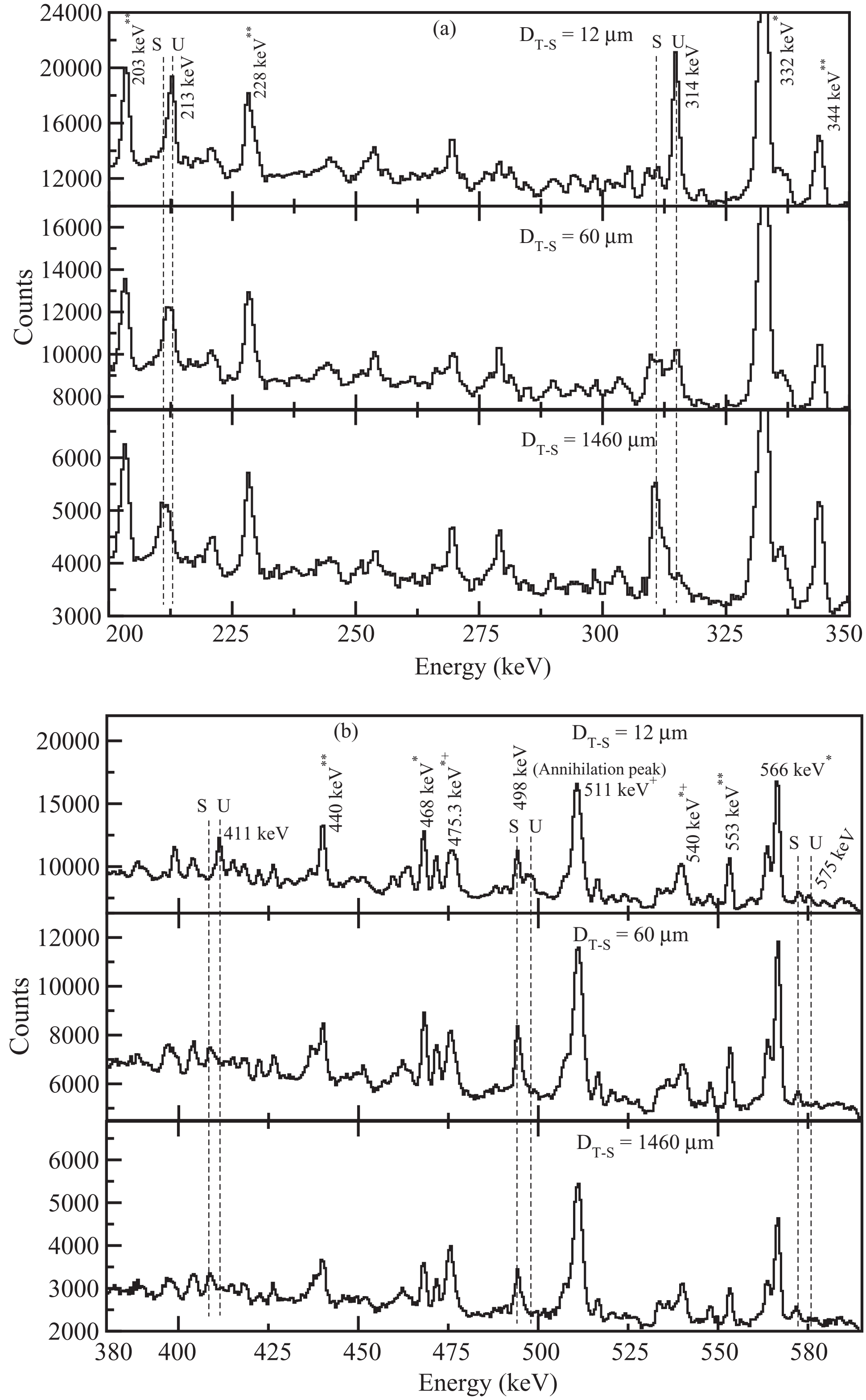

FIG. 1. Spectrum showing shifted (S) and unshifted (U) peaks of all γ-ray transitions of interest of the yrast band in ^{167}Lu at three different target-stopper distances (D_{T-S}) obtained with detectors at 144° with respect to beam direction. [$\star$ marked: γ-ray peaks for ^{197}Au(^{12}C, 4$n\gamma$)^{205}At, + marked: e^--e^+ annihilation peak, $\star\star$ marked: unknown γ-ray peaks, ++ marked: Coulex peaks for ^{197}Au (197.5 keV) and ^{59}Fe (192.3 keV), $\star$+ marked: γ-ray peaks for ^{197}Au(^{12}C, 5$n\gamma$)^{204}At].

of 12 Compton Suppressed HPGe detectors (each with relative efficiency ≈23% and energy resolution $\Delta E \approx 2.1$ keV) and a 14-element BGO multiplicity array. The detectors in the GDA setup are arranged in three different rings with four detectors in each ring, making an angle of 50° (forward angle), 99° (almost right angle), and 144° (backward angle) with respect to the beam direction. As the data rate in the coincidence mode was very poor, data was recorded only in the singles mode with the condition that at least two BGO crystals should fire ($M \geqslant 2$) in coincidence with one HPGe detector. The higher BGO multiplicity condition helped in reducing the background coming from low multiplicity processes, such as Coulomb excitation, radioactivity, etc. The quality of the data obtained with detectors at backward angle (144°) at three target-stopper distances is shown in Fig. 1(a) and 1(b). In the figure, shifted (S) and unshifted (U) peaks of all γ-ray transitions of interest have been marked.

III. DATA ANALYSIS

For the analysis purpose, the singles data obtained with four detectors at backward (forward) angles 144° (50°) of the GDA array were gain matched and added together to form the raw spectra. The level schemes for ^{167}Lu already exists (shown in Fig. 2) so various γ-ray transitions of interest were easily identified. The lifetime information was reliably extracted for yrast transitions up to the spin $29/2^- \hbar$. The rays from the higher transitions were either already shifted or were not resolved from the background due to poor statistics. As the quality of the data with the detectors at the backward angle was much better, the analysis was done with that data only. In the analysis the backward angle detector data at each target-stopper distance were fitted with GAMMAFIT program [21] and the areas of the shifted (wherever possible) and unshifted peaks were obtained. After efficiency correction, the obtained areas resulted in the intensity of the unshifted (U) and the shifted (S) ray energy. For normalization purpose, the 197 keV Coulomb excited peak of Au observed in the spectrum was used. The resulting normalized intensities of unshifted energy component are then plotted as a function of target-stopper distance to yield the intensity decay curves of various γ-ray transitions of interest. The decay curves were then fitted with the computer code LIFETIME [22] and the lifetime values of various excited states were extracted. The LIFETIME code determines level population by solving Bateman's equation [23] and the value of shifted and unshifted intensities for each γ-ray transition of interest are obtained. Before starting the fitting process, the LIFETIME program applies various standard corrections such as correction for the change in solid angle due to the motion of the recoils, correction for finite target thickness, and also the correction for loss of total γ-ray intensity due to nuclear deorientation effect, in the raw data. In addition corrections were also made to the data to account for the internal conversion. An important aspect of data analysis was to account for the effects of cascade feeding (both observed and unobserved) from higher-lying states. So in the data analysis, two types of feeding are considered at each level, namely, the cascade feeding from

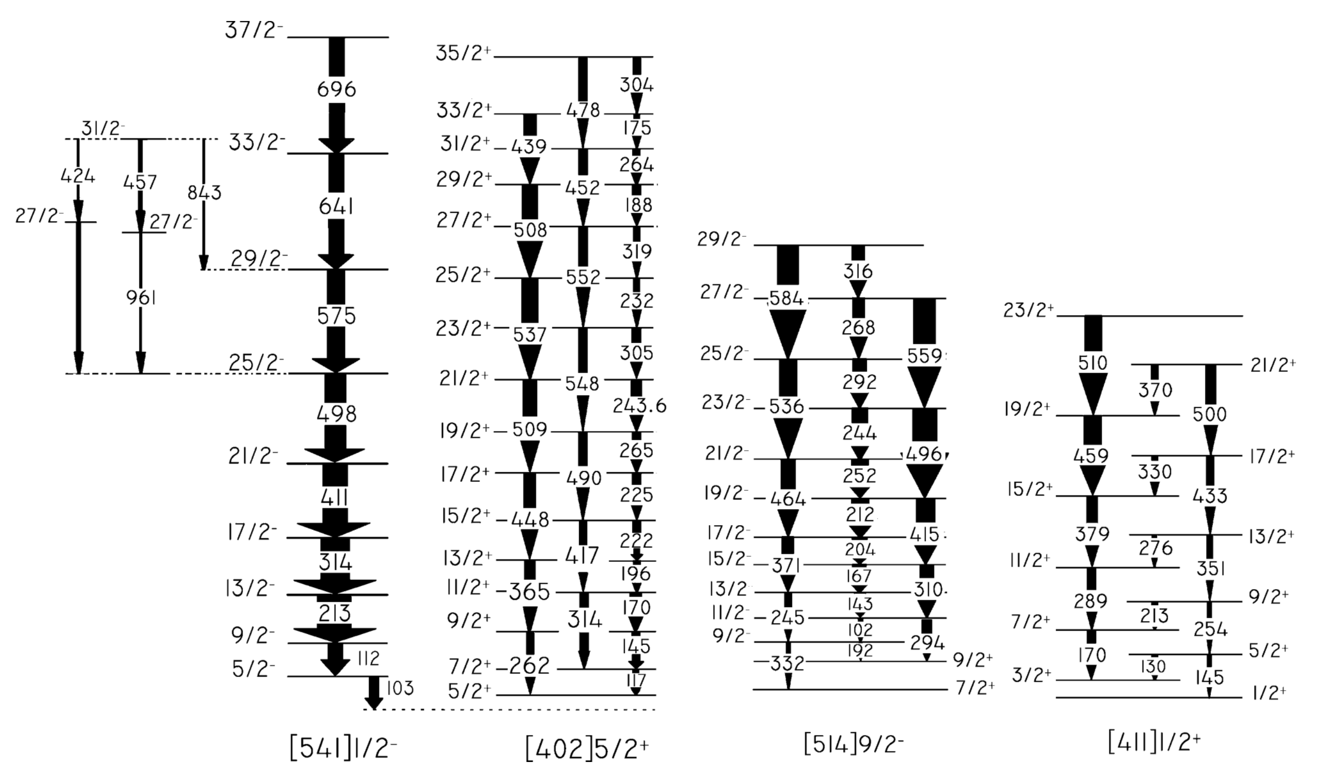

FIG. 2. Partial level scheme for ^{167}Lu, relevant to the present work showing $[541]1/2^-$ yrast band for which lifetime measurement is done and other high spin bands. γ-ray transitions in the band C and D are from positive parity structures. Width of transitions are proportional to γ-ray intensities. The data is taken from Refs. [5] and [16].

the above and the side feeding, except for the highest level, for which only the feeding from the top is assumed through an unknown rotational band of constant quadrupole moment. The quadrupole moment of this modeled rotational band and the initial population of the highest level are treated as variable parameters. The side feeding includes all unobserved feedings, i.e., feeding from the γ-ray continuum and non-yrast states. An initial estimate of relative intensities for the levels representing the unobserved feeding were done by taking the difference between the observed intensity into a given level and the observed intensity out of the said level, while the final intensities of side feedings is determined by the LIFETIME program. The various details of the data analysis can be found in Ref. [19]. To calculate the uncertainties in the measured lifetimes, the subroutine MINUIT [24] is used by the LIFETIME program.

On carefully looking at the γ transitions of various bands in the decay scheme shown in Fig. 2 and in Ref. [5], and the energy spectra shown in Fig. 1, it is observed that in the present experiment, only the first few γ transitions of the yrast band got populated with enough intensity. Contrary to what the level scheme suggests, the transitions of the other competing bands such as $5/2^+[402]$, $7/2^+[404]$, and $9/2^-[514]$ bands were populated with such low intensity that their analysis was difficult due to large background obtained in the spectra. On close observation of level scheme in Ref. [5], it is seen that few observed γ transitions of the yrast band, such as 213 keV ($13/2^- \rightarrow 9/2^-$) transition has an overlap with the 212 keV ($19/2^- \rightarrow 17/2^-$) γ transition of the $9/2^-[514]$ band, the 314 keV ($17/2^- \rightarrow 13/2^-$) has an overlap with 314 keV ($11/2^+ \rightarrow 7/2^+$) γ transition of the $5/2^+[402]$ band, and the 498 keV ($25/2^- \rightarrow 21/2^-$) transition has a bit of overlap with the 496 keV ($23/2^- \rightarrow 19/2^-$) γ transition of the $9/2^-[514]$ band. Since, in the present experiment, as no other γ transitions from these competing bands has been observed with enough intensity, so in the analysis, it is assumed that the intensity contribution from these contaminating transitions is negligibly small. However, to accommodate the effect of the possible contamination by them, the errors in the lifetimes have been increased to twofold of the values obtained by fitting these transition through the LIFETIME program.

In the present analysis, the side-feeding levels do not seem to have much influence on the level lifetimes. For every γ transition considered in the present analysis, the major part of the intensity comes through the cascade feeding from the level above it, and a very small portion comes from the side-feeding level. Furthermore, the fitted values of the side-feeding level lifetimes are found to be much smaller than the respective level fed by them for all γ transitions in the yrast band.

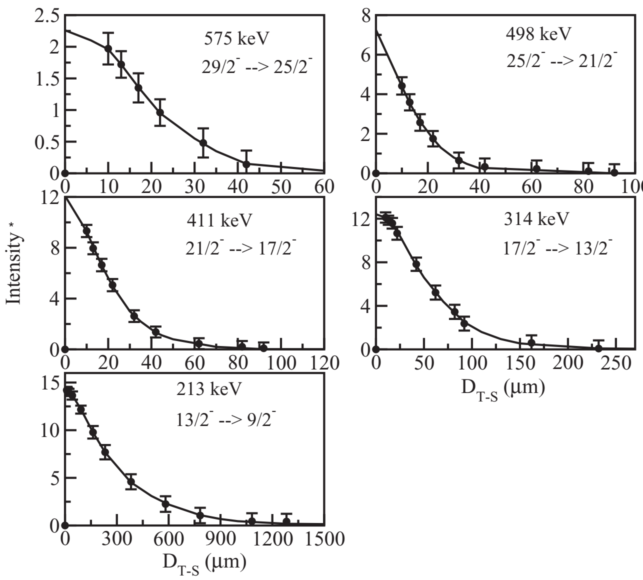

FIG. 3. The normalized unshifted intensity for various γ-ray transitions of interest for the yrast band of the ^{167}Lu nucleus obtained by fitting through the LIFETIME code. *(Intensities are normalized to the intensity of 197 keV γ ray from Coulomb excitation of Au.)

IV. RESULTS AND DISCUSSION

The (normalized) intensity decay curves for the unshifted γ-ray transitions observed for the yrast band, as a function of target-stopper distance are shown in Fig. 3 and the results of the lifetime analysis of these transitions are tabulated in Table I. From the extracted level lifetimes, the reduced transition probability values $[B(E2)]$ and the reduced transitional quadrupole moment (Q_t) are obtained in a model-dependent way (considering the rotational model) using the following equations:

$$B(E2) = \frac{0.08156}{\tau E_\gamma^5(1+\alpha_\tau)}|e^2b^2| \quad (1)$$

and

$$Q_t^2 = \left(\frac{16\pi}{5}\right)\frac{B(E2; I \rightarrow I-2)}{\langle I2K0 \mid I-2\ K\rangle^2} \quad (2)$$

being τ, the level lifetime (in picoseconds), E_γ, the γ energy (in MeV), α, the conversion coefficient, and $\langle I2K0 \mid I-2\ K\rangle$,

TABLE I. The results of the present experiment for different γ-ray transitions in the $\pi h_{9/2}[541]1/2^-$ yrast band of ^{167}Lu.

S. No.	Energy (keV)	Spin ($\hbar$) $I_i \rightarrow I_f$	Lifetime τ (ps)	$B(E2)$ (e^2b^2)	Q_t (eb)
1	213	$13/2^- \rightarrow 9/2^-$	$117.3 \pm ^{10.5}_{11.7}$	$1.58 \pm ^{0.14}_{0.14}$	$7.3 \pm ^{0.7}_{0.7}$
2	314	$17/2^- \rightarrow 13/2^-$	$17.4 \pm ^{2.1}_{1.9}$	$1.53 \pm ^{0.18}_{0.16}$	$6.9 \pm ^{0.8}_{0.8}$
3	411	$21/2^- \rightarrow 17/2^-$	$4.6 \pm ^{0.8}_{0.4}$	$1.51 \pm ^{0.27}_{0.49}$	$6.8 \pm ^{0.6}_{1.2}$
4	498	$25/2^- \rightarrow 21/2^-$	$1.7 \pm ^{0.4}_{0.2}$	$1.56 \pm ^{0.34}_{0.34}$	$6.8 \pm ^{1.5}_{1.5}$
5	575	$29/2^- \rightarrow 25/2^-$	<0.7	>1.73	>7.1

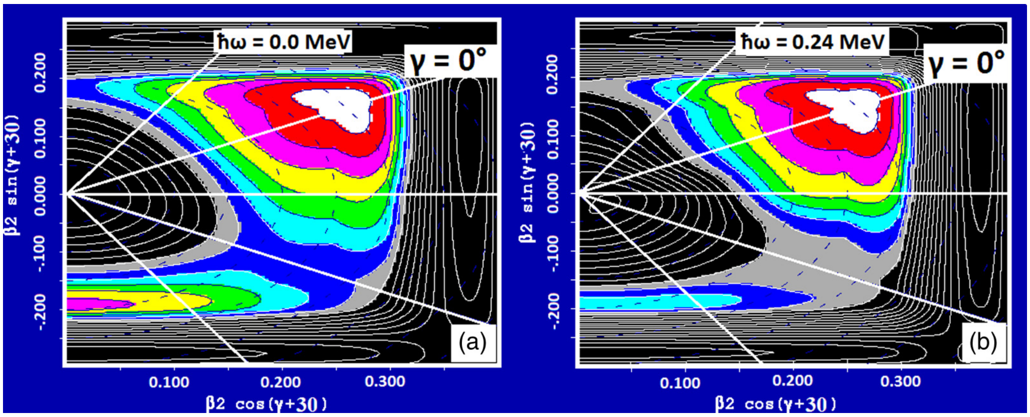

FIG. 4. The total Routhian surfaces (TRS) plot for the negative parity $\pi h_{9/2}$ yrast band in ^{167}Lu calculated at rotational frequency (a) $\hbar\omega = 0.0$ MeV and (b) $\hbar\omega = 0.24$ MeV, respectively. The energy separation between the contours is 0.04 MeV.

the Clebsch-Gordon coefficient, given by

$$\langle I2K0|I-2K\rangle = \sqrt{\frac{3(I-K)(I-K-1)(I+K)(I+K-1)}{(2I-2)(2I-1)I(2I+1)}}. \quad (3)$$

In the present calculations, $K = 1/2$ has been used for the yrast band. From the results of lifetime measurements shown in the table, it is observed that the $B(E2)$ values are large and more or less constant as a function of spin. The large $B(E2)$ values indicates a highly deformed nature of this yrast configuration in ^{167}Lu, a typical characteristic of this mass region. The almost constant nature of the measured $B(E2)$ values with spin indicates that the band does not undergo any serious interaction with other neighboring bands, thus preserving its properties.

In order to understand the effect of increasing rotational frequency on the shape of ^{167}Lu in this yrast configuration, the total Routhian surfaces (TRS) calculations, within the cranked Hartree-Fock-Bogoliubov (CHFB) model [25,26] were performed. The single-particle energy values were calculated for the Woods-Saxon potential, including a monopole pairing interaction [27,28]. In these calculations the monopole pairing term, $\Delta_0 (= \Delta_p = \Delta_n)$ and the Fermi level, λ was calculated by solving the BCS gap equation at zero rotational frequency [29]. To get the equilibrium shape of the nucleus, the total energy of the nucleus in the rotating frame (TRS) is minimized with respect to the deformation parameters (β_2, β_4, γ) at various rotational frequencies. The results of such minimization, the TRS contours, for the yrast band in ^{167}Lu at $\hbar\omega = 0.0$ and 0.24 MeV are shown in Fig. 4. In the plots, the equilibrium shape of the nucleus is represented by the minimum of the contours (white patch). The values of deformation parameters (β_2, β_4, γ) corresponding to the minimum of contours define the equilibrium shape of the nucleus. For comparison with experimental values, the theoretical Q_t values have been extracted from β_2 and γ values (corresponding to minima of contours obtained in the TRS calculations) at various rotational frequencies using the following relation:

$$Q_t = \frac{6}{\sqrt{15}} Zer_0{}^2\beta_2(1 + 0.36\beta_2)\mathrm{Cos}(30^\circ + \gamma), \quad (4)$$

where, Ze is the charge of the nucleus and $r_0 = 1.2\ fm$ (often used for the nuclei of this mass region). The comparison of the experimental and the theoretical (TRS) values at various rotational frequencies is tabulated in Table II. In Fig. 4, since almost no change in minima lying along the $\gamma \approx 0^\circ$ line is seen at two rotational frequencies, we conclude that ^{167}Lu has a stable prolate deformed shape in this yrast configuration. This conclusion is further supported by the values in Table II where deformation parameters (β_2 and γ) are found to remain constant with increasing rotational frequency. In fact, as can be seen from the plot of theoretical (TRS) Q_t values with the experimental Q_t values at various rotational frequencies (Fig. 5), the two Q_t values match well at low frequencies, but tend to deviate a bit afterward. At high frequencies, the experimental Q_t values have a slight decreasing trend while the TRS values remain almost constant. This slight decrease of experimental Q_t values with increasing spin can be a hint of a small involvement of triaxiality parameter (γ) at higher spins in this yrast configuration due to the neutron pair alignment at the first band crossing. However, the decrease could also be an indication of reducing collective behavior with spin in the ^{167}Lu. The results of TRS calculations do not favor the possibility of emerging triaxiality in ^{167}Lu in the yrast configuration as its value is close to $\gamma \approx 0^\circ$ and found to be almost constant with increasing frequency. The observation of constant high deformation of $\pi h_{9/2}$ band with almost no triaxiality, in a way, confirms that the measured

TABLE II. Comparison of experimental and calculated Q_t values (with TRS) at different rotational frequencies for $\pi h_{9/2}$ yrast band observed in ^{167}Lu.

Experimental	values	Total	Routhian	surface	values
$\hbar\omega$ (MeV)	Q_t (eb)	$\hbar\omega$ (MeV)	β_2	γ	Q_t (eb)
0.107	$7.3 \pm ^{0.7}_{0.7}$	0.12	0.32	4.3	7.3
0.157	$6.9 \pm ^{0.8}_{0.8}$	0.16	0.32	4.2	7.3
0.206	$6.8 \pm ^{0.6}_{1.2}$	0.20	0.32	4.0	7.4
0.249	$6.8 \pm ^{1.5}_{1.5}$	0.24	0.31	2.2	7.3
0.288	> 7.1	0.28	0.31	−6.1	7.8

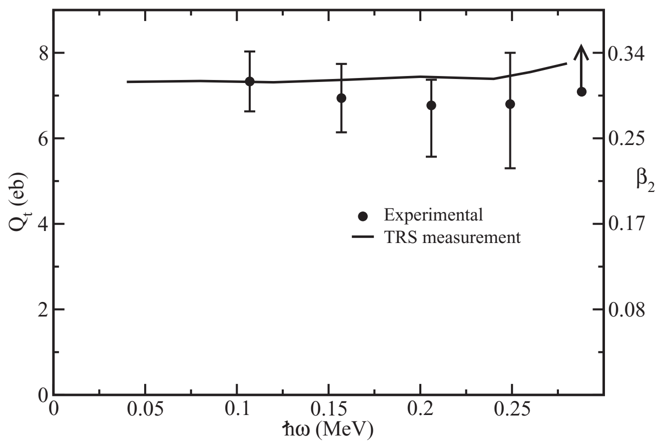

FIG. 5. Comparison of experimental and theoretical (TRS) transitional quadrupole moment at different rotational frequency for the negative parity $\pi h_{9/2}$ yrast band in ^{167}Lu.

deformation of the band is not high enough to create the shell gap with stable triaxial deformation and only the $\pi i_{13/2}$ band can produce that large deformation.

V. SUMMARY

A LIFETIME measurement experiment has been carried out in the normal deformed yrast sequence of ^{167}Lu, using recoil distance Doppler shift method. In the experiment the lifetimes of the five lowest states of the yrast band have been obtained. The transition quadrupole moment (Q_t) and $B(E2)$ values are extracted from the obtained lifetimes. For the interpretation of the experimental results, the experimental Q_t values are compared with Q_t values obtained for TRS calculations (i.e., for β_2, γ values). The large and almost constant nature of $B(E2)$ values indicate the large but stable deformation for ^{167}Lu in the yrast configuration, as expected for the nuclei of this mass region. A small dip in the experimental Q_t values at higher rotational frequencies may be a hint of emergence of little triaxiality due to changing nuclear structure after the neutron pair alignment at the first band crossing, or could also be due to reducing collectivity with spin in the yrast configuration in ^{167}Lu nucleus. The TRS calculations, however, tend to negate the emergence of triaxiality this as the calculated Q_t values are constant with rotational frequency.

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