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Lifetimes of triaxial superdeformed states in ^{163}Lu and ^{164}Lu

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Abstract. Lifetimes of states in the yrast superdeformed bands of ^{163}Lu and ^{164}Lu were determined in a Doppler-shift attenuation-method experiment. From fractional Doppler shifts and line shapes, average transition quadrupole moments, $Q_{\mathrm{t}} = 8.2^{+1.0}_{-0.6}$ b and $7.1^{+0.5}_{-0.6}$ b, were deduced for one of the bands in ^{163}Lu and ^{164}Lu, respectively. These values are much larger than the quadrupole moment of the normal-deformed yrast band in ^{163}Yb, $Q_{\mathrm{t}} = 4.9^{+1.3}_{-0.4}$ b, that was also determined in this experiment. Comparison to cranking calculations indicates that both superdeformed bands correspond to a local potential energy minimum with a pronounced triaxiality, $\gamma \sim 20°$.

PACS. 21.10.-k Properties of nuclei; nuclear energy levels – 21.10.Tg Lifetimes – 25.70.-z Low and intermediate energy heavy-ion reactions – 27.70.+q $150 \leq A \leq 189$

1 Introduction

Since the first discovery of a superdeformed (SD) rotational band in ^{163}Lu [1,2] almost ten years ago, a large number of bands with similar properties have been found experimentally in this mass region [3–7]. Some very weakly populated bands could only be detected recently with the large, highly efficient γ-ray spectrometer arrays EUROBALL and GAMMASPHERE [5–7]. Theoretical calculations using different approaches [2,8,9] had predicted that this region of superdeformation is characterized by a pronounced triaxiality ($\epsilon \sim 0.38, |\gamma| \sim 20°$). Although triaxiality is difficult to prove experimentally, a unique signature is the occurrence of the so-called wobbling excitations which have been proposed [10] for nuclei if the three principal axes are distinctly different. Indeed, first evidence for the wobbling mode has recently been reported [11,12] from an experiment using the EUROBALL γ-ray spectrometer array for an excited band in ^{163}Lu, which decays in a characteristic way into the yrast band studied in this work.

Systematic total-energy surface calculations with the Ultimate Cranker (UC) code [13] predict that triaxial superdeformed (TSD) minima exist at high spins for the region of nuclei around $N \sim 90$–98 and $Z \sim 72$. These minima are the result of favourable shell effects and appear in all four combinations of parity and signature. In these calculations the quadrupole moments are obtained directly from the wave functions and vary between 8.5 b and 11.5 b for positive gamma values and between 10.0 b and 15.0 b for negative gamma values. For a given nucleus the quadrupole moment is always larger for negative gamma than for positive gamma. The variation in the quadrupole moments reflects a variation in the nuclear shape. Thus, the energy minima with positive gamma values lie in the deformation range $0.36 < \epsilon < 0.44$ and $16° < \gamma < 23°$, while the minima with negative gamma lie in the range $0.35 < \epsilon < 0.43$ and $-23° < \gamma < -15°$.

In this work, we report on the results of lifetime measurements of states in the strongest populated TSD bands (bands 1) in ^{163}Lu and ^{164}Lu [5,6] from which we determine the transition quadrupole moments. Lifetimes for band 1 in ^{163}Lu have been measured previously using the Doppler-shift recoil-distance (RDM) and attenuation methods (DSAM) for the low- and high-spin regions, respectively [2]. Our new measurement results in somewhat

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smaller values for the quadrupole moments of this band than reported in the previous work. Furthermore, we observe a clear difference between the quadrupole moments for TSD bands 1 in ^{163}Lu and ^{164}Lu. In the following section the experimental details and results are presented. In the last section the results are discussed and compared to UC calculations.

2 Experimental details and results

The reaction ^{139}La(^{29}Si, xn) was used to populate high-spin states in ^{163,164}Lu. The ^{29}Si beam of 145 MeV was provided by the Tandem Van-de-Graaf accelerator at Legnaro. The target consisted of a ^{139}La foil of 1.5 mg/cm^2 thickness on a 10 mg/cm^2 thick gold backing. To prevent oxidation, a thin Au layer (100 μg/cm^2) was evaporated on the front of the La target. As a further precaution the target was handled and mounted in an argon atmosphere.

Gamma-ray coincidences were measured with the GASP array [14] which comprises 40 Compton-suppressed Ge-detectors and an inner ball of 80 BGO scintillators serving as multiplicity filter. For the analysis, the Ge-detectors were grouped in seven rings at the following angles with respect to the beam direction: 31.7°–36.0°, 58.3°–60.0°, 72.0°, 90.0°, 108.0°, 120.0°–121.7° and 144.0°–148.3°. In two experiments with a total measuring time of 8 days, 2.5×10^9 events were collected with the requirement that two or more Ge-detectors with Compton suppression and eight or more BGO-detectors of the inner ball gave a coincidence signal.

In the off-line analysis, coincidence spectra were produced by setting energy gates on uncontaminated γ-ray lines in all Ge-detectors and incrementing spectra for the detectors in the different angle groups. While for band 1 in ^{163}Lu the number of collected three- and higher-fold coincidences allowed to create double-gated spectra, for band 1 in ^{164}Lu, which is about ten times weaker, the statistics limited the analysis to single-gated spectra. In order to compare the results for the TSD bands to those of a normal-deformed (ND) band, similar spectra were produced for the yrast band in ^{163}Yb [15] which was also populated in the reaction. The ND band in ^{163}Yb was analysed instead of a ND band in ^{163}Lu or ^{164}Lu because these bands have strongly populated signature partners which makes the analysis more complicated. Furthermore, the ND band in ^{163}Yb is the only band populated in this experiment for which the side-feeding and the in-band quadrupole moments were measured previously [16]. In the case of TSD band 1 in ^{163}Lu the statistics was sufficient to compare spectra with gates on transitions below and above the states for which the lifetimes were analysed. For TSD band 1 in ^{164}Lu and the ND yrast band in ^{163}Yb only spectra that were obtained with gates on the transitions below the states of interest could be used. As examples, two pairs of coincidence spectra from detectors in different angle groups for ^{163}Lu and ^{164}Lu, respectively, are shown in fig. 1. Spectra for the 90° detectors were also produced and used to locate contaminations at the positions of the shifted peaks in the spectra from the forward and backward detectors.

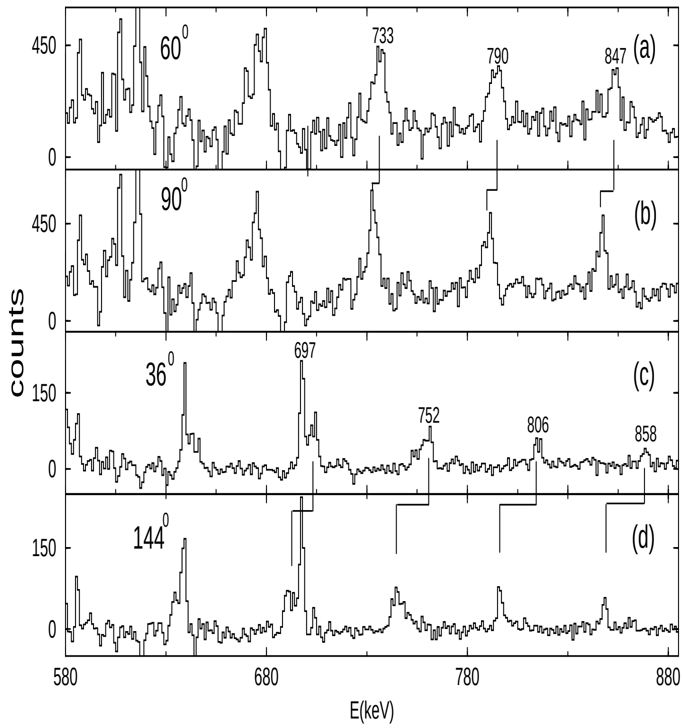

Fig. 1. Single-gated spectra from detectors in different angle groups for TSD band 1 in ^{164}Lu (a), (b) and double-gated spectra for TSD band 1 in ^{163}Lu (c), (d). The statistical fluctuations in the upper spectra are large since a much larger background contribution had to be subtracted.

From the centroid shifts of the γ-ray lines in the spectra fractional Doppler shifts, $F(\tau)$, were determined, where $F(\tau) = (\langle E_\gamma(\theta)\rangle - E_\gamma^0)/(E_\gamma^0 \beta(0)\cos(\theta))$. Here, the centroid of the Doppler-shifted energy peak $\langle E_\gamma(\theta)\rangle$ (including its line shape) depends on the angle θ relative to the beam direction. E_γ^0 is the energy of the unshifted line and $\beta(0) = v(0)/c$ [17]. The initial average recoil velocity, $v(0)/c = 0.0176$, was calculated from the reaction parameters at the middle of the target. The experimental $F(\tau)$ values extracted for the TSD bands 1 in ^{163}Lu and ^{164}Lu and for the ND band in ^{163}Yb are compared in fig. 2. Calculated $F(\tau)$ curves, assuming a rotational cascade with a constant quadrupole moment $Q_{\rm t}$ for each band, were fitted to the data. The electronic stopping powers were calculated using the tables of Ziegler *et al.* [18] and the nuclear stopping was treated according to the theory of Lindhard *et al.* [19]. In addition to the stopper foil, the target was also included in the calculation of the stopping process. The side feeding was modeled by a single rotational cascade with the number of transitions proportional to the number of transitions in the main band above the state of interest and with the same moment of inertia as that of the band. The side-feeding quadrupole moment $Q_{\rm sf}$ was treated as a free parameter. The side-feeding intensities were determined from the data of this

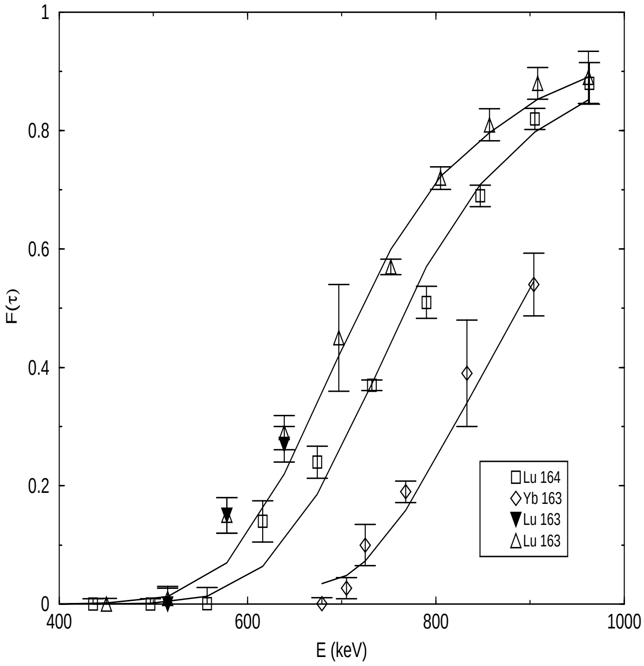

Fig. 2. Fractional Doppler shifts $F(\tau)$ for the TSD bands 1 in ^{163,164}Lu and for the ND yrast band in ^{163}Yb. The curves are least-square fits to the experimental data points from which the transition quadrupole moments are determined (see text). Open (full) symbols represent experimental $F(\tau)$ values determined from spectra gated below (above) the analysed transitions.

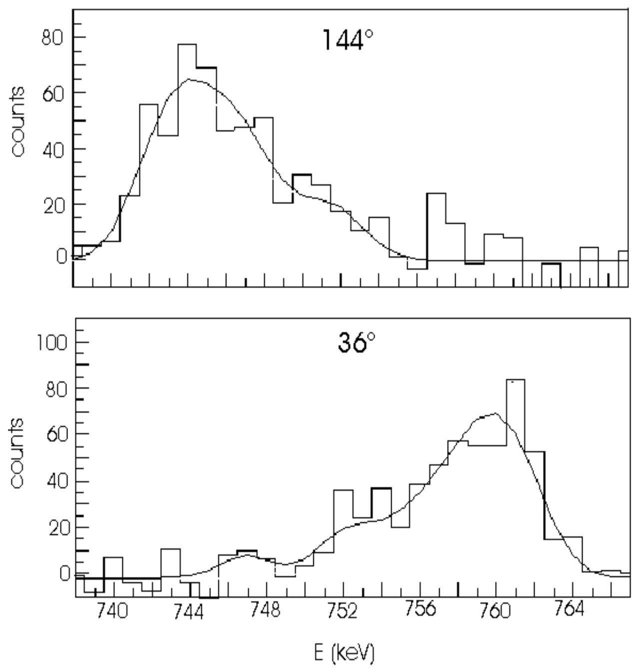

Fig. 3. Line shapes of the 752 keV transition in ^{163}Lu measured at forward (bottom) and backward (top) angles. The curves show the fitted line shape.

experiment. As the in-band quadrupole moment Q_t and the quadrupole moment of the side-feeding cascade Q_{sf} are correlated parameters, this fitting procedure did not give consistent results. In order to obtain independent information on the side-feeding quadrupole moments, fractional Doppler shifts were determined from spectra which were obtained by gating above the states of interest in ^{163}Lu. In this way, the influence of lifetimes in the side-feeding cascade on the lifetimes of the states within the band is eliminated. These $F(\tau)$ values are included in fig. 2 as full symbols. Although this $F(\tau)$ analysis could only be performed for the lower-spin range of band 1 in ^{163}Lu, the agreement with the $F(\tau)$ values determined from spectra with gates below the states of interest shows that Q_{sf} is probably very similar to Q_t. This is in agreement with a recent systematic comparison of side-feeding and in-band lifetimes in the $A = 140$ region [20] which shows that $\tau_{sf} = 1.2\tau_{band}$ is a reasonable assumption. We have, therefore, adopted the fixed relation $Q_{sf} = 0.91 Q_t$ in the final analysis. We assume an uncertainty of 10% for Q_{sf} and, thus, allow a range of $Q_t \geq Q_{sf} \geq 0.82 Q_t$ in order to determine this contribution to the systematical error of the transition quadrupole moments.

An inspection of the fits to the data presented in fig. 2 for the two TSD bands shows that the measured $F(\tau)$ values lie systematically above the fitted curves in the lower-spin regions of the bands. This indicates larger quadrupole moments in this range. Indeed, fits only up to γ-ray transitions of about 700 keV result in Q_t values that are 7% and 4% larger for ^{163}Lu and ^{164}Lu, respectively, than those obtained in the fits assuming a constant quadrupole moment for the whole band.

For three transitions in TSD band 1 of ^{163}Lu it was possible to analyse the line shapes of the peaks. As an example, the experimental line shapes of the 752 keV transition together with the fitted curves are shown in fig. 3. To calculate the line shapes, a program based on the one developed by Bacelar *et al.* [21] and modified by Gascon *et al.* [22] was used. In a first step of the calculations, a Monte Carlo simulation of 10000 histories of nuclei recoiling through the target and stopper foils is performed. Starting with the initial recoil velocity $v/c = 0.0179$, at the front of the target, this results in statistical velocity distributions at an average number of 1200 time steps with time intervals of 0.8 fs. In the second step, the details of the detector geometry are taken into account and a line shape for each decay time is calculated, using the velocity distributions obtained in the first step and the stopping powers as mentioned above for the $F(\tau)$ analysis [18,19, 23]. In the final step, the calculated line shapes are fitted to the experimental ones with the quadrupole moments as free parameters. The side feeding was modeled in the same way as described for the $F(\tau)$ analysis above, but always with 5 transitions in the side-feeding cascade, with similar restrictions on Q_{sf}.

The transition quadrupole moments of the three bands analysed in this work are summarized in table 1. The experimental errors do not include a possible systematic

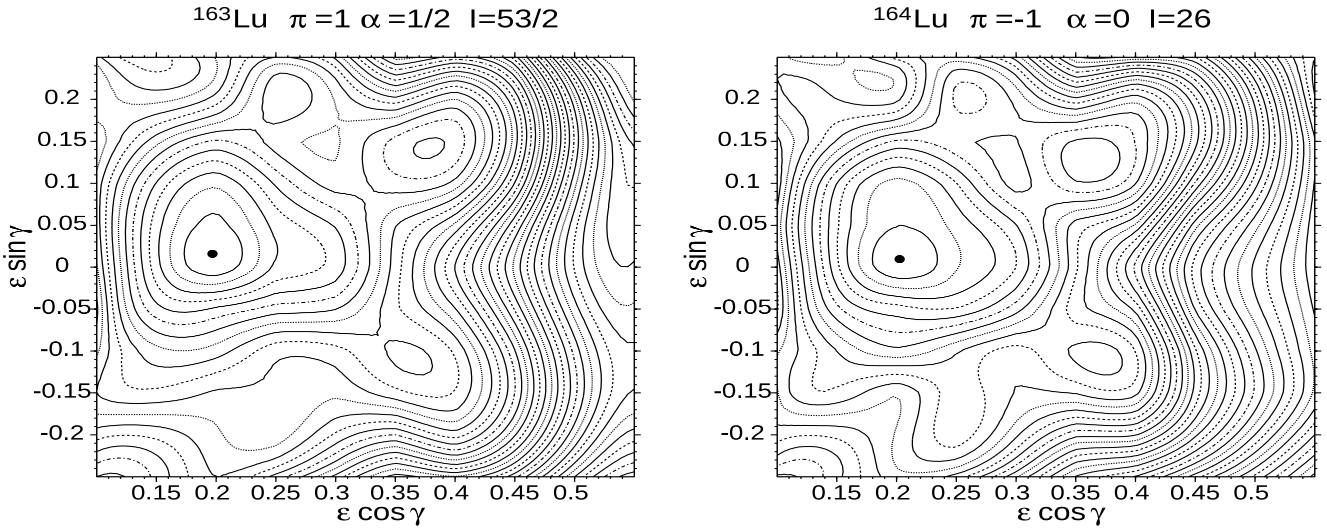

Fig. 4. Calculated (UC) potential energy surfaces. Each isotope has two local minima at $\epsilon \approx 0.38$ and $\gamma \approx \pm 20°$. The separation between the contour lines is 0.2 MeV.

Table 1. Experimental transition and side-feeding quadrupole moments for TSD bands 1 in ^{163,164}Lu and for the yrast ND band in ^{163}Yb.

Isotope	Band	Transition (keV)	τ (fs)	Q_{t} (b)	Q_{sf} (b)
$F(\tau)$ analysis					
^{163}Lu	TSD 1			$8.2^{+1.0}_{-0.6}$	$7.5^{+0.8}_{-0.8}$
^{164}Lu	TSD 1			$7.1^{+0.5}_{-0.6}$	$6.4^{+0.6}_{-0.6}$
^{163}Yb	ND			$4.9^{+1.3}_{-0.4}$	$4.4^{+0.4}_{-0.4}$
Line shape analysis					
^{163}Lu	TSD 1	752	144	$8.1^{+1.0}_{-1.1}$	$7.4^{+1.0}_{-0.7}$
		805	97	$8.3^{+1.9}_{-1.8}$	$7.9^{+2.1}_{-1.9}$
		858	76	$8.0^{+1.6}_{-1.5}$	$7.8^{+0.9}_{-1.8}$

uncertainty of 10–15% from insufficient knowledge of the stopping powers.

3 Discussion

The average transition quadrupole moments for the TSD bands 1 in ^{163}Lu and ^{164}Lu are $Q_{\mathrm{t}} = 8.2^{+1.0}_{-0.6}$ b and $7.1^{+0.5}_{-0.6}$ b, respectively. Clearly, these values are much larger than that of the ND yrast band in ^{163}Yb (see fig. 2 and table 1) showing that the TSD bands belong to a second potential-energy minimum with large deformation. The value for ^{163}Yb is somewhat smaller than the quadrupole moments measured previously by McGowan *et al.* [16], but within the error limits, it is in agreement with their results. These authors used the RDM to measure lifetimes in the lower-spin region of the band from which they deduced quadrupole moments between 5.27 ± 0.75 b and 6.67 ± 0.34 b.

Our result for TSD band 1 in ^{163}Lu can be compared to the previously determined average quadrupole moment for this band of $Q_{\mathrm{t}} = 10.7 \pm 0.7$ b [2]. In the previous work RDM as well as DSAM data were analysed. However, the treatment of the side-feeding quadrupole moment has been different which could be the reason for the discrepancy. Another uncertainty stems from insufficient knowledge of the stopping powers. In the previous experiment the reaction ^{19}F + ^{147}Sm has been used which resulted in a much lower recoil velocity. It is interesting to note that the previous RDM results which do not depend on the stopping powers are lower than the average value and lie closer to the quadrupole moment obtained in the present work. In particular, if we make a fit only to our data for the low-spin part of the band, the results are in agreement.

The average transition quadrupole moments for TSD bands 1 in ^{163}Lu ($Q_{\mathrm{t}} = 8.2^{+1.0}_{-0.6}$ b) and ^{164}Lu ($7.1^{+0.5}_{-0.6}$ b) are different which is evident, without any analysis, when comparing the experimental $F(\tau)$ curves of fig. 2. As these values are determined from the same experiment under identical conditions their ratio is very reliable, even if the absolute values might be subject to rather large systematic uncertainties. It is unlikely that the difference results from a different behaviour of the side feeding, as very similar structures are investigated in neighbouring isotopes. On the other hand, our UC calculations (see fig. 4) show TSD minima at approximately the same deformation for the two isotopes (which give $Q_{\mathrm{t}} \approx 9.2$ and 11.5 b for positive and negative deformation parameter γ, respectively). The quadrupole moments calculated from the wave functions with the UC code are plotted as a function of spin for the configurations assigned to TSD bands 1 in ^{163}Lu and ^{164}Lu in fig. 5. They are rather similar for both isotopes. The difference is certainly smaller than the

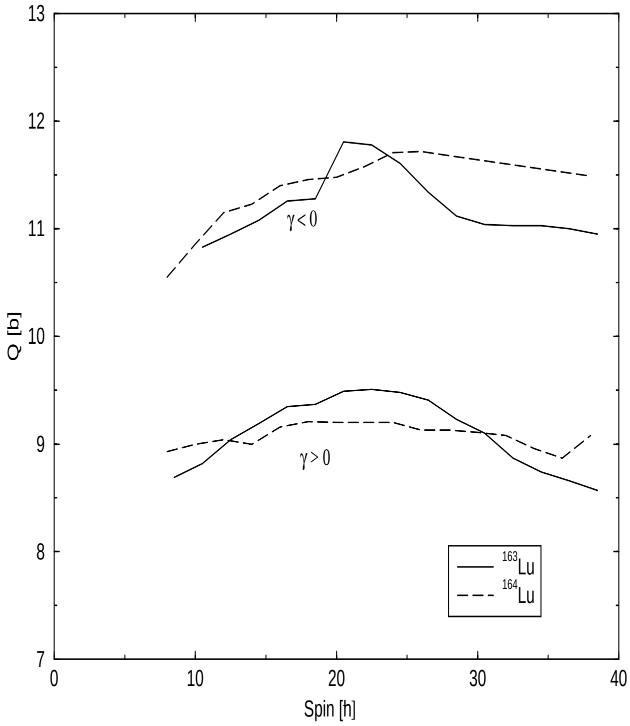

Fig. 5. Calculated (UC) quadrupole moments for positive and negative deformation parameter γ for the configurations of TSD 1 bands in ^{163}Lu and ^{164}Lu.

experimental deviation of about 15%. The experimental quadrupole moments clearly favour the minima with positive γ deformation ($\epsilon = 0.38, \gamma = 20°$). In the calculations, this minimum appears to be lower in energy than the one with negative γ. Thus, we conclude that TSD bands 1 in both isotopes correspond to the local minimum with positive γ deformation. This is consistent with the previous configuration assignments to these bands: $(\pi = +, \alpha = \frac{1}{2})$ (mainly $\pi i_{\frac{13}{2}}$) and $(\pi = -, \alpha = 0)$ (mainly $\pi i_{\frac{13}{2}} \otimes \nu h_{\frac{9}{2}}$) for TSD bands 1 in ^{163}Lu and ^{164}Lu, respectively [1,2,5,6].

The similarity of the theoretical quadrupole moments of the TSD bands in ^{163}Lu and ^{164}Lu is inconsistent with the experimental observations. Another, probably related discrepancy, is that the calculated excitation energy of the TSD bands in ^{164}Lu is larger than experimentally observed [5]. This has been investigated in ref. [13], where it is concluded that the exact position of a few intruder orbitals ($\pi i_{13/2}$, $\pi h_{9/2}$, $\nu i_{11/2}$) is crucial. The standard potential parameters used in the UC calculations do not place these orbitals at optimal positions. Since these are strongly deformation-driving orbitals, they might have an important influence on the quadrupole moments.

4 Summary

In summary, we have measured fractional Doppler shifts for the TSD bands 1 in ^{163}Lu and ^{164}Lu. In addition, for three transitions in ^{163}Lu the line shapes could be analysed. The average transition quadrupole moments $Q_t = 8.2^{+1.0}_{-0.6}$ and $Q_t = 7.1^{+0.5}_{-0.6}$ b for ^{163}Lu and ^{164}Lu, respectively, strongly assert positive γ deformation when compared to the results of UC calculations. However, these calculations cannot account for the difference in the experimental quadrupole moments of the TSD bands 1 in the two isotopes.

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