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One- and two-phonon wobbling excitations in triaxial ^{165}Lu

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Abstract

High-spin states in ^{165}Lu have been investigated by in-beam γ-ray coincidence spectroscopy using the EUROBALL spectrometer array. Two new excited rotational bands have been discovered with features similar to a previously known triaxial superdeformed band in that nucleus. Comparison of the decay pattern of these bands, in particular the unusually large E2 transition strength from the first excited to the yrast superdeformed band, to theoretical calculations shows that they belong to a family of wobbling excitations with phonon numbers $n_{\mathrm{w}} = 0$, 1 and 2. These results, together with evidence for nuclear wobbling in the neighbouring isotopes ^{163}Lu and ^{167}Lu, firmly establish this mode of excitation in the $A = 165$ mass region. The observation of wobbling is a unique signature of stable nuclear triaxiality.

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Keywords: Nuclear energy levels; Triaxial superdeformation; Wobbling excitation

The investigation of deviations from spherical symmetry of atomic nuclei has been a prominent subject of nuclear structure studies for many years. Only nuclei with magic proton or neutron numbers, corresponding to closed shells, are spherical at low excitations energies, while the majority of nuclei are deformed. The observed deformations span a wide range from

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the well-known 'normal' deformation to 'superdeformation' [1] and even to possible 'hyperdeformation' [2,3]. Nuclear shapes can be calculated using the Strutinsky prescription [4] and taking the effects of rotation into account [5,6]. Stable shapes correspond to minima in calculated total routhian surfaces. An example of such calculations, using the Ultimate Cranker (UC) code [7], is shown in Fig. 1 for ^{165}Lu, the nucleus which is the subject of investigation in the present Letter. It is interesting to note that, in addition to a minimum at a normal deformation of $\epsilon = 0.23$, strongly deformed minima exist with a substantial deviation from axial symmetry ($\epsilon = 0.38$, $\gamma = \pm 20°$).

The possible existence of nuclei with stable triaxiality has been discussed for a long time. However, such a deviation from axial symmetry is very difficult to prove experimentally. It was predicted about 25 years ago [8] that triaxial nuclei could show wobbling excitations, a rotational excitation mode unique to a triaxial body. It occurs when the axis of collective rotation does not coincide with one of the principal axes. For triaxial nuclei with moments of inertia with respect to the three principal axes, $J_x > J_y, J_z$, and in the high-spin limit with most of the angular momentum aligned along the x-axis, a sequence of wobbling bands with increasing number of wobbling quanta, n_{w}, may be expected at low excitation energy.

The wobbling mode was first discovered in ^{163}Lu [9,10] and there is also recent evidence for a one-phonon wobbling excitation in ^{167}Lu [11]. In these

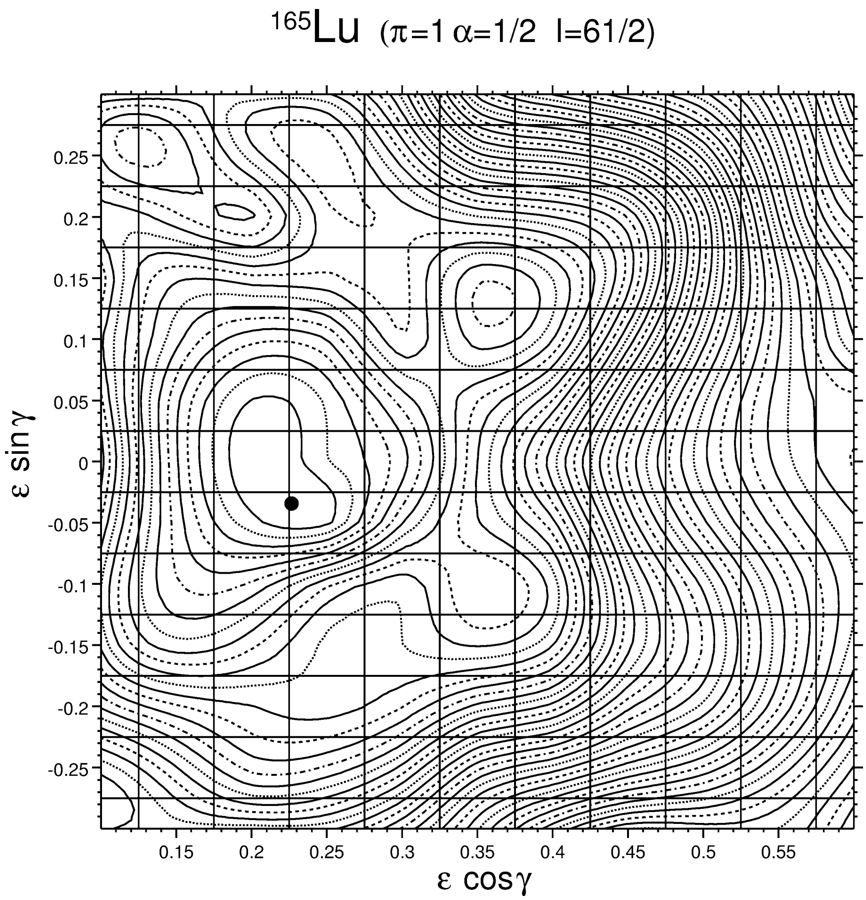

Fig. 1. Total energy surface for ^{165}Lu at $I^{\pi} = 61/2^{+}$ calculated using the Ultimate Cranker code [7]. The normal-deformed minimum at $\epsilon = 0.23$ and the two strongly-deformed triaxial minima at $\epsilon \approx 0.38$, $\gamma \approx \pm 20°$ are clearly seen. The minimum with the positive γ value is deeper than the one with negative γ.

odd-Z nuclei, as in the present case of ^{165}Lu, an aligned $i_{13/2}$ proton favours the triaxial strongly-deformed shape that can be seen in Fig. 1 as the local minimum at $\epsilon = 0.38$ and $\gamma = 20°$. Particle-rotor calculations show [12] that in this case a unique pattern of electromagnetic transitions occurs between the bands with wobbling quanta $n_w = 0$, 1 and 2. In this Letter we present evidence for the first- and second-phonon nuclear wobbling bands in ^{165}Lu. The properties of the wobbling bands and the decay between them show great similarities to ^{163}Lu and ^{167}Lu. Thus, the present results establish the wobbling mode as a general phenomenon in this mass region and prove the triaxiality of these nuclei.

High-spin states in ^{165}Lu were populated in the reaction ^{139}La(^{30}Si, 4n) at a beam energy of 152 MeV. The ^{30}Si beam was provided by the Vivitron accelerator at IReS, Strasbourg. The target consisted of two 500 µg/cm^2 thick La foils which were produced a few days before the experiment and handled in an Argon atmosphere to prevent oxidation. Gamma-ray coincidences were measured with the EUROBALL γ-ray spectrometer array [13] which comprises 30 conventional large-volume Ge detectors as well as 26 Clover and 15 Cluster composite Ge detectors. Out of the total of 239 Ge crystals, ten crystals were rejected during the presorting procedure, because they showed very strong gain-shifts which could not be recovered by the gain-matching routines. All detectors are surrounded by BGO scintillators for Compton suppression. In addition, an inner ball of 210 BGO detectors was used as multiplicity filter to enhance the detection of long γ-ray cascades.

Coincidence events were written to magnetic tape with a hardware trigger condition of 5 or more γ rays before Compton suppression detected in coincidence in the Ge detectors, and 10 or more γ rays detected in the BGO inner ball. After presorting and gain-matching a total of 3.2×10^9 three- or higher-fold Compton-suppressed coincidence events remained for further analysis. These events were sorted into a three-dimensional matrix (3D Radware cube [14]). In addition, a BLUE data base [15] was created for an easy access to coincidence spectra and for the analysis of γ-ray directional correlations from the oriented nuclei (DCO ratios).

The data confirm the previously known triaxial superdeformed band (TSD 1) in ^{165}Lu [16] and extend it to higher spins. In addition, its decay to lower-lying normal-deformed (ND) states has been uniquely established. The analysis revealed also two new TSD bands with properties very similar to those of TSD 1. Gamma-ray coincidence spectra for these three bands are shown in Fig. 2. A partial level scheme of ^{165}Lu, showing the three bands and their decay, is displayed in Fig. 3. The bands TSD 1, 2 and 3 have intensities of approximately 1.3%, 0.4%, 0.1% of the total four-neutron-evaporation channel. Fig. 4 shows the similarity of the dynamic moments of inertia $J^{(2)}$ and the relative alignments i_x for the three bands.

We observe that bands TSD 2 and 3 decay into TSD 1 via several transitions. The decay pattern, which is the main experimental evidence for the wobbling excitations, is very similar to that in ^{163}Lu [10]. In fact TSD 2 and TSD 3 are almost isospectral with their homologues in ^{163}Lu. The excitation energies of these bands relative to TSD 1 are only about 10 keV higher in ^{165}Lu than found in ^{163}Lu and the energies of the inter-band transitions are also very similar. The DCO ratios of two of the six observed transitions from TSD 2 to TSD 1, the 667.9 and 682.5 keV transitions, could be determined. The results, 0.37 ± 0.14 and 0.38 ± 0.13, respectively, are compatible with mixed $\Delta I = 1$ transitions. These ratios are very close to those obtained for transitions connecting the corresponding bands in ^{163}Lu [9,10]. In ^{163}Lu the population of the TSD bands is larger than in ^{165}Lu and angular correlations as well as linear polarisations could be determined. These data established that the inter-band transitions have a predominantly E2 multipolarity (90.6 ± 1.3%) with a small M1 admixture (9.4 ± 1.3%). For ^{165}Lu the mixing ratio of the connecting transitions is calculated from the DCO ratios given above. The first of the two solutions gives $92.3^{+5.3}_{-11.2}$% E2 and $7.7^{+11.2}_{-5.3}$% M1 multipolarity, which is in good agreement with the result obtained for ^{163}Lu. The second solution with a mixing of $2.8^{+7.4}_{-2.4}$% E2 and $97.2^{+2.4}_{-7.4}$% M1 is excluded by the analogy to ^{163}Lu, where the linear polarisation measurement proved the predominant E2 character of the inter-band transitions [9]. Table 1 summarises the experimental branching ratios and ratios of $B(\mathrm{E2})_{\mathrm{out}}/B(\mathrm{E2})_{\mathrm{in}}$ for three transitions linking TSD 2 and TSD 1. Of the three transitions that are linking TSD 3 to TSD 1, none has sufficient intensity for a DCO analysis.

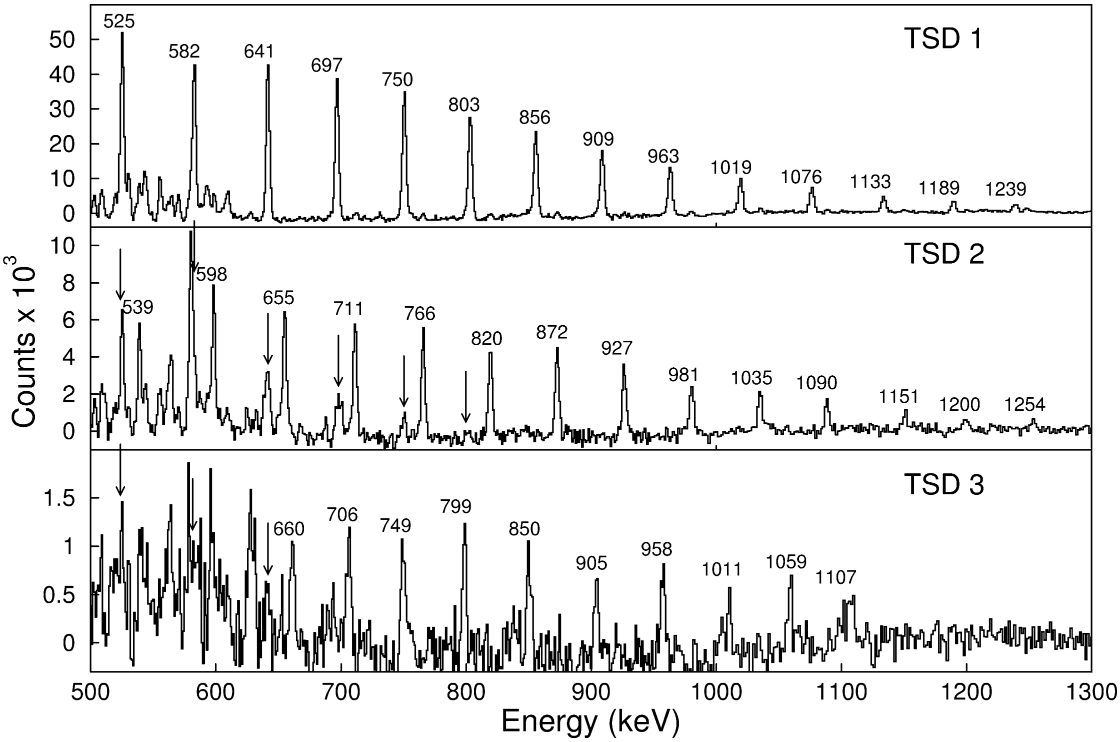

Fig. 2. Gamma-ray coincidence spectra for the three TSD bands in ^{165}Lu. The transitions of TSD 1 observed in the two lower spectra are marked by arrows.

Three transitions link band TSD 1 to the ND level scheme, see Fig. 3. The 445.3 and 486.5 keV lines are unresolved doublets, but for the 590.7 keV transitions a DCO ratio of 1.03 ± 0.20 could be determined which suggests that it is of stretched E2 character. This result suggests that the spins of band TSD 1 have to be increased by $2\hbar$ compared to the previous work [16]. In neighbouring ^{163}Lu, TSD 1 extends down to the $13/2^+$ level, but partly decaying into ND states around spin $21/2^+$ where band mixing occurs [17]. In the present case of ^{165}Lu, the lowest-spin state that can be observed is the $25/2^+$ level. Here, the band mixing occurs at spins $25/2^+$ and $29/2^+$ causing TSD 1 to decay into the [402] $5/2^+$ and [411] $1/2^+$ bands. The level mixing can also be seen as an irregularity in the dynamic moments of inertia $J^{(2)}$ of TSD 1 in the lower panel of Fig. 4. However, in the medium-frequency range, outside level-mixing regions, the moments of inertia of the three bands are very similar. The similarities in the moments of inertia and the alignments suggest that the bands TSD 1, 2 and 3 have a similar intrinsic structure. They probably belong to the same local potential energy minimum with $(\epsilon, \gamma) = (0.38, 20°)$ seen in Fig. 1. In Fig. 5 the excitation energies of the three TSD bands are compared to those of several ND bands. In this plot, the transitions connecting TSD 2 and 3 to TSD 1 and the transitions from TSD 1 to the ND states are indicated by dotted arrows.

Table 1
Experimental γ-ray branching ratios and $B(\text{E2})_{\text{out}}/B(\text{E2})_{\text{in}}$ ratios for the inter-band transitions from TSD 2 to TSD 1

E_γ^{out} [keV]	$I_{\text{out}}/I_{\text{in}}$	$B(\text{E2})_{\text{out}}/B(\text{E2})_{\text{in}}$
638.2	0.43 ± 0.12	0.17 ± 0.05
654.1	0.28 ± 0.05	0.16 ± 0.03
667.9	0.26 ± 0.09	0.22 ± 0.08

A unique feature of the inter-band decay from TSD 2 to TSD 1 is the unusually large $B(\text{E2})$ ratios (see Table 1) which can only be explained under the assumption that they are wobbling excitations

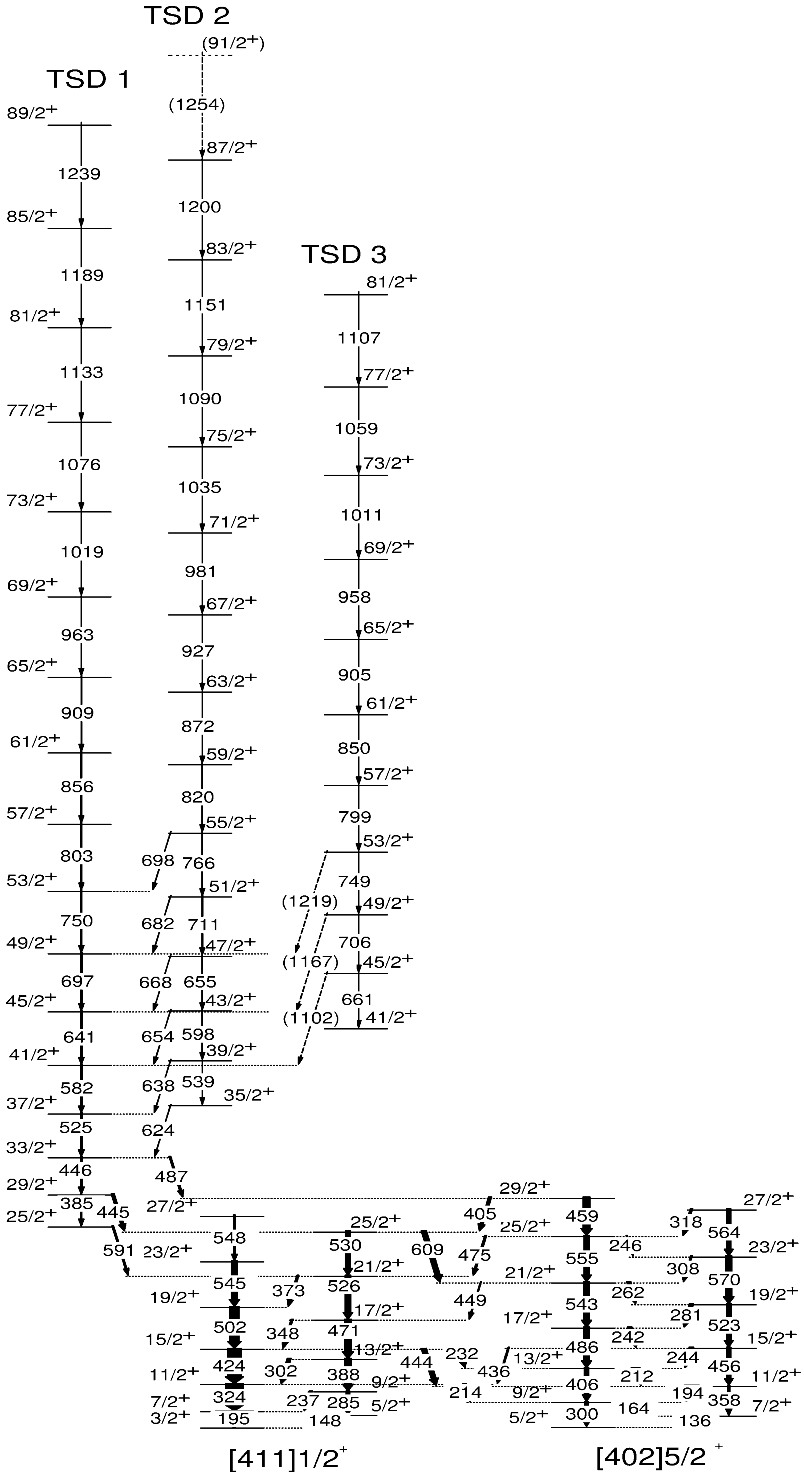

Fig. 3. Partial level scheme of ^{165}Lu showing the three TSD bands together with the ND structures to which they decay.

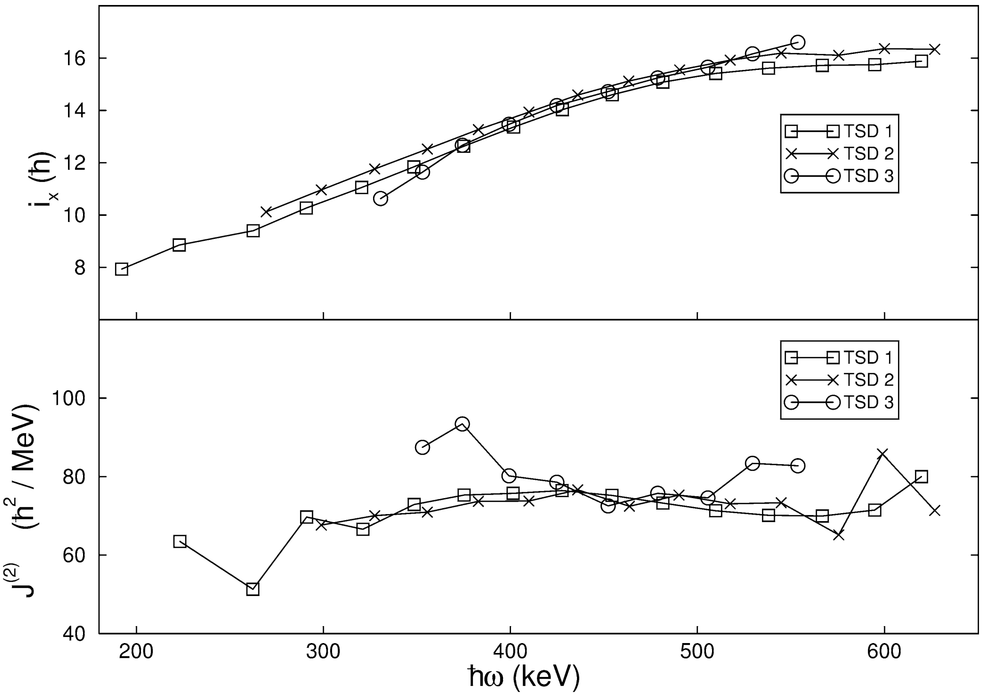

Fig. 4. Alignment i_x (upper panel) and dynamic moment of inertia $J^{(2)}$ (lower panel) for the three TSD bands in ^{165}Lu as a function of rotational frequency. The reference for the alignment is $I_{\mathrm{ref}} = \Im_0\omega + \Im_1\omega^3$ with $\Im_0 = 30\hbar^2\ \mathrm{MeV}^{-1}$ and $\Im_1 = 40\hbar^4\ \mathrm{MeV}^{-3}$.

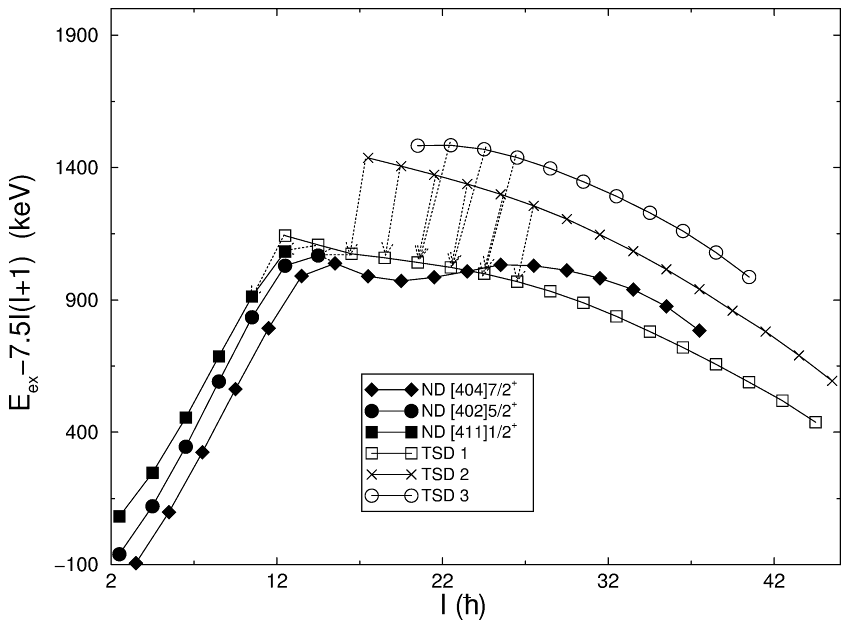

Fig. 5. Excitation energies relative to a rigid rotational core for the three TSD bands (open symbols) and some of the ND structures (filled symbols) in ^{165}Lu. The transitions between the bands are marked by dotted arrows.

[12]. The rotational motion of a triaxial nucleus with three different moments of inertia connected with the rotation about the three principal axes may give rise to a sequence of wobbling bands. Their energies for $J_x > J_y, J_z$ are

$$E_R(I, n_\mathrm{w}) = \frac{\hbar^2 I(I+1)}{2J_x} + \hbar\omega_\mathrm{w}(n_\mathrm{w} + 1/2),$$

where n_w is the wobbling phonon number and

$$\hbar\omega_\mathrm{w} = \hbar\omega_\mathrm{rot}\left[\frac{(J_x - J_y)(J_x - J_z)}{J_y J_z}\right]^{1/2}$$

with $\hbar\omega_\mathrm{rot} = \hbar^2 I/J_x$ [8]. The excitation energies of the bands increase with increasing wobbling phonon numbers n_w. A characteristic signature of the wobbling excitation is the occurrence of $\Delta I = \pm 1$ inter-band transitions with unusually large $B(\mathrm{E2})_\mathrm{out}$ values. Thus, the inter-band transitions can compete with the very enhanced $\Delta I = 2$ E2 transitions within the strongly deformed bands.

For the neighbouring odd-Z nucleus ^{163}Lu the spectroscopic properties of excited states and, in particular, the transition probabilities between the bands have been calculated [12] within the framework of the particle-rotor model. In these calculations one $i_{13/2}$ quasiproton coupled to the core with a triaxial shape was considered. The calculations show that four bands out of the six lowest-energy bands, two with favoured signature α_f and two with unfavoured signature α_u, can be identified as a family of wobbling bands. For these bands the collective angular momentum $\vec{R}$ of the core is almost the same, while the direction of $\vec{R}$ is tilted away from the x-axis with increasing angles as one goes from the yrast band with $n_\mathrm{w} = 0$ to the higher-lying bands with $n_\mathrm{w} = 1$ and higher. The calculated quasiparticle alignments remain almost constant for these bands. The ratios of $B(\mathrm{E2})$ values, $B(\mathrm{E2})_\mathrm{out}/B(\mathrm{E2})_\mathrm{in}$, calculated within this approach are compared to the experimental values determined in this work in Fig. 6 for the inter-band transitions with $\Delta I = 1$ from TSD 2 to TSD 1. The great similarity of the band structures, of the excitation energies of TSD 2 and TSD 3 relative to TSD 1 and of the $B(\mathrm{E2})_\mathrm{out}/B(\mathrm{E2})_\mathrm{in}$ ratios observed in ^{163}Lu and ^{165}Lu justifies a comparison to the same calculations. As can be seen, the agreement between calculation and experiment is reasonable, given the large experimental uncertainties. The calculations predict a

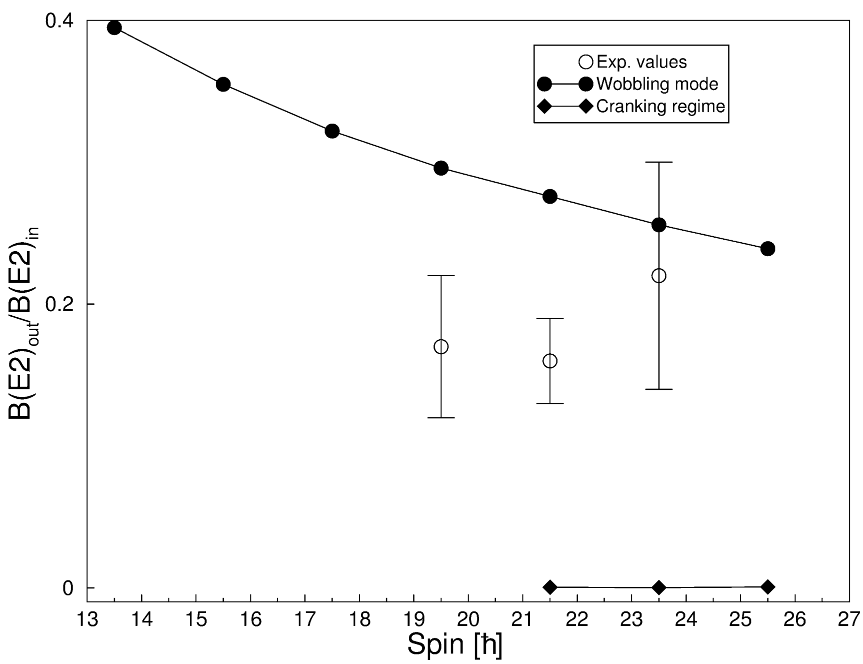

Fig. 6. Experimental and calculated $B(\mathrm{E2})$ ratios of the $\Delta I = 1$ inter-band transitions to $\Delta I = 2$ in-band transitions for bands TSD 2 and TSD 1. Values for the wobbling mode correspond to $n_\mathrm{w} = 1 \to n_\mathrm{w} = 0$ transitions.

$1/I$ dependence for the $B(\mathrm{E2})$ ratios, assuming a constant γ-deformation. Different values of γ would affect the calculated $B(\mathrm{E2})$ ratios [18]. The transitions from TSD 3 to TSD 1 arise from anharmonicities [10,12].

The total-energy surface calculations predict a well pronounced minimum with large deformation and a substantial triaxiality as seen in Fig. 1. The observation of wobbling bands in the $A = 165$ mass region is a unique evidence for a stable triaxial shape which is difficult to prove in other ways. Different explanations for the observed bands TSD 2 and 3 meet with great difficulties. In particular, the unusually large $B(\mathrm{E2})$ ratios are impossible to explain in another way. Calculations with the UC code [7] do not predict a stable strongly-deformed minimum for the signature partner of the proton $i_{13/2}$ orbital for either of the two nuclei ^{163}Lu and ^{165}Lu. Therefore, it is expected that the highly excited signature partner to TSD 1 should have rather different features, unlike those of TSD 2 or 3. Furthermore, a possible signature-partner band would have a vanishingly small E2 transition strength to band TSD 1 [9,12]. A more complicated configuration of TSD 2 or 3 seems also unlikely as one would expect additional alignments relative to TSD 1 which are not observed experimentally.

In summary, high-spin states in ^{165}Lu have been investigated by in-beam γ-ray coincidence spectroscopy using the EUROBALL spectrometer array. Two TSD bands have been found which decay into the previously known TSD band 1. The unusually large $B(\mathrm{E2})$ values of the decay of TSD 2 to TSD 1 can only be explained by the wobbling mode. The bands TSD 1, 2 and 3 form a family of wobbling excitations with wobbling-phonon quanta $n_{\mathrm{w}} = 0$, 1 and 2. The observation of wobbling uniquely establishes stable nuclear triaxiality in the $A = 165$ region.

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References

[1] P.J. Twin, et al., Phys. Rev. Lett. 57 (1986) 811.
[2] J. Blons, et al., Nucl. Phys. A 477 (1988) 231.
[3] A. Krasznahorkay, et al., Phys. Lett. B 461 (1999) 15.
[4] V.M. Strutinsky, et al., Nucl. Phys. A 122 (1968) 1.
[5] G. Andersson, Nucl. Phys. A 268 (1976) 205.
[6] I. Ragnarsson, Phys. Rev. Lett. 62 (1989) 2084.
[7] T. Bengtsson, Nucl. Phys. A 496 (1989) 56;
T. Bengtsson, Nucl. Phys. A 512 (1990) 124.
[8] A. Bohr, B.R. Mottelson, Nuclear Structure, Benjamin, New York, 1975, Vol. II.
[9] S.W. Ødegård, et al., Phys. Rev. Lett. 86 (2001) 5866.
[10] D.R. Jensen, et al., Phys. Rev. Lett. 89 (2002) 142503.
[11] H. Amro et al., Contributions to FNS2002, Berkeley, 2002.
[12] I. Hamamoto, Phys. Rev. C 65 (2002) 044305.
[13] J. Simpson, Z. Phys. A 358 (1997) 139.
[14] D.C. Radford, Nucl. Instrum. Methods A 361 (1995) 297.
[15] M. Cromaz, et al., Nucl. Instrum. Methods A 462 (2001) 519.
[16] H. Schnack-Petersen, et al., Nucl. Phys. A 594 (1995) 175.
[17] J. Domscheit, et al., Nucl. Phys. A 660 (1999) 381.
[18] I. Hamamoto, private communication.