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Triaxial strongly deformed bands in ^{160,161}Tm

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High-spin states in ^{160,161}Tm were populated using the ^{128}Te(^{37}Cl, 5n and 4n) reactions at a beam energy of 170 MeV. Emitted γ rays were detected in the Gammasphere spectrometer. Two rotational bands with high moments of inertia were discovered, one assigned to ^{160}Tm, while the other tentatively assigned to ^{161}Tm. These sequences display features similar to bands observed in neighboring Er, Tm, Yb, and Lu nuclei which have been discussed in terms of triaxial strongly deformed structures. Cranked Nilsson Strutinsky calculations have been performed that predict well-deformed triaxial shapes at high spin in ^{160,161}Tm.

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Stable triaxial strongly deformed (TSD) shapes near $A =$ 160 were predicted at high spin over 30 years ago [1]. It took decades before such structures were clearly identified in ^{163}Lu ($Z = 71$, $N = 92$) [2]. Experimental observations indicate co-existing TSD and superdeformed (SD) structures at high spin in the lower-mass nucleus ^{154}Er [3]. The latter nucleus, with $Z = 68$ and $N = 86$, lies on the boundary of the well known $A = 150$ SD region (see Fig. 1). It was, therefore, natural to consider whether other nuclei lying between the Lu nuclei ($N = 90$–96) and ^{154}Er also possessed a TSD shape and to investigate their properties.

Recently, evidence has been presented for TSD sequences in ^{157,158}Er [4], ^{163}Tm [5], and ^{160}Yb [6]. In higher$-Z$ nuclei evidence for TSD structures has proven inconclusive except in ^{168}Hf [7]. These results are summarized in Fig. 1, which shows nuclei above the semimagic ^{146}Gd ($Z = 64$, $N = 82$) nucleus which exhibit TSD or SD characteristics at high spin ($I \gtrsim 50\hbar$). The present work reports on the observation of two weakly populated rotational bands in the $Z = 69$ nuclei ^{160,161}Tm. These bands exhibit the high moments of inertia typical for TSD structure.

High-spin states in ^{160,161}Tm were populated by a 170 MeV ^{37}Cl beam, provided by the ATLAS facility at Argonne National Laboratory. ^{128}Te foils of various thicknesses ranging from 400 to 500 μg/cm^2 were mounted on a rotating target wheel. The side of the targets facing the beam was coated with a $\sim 75 - \mu$g/cm^2 thick gold foil. The target was also backed with 500-μg/cm^2 thick gold. In addition a beam "wobbling" device was utilized so that a higher beam intensity could be deposited ($\sim$2 pnA) on the Te target. A total of 3.5×10^9 five-fold or higher γ-ray coincidence events was collected by the Gammasphere spectrometer [8]. These events were then "unfolded" into a RADWARE format [9] three-dimensional cube and a four-dimensional hypercube for γ-ray coincidence analysis. The dominant reaction channels were associated with the 4n(^{161}Tm) and 5n(^{160}Tm) residues.

A search for rotational bands with high moment of inertia was performed. Two such sequences were found and these are displayed in Fig. 2. Figure 2(a) shows one of the proposed bands detected in coincidence with 680, 732, 784, 836, 884, 940, 991, and 1049 keV. The transitions of this band were detected in coincidence with γ rays in the known (see insert) $\nu i_{13/2} \otimes \pi h_{11/2}$ yrast band in ^{160}Tm [10] and have an intensity of $\sim$1% of the 580-keV γ ray in the yrast band. The second structure is shown in Fig. 2(b) with energies 881, 933, 981, 1030, 1079, 1130, 1181, 1231, and tentatively 1292 keV. The coincidence relationships of this band are inconclusive, since it includes known γ-ray transitions from both ^{160}Tm and ^{161}Tm. We tentatively assign this band to the 4n channel, ^{161}Tm, owing to the fact that this sequence is composed of higher γ-ray energies and thus presumably higher spins than the one shown in Fig. 2(a). The band we associate with ^{161}Tm has an intensity of $\sim$0.3% of the 517-keV γ ray in the yrast band of this nucleus [11].

Figure 3 displays the dynamic moment of inertia as a function of rotational frequency for the two bands in ^{160,161}Tm, together with selected bands in neighboring nuclei. Of particular note is how close the ^{161}Tm band follows the TSD band in ^{157}Er [4]. Both of the ^{160,161}Tm sequences display higher moments of inertia than those of the suggested TSD structures in ^{163}Tm [5].

Theoretical calculations for ^{160,161}Tm have been carried out using the configuration-dependent cranked Nilsson-Strutinsky (CNS) formalism without pairing [12,13]. Figure 4 presents potential-energy surfaces (PES) as a function of increasing angular momentum ($I = 20$–$70\hbar$) for ^{161}Tm. The equivalent

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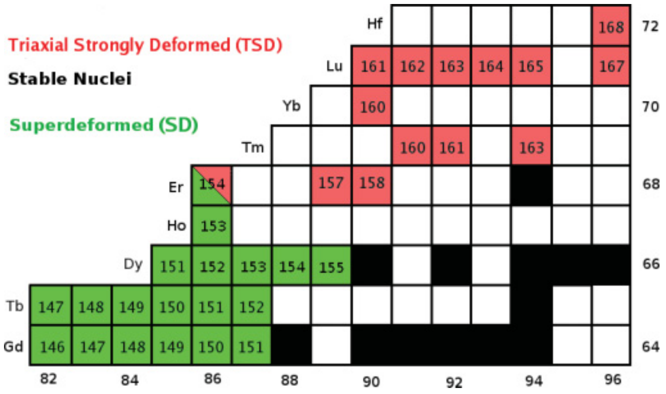

FIG. 1. (Color online) Section of the nuclear chart showing nuclei that exhibit superdeformed (SD) and triaxial strongly deformed (TSD) band structures.

PES plots for ^{160}Tm have similar features. At low spin values ($I = 20\hbar$), a prolate collective minimum ($\gamma = 0^\circ$) is lowest in energy. At higher spins ($I = 50$–$60\hbar$), an oblate noncollective configuration ($\gamma = 60^\circ$) becomes yrast. At $I = 70\hbar$, a well-developed triaxial strongly deformed minimum ($\varepsilon_2 \sim 0.39$–0.47, $\gamma \sim 20^\circ$) is observed and this shape minimum is in fact present for all lower spin values. We interpret the new sequences with high moments of inertia as being associated with this TSD shape.

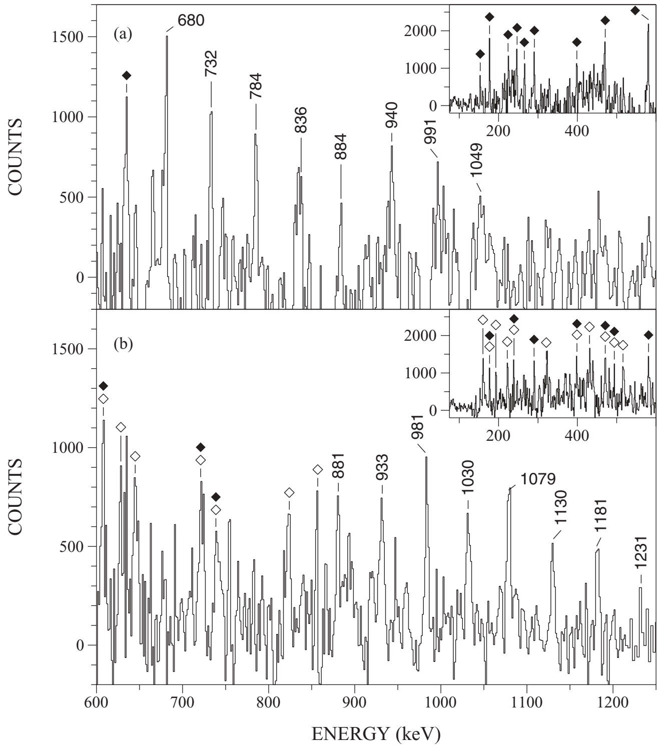

FIG. 2. Background-subtracted spectra of γ rays resulting from summing all triple coincidences of in-band transitions in the TSD bands assigned to ^{160}Tm (a) and ^{161}Tm (b). The insets show the low-energy part of the spectra where the solid diamonds indicate γ rays associated with ^{160}Tm while the open diamonds indicate known γ-ray transitions in ^{161}Tm.

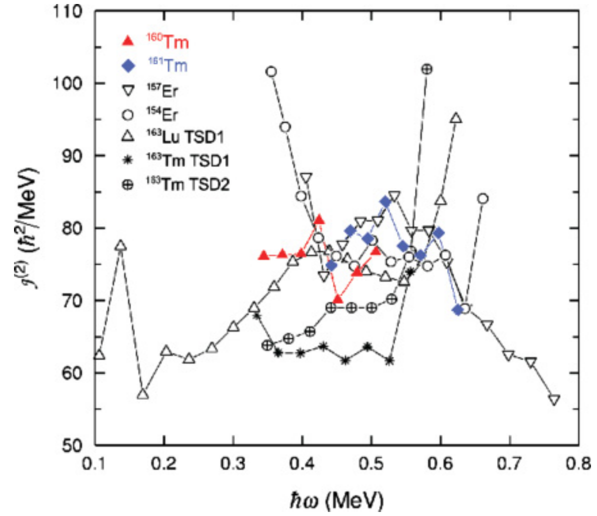

FIG. 3. (Color online) Experimental dynamic moments of inertia as a function of rotational frequency for the new sequences in ^{161,160}Tm along with selected structures showing TSD characteristics in neighboring nuclei.

In the calculations, configurations are labeled relative to a ^{146}Gd ($Z = 64$, $N = 82$) core, i.e.,

$$\pi(h_{11/2})^{p_1}(h_{9/2}f_{7/2})^{p_2}(i_{13/2})^{p_3}\cdots$$
$$\nu(N_{\rm osc} = 4)^{-n_1}(h_{11/2})^{-n_2}(i_{13/2})^{n_3},$$

specifying the number of particles and holes in orbitals outside the core. It is convenient to use the shorthand notation, $[p_1(p_2p_3), (n_1n_2)n_3]$, where the numbers in parentheses are only given when they are different from zero.

The nuclei ^{161}Tm and ^{160}Tm lie close to ^{163}Lu (see Fig. 1), with ^{161}Tm having two protons removed from ^{163}Lu. The spin and excitation energy of the yrast TSD band in ^{163}Lu is known experimentally and its configuration is well established. It is, therefore, instructive to use this band as a reference when discussing the configurations of the TSD bands in ^{160,161}Tm. In view of this, these bands are drawn relative to the rotating liquid drop energy for the respective nuclei in Fig. 5(a). With this reference, it becomes meaningful to compare the absolute energies as discussed in Ref. [13]. In the middle panel [Fig. 5(b)], the calculated bands (with assignments as discussed below) are plotted while the difference between calculations and experiment is illustrated in the lower panel [Fig. 5(c)].

According to our CNS calculations, the yrast normal-deformed (ND) band of ^{160}Tm [10] is assigned to the $\pi(h_{11/2})^7$ configuration ([7,3] in Fig. 5(b)) below the crossing at $I \approx 38\hbar$, while it is assigned to a $\pi(h_{11/2})^5$ configuration ([5,3]) above this crossing. This is consistent with the interpretation in Ref. [10] where the crossing is assigned as a proton crossing. With this interpretation, a good agreement between experiment and calculations is obtained [see Fig. 5(c)], with a discrepancy which stays well within the expected range of uncertainty (±1 MeV) in the high-spin region. At low spins the difference between experiment and theory increases, indicating the importance of pairing correlations, which are not included in the CNS calculations. The $\pi(h_{11/2})^5$ configuration

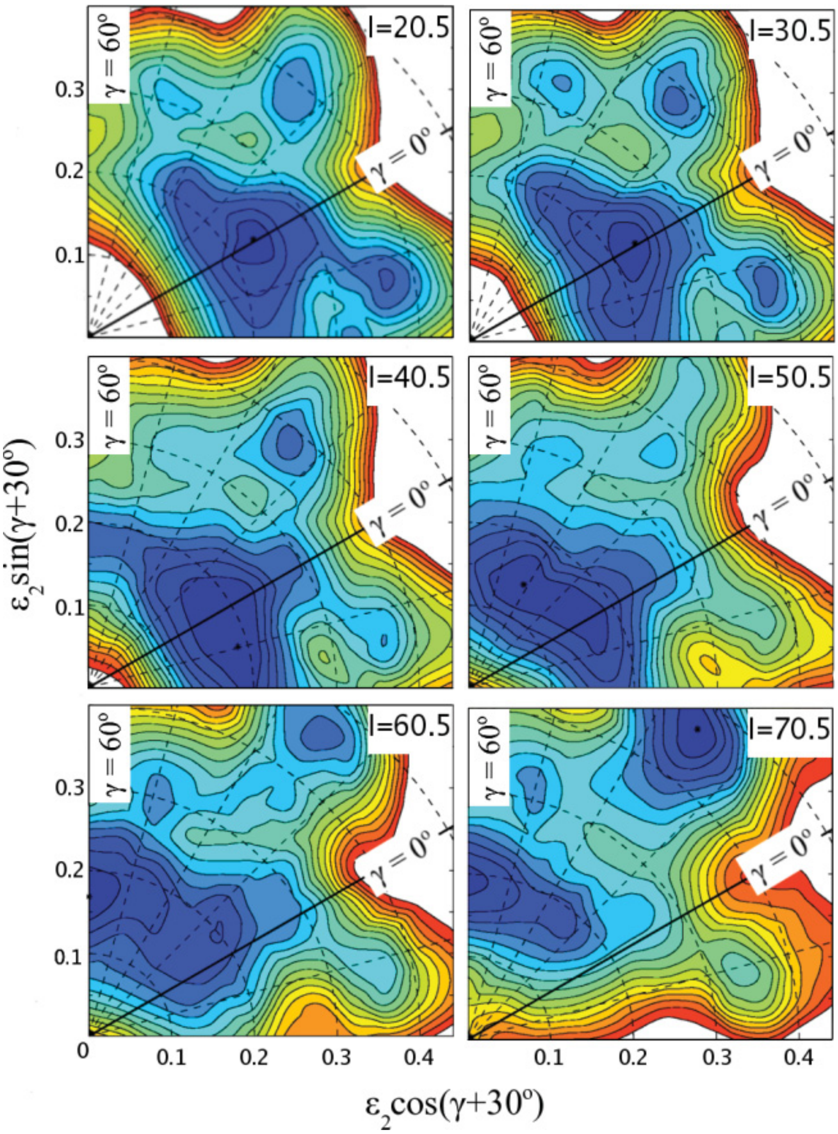

FIG. 4. (Color online) Calculated potential-energy surfaces versus quadrupole deformation ε_2 and triaxiality parameter γ for spins $I = 20.5$, 30.5, 40.5, 50.5, 60.5, and $70.5\hbar$ for (parity, signature) $= (\pi, \alpha) = (+, 1/2)$ structures in ^{161}Tm. The other combinations of (π, α) show similar features. The bottom left corner corresponds to a spherical shape, and the prolate axis ($\gamma = 0°$) and oblate axis ($\gamma = 60°$) are indicated. Contour lines are 250 keV apart. The red regions indicates high energy and the blue regions represent low energy. The absolute minimum is labeled with a dot.

is calculated to terminate as yrast at $I = 52\hbar$ in a state with the spin vectors of all 14 valence particles aligned along one axis. In Fig. 5(b) this terminating state is indicated by an open circle. The calculated termination above $I = 50\hbar$ is consistent with the general features of the potential energy surfaces shown for ^{161}Tm in Fig. 4.

With the spin and energy of the TSD band in ^{163}Lu known, it can be compared with calculations in the same way as the yrast band in ^{160}Tm. In this case too, the difference between calculations and experiment comes out as expected, i.e., with a difference close to zero for $I = 30$–$50\hbar$ and an increasing difference with decreasing spin, indicating that the pairing correlation energy starts to become important. The shorthand notation for the configuration of this TSD band in ^{163}Lu is [8(21),(22)6].

Because neither spin nor excitation energy is known for the two bands in ^{160,161}Tm, these quantities have been chosen from a comparison with the calculations. It seems reasonable to assume similar differences between calculations and experiment for the new bands as for ^{163}Lu, since, in general, there are smooth variations with the addition or removal of a few particles from a strongly collective configuration. With this in mind, the bands are placed as in the upper panel of Fig. 5, assuming the configurations used for the bands in the middle panel. These are the lowest calculated bands in the triaxial minimum at $I = 35$–$40\hbar$ for the respective nuclei (although one should note that several bands are found within a few hundred keV above yrast). The ^{161}Tm band is formed with two proton holes in $h_{11/2}$ orbitals relative to ^{163}Lu, while there is an additional $i_{13/2}$ neutron hole in ^{160}Tm.

While the present analysis indicates possible configurations for the reported bands, this is clearly not the only interpretation, considering that only the transition energies within the bands have been established. On the other hand, one should note that if a band is assigned to a specific configuration, the signature is fixed which means that the spin values can only be shifted by $\Delta I = 2\hbar$ and that this will have drastic consequences on the differences in the lower panel of Fig. 5. Thus, proposing assignments so that the discrepancies for the three nuclei are almost identical is not trivial.

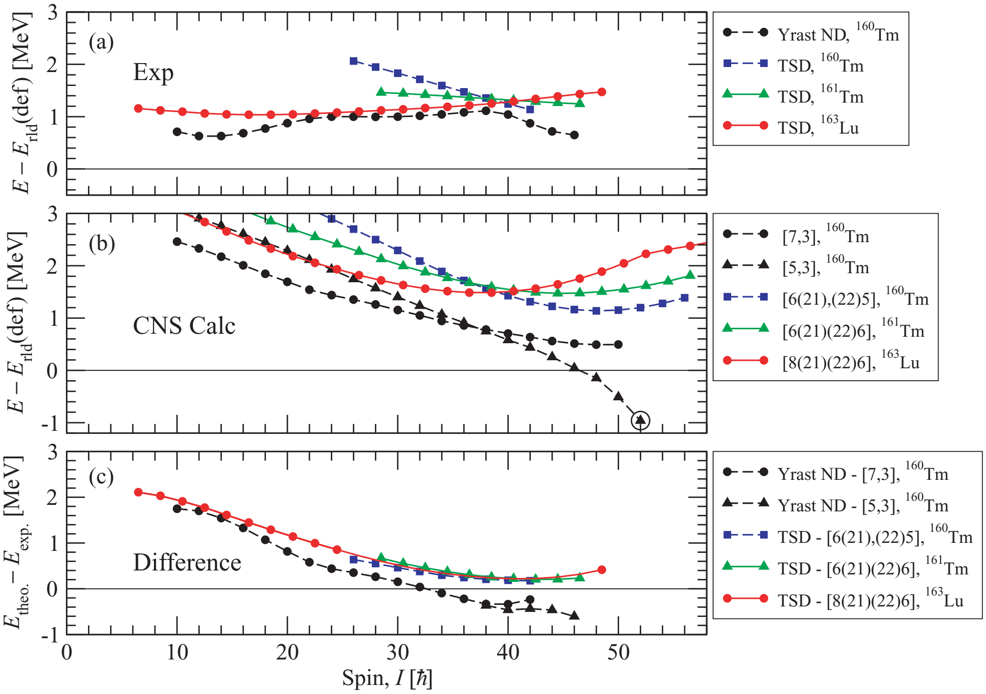

FIG. 5. (Color online) Calculated excitation energy relative to that of a rotating liquid drop as a function of angular momentum for selected bands in ^{160}Tm, ^{161}Tm, and ^{163}Lu [2]. See the text for an explanation of the labeling scheme.

A crossing is visible in some bands at $\hbar\omega \approx 0.4$ MeV, as illustrated for ^{157}Er in Fig. 3. As discussed in Ref. [6], this crossing can be understood as arising from an interaction between the second and third $\alpha = -1/2\, i_{13/2}$ (where α is the signature) neutron orbitals. Thus, if only the lower of these orbitals is occupied, the crossing will be visible as is the case for ^{158}Er and ^{160}Yb [6]. ^{160}Tm has one more neutron, which according to the interpretation, is placed in the third $\alpha = -1/2\, i_{13/2}$ orbital, which means that no crossing is expected. However, according to the calculations, there is another band at a slightly higher energy, where the third $\alpha = 1/2\, i_{13/2}$ neutron orbital becomes occupied instead so that a crossing is expected in this band. In ^{161}Tm and ^{163}Lu, the calculations suggest that both signatures of the third $i_{13/2}$ neutron orbital are occupied so that no crossing is expected. This agrees with experiment for ^{163}Lu while the situation for the ^{161}Tm band is uncertain since the latter is not observed in the low-frequency range ($\hbar\omega \sim 0.4$ MeV) where this crossing takes place.

In summary, two high-spin rotational bands with high moments of inertia have been observed, one in ^{160}Tm, and the other tentatively assigned to ^{161}Tm. These sequences display characteristics similar to triaxial strongly deformed structures discussed in neighboring Er and Lu nuclei. Detailed cranked Nilsson-Strutinsky calculations suggest that these new structures in ^{160,161}Tm may also be associated with a triaxial minimum ($\varepsilon_2 \sim 0.39$, $\gamma \sim 20^\circ$). A well-developed minimum is present in the potential energy landscapes in both ^{160}Tm and ^{161}Tm from low spin ($I = 20\hbar$) to high spin ($I = 70\hbar$), where it becomes yrast. It is now becoming clear that strongly deformed triaxial structures may be present in nuclei other than the well established chain of Lu isotopes. However, these new TSD sequences generally occur at higher spins and with lower intensity in $N \sim 90$–92 Er, Tm, and Yb nuclei.

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