Persistence of collective behavior at high spin in the $N = 88$ nucleus ^{153}Tb

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Excited states in the $N = 88$ nucleus ^{153}Tb were observed up to spin ∼40 in an experiment utilizing the Gammasphere array. The ^{153}Tb states were populated in a weak $\alpha 4n$ evaporation channel of the ^{37}Cl + ^{124}Sn reaction. Two previously known sequences were extended to higher spins, and a new decoupled structure was identified. The $\pi h_{11/2}$ band was observed in the spin region where other $N = 88$ isotopes exhibit effects of prolate to oblate shape changes leading to band termination along the yrast line, whereas ^{153}Tb displays a persistent collective behavior. However, minor perturbations of the very highest state in both signatures of this $h_{11/2}$ band are observed, which perhaps signal the start of the transition towards band termination.

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The $N = 88$, $Z \approx 66$ region is known to be transitional between spherical-vibrational ($N \leqslant 86$) and well-deformed shapes ($N > 90$) at low spin. These nuclei at high spin ($I > 30$) systematically exhibit rapid changes in structure from prolate collective rotation to oblate noncollective behavior via the mechanism of band termination [1–5], where angular momentum is generated by the successive alignments of single-particle angular momenta along the same axis. Band termination occurs at high spin ($I \geqslant 36$) in this region as the particles outside of the $^{146}_{64}$Gd$_{82}$ core generate states located lower in energy than the collective levels. These band-terminating states exhibit reduced quadrupole moments (compared with the rotational states), and an increasing energy, with respect to a rigid-rotor reference, versus spin. Band-termination effects are observed in both even-even nuclei (^{158}Yb [1,2,6], ^{156}Er [3,7,8], ^{154}Dy [9–12], and ^{152}Gd [13]) and odd-Z nuclei ^{157}Tm [14] and ^{155}Ho [15]. However, the new results presented here indicate that collective behavior persists in ^{153}Tb through the spin region where shape changes and band termination are observed in other $N = 88$ isotones.

High-spin states of ^{153}Tb were populated in the reaction ^{37}Cl + ^{124}Sn, where the ^{37}Cl beam was provided by the ATLAS facility at Argonne National Laboratory and was accelerated to an energy of 180 MeV. Gammasphere [16] was used to detect the emitted γ rays with 100 Compton-suppressed germanium detectors. A weak $\alpha 4n$ reaction channel led to the states in ^{153}Tb. These were identified with the use of a Radware [17] hypercube. As this reaction channel was weak, an angular-correlation analysis could not be performed; therefore, new transitions were assumed to follow normal rotational behavior.

The last high-spin study of ^{153}Tb reported four strongly coupled sequences and one decoupled band [18]. All of these structures were verified in the present work; however, only two of them could be extended to higher spin and a new decoupled sequence was observed. A partial level scheme displaying the extended and new sequences is given in Fig. 1.

The yrast sequence is based on an isomer at 163.3 keV with a half-life of 173 (10) μs [19] and is labeled as band 1 in Fig. 1. This structure was extended from the previously known 57/2 state up to a tentative 77/2 level. A spectrum that justifies the extension of the $\alpha = -1/2$ signature is shown in Fig. 2(a), while a spectrum for its signature partner is given in Fig. 2(b). This band (or signature pair of bands) has been associated with a low-K $h_{11/2}$ quasiproton orbital [18,20], based on its

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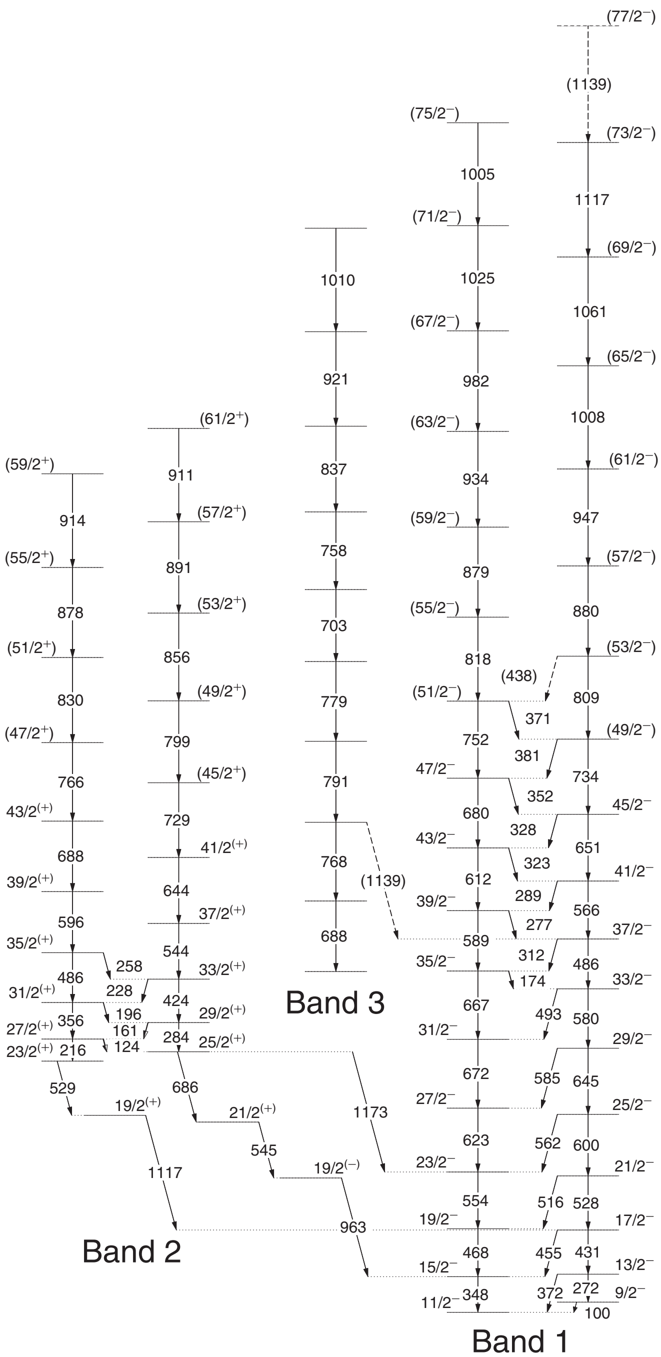

FIG. 1. Partial level scheme for ^{153}Tb from the present analysis. Tentative levels and γ rays are shown as dashed lines.

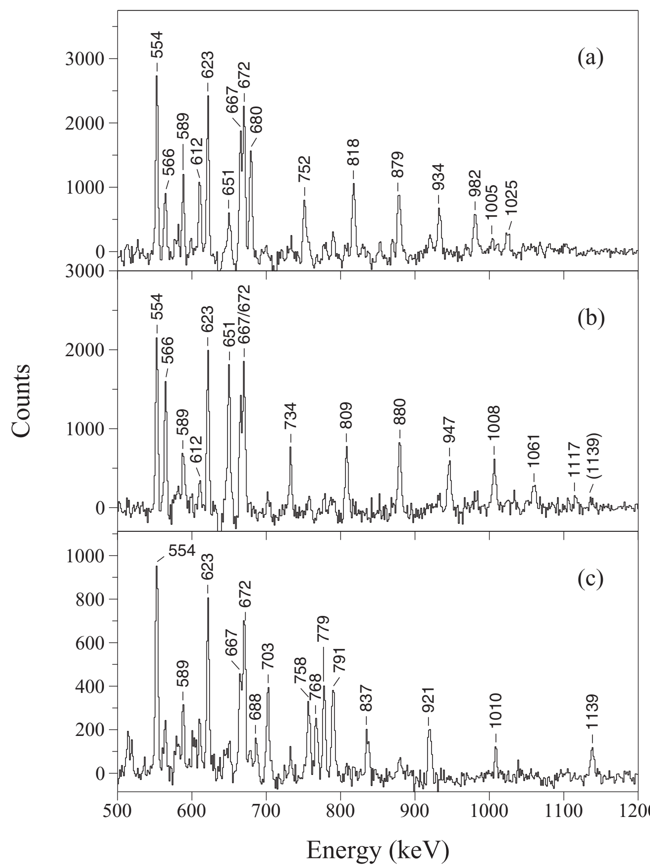

FIG. 2. (a) A spectrum of the $\alpha = -1/2$ signature for band 1 ($\pi h_{11/2}$) resulting from the sum of many triple coincidence gates of in-band transitions in the hypercube. (b) A spectrum produced in a similar manner as that in panel (a) to display the new transitions of the $\alpha = +1/2$ signature of band 1. (c) The newly observed band 3, where coincidences between all combinations of two in-band transitions with the 348-keV line in band 1 were summed.

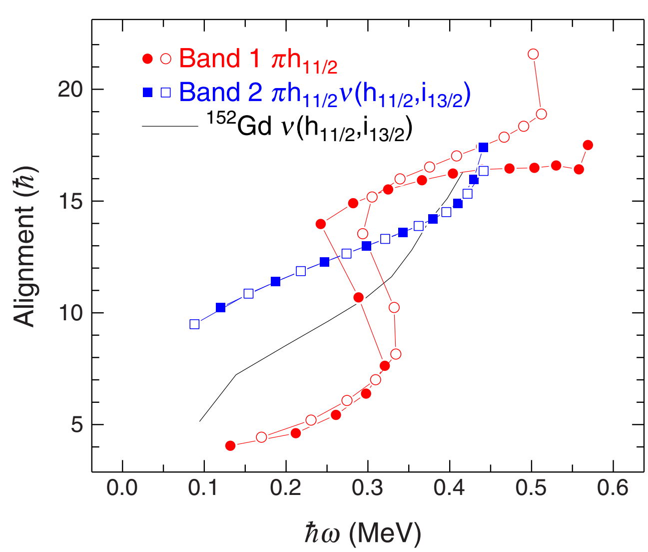

FIG. 3. (Color online) Alignment for bands 1 and 2 in ^{153}Tb, as well as for the high-K $\nu(h_{11/2},i_{13/2})$ sequence in ^{152}Gd [13]. Harris parameters [21] of $\mathcal{J}_0 = 12\ \hbar^2$/MeV and $\mathcal{J}_1 = 74\ \hbar^4$/MeV^3 were used.

high initial alignment (see Fig. 3) and agreement between theoretical and experimental $B(M1)/B(E2)$ ratios [18].

In the alignment plot of Fig. 3 a backbend near 0.3 MeV is observed in band 1. As discussed in Ref. [18], this is the result of the lowest pair of $i_{13/2}$ quasineutrons aligning (known as the AB crossing). With the extension of this band, it can now be observed that the alignment remains smooth up to ~0.5 MeV, indicating that no other crossing takes place. The last transitions in both signatures create significant discontinuities in the alignment diagram and may be the

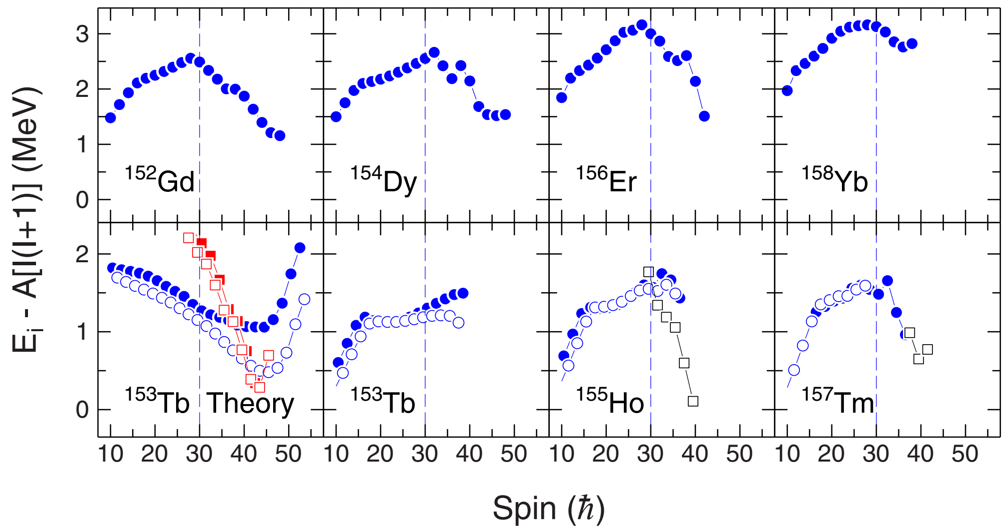

FIG. 4. (Color online) Yrast states (minus a rigid-rotor reference) with positive parity and even spins in the denoted even-even $N = 88$ nuclei are displayed in the upper panels. The lower panels provide energies of the yrast negative-parity, $\alpha = +1/2,-1/2$ states in the odd-Z isotopes (filled and empty blue [gray] circles, respectively). The negative-parity, $\alpha = -1/2$ states leading toward terminating states for ^{155}Ho and ^{157}Tm are shown as black squares. In addition, the cranked Nilsson-Strutinsky (CNS) calculations for the yrast negative-parity bands in ^{153}Tb are given in the lower-left panel. Configurations for these calculated bands are described in the text, as is the choice of reference parameters. A dashed line at $I = 30$ is given only to guide the eye.

first indication of a structure change to band termination, as discussed below.

Band 2 was observed previously [18] and was associated with the $\pi h_{11/2}\nu(i_{13/2},h_{11/2})$ three-quasiparticle configuration, where the $h_{11/2}$ quasineutron results from the high-K [505]11/2 orbital. Since there is a large change in K between bands 1 and 2, the decay out of band 2 is quite fragmented and goes through states that likely have intermediate K values between those in bands 1 and 2. Band 2 was extended from the 47/2 to the 61/2 state, as seen in Fig. 1. In Fig. 3, the initial alignment of band 2 is observed to be approximately $4\hbar$ larger than the $\nu(h_{11/2},i_{13/2})$ structure in ^{152}Gd [13]. Therefore, proposing a configuration adding an $h_{11/2}$ quasiproton to this two-quasineutron sequence to form band 2 in ^{153}Tb is natural. One may note that the band in ^{152}Gd gains alignment just below 0.4 MeV, which is likely attributable to the second $i_{13/2}$ quasineutron alignment (known as the BC crossing). However, the first indication of a crossing in band 2 of ^{153}Tb does not occur until above 0.4 MeV. Perhaps this is an indication of a larger deformation in the latter nucleus, herewith delaying the crossings.

A spectrum for the newly observed band 3 is found in Fig. 2(c). The ordering of the 703-, 758-, 779-, and 791-keV lines is uncertain as these transitions have similar intensities. Band 3 is clearly in coincidence with band 1, and a likely linking transition is evident in Fig. 2(c) at 1139 keV. This 1139-keV line is in coincidence with the transitions above the 768-keV γ ray (see Fig. 1), and it appears to likely feed into the 37/2 state of band 1. Unfortunately, no other linking transitions could be identified, although coincidence relationships between band 3 and higher-lying levels in band 1 are observed [note the presence of the 589-keV line in Fig. 2(c)]. The lack of other linking transitions makes the assignment of a spin or parity for band 3 difficult.

The $N = 88$ isotones are well known for displaying characteristics consistent with band termination effects; e.g., the generation of angular momentum switches from a primarily collective mode to noncollective single-particle alignment of the individual spins of nucleons outside the core. In this region, it is common to label the configurations relative to a ^{146}Gd core [5]. When the valence particles have maximally aligned their spins, the core must be broken to generate any further angular momentum, herewith requiring significant energy. If the band can be followed to its maximally aligned state, this level is referred to as a band-terminating state.

The yrast states with positive parity and even spins of the $N = 88$ even-even nuclei displaying band termination effects have been plotted in the upper panels of Fig. 4, minus a rigid-rotor reference, while the yrast negative-parity states in the odd-Z nuclei are plotted as blue (gray) circles in the lower panels. The rigid-rotor reference parameter was taken to be 0.007 MeV for ^{158}Yb and was scaled by an $A^{-5/3}$ factor in the other nuclei [4].

In the two lighter, even-Z cases (^{152}Gd and ^{154}Dy), the energy of the $I = 36$ state is relatively low; see Fig. 4. For ^{154}Dy, this is the result of the lowest band terminating state from the maximal alignment of the $\pi(h_{11/2})^2_{10^+}\nu[(f_{7/2}/h_{9/2})^4(i_{13/2})^2]_{26^+}$ configuration [9,12] at $I = 36$. This configuration can be more simply represented as $[p,n] = [2,2]$, where p and n represent the number of $h_{11/2}$ protons and $i_{13/2}$ neutrons associated with the configuration, respectively. In ^{152}Gd, the similarity with ^{154}Dy suggests the same configuration for the $I = 36$ state [13], which requires that the two holes in the $Z = 64$ core are paired to $I = 0$. In both cases, the $I = 36$ terminating state is fed by a configuration that contains two more $h_{11/2}$ quasiprotons (the [4,2] configuration) and has higher terminating states at $I = 48$ and 52, respectively. Indeed, the ^{154}Dy band ends at this higher spin (Fig. 4), while the ^{152}Gd band is observed $4\hbar$ short of termination. The ^{156}Er sequence fully aligns at spin $I = 42$, and recently Paul *et al.* [8] found evidence for states above this terminating state with properties consistent with the breaking of the ^{146}Gd core.

The negative slope in the various plots of Fig. 4 between spins 30 and 50 has long been associated with a band approaching a favored terminating state [5]. Structures with slightly positive slopes at high spin are usually associated with collective behavior, while "smooth" (unfavored) terminations correspond to curves with a positive curvature.

For the odd-Z nuclei (lower panels of Fig. 4) the odd-A ^{157}Tm nucleus displays a negative slope in the negative-parity, $\alpha = +1/2$ sequence and another sequence (with $\alpha = -1/2$, shown as black squares) exhibits a sharp negative slope and leads towards a predicted terminating state at 87/2 [14]. In ^{155}Ho, the negative-parity sequence is crossed by a structure (denoted with black squares) with a strong negative slope which resembles the structures approaching band termination in ^{157}Tm and ^{154}Dy. In fact, the sequence in ^{155}Ho has been interpreted as terminating at 79/2 [15]. For both ^{157}Tm and ^{155}Ho, these sequences leading to terminating states were strongly populated, as they lie at, or near, the yrast line. However, in this same spin region, there is no clear experimental evidence for a sequence with a negative slope in ^{153}Tb. This suggests that collective behavior persists through the $I = 30$–40 spin region in ^{153}Tb; however, the discontinuity seen at the highest rotational frequency (spin) in the alignment plot for both signatures of the $\pi h_{11/2}$ band (see Fig. 3) may indicate that a change in behavior is imminent.

Cranked Nilsson-Strutinsky (CNS) calculations for ^{153}Tb were performed, similar to those in Refs. [8,12–15], and are presented in the lower-left panel of Fig. 4. The sequences shown as blue (gray) circles correspond to the collective $\pi h_{11/2}$ bands in ^{153}Tb, where the closed (open) symbols represent the $\alpha = +1/2$ $(-1/2)$ signature. These structures contain five $h_{11/2}$ quasiprotons and the configurations are expressed as [5,2]. Strongly down-sloping, negative-parity sequences are found to cross the collective bands and are given as red (gray) squares in Fig. 4. These have two fewer $h_{11/2}$ protons (leading to the [3,2] configuration), and the $\alpha = +1/2$ sequence terminates at $I = 85/2$ while the $\alpha = -1/2$ one does so at 91/2. Although the experimental data fall short of these spins, one can see that the [3,2] configurations are predicted to cross the [5,2] ones at $I = 77/2$ and 81/2 for the $\alpha = +1/2$ and $-1/2$ sequences, respectively. This is at the limit of what is observed experimentally and may well explain the discontinuities in the alignment plot, Fig. 3. Thus, there may be a crossing of the collective structures from the [5,2] configuration by the noncollective [3,2] structures that could lead to band-terminating states. Further extension of these sequences is necessary to fully explore this possibility.

In summary, excited states in ^{153}Tb were identified up to high spins (~40) where effects from the band-termination phenomenon have been observed in neighboring nuclei. However, a characteristic negative slope in the excitation energy (minus a rigid rotor) plot of the $\pi h_{11/2}$ bands was not found, suggesting that collective behavior persists through this spin region. This is different from what was found in neighboring $N = 88$ isotopes. However, the anomalies at the very highest observed states in both signatures of the yrast $h_{11/2}$ band may signal the start of a prolate to oblate shape change as the nucleus transitions towards band termination. CNS calculations suggest that effects from terminating states may become present at spins near 81/2. The $\pi h_{11/2}$ band needs to be extended to higher spins for confirmation.

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