New insight into the shape coexistence and shape evolution of ^{157}Yb

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High-spin states in ^{157}Yb have been populated in the ^{144}Sm(^{16}O,3n)^{157}Yb fusion-evaporation reaction at a beam energy of 85 MeV. Two rotational bands built on the $\nu f_{7/2}$ and $\nu h_{9/2}$ intrinsic states, respectively, have been established for the first time. The newly observed $\nu f_{7/2}$ band and previously known $\nu i_{13/2}$ band in ^{157}Yb are discussed in terms of total Routhian surface methods and compared with the structures in the neighboring $N =$ 87 isotones. The structural characters observed in ^{157}Yb provide evidence for shape coexistence of three distinct shapes: prolate, triaxial, and oblate. At higher spins, both the $\nu f_{7/2}$ band and $\nu i_{13/2}$ band in ^{157}Yb undergo a shape evolution with sizable alignments occurring.

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I. INTRODUCTION

The light rare-earth nuclei around $A = 150$, which are situated in the transitional region between spherical and deformed nuclei, exhibit rich and varied structural characteristics. Due to the competition of the collective vibrational, rotational, and single-particle degrees of freedom, the level schemes in these transitional nuclei are very complex even in the low-excitation-energy region. Since the nuclear shape is determined by the nature of the intrinsic states and usually contains valuable information regarding the interplay of the single-particle and collective degrees of freedom, studies of the evolution of the nuclear shape along with the mass number, the angular momentum, and the coexistence of various shapes can serve as a sensitive probe of the underlying nuclear structure in this mass region and have attracted a lot of experimental and theoretical attention.

Due to the complexity of the structure in these transitional nuclei, the spectroscopy of odd-A nuclei is particularly useful in identifying the active single-particle orbitals and providing more unambiguous clues for understanding the mechanism behind the shape evolution and shape coexistence in the transitional region. For the $N = 87$ even-Z isotones above $^{146}_{64}$Gd$_{82}$, which have five valence neutrons beyond the $N =$ 82 closed shell and a few valence protons beyond the $Z =$ 64 closed subshell, the $f_{7/2}$, $h_{9/2}$, and $i_{13/2}$ neutron orbitals are close to each other and to the Fermi surface. The $f_{7/2}$ structure of the ground state has been found in the $N =$ 87 even-Z ^{151}Gd, ^{153}Dy, ^{155}Er, ^{157}Yb, and ^{159}Hf isotones. In previous studies [1–5], the collective structures observed in these isotones have revealed the coexistence of different nuclear shapes. But with different valence proton number, the pictures of shape coexistence in these isotones are somewhat different. In the studies by Kleinheinz *et al.* [1,2], ^{151}Gd and ^{153}Dy isotones were found to have quite similar high-spin level spectra. Several $\Delta I = 2$ bands built on weakly deformed $f_{7/2}$, $h_{9/2}$, and $i_{13/2}$ neutron intrinsic states and a well-developed $\Delta I = 1$ band built on a strongly deformed $\nu h_{11/2}$ state have been found. For the ^{155}Er [3] and ^{157}Yb [4] isotones, a moderately collective band, which was built on the $i_{13/2}$ neutron intrinsic state and corresponds to a slightly deformed prolate shape, and a less-regular positive-parity sequence, which most likely has the oblate configuration of $\nu(f_{7/2}{}^3)(h_{9/2})(i_{13/2})$, were observed. In a recent study of ^{159}Hf by Ding *et al.* [6], the $\nu h_{9/2}$ band in ^{159}Hf has been established. The band structure of ^{159}Hf, which has more vibration-like spacings, is different from those observed in the lighter isotones ^{151}Gd, ^{153}Dy, ^{155}Er, and ^{157}Yb, in which the yrast cascades are rotational bands built upon the $\nu i_{13/2}$ configuration. In view of these varied structure features, to get a systematic understanding of how these single orbitals and corresponding shapes in these isotones evolve, investigating the excitations built on the $\nu f_{7/2}$ and $\nu h_{9/2}$ configurations in ^{157}Yb as well as the $\nu i_{13/2}$ configuration in ^{159}Hf would be very helpful.

In this work, we present the results of a new investigation of ^{157}Yb. The band structures observed in ^{157}Yb are discussed in terms of total Routhian surface (TRS) methods and provide evidence for shape coexistence of three distinct shapes: prolate, triaxial, and oblate.

II. EXPERIMENT AND RESULTS

The present experiment was performed at the HI-13 tandem facility of the China Institute of Atomic Energy. The ^{144}Sm(^{16}O, 3n)^{157}Yb reaction was used to populate the

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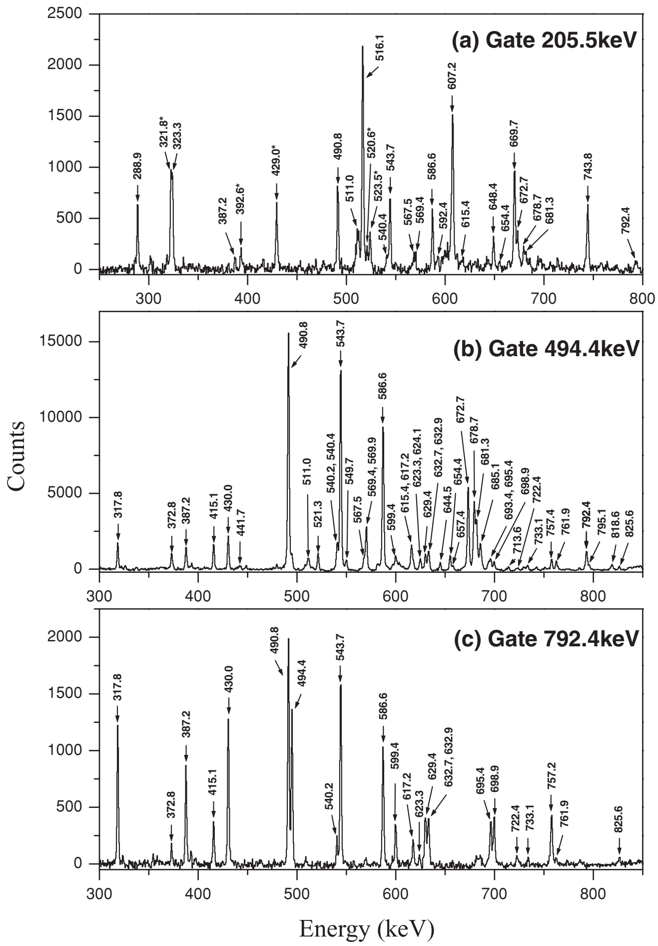

FIG. 1. Coincident γ-ray spectra with gating on (a) 205.5-keV transition, (b) 494.4-keV transition, and (c) 792.4-keV transition. The peaks marked with stars are known contaminants from the neighboring Tm and Yb nuclei.

high-spin states in ^{157}Yb. The target was ^{144}Sm, with a thickness of 3.1 mg/cm^2. It is on a 13.2 mg/cm^2 Pb backing. The deexcitation γ rays were detected by a γ detector array that consists of 10 high-purity germanium (HPGe) detectors with bismuth germanate (BGO) anti-Compton suppressors and one clover HPGe detector. Two additional planar HPGe detectors were also used to detect low-energy γ rays. The energy resolutions of these detectors were 2.0–3.0 keV at 1.33 MeV. All detectors were calibrated using the standard ^{152}Eu and ^{133}Ba γ-ray sources. The beam energy of 85 MeV was chosen to produce the ^{157}Yb nucleus.

A total of 1.7×10^8 coincident events were collected, from which a symmetric γ-γ matrix was built. The level scheme analysis was performed using the RADWARE program [7]. The typical γ-ray spectra gated on the known γ-ray transitions in ^{157}Yb are shown in Fig. 1. In order to obtain the directional correlations of γ rays deexciting oriented states (DCO) intensity ratios to determine the multipolarities of γ-ray transitions, the detectors around 90° with respect to the beam direction were sorted against the detectors around 40° to produce a two-dimensional angular correlation matrix. To get clean DCO values for transitions in ^{157}Yb, gates were set on uncontaminated

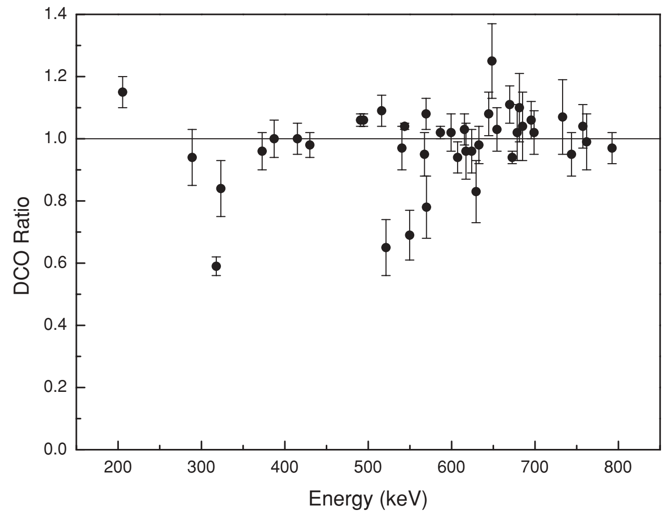

FIG. 2. The DCO ratio as a function of γ-ray energy for transitions in ^{157}Yb.

stretched $E2$ transitions. In general, stretched quadrupole transitions were adopted if DCO ratios were larger than 1.0, and stretched dipole transitions were assumed if DCO ratios were less than 0.8. The DCO ratio is plotted as a function of γ-ray energy for most of the observed transitions in ^{157}Yb in Fig. 2.

The structure of ^{157}Yb has been previously studied via ^{144}Sm(^{16}O,3n)^{157}Yb reaction [4,8–10]. A collective band built on the $\nu i_{13/2}$ configuration and an irregular $E2$ transition sequence have been established by Zheng et al. [4]. The partial level scheme of ^{157}Yb, deduced from the present work, is shown in Fig. 3. It was constructed from γ-γ coincidence relationships, intensity balances, and DCO analyses. The present analysis confirms most of the transitions found in the previous study [4], and only a few level sequences have been reordered.

The $13/2^+$ isomer, which was observed in all of the neighboring $N = 87$ isotones, has been reported to have an excitation energy of 528.8 keV in ^{157}Yb [4,10] and decays to the $\nu f_{7/2}$ ground state via two parallel transition cascades [4]. One deexcites via a transition sequence of 323.3 and 205.5 keV. The other decays via a low-energy 34.4-keV transition to the $11/2^-$ excited state at 494.4 keV. In Ref. [4], the order of the 323.3- and 205.5-keV transitions is uncertain because of their weak intensities. In the present work with more statistics, as shown in Fig. 1(a), a coincidence spectrum gated with the γ-ray 205.5-keV transition shows the presence of a new 288.9-keV line, which was also found to be in coincidence with the above transition cascades but not with the 494.4-keV transition. With the new observation of 288.9-keV transitions and their coincidence relationships, the order of the 323.3- and 205.5-keV transitions is fixed compared with the level scheme in Ref. [4]. The DCO ratio analyses and intensity considerations suggest that both the 205.5- and 288.9-keV transitions are likely to have the same multipolarities (mixed $M1/E2$). Here the spin and parity $9/2^-$ are tentatively assigned to the level at 205.5 keV. This level fits well into the overall energy level systematics of $N = 87$ even-Z isotones ^{159}Hf, ^{155}Er, ^{153}Dy, and ^{151}Gd [2,6,11] and is strongly believed to be

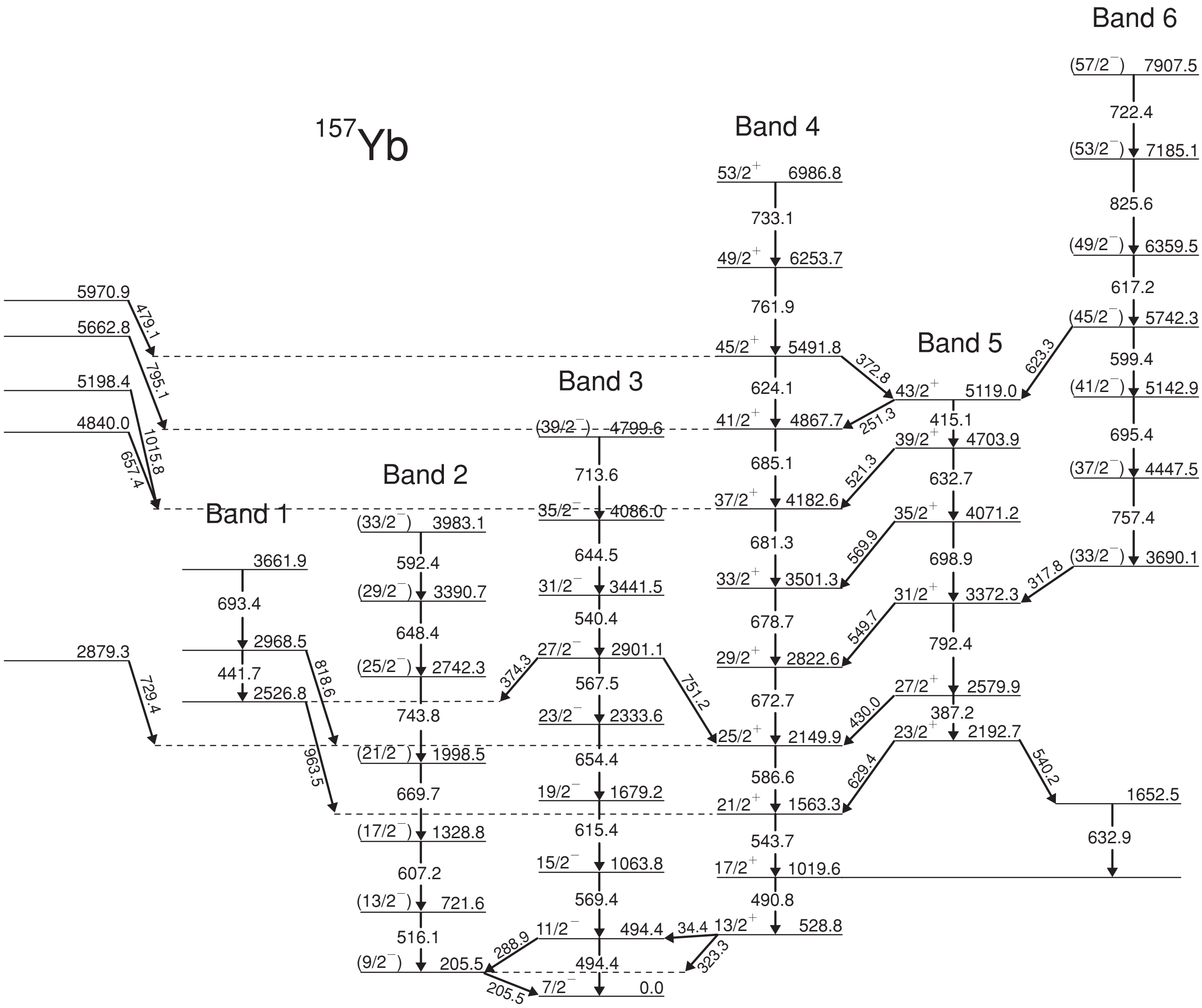

FIG. 3. Partial level scheme of ^{157}Yb. Energies are in keV.

associated with the $\nu h_{9/2}$ configuration, which will be further discussed in Sec. III.

Bands 2 and 3, which are built on the $9/2^-$ and $7/2^-$ states, respectively, are observed for the first time. Figure 1(b) shows γ rays of 569.4, 615.4, 654.4, 567.5, 540.4, 644.5, and 713.6 keV observed in coincidence with the 494.4-keV transition. The DCO ratio analyses suggest that all these γ-ray transitions except the 713.6-keV transition have quadrupole transition characters. The γ-ray decay of 713.6 keV for which the DCO ratio could not be extracted is also assumed to be a stretched $E2$ transition. Furthermore, an interband transition with an energy of 751.2 keV, which links the $27/2^-$ state of band 3 to the $25/2^+$ level of band 4, was observed.

In the present work, the yrast $\nu i_{13/2}$ band (band 4 in Fig. 3) built upon the $13/2^+$ state at 528.8 keV was extended up to the same level at 6986.8 keV as in Ref. [4]. In Ref. [4], no spins and parities were assigned to the levels at 6986.8 and 6253.7 keV. According to the DCO values obtained in the current work, the quadrupole assignments are made for the two transitions of 761.9 and 733.1 keV. A new transition with an energy of 251.3 keV was found to link the $43/2^+$ state of band 5 to the $41/2^+$ level of band 4. The ordering of the 387.2- and 629.4-keV transitions between the $21/2^+$, 1563.3-keV state in band 4 and the $27/2^+$, 2579.9-keV state in band 5 is inverted. As shown in Fig. 1(c), a new sequence of two transitions of 540.2 and 632.9 keV was observed and placed above the level $17/2^+$, 1019.6 keV in band 4. This new transition sequence was found to be in coincidence with the 387.2-keV transition but not with the 629.4-keV transition. The coincidence relationships give support to the placement of the transitions.

Band 6 has been established in Ref. [4], where a transition cascade of 617.2, 599.4, 757.4, 695.4, and 317.8 keV was observed. In that study, no spins and parities were assigned to the states in band 6. The present DCO analyses suggest a pure stretched dipole nature for the 317.8-keV transition and stretched quadrupole characters for the other four transitions. With respect to previous experimental work [4], the sequence of the 617.2-, 599.4-, 757.4-, and 695.4-keV transitions has been modified according to their transition intensities. The observation of one cross-band 623.3-keV transition, as shown in Fig. 1(c), further confirms the validity of the present transition sequence in band 6. In the neighboring isotone ^{155}Er [3,5], a negative-parity band, which has a similar decay cascade to band 6 in ^{157}Yb, has been found in almost the same excitation energy range. Here we tentatively take band 6 to have the same negative-parity starting. The present work added two γ rays of energy of 825.6 and 722.4 keV to the top of band 6.

From a careful analysis of the coincidence data, a sequence of 441.7- and 693.4-keV transitions, which constitutes another previously unobserved band (band 1 in Fig. 3), was found. The ordering of transitions is well defined due to the presence of three crossing-band transitions 374.3, 818.6 and 963.5 keV. Besides the main transition sequences in ^{157}Yb, five new transitions have also been placed in the proposed level scheme on the basis of the coincidence relationships. The intensities of these transitions are too weak to allow multipolarity assignments.

III. DISCUSSION

The new structure information obtained in the present study for ^{157}Yb, together with that known previously for ^{151}Gd, ^{153}Dy, ^{155}Er, and ^{159}Hf, now allows a discussion of the systematics of $N = 87$ even-Z isotones. The systematics of the excitations associated with the $f_{7/2}$, $h_{9/2}$, and $i_{13/2}$ neutron intrinsic states in the $N = 87$ even-Z isotones are shown in Fig. 4. We can see that with increasing proton number, the excitation energies associated with the $\nu h_{9/2}$ and $\nu i_{13/2}$ intrinsic states decrease regularly. In Ref. [12], the onset of nuclear deformation at $N = 88$, $Z \geqslant 64$ in the rare-earth region has been successfully interpreted in terms of the strong attractive interaction between protons and neutrons in the spin-orbit partner orbitals $\pi h_{11/2}$ and $\nu h_{9/2}$ as well as the relatively weaker attractive interaction between the $\pi h_{11/2}$ and $\nu i_{13/2}$ configurations. Thus, with increasing valence proton number, the increase occupation of $\pi h_{11/2}$ orbitals will gradually increase the overall attractive proton-neutron interaction and lower the energies of the $\nu h_{9/2}$ and $\nu i_{13/2}$ orbitals. This very regular trend of the excitation energies related to the $\nu h_{9/2}$ and $\nu i_{13/2}$ intrinsic states observed in the $N = 87$ even-Z isotones presents straightforward evidence of the effects of strong attractive interaction between protons and neutrons.

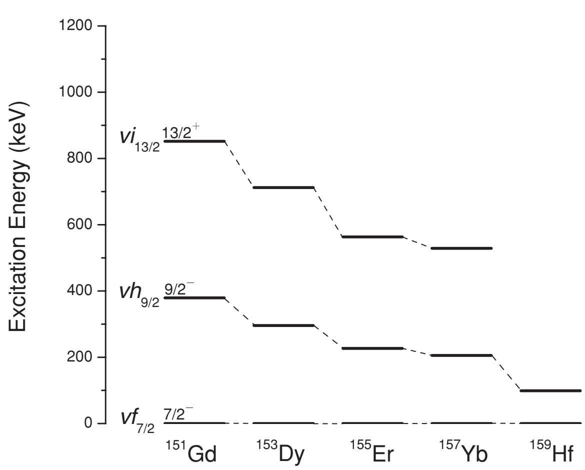

FIG. 4. Systematics of known excitations associated with the $f_{7/2}$, $h_{9/2}$, and $i_{13/2}$ intrinsic states in the $N = 87$ even-Z isotones.

In previous studies [3,5], no collective $\nu f_{7/2}$ band was found in ^{155}Er. The shape coexistence between the noncollective $f_{7/2}$ structure of the ground state and the dominating $i_{13/2}$ character of the rotational band in ^{155}Er has been studied by Beck *et al.* [5] using the deformed Woods-Saxon cranking approximation. Their theoretical calculations for the total energy surfaces in ^{155}Er show that the ground-state $(7/2^-)$ equilibrium deformation corresponds to a nearly spherical shape configuration ($\beta_2 = 0.05$, $\gamma = 60°$), while the calculated equilibrium deformation for the $I^\pi = 13/2^+$ is $\beta_2 = 0.18$, $\gamma = -5°$. In the present work, the new observed $\nu f_{7/2}$ band in ^{157}Yb exhibits the rotation-like spacings, while the $\nu i_{13/2}$ band shows energy spacings following the $E \sim I(I+1)$ rotational law under the spin $I = 25/2^+$ and four unusual consecutive transitions with almost-constant energy occurring above the spin $I = 25/2^+$. The different structure pictures between ^{155}Er and ^{157}Yb imply that the underlying cause of shape coexistence in these isotones may be different. Here, to get a further understanding of the underlying mechanism of the shape coexistence and shape evolution in these isotones, cranked Woods-Saxon-Strutinsky calculations have been performed by means of TRS methods in a three-dimensional deformation space (β_2, γ, β_4 [13,14].

The TRS theoretical values for $I^\pi = 7/2^-$ and $I^\pi = 13/2^+$ states in ^{157}Yb are illustrated in Fig. 5, which shows that the ground state $7/2^-$ of ^{157}Yb has a prolate deformation with a near-zero γ deformation value ($\beta_2 = 0.16$, $\gamma \approx 0°$), which gives rise to the collective rotational $\nu f_{7/2}$ band observed in ^{157}Yb. The calculated equilibrium deformation for the $I^\pi = 13/2^+$ state is $\beta_2 = 0.17$, $\gamma = 21°$. These results suggest that the low-lying $I^\pi = 13/2^+$ state in ^{157}Yb is triaxial and a marked difference in γ deformation between the ground state $7/2^-$ and the $I^\pi = 13/2^+$ state. The experimental $B(M1)/B(E2)$ ratios are deduced for bands 4 and 5. The

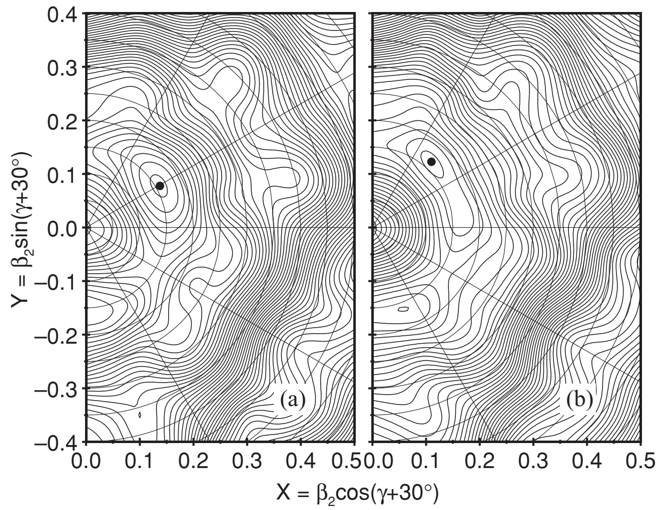

FIG. 5. TRS calculations for ^{157}Yb: (a) parity and signature $(\pi, \alpha) = (-, -1/2)$ at spin $I = 7/2$ and (b) $(\pi, \alpha) = (+, +1/2)$ at spin $I = 13/2$. The energy contours are at 200-keV intervals.

experimental values average around 0.44 $\mu_N^2/(eb)^2$, which is an order of magnitude smaller than what can be expected from the $\nu i_{13/2}$ orbital using the semiclassical model of Dönau and Frauendorf [15,16]. This disagreement indicates that band 5 is not the signature partner of band 4. In Ref. [3], the irregular positive-parity and irregular negative-parity sequences in ^{155}Er have been suggested to have structures dominated by the oblate configurations of $\nu(f_{7/2}{}^3)(h_{9/2})(i_{13/2})$ and $\nu(f_{7/2}{}^2)(h_{9/2})(i_{13/2}{}^2)$, respectively. These two sequences in ^{155}Er are very similar to the sequences of bands 5 and 6 in ^{157}Yb. This striking similarity and the irregular $E2$ transition sequences of bands 5 and 6 in ^{157}Yb indicate that bands 5 and 6 most likely have the same oblate configurations as ^{155}Er. Thus, the excitations observed in the ^{157}Yb nucleus provide a good picture of shape coexistence of three distinct shapes: prolate, triaxial, and oblate.

Furthermore, TRS calculations show that the low-lying states of the transitional nucleus ^{157}Yb have rather soft potential-energy surfaces and the nuclear shapes are susceptible to the increased angular momentum, especially the alignment of a high-j intruder nucleon pair. Experimental alignments as a function of rotational frequency for bands 2, 3, and 4 in ^{157}Yb, together with that for the yrast band in ^{156}Yb, are plotted in Fig. 6(a).

In Fig. 6(a), bands 2 and 3 show a similar sharp backbend around rotational frequencies of 0.30–0.33 MeV. In Ref. [17], the first band crossing occurring in the neighboring ^{156}Yb nucleus was ascribed to the alignment of a pair of $h_{11/2}$ protons. The similar crossing frequencies between bands 2 and 3 of ^{157}Yb and the yrast band of ^{156}Yb indicate that the $h_{11/2}$ proton-pair alignment may also be responsible for the band crossings observed in bands 2 and 3 of ^{157}Yb. In Fig. 6(b), we compare the experimental moments of inertia (MOE) with our theoretical results for band 3 of ^{157}Yb. The overall agreement between the experimental data and theoretical results is good. The calculations show that the first band crossing in the $\nu f_{7/2}$ band of ^{157}Yb caused by an $h_{11/2}$ proton-pair alignment occurs around a rotational frequency of 0.30 MeV, which reproduces well the experimental value. The small variation in the crossing frequencies for the $h_{11/2}$ proton-pair alignments observed in bands 2 and 3 of ^{157}Yb may be due to the small variation in their deformation. According to the TRS calculations, with the first $h_{11/2}$ proton-pair alignment, band 3 undergoes a shape evolution: from prolate ($\gamma \approx 0^\circ$) to triaxial ($\gamma \approx -39^\circ$). An $i_{13/2}$ neutron-pair alignment is predicted to occur around a rotational frequency of 0.38 MeV. After this alignment, the shape of band 3 will become oblate.

In contrast to the sharp backbends observed in bands 2 and 3 of ^{157}Yb, band 4 shows a long upbend around a rotational frequency of 0.34 MeV. As discussed, the low-lying states of band 4 are interpreted as having a triaxial shape ($\beta_2 = 0.17$, $\gamma = 21^\circ$). Theoretical calculations performed with the cranked Woods-Saxon model by Appelbe *et al.* [18] have suggested that the proton $h_{11/2}$ paired crossing, at moderate deformations, is sensitive to the γ degree of freedom and is expected to become quenched for large positive γ values. In contrast, the $h_{11/2}$ paired proton crossing is expected if the γ value is negative [18]. Our TRS calculations, which are shown in Fig. 7, indicate that with increasing

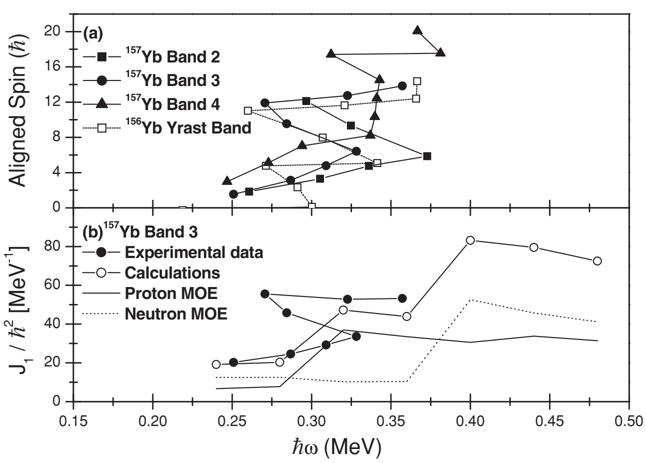

FIG. 6. (a) Aligned spins as a function of the rotational frequency for bands 2, 3, and 4 in ^{157}Yb and the yrast band in ^{156}Yb. Harris parameters of $J_0 = 10.0\hbar^2$/MeV and $J_1 = 50.0\hbar^4$/MeV^3 have been assumed. (b) Experimental and calculated moments of inertia for band 3 of ^{157}Yb. Partial contributions to moments of inertia from protons (solid line) and neutrons (dashed line) are also shown.

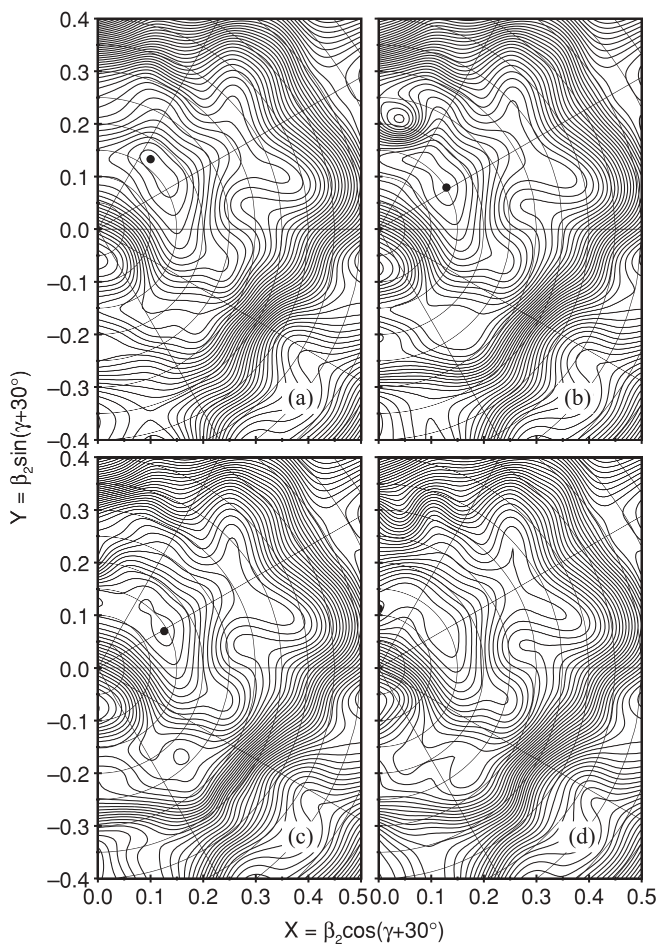

FIG. 7. TRS calculations for ^{157}Yb based on the $(\pi, \alpha) = (+, +1/2)$ configuration (corresponding to band 4) at (a) $\hbar\omega = 0.33$ MeV, (b) $\hbar\omega = 0.35$ MeV, (c) $\hbar\omega = 0.36$ MeV, and (d) $\hbar\omega = 0.37$ MeV. The energy contours are at 200-keV intervals.

rotational frequency, the large positive γ deformation value of band 4 will decrease and finally become a small negative value around the rotational frequency of 0.35–0.36 MeV. According to the TRS calculations, the $h_{11/2}$ proton-pair alignment will occur in the vicinity of a rotational frequency of 0.35-0.36 MeV, which is almost simultaneous with the first $h_{9/2}$ neutron-pair alignment. It is in good agreement with the experimental values. Thus, the long upbend observed in band 4 of ^{157}Yb can be ascribed to the nearly simultaneous alignments of a pair of $h_{11/2}$ protons and a pair of $h_{9/2}$ neutrons. Similar to band 3, after these two alignments, the shape of band 4 will arrive around $\gamma = 60^\circ$ and band termination occurs, which has been observed in the neighboring ^{155}Er isotone [3,5].

In Ref. [4], the behavior of the high-lying part of band 4 was explained in terms of the quasivibrational excitations rather than proton and neutron alignments because four consecutive transitions with almost-constant energy were observed in band 4 and the corresponding alignments occur at higher frequencies in neighboring nuclei $^{156-159}$Er [19,20] and $^{160-162}$Yb [21]. However, the rotational frequency at which the $h_{11/2}$ proton pair aligns has been found to increase with increasing nuclear quadrupole deformation [19]. With more neutron numbers, the $^{156-159}$Er (N = 88–91) and $^{160-162}$Yb (N = 90–92) nuclei were found to have larger quadrupole deformations than the ^{157}Yb (N = 87) nucleus. In addition, theoretical calculations by Leander *et al.* [22] as well as our TRS calculations showed that the γ deformations for these nuclei have very small values around the band crossing region. Therefore, compared with ^{157}Yb, the higher crossing frequencies observed in $^{156-159}$Er and $^{160-162}$Yb could result from their larger quadrupole deformations. Furthermore, similar vibration-like excitations observed in the neighboring ^{158}Yb nucleus at spin = $26^+ - 36^+$ has been interpreted in terms of the particle-alignments in Ref. [23]. Based on the systematics and theoretical calculations, we believe that the behavior of high-lying part of band 4 can be attributed to the nearly simultaneous alignments of an $h_{11/2}$ proton pair and an $h_{9/2}$ neutron pair.

IV. SUMMARY

High-spin states in ^{157}Yb have been studied via ^{144}Sm(^{16}O, $3n$)^{157}Yb fusion-evaporation reaction at a beam energy of 85 MeV. Two collective bands built on the $\nu f_{7/2}$ and $\nu h_{9/2}$ intrinsic states, respectively, were observed for the first time. Experimental observations are discussed in terms of TRS methods and compared with similar structures observed in the neighboring N = 87 isotones. It is proposed that the low-lying part of the new observed $\nu f_{7/2}$ band in ^{157}Yb has a prolate deformation with a near-zero γ deformation value, while the low-lying part of $\nu i_{13/2}$ band is associated with a triaxial shape with a large positive γ deformation value and bands 5 and 6 have oblate deformations. These structural characters observed in ^{157}Yb constitute good evidence for shape coexistence of three distinct shapes: prolate, triaxial, and oblate. The underlying mechanism of the behaviors of the high-lying part of $\nu i_{13/2}$ band in ^{157}Yb has been reinterpreted as the nearly simultaneous alignments of an $h_{11/2}$ proton pair and an $h_{9/2}$ neutron pair. At higher spins, both the $\nu f_{7/2}$ band and $\nu i_{13/2}$ band in ^{157}Yb undergo a shape evolution with sizable alignments occurring.

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