Rotational band properties in ^{165}Er

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High-spin states in ^{165}Er have been studied experimentally using the ^{160}Gd(^{9}Be, $4n$) reaction at beam energies of 42 and 45 MeV. The previously known bands based on the $5/2^+[642]$, $5/2^-[523]$, and $11/2^-[505]$ configurations are extended to $(49/2^+)$, $(45/2^-)$, and $(31/2^-)$ states, respectively. The rotational bands in ^{165}Er generally show gradual alignment processes, indicating strong band interactions associated with the $i_{13/2}$ neutron alignments. The band properties are compared with those in the neighboring nuclei and discussed within the framework of the cranked shell model.

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The Er nuclei near the stability line are located in a well-deformed region, and rotational bands based on the configurations of the $i_{13/2}$, $h_{9/2}$, $f_{7/2}$, and $h_{11/2}$ parentages have been observed experimentally [1,2]. These bands exhibit interesting alignment processes, which can be well explained by the cranked shell model [3] and the particle-rotor model [4]. The interaction strength between the two crossing bands in Dy, Er, and Yb isotopes is predicted to be an oscillating function of the position of the Fermi level in the $i_{13/2}$ subshell [3,4]. Nuclei with neutron number around 98 are found to have a strong band interaction, which results in a gradual alignment process [5,6]. In the present work, we aim at extending the level scheme of the $N = 97$ nucleus ^{165}Er to high-spin states and studying the behavior of the band crossings. Partial results of this work were reported previously [7].

High-spin states in ^{165}Er were populated via the ^{160}Gd(^{9}Be, $4n$)^{165}Er reaction. The ^{9}Be beam was provided by the HI-13 Tandem Accelerator at China Institute of Atomic Energy. The target was a self-supporting ^{160}Gd (isotopically enriched to 98.1%) metallic foil with a thickness of 2.1 mg/cm^2. An array consisting of 11 HPGe detectors with BGO anti-Compton shields and two low-energy planar HPGe detectors was employed to measure the in-beam γ rays. The 11 HPGe detectors had an efficiency of 30% each, and the planar detectors had 20% relative to 3 in. $\times$ 3 in. NaI. The detectors were calibrated using standard ^{152}Eu and ^{133}Ba sources. The energy resolution of the HPGe detectors was 2.0 $\sim$ 2.8 keV for the 1332.5-keV γ ray. The γ-γ coincidence measurements were performed at beam energies of 42 and 45 MeV. A total of 80×10^6 coincidence events requiring two or more detectors fired within 200 ns were collected. After gain matching, the coincidence data were sorted into a $4k \times 4k$ symmetric matrix and a DCO matrix for off-line analysis.

In the previous work, low-lying states in ^{165}Er were well established from the decay studies of ^{165}Tm and the in-beam experiments [8,9]. The spins and parities for the known low-lying states were adopted from the previous work [8,9], and these values were used as the reference for spin and parity assignments to high-spin states. From the analysis of γ -γ coincidence relationships, a level scheme for ^{165}Er was built and presented in Fig. 1. The low-lying transitions identified in the decay work are also shown in Fig. 1 for completeness.

Band 1 was proposed to be associated with the $5/2^+[642]$ configuration [9]. The $5/2^+$ and $7/2^+$ band-head energies were determined to be 47.2 and 62.9 keV, respectively [9]. In the present work, the $\alpha = +1/2$ sequence is extended from $I^\pi = 29/2^+$ to $(49/2^+)$, and for the $\alpha = -1/2$ sequence from $23/2^+$ to $(43/2^+)$. Gated spectra demonstrating the existence and extension of band 1 are shown in Fig. 2. It should be noted that the previously observed 468.7-keV ($29/2^+ \rightarrow 25/2^+$) transition is replaced by the 456.9-keV transition [9]. The 134.4-, 214.6-, 310.0-, and 417.0-keV transitions from the unfavored states to the favored states were observed. As shown in Fig. 2, the 456.9-keV transition shows evident coincidences with the 401.9- and 205.2-keV transitions in the $\alpha = -1/2$ branch, indicating the existence of low-energy transitions from the favored states to the unfavored states. However, these low-energy linking transitions were not identified in the present work.

Band 2 is the ground-state band built on the $5/2^-[523]$ configuration [9]. We extend this band from $11/2^-$ to $(43/2^-)$. The 77.6-, 98.5-, and 120.1-keV $M1$ transitions at the bottom of band 2 were identified previously [9], and they were placed into the level scheme for completeness. No other $M1$ transition linking the two signature branches is observed in this work. Nine interband $E1$ transitions are observed. The 197.8-, 357.5-, 507.4-, 643.5-, and 761.0-keV transitions feed the $\alpha = +1/2$ levels in band 1 from the $\alpha = -1/2$ levels in band 2, and the 267.6-, 399.3-, 501.1-, and 567.8-keV transitions link the $\alpha = +1/2$ sequence in band 2 and the $\alpha = -1/2$ sequence in band 1.

Band 3 shows a character typical for a coupled band. This band is built on the 551.0-keV $11/2^-[505]$ isomer [9]. We extend band 3 from $I^\pi = (17/2^-)$ to $(31/2^-)$.

The standard plots of the quasiparticle aligned angular momenta (i) as a function of rotational frequency ($\hbar\omega$) are shown in Fig. 3. The Harris parameters used are

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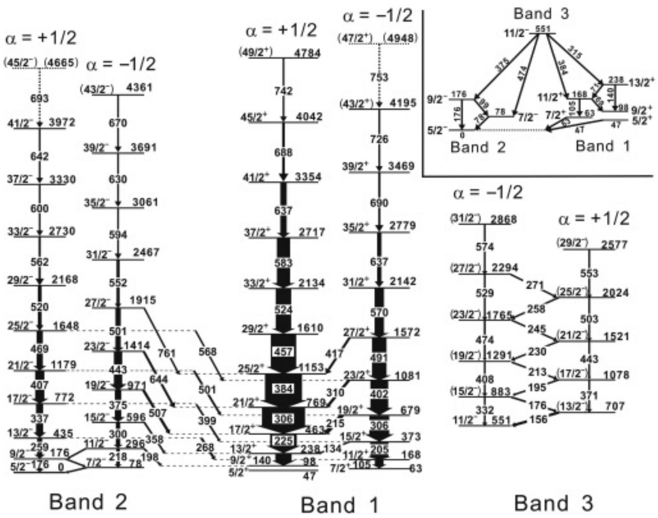

FIG. 1. Level scheme of ^{165}Er deduced from the present work. The low-lying levels and transitions identified in the decay work [8] are shown in the top right corner.

$J_0 = 30\hbar^2\text{MeV}^{-1}$ and $J_1 = 100\hbar^4\text{MeV}^{-3}$, which give a nearly constant alignment in the yrast band of ^{164}Er before the band crossing. For comparison, the alignment of the yrast band in ^{164}Er is also shown in Fig. 3.

To have a deeper understanding of the band structures in ^{165}Er, we have performed cranked shell model (CSM) calculations by means of the total Routhian surface (TRS) method in the three-dimensional β_2, β_4, and γ deformation space [10]. The detailed description of the calculation was presented in the publication [11]. At a given frequency, the deformation of a state is determined by minimizing the calculated TRS. Theoretical predictions of the nuclear deformation for various quasiparticle configurations are obtained. At a rotational frequency of 0.0 MeV, the ground-state configuration $5/2^-[523]$ is predicted to have a prolate deformation with $\beta_2 = 0.26$. The deformation corresponding to the ground-state band is used to calculate the quasineutron Routhians within the fixed-deformation cranked shell model. The calculated

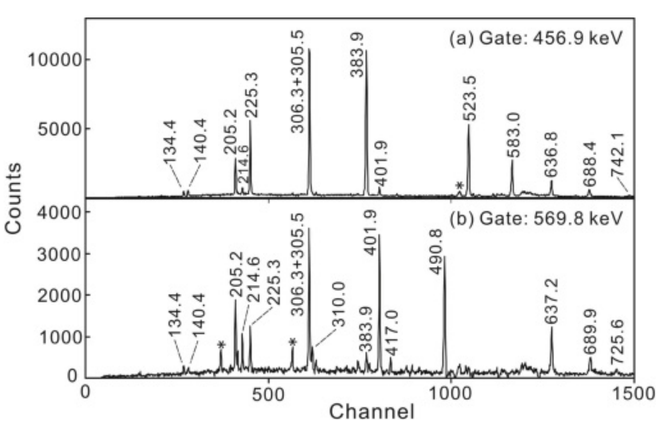

FIG. 2. The γ-ray spectra gated on the (a) 456.9- and (b) 569.8-keV transitions. They are representative for band 1. The asterisks indicate the contaminations mainly from ^{164}Er and ^{162}Dy.

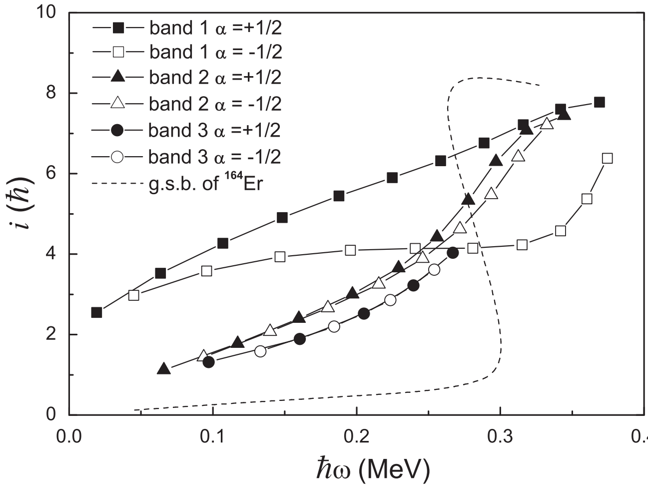

FIG. 3. Extracted alignments for bands in ^{165}Er. The labels in the legends indicate the bands as they are labeled in Fig. 1. The alignment for the yrast band of ^{164}Er is also shown for comparison.

quasineutron Routhians (e') for ^{165}Er are presented in Fig. 4.

The two signature branches of band 1 show a rather large initial alignment of about 3.0 $\hbar$ as shown in Fig. 3. The alignments were deduced by assuming a band-head K value of 2.5, since the theoretical calculation suggests a main component of the $5/2^+[642]$ orbit in the configuration. In this band, the quasineutron orbit A or B is occupied depending on its signature, and the first band crossing should be caused by the BC (AD) alignment. As shown in Fig. 3, the band crossing of the $\alpha = -1/2$ signature branch is apparently delayed with respect to that of the yrast band of ^{164}Er. The $\alpha = -1/2$ signature branch begins an up bending at $\hbar\omega \approx 0.35$ MeV, and the band crossing is not yet completed at the last transition observed. This band crossing is interpreted as the AD alignment. The calculation predicts that the AD crossing

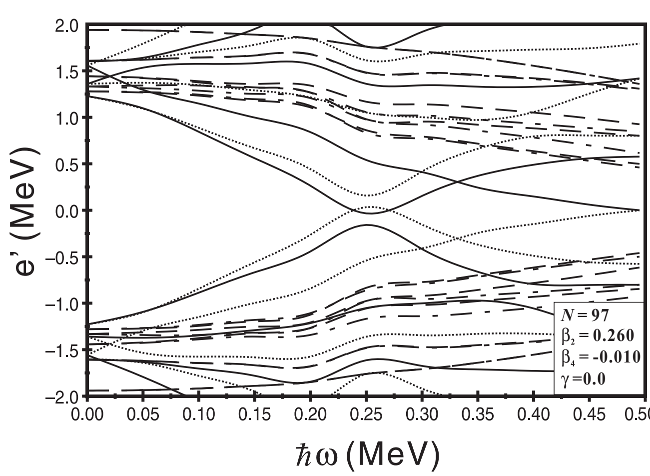

FIG. 4. The calculated quasineutron Routhians (e') as a function of rotational frequency ($\hbar\omega$) in ^{165}Er. The parity and signature (π, α) of the Routhians are represented as follows: $(+, +1/2)$ solid lines, $(+, -1/2)$ dotted lines, $(-, +1/2)$ dash-dotted lines, and $(-, -1/2)$ dashed lines.

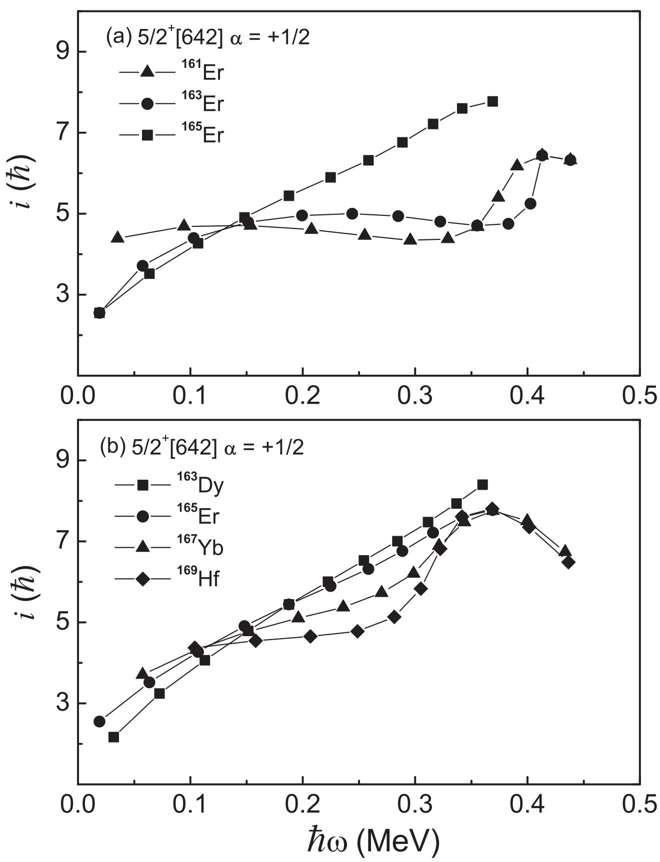

FIG. 5. Comparison of the alignments for the $\alpha = +1/2$ branches of the $5/2^+[642]$ bands in (a) the isotopes ^{161,163,165}Er and (b) the isotones ^{163}Dy, ^{165}Er, ^{167}Yb, and ^{169}Hf.

occurs at $\hbar\omega \approx 0.38$ MeV. The $\alpha = +1/2$ signature branch experiences a gradual gain in alignment through the frequency range observed, which indicates a strong band interaction. This smooth gain in alignment should be resulting from the BC alignment. However, the calculation does not give a defined BC crossing.

In order to understand the behavior of the BC crossing, Fig. 5 presents the systematics of alignments for the $\alpha = +1/2$ signature branches of the $5/2^+[642]$ bands in the isotopes and isotones of ^{165}Er. As shown in Fig. 5(a), the alignment of the $5/2^+[642]$ band in ^{165}Er shows a completely different behavior from those in ^{161}Er and ^{163}Er. In the lighter isotopes, obvious up bendings can be seen, which indicates a weak band interaction strength. Inspecting Fig. 5(b), we can find that the interaction strength becomes stronger from ^{169}Hf to ^{163}Dy while decreasing the proton number. In the isotones, the interaction strength might be sensitive to the position of the neutron Fermi surface and the position of the available low-Ω $i_{13/2}$ quasineutron orbits [12], which are deformation dependent. Therefore, the trend of the interaction strengths associated with the BC alignments in the $N = 97$ isotones could be explained by the gradual increase in quadrupole deformation with decreasing the proton number [12].

As shown in Fig. 3, the two signature branches of band 1 show different behaviors in the alignment processes. In contrast, the two signatures of the same configuration in the lighter Er isotopes behave similarly [1,2]. Such a feature in ^{165}Er was also observed in the $N = 97$ isotone ^{167}Yb [5]. This phenomenon was suggested to be connected to the mixture of the low-Ω $i_{13/2}$ orbits into the configuration [5]. The mixing of the low-Ω components into the $(+, +1/2)$ quasineutron orbits is enhanced for $N \geqslant 97$ [5]. As a consequence, the $(+, +1/2)_2$ orbit is depressed with respect to the $(+, -1/2)_2$ orbit, which is supported by the calculation shown in Fig. 4.

In band 2, the two signature branches are associated with the E and F orbits originating from the $5/2^-[523]$ Nilsson state. As illustrated in Fig. 3, band 2 shows a small initial alignment of about $1.0\hbar$, which is consistent with that expected for the $5/2^-[523]$ configuration. Figure 3 displays that the two signature branches behave similarly, and the band crossing occurs at $\hbar\omega \approx 0.28$ MeV. In this negative-parity band, the band crossing should be caused by the AB alignment of the $i_{13/2}$ neutrons. The band-crossing frequency is about the same as that of the yrast band in ^{164}Er, but it is apparently larger than those of the $5/2^-[523]$ bands in the lighter Er isotopes [1,2]. In the $N = 97$ isotone ^{167}Yb, it is also observed that the band crossing of the $5/2^-[523]$ band is delayed with respect to those in the lighter Yb isotopes [5,6]. For the nuclei with neutron number $N \geqslant 97$, the neutron Fermi level is away from the low-Ω $i_{13/2}$ orbits. Since the neutron Fermi level is above the low-Ω $i_{13/2}$ neutron orbits, an increased Fermi level corresponds to an increased quasineutron energy, resulting in a delayed band crossing [6].

As shown in Fig. 3, the two signature branches in band 3 show almost identical behaviors, and they have not gained significant alignments up to the band-crossing frequency of the yrast band in ^{164}Er. We would expect that the alignment process of band 3 is likely similar to that of the $5/2^-[523]$ band, for which the band crossing occurs at $\hbar\omega \approx 0.28$ MeV as that of the yrast band in ^{164}Er. The band crossing in band 3 should be caused by the neutron AB alignment.

In summary, the well deformed nucleus ^{165}Er was produced in the bombardment of a ^{160}Gd target with ^{9}Be projectiles. Based on the γ-γ coincidence measurement, the $5/2^+[642]$, $5/2^-[523]$, and $11/2^-[505]$ bands have been extended to the $(49/2^+)$, $(45/2^-)$, and $(31/2^-)$ states, respectively. The $\alpha = +1/2$ signature branch of the $5/2^+[642]$ band shows a gradual alignment process, while the $\alpha = -1/2$ one starts an up bending at $\hbar\omega \approx 0.35$ MeV. This difference has been attributed to the enhancement of the mixing of the low-Ω orbits into the $\alpha = +1/2$ quasineutron orbits. The $5/2^-[523]$ band experiences a band crossing at $\hbar\omega \approx 0.28$ MeV, which is associated with the neutron AB alignment. The band crossing in the $5/2^-[523]$ band of ^{165}Er is delayed with respect to those in the lighter Er isotopes, resulting from an increased Fermi level in the $i_{13/2}$ subshell while increasing the neutron number. The $11/2^-[505]$ band shows a gradual alignment process up to the highest spins observed experimentally.

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