Rotational bands in neutron-rich ^{169,171,172}Er

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The neutron-rich ^{169,171,172}Er nuclei were populated by few-neutron transfer reactions between ^{170}Er and ^{238}U at a near barrier energy. The spectroscopy of these Er isotopes was studied using prompt γ rays correlated with delayed transitions or events involving at least three prompt transitions. The ground-state band of ^{172}Er was populated up to spin 22^+ at an excitation energy of 5528 keV. Rotational bands built on the $1/2^-[521]$, $5/2^-[512]$, and $7/2^+[633]$ neutron configurations in ^{169,171}Er were extended to substantially higher spins than previously known. The signature splitting observed in these rotational bands is addressed within the framework of the particle-rotor model in terms of triaxiality and Coriolis attenuation. The signature inversion observed in the $5/2^-[512]$ band is well reproduced by including the triaxial degree of freedom in the calculation. Attenuating the Coriolis interaction in the calculation is found to be necessary to reproduce the signature splitting observed in the $7/2^+[633]$ band. A similar Coriolis attenuation also is needed to account for the signature splitting as well as the $B(M1)/B(E2)$ ratios in the $7/2^+[633]$ ground-state band in the neighboring $N=99$ isotones, ^{167}Er and ^{169}Yb.

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I. INTRODUCTION

Rotational motion and its interplay with single-particle and pairing degrees of freedom has been studied mostly with heavy-ion induced fusion-evaporation reactions for nuclei in the rare-earth region. However, this technique limits such studies to neutron-deficient nuclei, and far less attention has been paid to heavy neutron-rich nuclei near or away from the valley of β stability. Deep-inelastic reactions using either thick [1] or thin [2] targets have been applied to the study of neutron-rich nuclei, where the interplay between rotational motion and single-particle degrees of freedom can be explored in an environment of weaker pairing [3]. For example, the pairing gap parameter for neutrons in ^{170}Er drops below 60% of that for ^{156}Er. The present work is part of our efforts to study neutron-rich nuclei using quasielastic, few-nucleon transfer reactions. Results for the neutron-rich nucleus ^{166}Dy obtained from reactions between ^{164}Dy and ^{118}Sn at near barrier energy have been published earlier [4]. Results on neutron-rich ^{169,171,172}Er obtained by reactions between ^{170}Er targets and ^{238}U projectiles at near barrier energy are presented here.

Er isotopes on the neutron-rich side of the valley of β stability begin to fill orbits beyond the deformed subshell closure at $N=98$. A unique feature for these neutron-rich nuclei is that the kinematic moments of inertia for the yrast states of adjacent even-A isotopes closely parallel each other with variations of no more than 20% up to rotational frequencies of ≈ 350 keV for $A \geqslant 168$, as shown in Fig. 1. The lack of major structural changes in the even Er isotopes makes the odd-A Er neighbors ideally suited to study the interplay between rotational motion and single-particle degrees of freedom up to a moderately high spin within the framework of the particle-rotor model. In particular, signature splitting in the rotational bands of ^{169,171}Er is addressed here in terms of triaxiality and Coriolis attenuation.

II. EXPERIMENT

The experiment was performed by bombarding ^{170}Er targets, with thickness 320 to 540 μg/cm^2, with a 1358 MeV

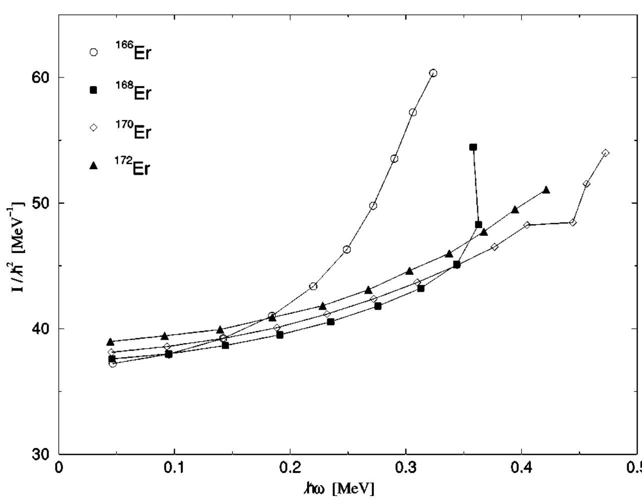

FIG. 1. Kinematic moment of inertia as a function of rotational frequency for the ground-state bands of ^{166,168,170,172}Er; the 611.7 and 646.4 keV γ rays were assigned, for the first time, to the $18^+ \rightarrow 16^+$ and $20^+ \rightarrow 18^+$ transitions in ^{166}Er from the present work. The ^{172}Er data beyond the spin 4^+ state are the result of this work.

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^{238}U beam provided by the ATLAS facility at Argonne National Laboratory. The projectile and bombarding energy were chosen to maximize inelastic excitation as well as to provide favorable Q-matching conditions for nucleon-transfer reactions populating neutron-rich Er-like nuclei. The deexcitation γ rays were measured with the 100 Compton-suppressed Ge detectors of Gammasphere [5] in coincidence with both the scattered and the recoiling particles. The scattering angles for both recoiling reaction products and their time-of-flight difference were measured by the highly segmented parallel-plate avalanche counter array, CHICO [6]. The latter covers polar angles from 20° to 85° and 95° to 168° relative to the beam axis and azimuthal angles totaling 280° out of 360°. A total of 2.4×10^8 events with a minimum of two coincident γ rays were collected during a three-day run with an average beam intensity of about 0.5 particle nA. About 36% of these events had a coincident γ-ray fold of three or more.

Quasi-two-body kinematics reconstruction was applied to every event using the measured angles of both recoiling reaction products and their time-of-flight difference. An angular resolution of $\approx 1°$ in θ and 4.6° in ϕ, together with a time resolution of ≈ 500 ps, results in a mass resolution, $\Delta m/m$, of about 5%, a value similar to that obtained in other experiments using CHICO [7–11]. This mass resolution is sufficient to distinguish the projectilelike from the targetlike recoiling reaction products. Such particle identification, together with the deduced velocity vector, allows the appropriate Doppler-shift corrections to be applied to the detected γ rays. The energy resolution for the total Doppler-corrected γ-ray spectrum was about 1.3% for a 1 MeV γ ray using the centroid angle of the individual Ge detectors. This resolution improved to 1.1% by utilizing the side-channel energy of individual Ge detectors to better locate the interaction point in the crystals [12].

III. RESULTS AND DISCUSSION

Both one and two-neutron transfer reactions, identified by known γ-ray transitions, were populated in addition to the inelastic channel. The population of rotational bands and isomers following inelastic excitations is discussed in our earlier publications [13,14]. The rotational bands of the nuclei of interest were established according to the observed γ-ray energies and intensities using events with at least three prompt γ rays or events where prompt γ rays were correlated with delayed transitions. The latter is a unique capability of this experimental setup. Since both outgoing particles were stopped by the cathodes of CHICO, γ rays from long-lived isomers experience no Doppler shift. Note that the detection efficiency for the delayed γ rays emitted by the stopped recoils is close to that for the prompt transitions since no heavy metal shield was used for the BGO component of Gammasphere for this experimental setup. An example is shown in Fig. 2, where the sharp peaks are recognized as delayed transitions in a spectrum obtained by requiring the arrival time of the γ rays to be at least 80 ns after the prompt coincident time.

Examples of correlations between prompt γ rays and between prompt and delayed γ transitions are illustrated in the two panels of Fig. 3 for the case of ^{169}Er. Based on the observed coincidence correlations, the rotational bands built on the $1/2^-[521]$ and $7/2^+[633]$ neutron configurations in ^{169}Er were extended to significantly higher spin than previously known [15]. The resulting level scheme is given in Fig. 4. The $1/2^-[521]$ band was extended from spin $11/2^-$ at 475 keV to spin $41/2^-$ at 4547 keV and the $7/2^+[633]$ band reached from spin $13/2^+$ at 526 keV to spin $29/2^+$ at 2148 keV. The level scheme for ^{171}Er is introduced in Fig. 5, where the $5/2^-[512]$ band was extended from spin $11/2^-$ at 304 keV to spin $43/2^-$ at 4936 keV, while the $1/2^-[521]$ band was traced from spin $11/2^-$ at 671 keV to spin $45/2^-$ at 5607 keV. The ground-state band of ^{172}Er was delineated from spin 4^+ at 255 keV to spin 22^+ at 5528 keV, as is shown in Fig. 6. The respective populations of these rotational bands relative to that of the ground-state band of the target nucleus ^{170}Er are listed in Table I. The strength varies between 0.21% and 1.4% for the one-neutron transfer channels and is about 1.0% for the two-neutron transfer reaction leading to ^{172}Er.

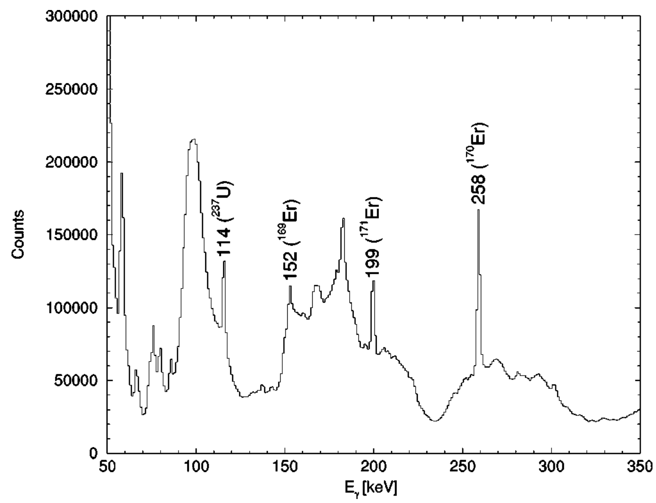

FIG. 2. Delayed γ-ray spectrum for the reaction between ^{170}Er and ^{238}U at $E_{\mathrm{c.m.}}=566$ MeV. The peaks labeled by their γ-ray energies are the known transitions from the nucleus specified under parentheses. No Doppler-shift correction was applied to these spectra.

The extension of rotational bands to significantly higher spins in these neutron-rich Er nuclei, particularly in the odd-A isotopes, provides an opportunity to study the interplay between rotational motion and single-particle degrees of freedom in an environment characterized by weaker pairing. Such studies can be carried out using the particle-rotor model [16–18]. They are applied here to the rotational bands associated with the $1/2^-[521]$, $5/2^-[512]$, and $7/2^+[633]$ neutron configurations in ^{169,171}Er, where the kinematic moments of inertia are nearly constant as a function of rotational frequency (variations are no more than 20% from the average as shown in Fig. 7). The particular emphasis is to discuss the dependence of the observed signature splitting in terms of triaxiality and Coriolis attenuation.

The particle-rotor model calculations were carried out using the triaxial rotor plus particle code described in Ref. [18].

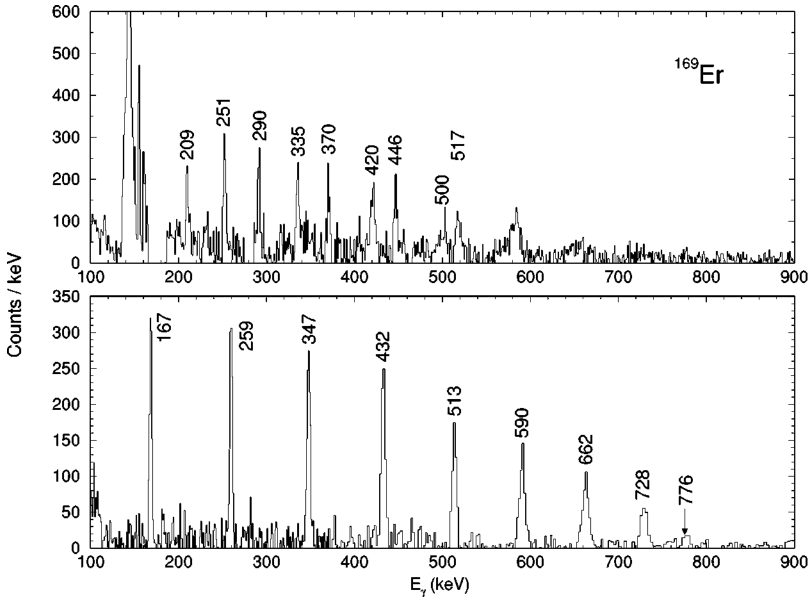

FIG. 3. Doppler-shift corrected prompt γ-ray spectrum in coincidence with the delayed 152 keV transition (top) and coincidence spectrum derived from multiple sets of double gates placed on prompt γ rays in ^{169}Er (bottom).

The default values were used for all the model parameters except for the magnitude (β) and asymmetry (γ) of a quadrupole deformation. The values for the pairing gap together with both β and γ are listed in Table II. Use of the rigid triaxial rotor model is not meant to imply the rigid triaxial shape for these nuclei, rather it provides a convenient way to incorporate the first-order effect of non-zero average triaxiality. The comparison between the results of these calculations and the experimental values for the signature splitting as a function of spin are presented in Fig. 8. The large signature splitting observed for the $1/2^-[521]$ band in ^{171}Er is well reproduced with either an axially symmetric or a triaxial quadrupole shape; the difference between those two approaches is small. A similar conclusion is reached for the $1/2^-[521]$ band in ^{169}Er. In contrast, the calculation is very

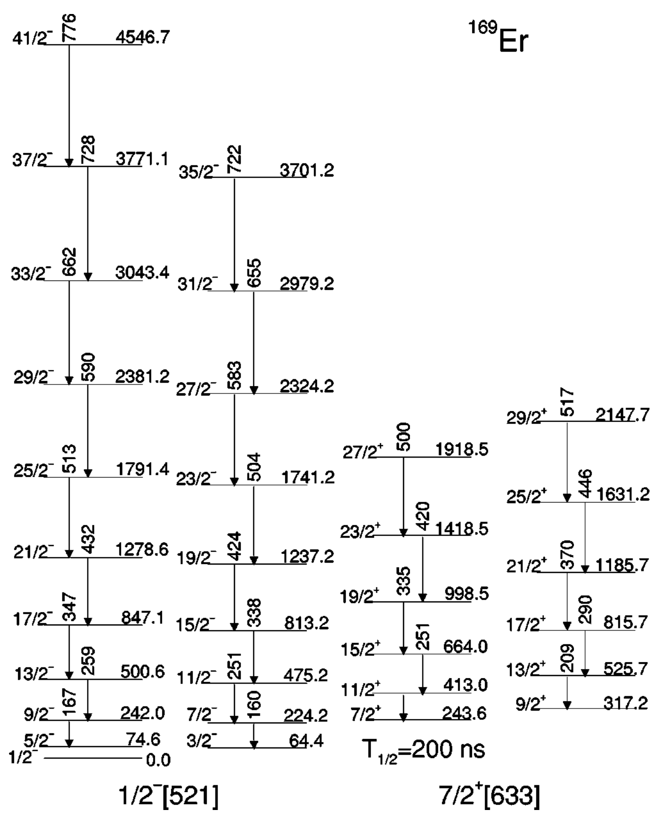

FIG. 4. Partial level scheme of ^{169}Er with energies labeled in keV. The uncertainty on the transition energies is $\approx$1 keV.

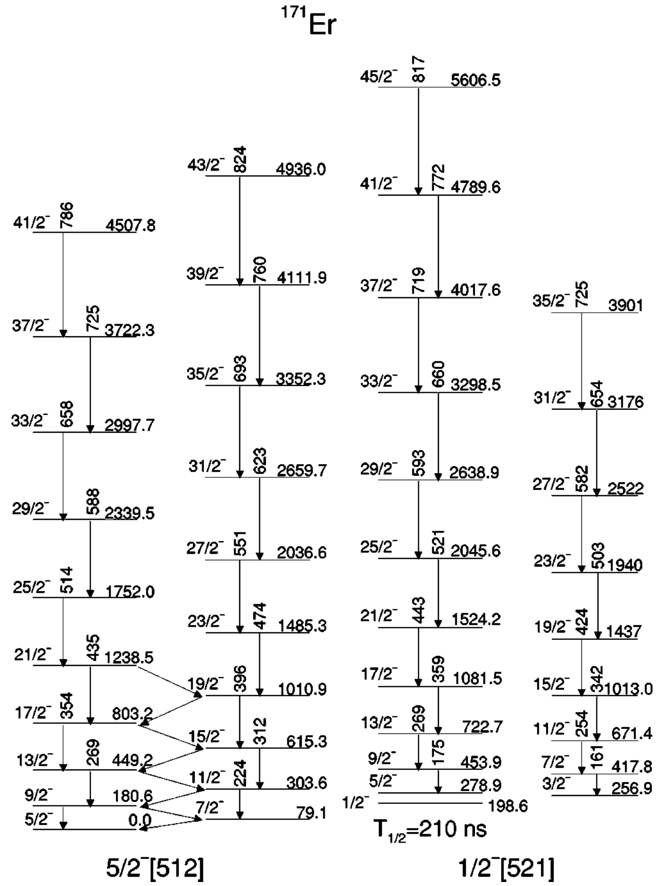

FIG. 5. Partial level scheme of ^{171}Er with energies labeled in keV. The uncertainty on the transition energies is $\approx$1 keV.

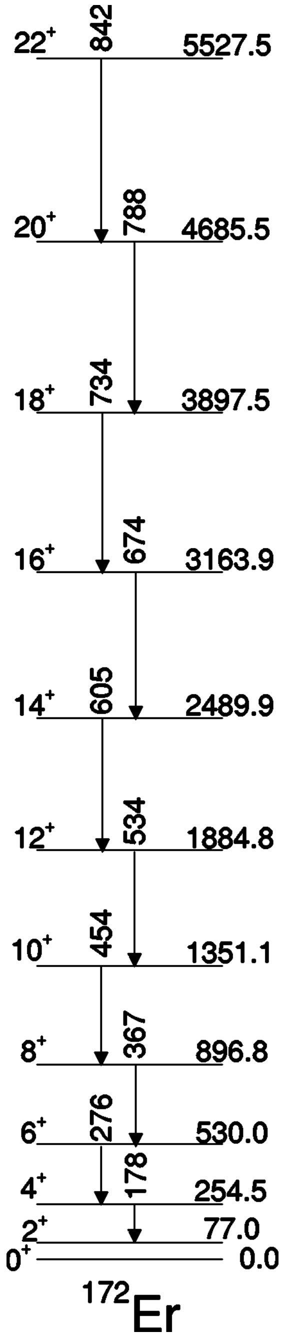

FIG. 6. Partial level scheme of ^{172}Er with energies labeled in keV. The uncertainty on the transition energies is $\approx$1 keV.

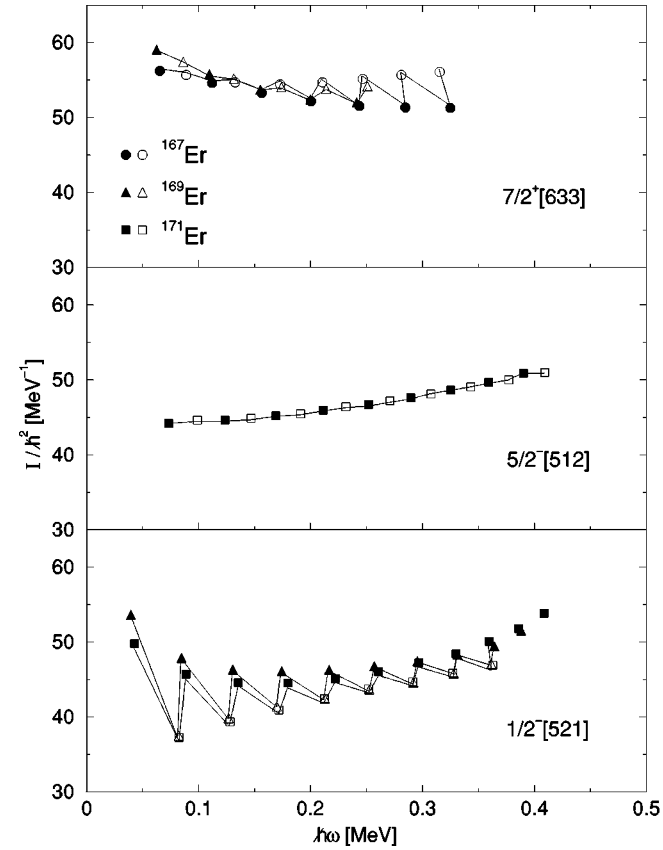

FIG. 7. The kinematical moment of inertia as a function of rotational frequency for the $7/2^{+}[633]$ (top), $5/2^{-}[512]$ (middle), and $1/2^{-}[521]$ (bottom) bands in the neutron-rich Er isotopes.

sensitive to the triaxiality of the $5/2^{-}[512]$ band in ^{171}Er, where the signature inversion occurring near the rotational frequency of 330 keV, or a spin of $33/2^{-}$, can only be reproduced by a calculation with an effective γ value of 12° [19].

The calculation is less sensitive to the triaxiality of the $7/2^{+}[633]$ band in ^{169}Er. However, calculations with either an axially symmetric or triaxial quadrupole shape fail to reproduce the observed signature splitting, particularly for the low-spin states. A reduction of 30% in the strength of the Coriolis interaction is required to reproduce the data satisfactorily. To further test this scenario, calculations were also carried out for the $7/2^{+}[633]$ band in the neighboring ^{167}Er and ^{169}Yb, where data are available not only for the transition energies, but also for the transition rates. Note that the

TABLE I. Relative probabilities for the population of rotational bands in neutron-rich isotopes produced in quasielastic reactions between ^{170}Er and ^{238}U at $E_{c.m.}=566$ MeV and $110° < \theta_{c.m.} < 140°$.

Nucleus	Reaction channel	Ground-state Q value (MeV)	Rotational band	Relative probability
^{170}Er	Inelastic	0.0	Ground state	100
^{172}Er	+2n transfer	1.25	Ground state	1.0
^{169}Er	−1n transfer	−2.45	$1/2^{-}[521]$	1.4
			$7/2^{+}[633]$	~0.21
^{171}Er	+1n transfer	−0.47	$1/2^{-}[521]$	1.3
			$5/2^{-}[512]$	~0.25

TABLE II. The pairing gap, Δ_n, used in the particle-rotor model with $\beta=0.32$ and $\gamma=12^{\circ}$.

Nucleus	Δ_n (MeV)
^{167}Er	0.912
^{169}Er	0.929
^{171}Er	0.911
^{169}Yb	0.884

$7/2^{+}[633]$ band is the ground-state band of these $N=99$ isotones. The comparison between calculations and data for the signature splitting and the $B(M1)/B(E2)$ ratios is presented in Figs. 9 and 10 for ^{167}Er and ^{169}Yb, respectively. The data were taken from Refs. [20,21] for ^{167}Er and Ref. [22] for ^{169}Yb. The same level of reduction in the strength of the Coriolis interaction is required to provide a consistent description of both the $B(M1)/B(E2)$ ratios and the signature splitting. This indicates the necessity to attenuate the Coriolis interaction in the particle-rotor model for the rotational band built on the $i_{13/2}$ orbital.

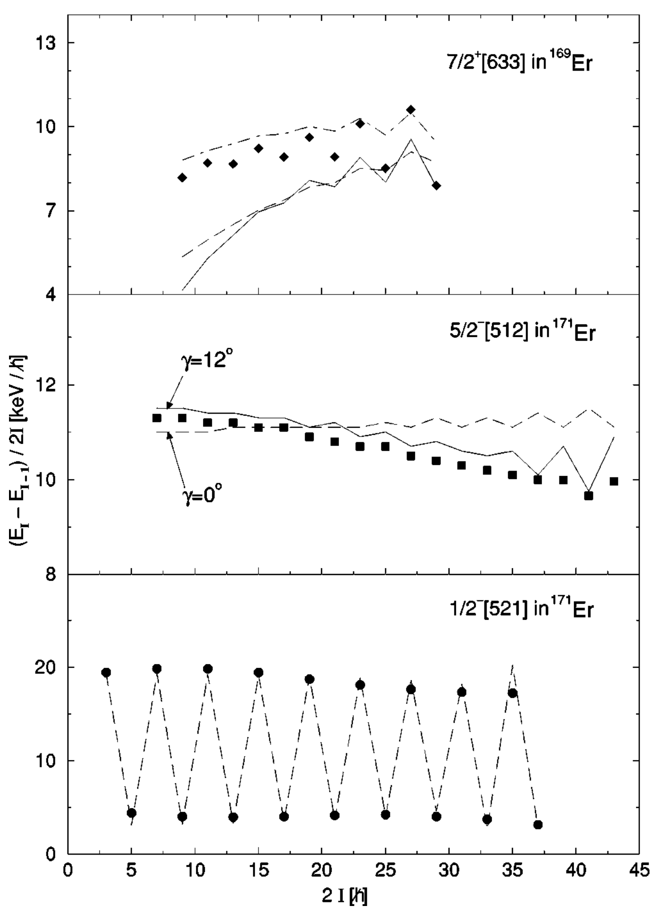

FIG. 8. Signature splitting as a function of spin for the $7/2^{+}[633]$ (top), $5/2^{-}[512]$ (middle), and $1/2^{-}[521]$ (bottom) bands in neutron-rich Er isotopes. The dashed and solid lines are the results of particle-rotor model calculations with γ values of 0° and 12°, respectively. Results of the same model calculations with a 30% reduction in the Coriolis interaction are indicated by the dashed-dotted line in the top panel.

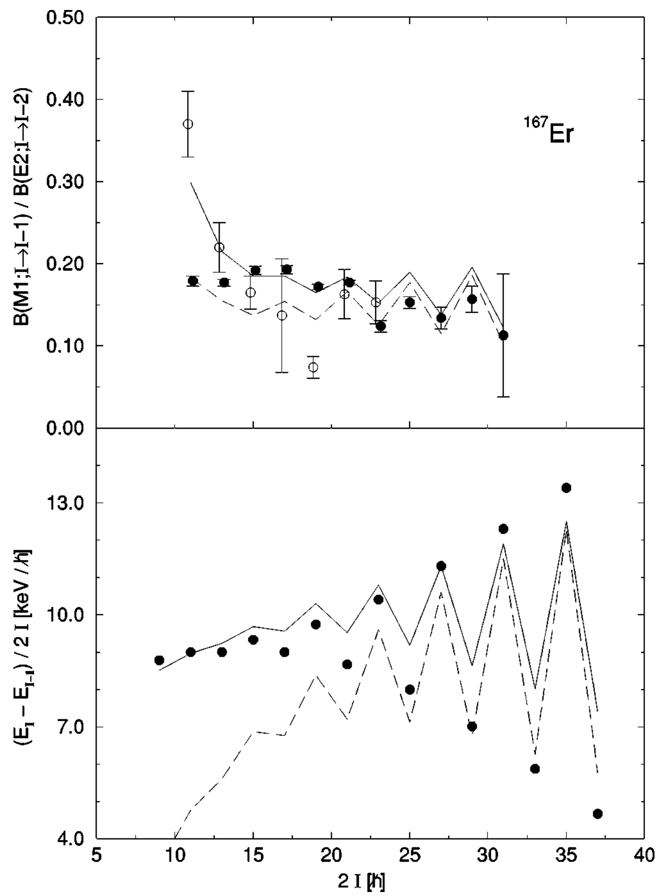

FIG. 9. The $B(M1)/B(E2)$ ratios (top) and signature splitting (bottom) as a function of spin for the $7/2^{+}[633]$ rotational band in ^{167}Er. The solid and dashed lines are the results of particle-rotor model calculations with and without an attenuation of the Coriolis interaction. There are two sets of experimental data for the $B(M1)/B(E2)$ ratios. The data with the open and filled circles are taken from Ref. [20,21], respectively.

In the context of the present description of ^{169,171}Er, it is noted that a systematic investigation of odd-A Xe and Ba nuclei with mass near 130 [23,24] was carried out within the framework of the triaxial rotor plus particle model in a manner similar to the approach described in the present paper. Even though these Xe and Ba nuclei are soft to quadrupole vibrations, Ref. [24] used the energy staggering of the $h_{11/2}$ intruder band, together with the lifetime of a K isomer, to extract their triaxial deformation parameters. The calculations show slowly varying deformation parameters with a triaxiality of $\gamma\approx 30°$ for these nuclei. It is interesting to note that in the work of Refs. [23,24], the values found for the Coriolis attenuation factors are similar to those reported here; they correspond to a reduction of up to 20% for some of the Xe and Ba isotopes investigated.

Coriolis attenuation is a well-known problem in the particle-rotor model, where the Coriolis coupling between Nilsson orbitals is too large, especially for unique parity orbitals. For example, a significant reduction of the Coriolis interaction strength within the framework of the particle-rotor model had been recognized long ago for the $j_{15/2}$ orbital in ^{235}U [25]. An extensive list of the possible physical ori-

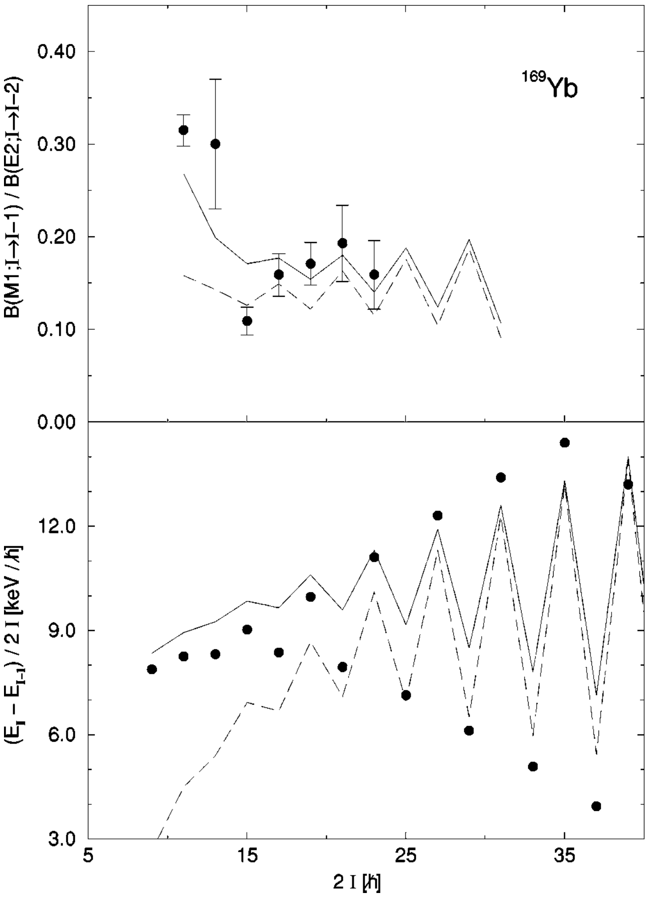

FIG. 10. The $B(M1)/B(E2)$ ratios (top) and signature splitting (bottom) as a function of spin for the $7/2^{+}[633]$ rotational band in ^{169}Yb. The solid and dashed lines are the results of particle-rotor model calculations with and without an attenuation of the Coriolis interaction, respectively. The experimental data are taken from Ref. [22].

gins for this attenuation is given in Ref. [26]. Microscopic calculations [27] claim to reproduce the observed Coriolis attenuation in ^{235}U by artificially reducing the observed monopole pairing strength by 20% and increasing the core moment of inertia by 15%. Nevertheless, the mechanism responsible for the Coriolis attenuation in this $j_{15/2}$ orbital remains an outstanding problem in nuclear structure physics [28,29]. The need to reduce the Coriolis interaction strength in the particle-rotor model has been shown experimentally again for the $i_{13/2}$ orbital by the present work and for the $h_{11/2}$ orbital by the work of Refs. [23,24]. Obviously, further theoretical and experimental investigations of these unique parity orbitals are warranted.

IV. SUMMARY

In summary, a study of heavy, neutron-rich, rare-earth nuclei was performed using quasielastic, few-nucleon transfer reactions between ^{170}Er targets and ^{238}U projectiles at near barrier energy. The probability of populating the neutron-rich ^{169,171,172}Er nuclei was measured to be on the order of 1% for both the one and two-neutron transfer channels. Rotational bands in these nuclei were extended to sufficiently high spins to allow for a study of the interplay between rotational motion and single-particle degrees of freedom. In particular, this work concentrated on signature splitting in terms of the average triaxiality and Coriolis attenuation. Such studies within the framework of the particle-rotor model are possible because a rigid nuclear core is a good approximation for the nuclei of interest. This is due to the fact that the band crossing has shifted to a higher rotational frequency in these neutron-rich Er isotopes because of weaker pairing, in addition to the weaker interaction between the ground-state and the rotationally aligned bands. However, this does not imply that these nuclei have rigid triaxial shapes. Particle-rotor calculations were performed for the rotational bands built on the $1/2^{-}[521]$, $5/2^{-}[512]$, and $7/2^{+}[633]$ neutron configurations in ^{169,171}Er. The successful reproduction of the data by the calculations points toward interesting physics; for example, the observed signature inversion for the $5/2^{-}[512]$ band in ^{171}Er is due to the centroid of the triaxial degree of freedom, while the Coriolis interaction has to be attenuated in order to achieve an adequate description of the rotational band built on the $7/2^{+}[633]$ neutron configuration.

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