Discrete line γ-ray spectroscopy in the $(50-60)\hbar$ spin domain of ^{161,162}Er

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Very high spin states ($I=50$–$60\,\hbar$) have been observed in the transitional nuclei ^{161}Er and ^{162}Er using the Euroball γ-ray spectrometer. In ^{161}Er, three bands are observed well above spin $50\hbar$. In the positive parity, positive signature $(+,+\frac{1}{2})$ band a discontinuity in the regular rotational behavior occurs at $\frac{109}{2}^{+}$ and a splitting into two branches occurs at $\frac{97}{2}^{-}$ in the negative parity, positive signature $(-,+\frac{1}{2})$ band. The $(-,-\frac{1}{2})$ band continues in a regular fashion to $\frac{115}{2}^{-}$, tentatively $(\frac{119}{2}^{-})$. In ^{162}Er the positive parity, even spin $(+,0)$ yrast band is observed to continue smoothly up to 58^{+} (60^{+}) and the negative parity, even spin $(-,0)$ and odd spin $(-,1)$ bands are extended from 30^{-} to 34^{-} and from 31^{-} to 47^{-} (49^{-}), respectively. The high spin experimental spectra are compared with both a simple model involving the occupation of specific single neutron states in the absence of neutron pair correlations and with more detailed cranked Nilsson-Strutinsky calculations in which both proton and neutron pairing correlations are neglected. The very high spin domain is found to comprise a series of unpaired rotational bands. Unpaired band crossings between bands with different neutron and proton configurations are identified in ^{161}Er. There is no evidence for aligned oblate or terminating states being close to the yrast line in ^{161,162}Er up to spin $\approx 60\hbar$ in contrast to the lighter Er isotopes.

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I. INTRODUCTION

A persistent theme in science is to investigate the behavior of physical systems under extreme conditions. The quest to observe increasingly high angular momentum states in atomic nuclei has driven the field of high spin nuclear spectroscopy for many years. With each step forward in detector technology the observation limit for discrete nuclear states has been pushed upward in spin and an increasingly rich variety of new phenomena have been discovered. It is in the light mass $A\sim160$ Dy and Er nuclei that the highest spin states in normal deformed nuclei have been observed (spin $\sim60\hbar$ and $E_{\mathrm{excit}}\sim30$ MeV) [1–12]. Aside from the question of the limiting spin at which discrete states in nuclei exist, other fundamental issues concern the effect of rotation on the nuclear equilibrium shape, on the nuclear pairing correlations and charting the correct single-particle spectrum of states at ultrahigh spins.

The nucleus displays well-established superfluid properties at low angular momentum values but collective rotation of the nucleus tends to destroy such correlated fermion motion and can lead to a superfluid to normal phase transition (the Mottelson-Valatin effect [13]). Thus, with increasing rotational frequency (spin) and valence particle alignments, a change from a regime dominated by strong superfluid properties (''static pairing regime'') to one where the effects of pairing correlations on the nuclear excitation spectrum will be greatly weakened [14] is expected. It is now realized however, that because of dynamic fluctuations, a complete quenching of the pair field will not occur in the finite particle number system of the nucleus [15–19]. In this new, often called ''unpaired'' regime the static pairing gap has vanished and the pair field consists of essentially dynamic contributions. As a result nuclear structure phenomena become very much more sensitive to the underlying single-particle spectrum of states. Band crossings can occur [20,21], but they are of a different nature to those at lower spins where the Coriolis and centrifugal forces break apart and align specific pairs of correlated nucleons [22]. In the high spin regime where pairing is not dominant, an ''unpaired'' band crossing can occur when a rearrangement of nucleons (conserving the parity and signature quantum numbers of the original configuration) becomes energetically favorable due to changes in energy of particular single-particle orbits with rotational frequency or spin [20,21]. Such changes give rise to band crossings at high angular momentum that are not correlated in

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rotational frequency in the same manner as standard quasiparticle alignments. The first experimental case of this type of band crossing was observed in ^{159}Er [6] and it was explained in terms of a model based on the spectrum of single-neutron states in the absence of neutron pair correlations. This simple model was also able to successfully explain subsequent measurements regarding the energy ordering and band crossing behavior in ^{160,161,162}Er up to spins 45–50$\hbar$ [7,8]. The present experiment advances these investigations into a higher spin domain (55–60$\hbar$) in ^{161,162}Er. However, it is found that the simple scheme involving only single-neutron states is no longer sufficient to fully understand these new data. Instead, the experimental observations can only be understood when a comparison is made with cranked Nilsson-Strutinsky calculations in which *both* neutron and proton pairing correlations have been assumed to be quenched.

In addition, the Er nuclei in this mass region, and some Dy isotopes [9,11,12], exhibit classic examples of the transition from prolate collective to oblate noncollective shape at high spin [23–26]. In $^{156-159}$Er there are many examples of aligned oblate (band-terminating) states near the yrast line that show evidence of this transition [1–4]. The present work demonstrates that these special aligned states rapidly move away from the yrast line in the more deformed heavier Er isotopes ^{161,162}Er where the high spin yrast states are dominated by collective prolate rotational band structures.

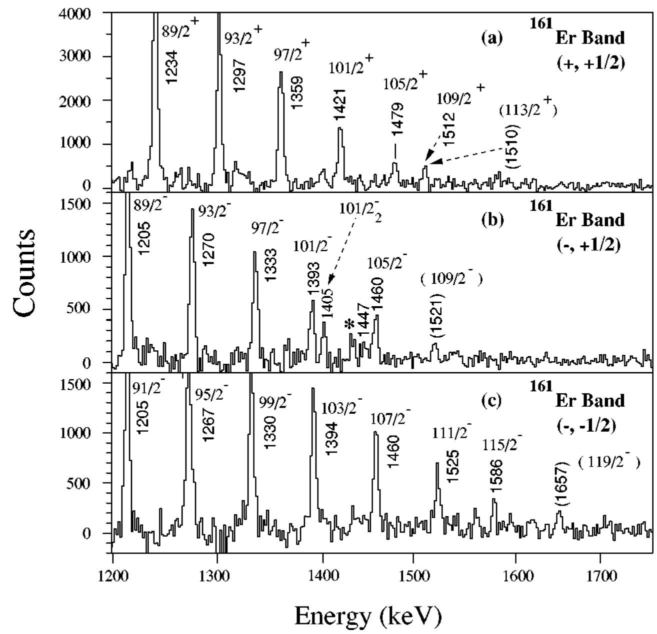

FIG. 1. Threefold coincidence spectra of the (a) $(+,+\frac{1}{2})$, (b) $(-,+\frac{1}{2})$, and (c) $(-,-\frac{1}{2})$ bands in ^{161}Er. These spectra were obtained by summing many spectra each with the requirement that there were two other coincident transitions in the band. The placement in the level scheme of the 1430 keV transition, marked with an asterisk in (b), has not been possible. However, it is definitely associated with the $(-,+\frac{1}{2})$ band at high spin.

II. EXPERIMENTAL DETAILS AND RESULTS

The nuclei ^{161,162}Er were populated at very high spin using the reaction ^{130}Te(^{36}S,5n)4n at a beam energy of 170 MeV. The beam was provided by the tandem accelerator at the Laboratori Nazionali di Legnaro, Italy. The target consisted of two stacked foils of ^{130}Te, each of thickness 0.5 mg cm^{-2} and with a 0.5 mg cm^{-2} Au backing. The Euroball array [27] was used to detect the deexciting γ rays. The array consisted of 14 seven-element Cluster detectors [28], 26 four-element Clover detectors [29], and 30 single-crystal Ge detectors [30]. A total of 2×10^9 events, when five or more Ge detectors were in coincidence, were collected. These were unfolded into $\approx 2\times10^{10}$ γ-γ-γ suppressed Ge detector coincidence events. The γ-γ-γ events were analyzed by the Radware software analysis package LEVIT8R [31]. Figure 1 shows examples of the coincidence spectra obtained from these data for the symmetry group (parity, signature), $(\pi,\alpha)=(+,+\frac{1}{2})$, $(-,+\frac{1}{2})$, and $(-,-\frac{1}{2})$ sequences in ^{161}Er. The sequences display rotational like behavior to high spin, thus all the transitions are assumed to be stretched $E2$'s. In ^{161}Er the $(+,+\frac{1}{2})$, $(-,+\frac{1}{2})$, and $(-,-\frac{1}{2})$ sequences have been extended from $\frac{97}{2}^+$, $\frac{97}{2}^-$, and $\frac{91}{2}^-$ [8] to $\frac{109}{2}^+$ tentatively $(\frac{113}{2}^+)$, $\frac{105}{2}^-$ $(\frac{109}{2}^-)$, and $\frac{115}{2}^-$ $(\frac{119}{2}^-)$, respectively. In the $(+,+\frac{1}{2})$ band a discontinuity in the regular rotational pattern occurs at $\frac{109}{2}^+$, see Figs. 1 and 6. In the $(-,+\frac{1}{2})$ band the $\frac{97}{2}^-$ state is fed by two transitions. These irregularities are both interpreted as evidence for band crossings, see discussion below. In ^{162}Er the (+,0), (−,0), and (−,1) sequences have been extended from 44$^+$, 30$^-$, and 31$^-$ [8] to 58$^+$ (60$^+$), 34$^-$, and 47$^-$ (49$^-$), respectively. Coincidence spectra for the (+,0) and (−,1) bands in ^{162}Er are shown in Fig. 2. Figure 2(c) is a classic example of the quantum nuclear rotational spectrum from 0^+ to 60^+, interrupted by the first neutron ($i_{13/2}$) alignment at $\approx 12^+$ and the first proton ($h_{11/2}$) alignment at $\approx 34^+$. The intensity of the $58^+ \rightarrow 56^+$ transition in ^{162}Er, being $\approx$0.005% of that of the $4^+ \rightarrow 2^+$ transition, is at the observational limit of the Euroball spectrometer [27,32,33]. The extension of the (−,1) band in ^{162}Er from 31$^-$ [8] to 47$^-$ (49$^-$) establishes, for the first time, the first $h_{11/2}$ proton alignment [34] at a rotational frequency of $\hbar\omega_c \approx$ 0.47 MeV in this band. This continues the trend of increasing crossing frequency $\hbar\omega_c$ with increasing neutron number in the Er isotopes [7,34]. The deduced level schemes of ^{161}Er and ^{162}Er for the highest spin states are shown in Fig. 3.

III. DISCUSSION

The experimental Routhians for high-spin sequences in ^{159,160,161,162}Er are plotted in Fig. 4. In Ref. [6] it was shown that the anomalous observation of a band crossing in the $(-,+\frac{1}{2})$ sequence in ^{159}Er near $\hbar\omega=0.55$ MeV ($\approx\frac{81}{2}^-$) could not be explained in terms of a standard quasiparticle alignment in a paired regime. Instead this discontinuity, along with the energy ordering of the various other rotational bands, in the same and neighboring nuclei, could be explained in terms of a suggested spectrum of single-neutron orbitals in the absence of neutron pair correlations. This

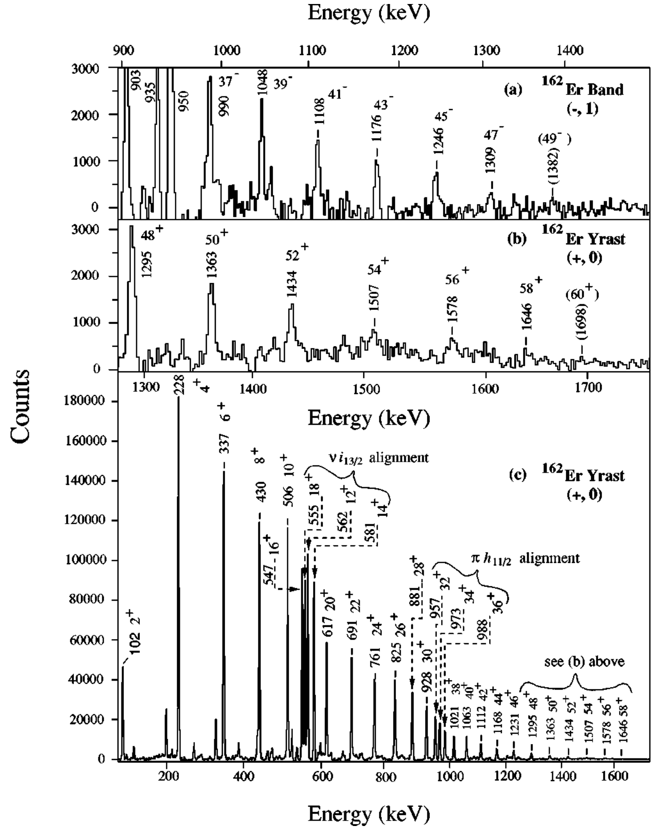

FIG. 2. Threefold coincidence spectra of the (a) (−,1), (b) and (c) (+,0) bands in ^{162}Er. These spectra were obtained by summing many spectra each with the requirement that there were two other coincident transitions in the band.

simple scheme was further extended and tested in a subsequent study of high spin states ($\sim$45–50$\hbar$) in ^{161,162}Er where it once more was found to be surprisingly successful [8]. The scheme of single-neutron levels that was used is

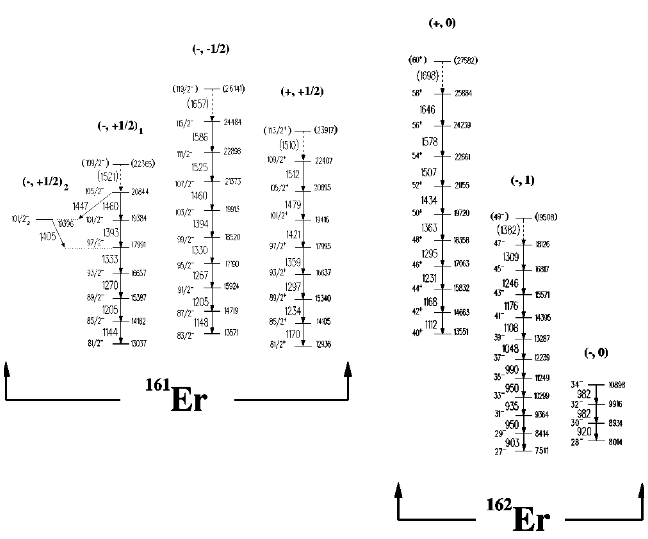

FIG. 3. Partial level schemes showing the high-spin states in ^{161}Er and ^{162}Er. Energies are given to the nearest keV. The sequences are labeled by their parity π and signature α, as (π,α). Tentative transitions are denoted by dotted lines.

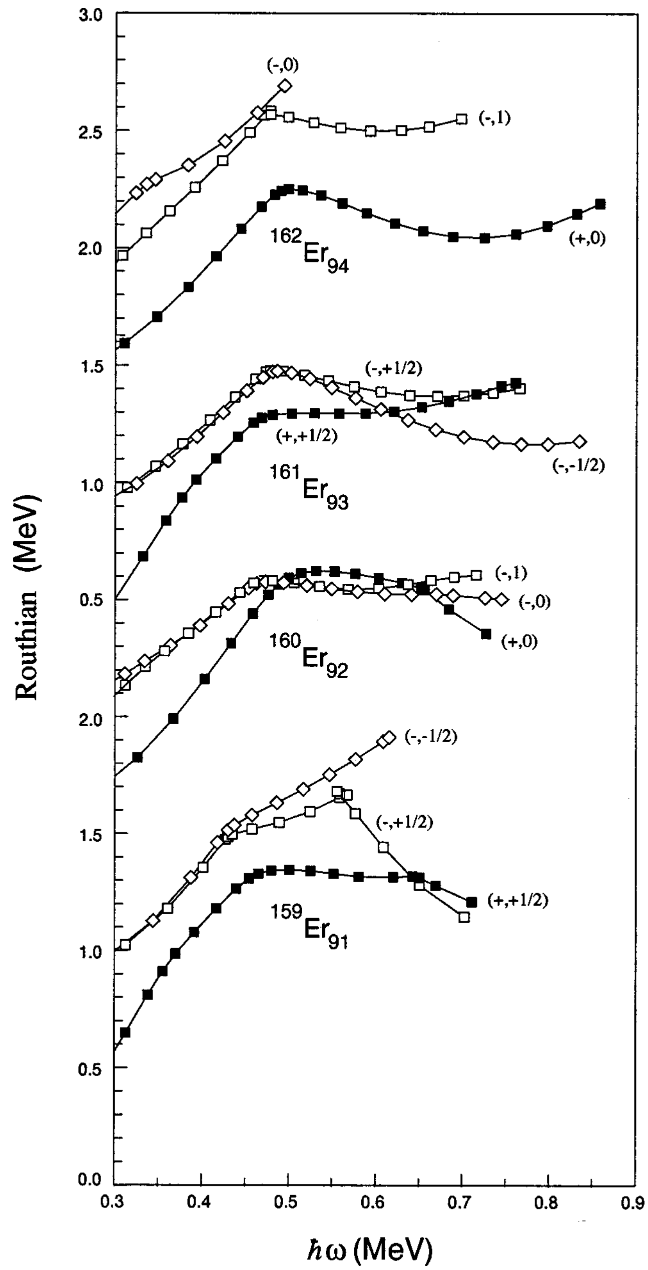

FIG. 4. Experimental Routhians for the high-spin sequences in ^{159,160,161,162}Er. The data are taken from Refs. [4,6] and this work. These Routhians are referred to a configuration with a constant moment of inertia (J_0) of 72 MeV$^{-1}\hbar^2$.

shown in Fig. 5(a). In this figure the model has been extended to cover the high frequency region observed in this work. The comparison of single-neutron states near $N=91$ in this schematic model with more realistic calculations based on the Nilsson model [35] allows an approximate frequency scale to be added to Fig. 5(a). The simple unpaired model can be used to predict the relative excitation energy of the various sequences expected in ^{161}Er and ^{162}Er and any unpaired neutron band crossings that may occur. The occupation of the various orbitals that form the lowest energy (π, α) configurations is shown in Figs. 5(b) and 5(c) for ^{161}Er and ^{162}Er, respectively.

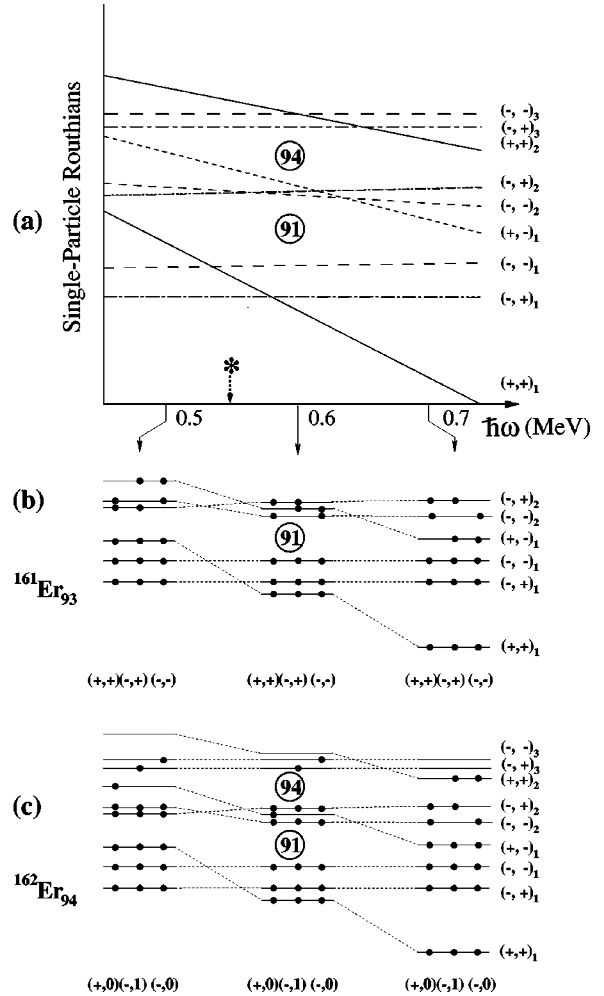

FIG. 5. (a) Scheme of single neutron energy levels in the absence of static neutron pair correlations. The rotational frequency that corresponds to the band crossing near $\hbar\omega = 0.55$ MeV in the $(-,+\frac{1}{2})$ sequence in ^{159}Er is indicated by an asterisk. The frequency values are given as a guide. The explicit occupation for the three lowest lying $(\pi,\ \alpha)$ configurations in ^{161}Er and ^{162}Er are shown in (b) and (c) at three values of rotational frequency. The rightmost diagram corresponds to the high frequency region established in this work. In this figure the $\frac{1}{2}$ for the signature (α) labels has been omitted for clarity. Note also that for comparison with Figs. 7, 8, and 9 all the above configurations have an additional two $i_{13/2}$ neutrons, in a lower lying $(+,+\frac{1}{2})$ and $(+,-\frac{1}{2})$ signature pair of orbitals.

In ^{161}Er, Fig. 5(b) shows that the model predicts the $(-,-\frac{1}{2})$ band to remain yrast at high spin. The $(-,+\frac{1}{2})$ sequence is also expected to become lower in energy relative to the $(+,+\frac{1}{2})$ band above $\hbar\omega \geqslant 0.6$ MeV. In these regards this model is again consistent with the new experimental results. This can be seen in Fig. 4 as well as Fig. 6 where the excitation energy of the bands is plotted relative to a rigid rotor reference as a function of spin. The model predicts that there are no preferred rearrangements of the uppermost pairs of valence neutrons, such that the (π,α) remains unchanged, into the available orbitals near the Fermi surface until extremely high frequency in ^{161}Er. This will occur when the

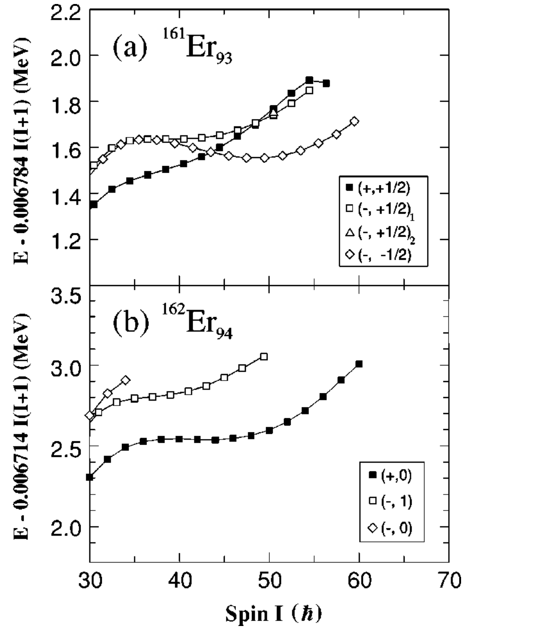

FIG. 6. Excitation energy minus a rigid rotor reference as a function of spin for the bands observed in (a) ^{161}Er and (b) ^{162}Er.

$(+,+\frac{1}{2})_2$ $i_{13/2}$ orbital comes down in energy and crosses the $(-,-\frac{1}{2})_2$ and $(-,+\frac{1}{2})_2$ Routhians near $\hbar\omega \approx 0.9$ MeV. This is beyond the bounds of Fig. 5(a) as well as above the highest frequency observed in this experiment.

In ^{162}Er the model predicts that the (+,0) band will remain as the lowest in energy at high spins and rotational frequencies. This is consistent with the experimental observation that the (+,0) band dominates the spectrum of states in ^{162}Er at high spin, see Figs. 3 and 6. However, for the $(-,0)$ and $(-,1)$ sequences in ^{162}Er when the $(+,+\frac{1}{2})_2$ orbital crosses the $(-,-\frac{1}{2})_3$ and $(-,+\frac{1}{2})_3$ orbitals it becomes favorable for a pair of valence neutrons to rearrange their occupations to form a lower energy configuration. This change is predicted to occur between $\hbar\omega = 0.6-0.7$ MeV and is illustrated in Fig. 5(c). Unfortunately these predicted band crossings are above the experimental data (Figs. 3 and 4). However, another consequence of this strongly downsloping positive parity $(+,+\frac{1}{2})_2$ orbital is that for rotational frequencies near $\hbar\omega = 0.8-0.9$ MeV, where it comes close in energy to the $(-,+\frac{1}{2})_3$ and $(-,-\frac{1}{2})_3$ levels, the $(-,0)$ and $(-,1)$ bands are predicted to have comparable (and eventually lower) excitation energies with the (+,0) yrast band. Although this behavior is predicted at much higher frequency than observed experimentally, it seems likely that the position of the $(+,+\frac{1}{2})_2$ orbital, as drawn in Fig. 5, is too low in energy. The reason for this is that in the above scenario, the three bands in ^{162}Er would all have similar excitation energies at ultrahigh spins, implying that they should therefore receive similar feeding and thus be of comparable intensity. This is obviously not the case experimentally. Moving the $(+,+\frac{1}{2})_2$ orbital higher in energy is also consistent with the spectrum of states used in the Nilsson-Strutinsky calculations described below, where band crossings involving configurations having a total of four or five

$i_{13/2}$ neutrons do not occur until near spin $70\hbar$, see Fig. 8 and related discussion.

Thus the behavior of the new extensions of the experimental bands at very high frequencies in both ^{161}Er and ^{162}Er seem to be reasonably well represented within this basic unpaired neutron model. This supports the suggested spectrum of single-neutron states at these particle numbers and deformation [except for the above mentioned $(+,+\frac{1}{2})_2$ orbital placement]. However, this model does not predict the discontinuity in the $(+,+\frac{1}{2})$ band at $\frac{109}{2}^+$ or the splitting in the $(-,+\frac{1}{2})$ band at $\frac{97}{2}^-$ in ^{161}Er. These anomalies are interpreted as band crossings, see Figs. 1, 3, and 6. Limitations in the model are perhaps not so surprising given that no consideration of deformation changes between the various configurations and between nuclei is included as well as the fact that no possible changes in the occupation of proton orbitals are considered. It may be expected that any changes in configuration involving two protons might affect all the bands in these Er nuclei equally and at similar rotational frequencies. However, if the configuration change involves a single proton and a single neutron such that there is no change in (π,α), then this model, since it only considers changes in the neutron configurations, will fail.

In order to investigate and interpret the detailed behavior of the high spin structures in ^{161,162}Er further, cranked Nilsson-Strutinsky calculations, based on the configuration-dependent formalism, have been performed. These calculations are described in detail in Refs. [21,23,24,36]. Within this formalism it is possible to trace a fixed configuration as a function of spin. Different bands are formed by fixing a configuration and searching for the lowest energy solutions within a particular configuration. An advantage of this method is that collective and noncollective configurations are treated in the same way. In these calculations both neutron and proton pairing correlations are neglected. The results of the calculations for ^{161}Er and ^{162}Er are displayed in Figs. 7 and 8, respectively. To facilitate the later discussion the calculated yrast configurations for each combination of (π,α) for ^{161}Er and ^{162}Er are shown in Fig. 9. The bands are labeled by the valence particles outside the ^{146}Gd closed core as $[p_1,p_2,n_1]$ where p_1 = number of $h_{11/2}$ protons, p_2 = number of $i_{13/2}$ protons (if a configuration does not involve these protons, p_2 is omitted from the label), and n_1 = number of $i_{13/2}$ neutrons. Fully aligned ($\gamma=60°$), band terminating states are denoted in the figures by large open circles.

The calculations predict that the high spin yrast states in both ^{161}Er and ^{162}Er are dominated by a series of rotational bands which maintain their prolate shape ($\varepsilon_2=0.20$–0.25, $\gamma\approx 0°$) up to $\approx 65\hbar$. There is, in general, good overall agreement between the calculations and the experimental results, see Figs. 6, 7, 8, and 9. While the slope of the experimental results and the theoretical predictions in these plots may appear to be rather different, these differences actually correspond to a small change in the moment of inertia of $\approx 4\%$. In addition, below spin $\approx 40\hbar$ pairing will be of importance and will have an effect on the energies of the configurations.

The calculated yrast configurations in ^{161}Er and ^{162}Er, between $I\approx 30$ to $70\,\hbar$, were found to be those with 3, 4, or 5 $i_{13/2}$ neutrons with the other valence neutrons in $(h_{9/2},f_{7/2})$ orbitals. For protons many more valence orbitals are active and form near yrast configurations. These generally involve 4, 5, 6, or 7 $h_{11/2}$ protons. At the very highest spins, $\approx 55\hbar$ and above, configurations involving 5 $h_{11/2}$ and 1 $i_{13/2}$ protons are important.

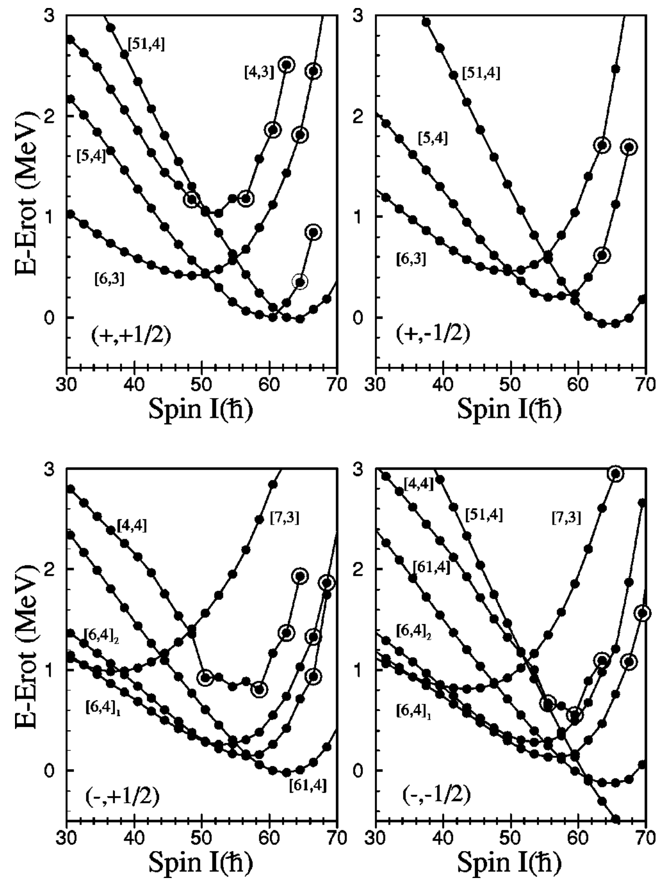

FIG. 7. The cranked Nilsson-Strutinsky calculations of the excitation energy minus a rigid rotor reference [Erot = 0.006784 $I(I+1)$ MeV] as a function of spin I for the lowest energy configurations in ^{161}Er for all combinations of (π,α). The bands are labeled according to the number of particles outside the ^{146}Gd core as $[p_1\ p_2,\ n_1]$ where p_1 = number of $h_{11/2}$ protons, p_2 = number of $i_{13/2}$ protons (if a configuration does not involve these protons p_2 is omitted from the label), and n_1 = number of $i_{13/2}$ neutrons. If configurations have the same $[p_1\ p_2,\ n_1]$ label then the subscript n denotes the nth such configuration. Fully aligned, band terminating states are denoted in the figure by large open circles.

In ^{161}Er the calculations predict, see Figs. 7 and 9, that the $(+,+\frac{1}{2})$ [6,3] configuration is lowest in energy up to $\frac{93}{2}^+$ where it is crossed by a $(-,-\frac{1}{2})$ [6,4] configuration. The $(-,-\frac{1}{2})$ band remains yrast up to $\approx 57\hbar$. The $(-,+\frac{1}{2})$ [6,4] configuration is also calculated to fall below the $(+,+\frac{1}{2})$ [6,3] configuration at $\approx 46\hbar$. These general trends agree well with the experimental data, see Fig. 6. In ^{162}Er the dominance in energy of the (+,0) sequence is reproduced in the calculations where the (+,0) [6,4] configuration remains yrast. Interestingly, the calculations predict a low lying (+,1) [6,4] configuration. Such a sequence was not observed experimentally. This nonobservation of the positive-parity, odd-spin band seems to be a general unexplained feature of

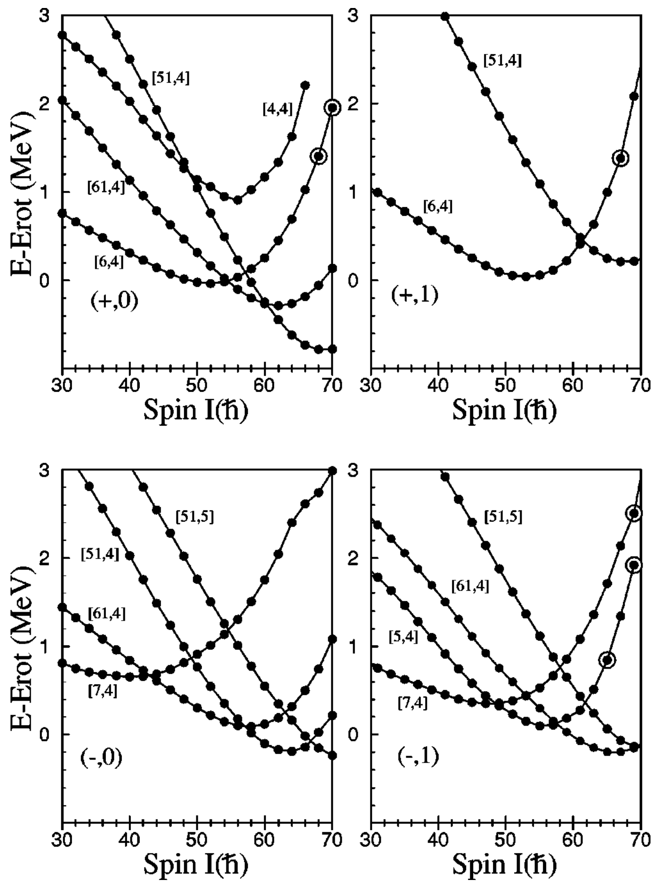

FIG. 8. Calculated excitation energy minus a rigid rotor reference [Erot = 0.006714 $I(I+1)$ MeV] as a function of spin I for the lowest energy configurations in ^{162}Er for all combinations of (π,α). The labeling convention is defined in Fig. 7.

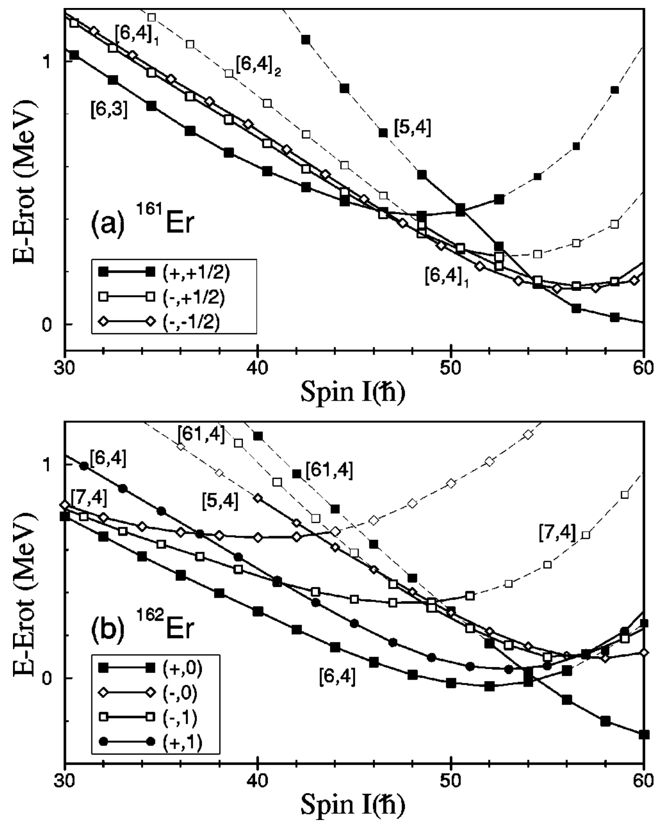

FIG. 9. The calculated lowest energy configurations between spin $30\hbar$ and $60\hbar$ for (a) ^{161}Er and (b) ^{162}Er. The labeling convention is defined in Fig. 7. Full lines are used to indicated roughly where states are observed experimentally, dotted lines otherwise.

nuclei in this region. One possible explanation for this is that this configuration is only relatively low in energy over a small spin range and quickly moves away from the yrast line, particularly below $\approx 40\hbar$ and above $60\hbar$, see Fig. 9. A similar explanation applies to the $(+,-\frac{1}{2})$ configuration in ^{161}Er.

In order to compare the experimental results with the calculations in more detail each band is discussed individually below. At the highest spins in the $(+,+\frac{1}{2})$ band in ^{161}Er there is evidence for a band crossing at $\approx \frac{105}{2}^{+}$ and $\hbar\omega = 0.76$ MeV. While the model involving just changes in neutron occupations fails to explain this crossing the more sophisticated configuration-dependent cranked Nilsson-Strutinsky formalism predicts a crossing between the [6,3] and [5,4] configurations at $\frac{101}{2}^{+}$, see Fig. 7. This crossing involves a change in both the single proton and neutron configurations. This agreement is consistent with the first experimental evidence for the demise of both single proton and neutron pairing correlations in the rare earth region.

For the $(-,+\frac{1}{2})$ states the calculations predict a crossing between the $[6,4]_1$ and $[6,4]_2$ configurations at $\approx \frac{101}{2}^{-}$. These configurations have different neutron and proton occupations. The splitting of the band into two branches at $\frac{97}{2}^{-}$ is interpreted as this crossing. In the $(-,-\frac{1}{2})$ states the [6,4] configuration remains yrast from $\approx 32\hbar$ to $58\hbar$. This is consistent with the experimental observations where one rotational band continues smoothly up to $\frac{115}{2}^{-}$ $(\frac{119}{2}^{-})$.

In ^{162}Er, the $(+,0)$ and $(-,1)$ bands observed to high spin are predicted to have crossings at 54^{+}, 60^{+}, and 49^{-}, respectively, see Fig. 8. Although distinct discontinuities are not present in the experimental data it is perhaps more than a coincidence to note that the spins at which these crossings are predicted to occur in ^{162}Er correlate almost exactly with the maximum spins observed in each of these band sequences, see Fig. 3. An explanation of this could lie in the fact that it is quite usual for the observed intensity of a band to drop quite considerably after a band crossing has occurred. It is thus a common experience, when close to the observation limit, to see only the portion of the band sequence just *below* the crossing point. It appears that this effect may be present in these data. This effect is also consistent with the $(-,-\frac{1}{2})$ band in ^{161}Er, which is observed to the point where a band crossing is predicted, namely the [6,4]→[61,4] crossing at $\frac{115}{2}^{-}$. Interestingly the data seem to lie just below the region where multiple band crossings and fully aligned oblate states are predicted to occur, see Figs. 7 and 8. In ^{161}Er, for example, configurations involving an $i_{13/2}$ proton are present at the yrast line. Also, it has been suggested [37] that it is the presence of many oblate states close to the yrast line at ultra high spins that helps funnel the γ-ray flux quickly down to the yrast line and make these nuclei favorable for high spin discrete-line spectroscopy.

The transitional erbium isotopes exhibit perhaps the classic examples of the angular momentum induced abrupt prolate-collective to oblate noncollective shape change at high spin in heavy nuclei [23,24]. This band termination effect, which is a consequence of the finite number of valence particles outside the $Z=64$ and the $N=82$ core and the available orbitals that they can favorably occupy, has been well documented in a long series of isotopes, ^{156,157,158,159}Er [1–4]. Especially favored fully aligned states, which exhaust the available valence spin space, have been observed at increasing high spin along the yrast line at 42^+ (^{156}Er), $\frac{89}{2}^+$ (^{157}Er), 46^+ (^{158}Er), and $\frac{101}{2}^+$ (^{159}Er). Many other aligned states have also been identified in these nuclei and their configurations are well established by comparison with cranked Nilsson-Strutinsky calculations [1,23,36]. In ^{160}Er there are possible indications of the presence of near-yrast aligned single-particle states close to spin 50 [7]. It is therefore of interest to extend the search for these special aligned states and their position relative to the competing more collective structures in the higher N isotopes.

In ^{158}Er the fully aligned, band-terminating state at 46^+ has the configuration

$$[\pi(h_{11/2})^4]_{16^+}\otimes[\nu(i_{13/2})^2(h_{9/2},f_{7/2})^6]_{30^+}$$

[1,20,23,38]. Correspondingly fully aligned states could be predicted for ^{161}Er if three neutrons are added to this configuration into the most energetically favorable neutron orbitals. In the negative-parity bands, for example, such states would be predicted at $\frac{109}{2}^-$ and $\frac{111}{2}^-$ with the configurations $[\pi(h_{11/2})^4]_{16^+}\otimes[\nu(i_{13/2})^4(h_{9/2},f_{7/2})^7]_{77/2^-}$ and $[\pi(h_{11/2})^4]_{16^+}\otimes[\nu(i_{13/2})^4(h_{9/2},f_{7/2})^7]_{79/2^-}$, respectively. The calculated lowest lying configurations with band terminating fully aligned states in ^{161}Er are plotted in Fig. 7. It is found that the most favored noncollective $\gamma=60°$ states have four $h_{11/2}$ protons and are predicted to be at least 500 keV above the yrast line for all (π,α) combinations. In the present data there is no evidence for a change in structure or perturbation in energy up to $\frac{115}{2}^-$ in the $(-,-\frac{1}{2})$ band and no evidence for a low lying $\frac{109}{2}^-$ state in the $(-,+\frac{1}{2})$ band in ^{161}Er.

The addition of a further neutron to these configurations could predict an oblate state at 56^+ in ^{162}Er that has the configuration $[\pi(h_{11/2})^4]_{16^+}\otimes[\nu(i_{13/2})^4(h_{9/2},f_{7/2})^8]_{40^+}$. However, the (+,0) yrast line of ^{162}Er behaves in a smooth regular manner up to very high spin and there is no evidence for this favored oblate state being close to the yrast line. The calculated lowest energy configuration with 4 $h_{11/2}$ protons for the (+,0) states is plotted in Fig. 8 and at no point does an oblate state become lowest in energy within this configuration in contrast to ^{161}Er. The calculations predict that the $\gamma=60°$ states are well above the yrast line for all (π,α) combinations in ^{162}Er.

These observations in ^{161,162}Er are consistent with the expectation that with increasing neutron number oblate noncollective structures move to higher excitation energy with respect to the yrast line and that the collective mode of generating angular momentum becomes increasingly favored in energy. In both ^{161,162}Er the configurations that form the collective yrast line between $50\hbar$ and $60\hbar$ are not predicted to terminate until above $65\hbar$, see Figs. 6, 7, and 8.

IV. SUMMARY

In summary, the new generation of very high efficiency γ-ray arrays enables the spectroscopy of nuclear structure phenomena at the very highest spins, to be performed. The data on ^{161,162}Er show discrete states in normal-deformed nuclei up to spin $60\hbar$. The high-spin band crossings and energy ordering behavior of the near-yrast rotational sequences has been compared and discussed with both a simple unpaired neutron model and also with a configuration-dependent cranked Nilsson-Strutinsky approach in which both proton and neutron pairing correlations are assumed to be quenched. Excellent agreement between experiment and theory for the relative energy of the bands at high rotational frequencies and for the observation and interpretation of band crossings in the $(+,+\frac{1}{2})$ and $(-,+\frac{1}{2})$ sequences in ^{161}Er was obtained. This is strong evidence for the demise of both proton and neutron static pairing correlations at these ultra high spins. In addition, the competition between prolate collective and oblate noncollective structures along the yrast line of the $N=88$–94 erbium isotopes together with the associated evolution towards band termination in ^{161,162}Er has been discussed. The experimental data and the theoretical predictions are consistent with such aligned oblate states being well above the yrast line in ^{161,162}Er and prolate collective structures dominating up to spin $60\hbar$. It will be exciting to continue the experimental quest to even higher spins ($\approx 60-70\hbar$) in this region of nuclei where many fully aligned oblate states and numerous unpaired band crossings, involving configurations with $i_{13/2}$ proton orbitals occupied, are predicted to occur. It is also of fundamental interest to find the actual limit of discrete nuclear states before the large rotational forces cause the nucleus to fission.

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