High-Spin Structure beyond Band Termination in ^{157}Er

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The angular-momentum induced transition from a deformed state of collective rotation to a noncollective configuration has been studied. In ^{157}Er this transition manifests itself as favored band termination near $I = 45\hbar$. The feeding of these band terminating states has been investigated for the first time using the Gammasphere spectrometer. Many weakly populated states lying at high excitation energy that decay into these special states have been discovered. Cranked Nilsson-Strutinsky calculations suggest that these states arise from weakly collective "core-breaking" configurations.

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The generation of angular momentum (spin) in the atomic nucleus has long been a topical question in nuclear physics [1]. A deformed prolate nucleus can increase its spin by collective rotation about an axis perpendicular to its symmetry axis leading to $I(I+1)$ quantum-rotor behavior and the observation of regular rotational bands. However, since the nucleus is a finite mesoscopic quantal system, such collective behavior must have an underlying microscopic basis which limits the spin that a particular nuclear configuration, or band, can generate. The low-spin states involve pairwise, time-reversed occupation of specific orbitals. A combination of Coriolis and centrifugal forces, induced by rapid rotation, can break the valence pairs and align the individual nucleonic spins along the collective rotation axis. These aligned nucleons move in equatorial orbits polarizing the nucleus from its original prolate shape towards an oblate one. The available spin is exhausted when all the valence nucleons outside a spherical, doubly magic core are aligned. This is known as valence-space *band termination* and is observed in γ-ray spectra by the sudden end to a rotational band.

High-spin terminating bands in heavy nuclei were first identified in nuclei around $^{158}_{68}$Er$_{90}$; see Refs. [2–7], and references therein; also see Ref. [8] for a recent summary of the field. At termination, this nucleus can be considered as a spherical core ($^{146}_{64}$Gd$_{82}$) plus 12 (four protons and eight neutrons) aligned valence particles which can generate a maximum spin of around $46\hbar$ at an excitation energy of ≈ 17 MeV, depending on the specific configuration. To produce higher-spin states, particle-hole excitations of the core are required, as seen at low spin in weakly deformed nuclei close to ^{146}Gd [9,10]. The question arises as to whether these excitations reintroduce collective prolate deformation or whether the nucleus remains oblate or near oblate. While clear examples of the special terminating states have been identified in a number of erbium isotopes, almost nothing is known about the specific states lying above band termination in isotopes close to the textbook example of ^{158}Er [11,12]. Indeed, in the experimental spectra a dramatic change in character occurs with the decays *from* the terminating states being strong and easily observed, but only very weak candidate γ rays, at least an order of magnitude less in intensity, decaying *to* the terminating states being hinted at [6]. Therefore, an experiment was performed to identify the nuclear excitation spectrum above these textbook band-termination cases and allow meaningful comparisons to state-of-the-art theoretical predictions.

The high-spin structure of ^{157}Er was studied using the Gammasphere spectrometer [13] with 102 Ge detectors. A 215-MeV ^{48}Ca beam, provided by the 88 Inch Cyclotron at the Lawrence Berkeley National Laboratory, was used to bombard two stacked foils of ^{114}Cd, of total thickness 1.1 mg/cm^2. A total of 1.2×10^9 events were collected when at least seven Compton-suppressed Ge detectors fired in prompt coincidence.

Approximately 6.5×10^{10} quadruples (γ^4) were unfolded from the data set and replayed into a Radware-format [14] four-dimensional hypercube for coincidence analysis to establish the level scheme. In addition, one-dimensional spectra, multiple gated by transitions in ^{157}Er, were unfolded from the data. These were sorted into the rings of Gammasphere at a fixed angle θ to the beam direction. The intensities of transitions measured at a specific θ were used for an angular-distribution analysis: for the strong γ rays it was possible to fit the data to the angular-distribution function $W(\theta) = 1 + A_2P_2(\cos\theta)$ in order to extract A_2 coefficients. For weaker transitions only an angular-intensity ratio $I_{\gamma,30^\circ(150^\circ)}/I_{\gamma,90^\circ}$ could be obtained. A γ^5 analysis,

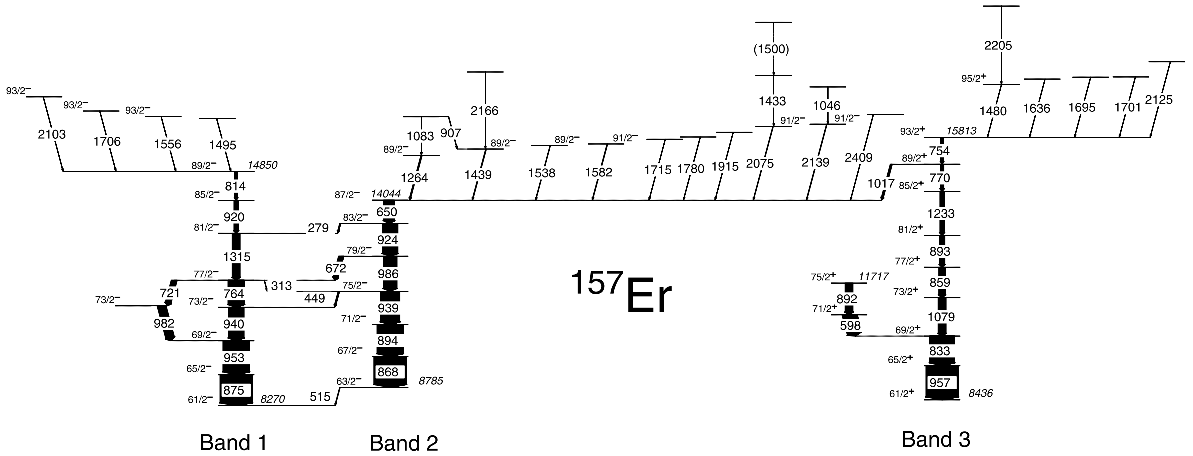

FIG. 1. Partial level scheme of the high spin structures observed in ^{157}Er above 30$\hbar$ showing the many transitions feeding the special terminating states at $87/2^-$, $89/2^-$, and $93/2^+$.

requiring coincidence with four γ rays from a list, gave the best results.

The high-spin level scheme of ^{157}Er is shown in Fig. 1 and greatly extends the previous work [7]. Bands 1 and 2 were previously established up to the band terminating states at $89/2^-$ and $87/2^-$, respectively, while band 3 has been extended from the $85/2^+$ state up to the new terminating state at spin $93/2^+$. A large number of weak high-energy γ rays feeding these states has been observed; moreover, a measurement of the multipolarity for a number of these transitions has been possible.

Four high-energy transitions feed into the terminating state of band 1 at $89/2^-$, of which three could be identified with $\Delta I = 2$ ($E2$) character. However, these four transitions only account for $\approx 33\%$ of the feeding intensity of the $89/2^-$ state. Ten high energy transitions have been identified feeding into the $87/2^-$ terminating state of band 2, again accounting for $\approx$33% of the feeding intensity. In addition, an $E1$ transition of energy 1017 keV decays into this state from the $89/2^+$ state of band 3, accounting for a further 22% of the feeding intensity. Figure 2 shows a spectrum in coincidence with the 650 keV ($87/2^- \rightarrow 83/2^-$) and 924 keV ($83/2^- \rightarrow 79/2^-$) transitions of band 2. The spectrum clearly shows several low intensity transitions visible from 1.0–2.5 MeV. The 1264, 1439, and 1538 keV transitions feeding the $87/2^-$ terminating state have angular-intensity ratios implying mixed $\Delta I = 1$ character. Of the remaining seven transitions, it was possible to identify three of them with $\Delta I = 2$ ($E2$) character. Finally, five high-energy transitions have been observed feeding into the new terminating state of band 3, accounting for $\approx$58% of the feeding intensity. The strongest of these feeding transitions, of energy 1480 keV, has an angular-intensity ratio consistent with mixed $M1/E2$ $\Delta I = 1$ character.

The excitation energies are shown relative to a rigid rotor reference in Fig. 3 for bands 1–3, which clearly shows the favored nature of the three terminating states at $89/2^-$, $87/2^-$, and $93/2^+$. In order to understand the nature of the states feeding the terminating states, calculations have been performed in the framework of the configuration-dependent, cranked Nilsson-Strutinsky

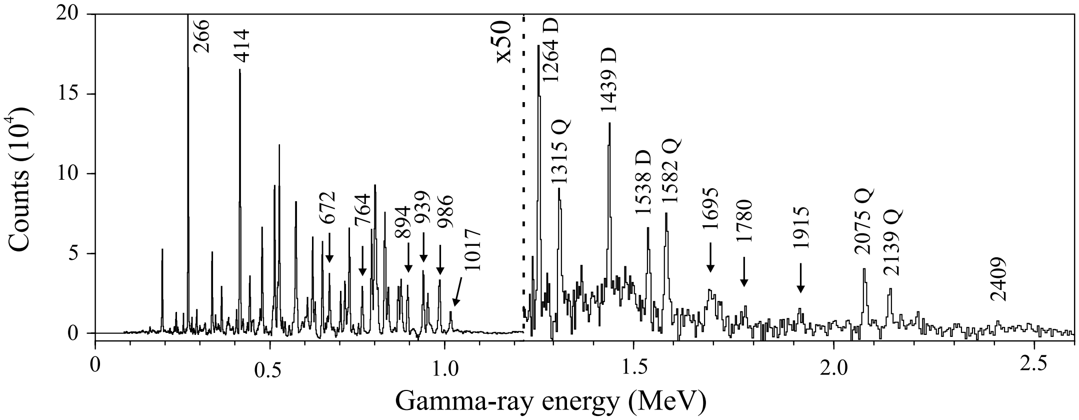

FIG. 2. Spectrum of γ rays in simultaneous coincidence with the 650 and 924 keV transitions in band 2. Note the large $\times 50$ multiplication factor needed above 1 MeV in order to illustrate the many weak feeding transitions. Above 1 MeV, $\Delta I = 1$ transitions are labeled by "D" (dipole) and $\Delta I = 2$ transitions by "Q" (quadrupole).

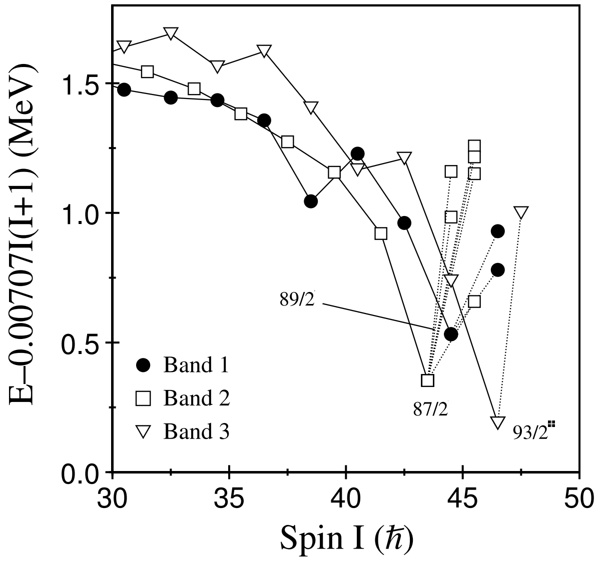

FIG. 3. Excitation energy minus a rigid-rotor reference plotted as a function of spin for bands 1, 2, and 3. The favored terminations at $87/2^-$, $89/2^-$, and $93/2^+$ are labeled.

formalism without pairing [8,15]. Within this approach, different bands are formed by fixing a configuration, specified by the number of particles in different oscillator N-shells of signature $\alpha = \pm 1/2$, and searching in a mesh of deformation space (ε_2, ε_4, γ) for the lowest-energy state at a given spin, thus treating the collective and noncollective states on the same footing. The present calculations have extended the model [16] to distinguish between proton orbitals of $d_{3/2}$, $s_{1/2}$, and $g_{7/2}, d_{5/2}$ character, and to consider excited states in fixed configurations [17], which were not possible in the previous work [7].

The three fully aligned terminating states at $87/2^-$, $89/2^-$, and $93/2^+$ are formed by coupling the $\pi[(h_{11/2})^4]_{16^+}$ proton configuration to the three neutron configurations, $\nu[(i_{13/2})^2(h_{9/2}, f_{7/2})^5]_{55/2^-,57/2^-}$ and $\nu[(i_{13/2})^3(h_{9/2}, f_{7/2})^4]_{61/2^+}$, respectively. The favored way found to make higher-spin states for $I = 45$–$55\hbar$ is to excite protons from the $g_{7/2}$ and $d_{5/2}$ orbitals below the $Z = 64$ gap into the 5th and 6th $h_{11/2}$ orbitals and into the two lowest $d_{3/2}$ orbitals. A systematic investigation was carried out for proton configurations with 1–4 particles excited across the $Z = 64$ gap. Of the possible 70 configurations of this type, 21 were low enough to enter the energy regime of the experimental levels in ^{157}Er, i.e., corresponding to $\Delta I = 2$ transitions up to ~2.5 MeV and $\Delta I = 1$ transitions up to ~2.0 MeV feeding the three fully aligned states. Four of the 21 configurations are excited with one hole in the next highest $g_{7/2}, d_{5/2}$ orbital of either signature, but with the highest $g_{7/2}, d_{5/2}$ orbitals occupied. In addition, four further low-lying proton configurations were found with a hole in the 4th $h_{11/2}$ orbital. These 25 proton configurations were then combined with the three favored neutron configurations given above to generate 75 possible high-spin configurations.

The resulting structures are predicted to build the yrast states in ^{157}Er up to $I \approx 55\hbar$. These configurations show little collectivity and terminate at a small oblate deformation $\varepsilon_2 \sim -0.15$. The yrast states for higher spin involve similar types of configurations but with one $i_{13/2}$ proton. For even higher spin values, the yrast configurations involve one or two $N = 4$ neutron holes and often one proton in the $h_{9/2}, f_{7/2}$ orbital; again these configurations show little collectivity. To obtain more collective structures requires configurations with one or two $N = 5$ ($h_{11/2}$) neutron holes together with at least one proton in $i_{13/2}$ and/or $h_{9/2}, f_{7/2}$ orbitals. However, these configurations do not approach the yrast line until $I \sim 70\hbar$ where deformed prolate and triaxial shapes with $\varepsilon_2 \sim 0.25$ are predicted. In addition, it is expected that superdeformed or hyperdeformed states become competitive in energy at very high spin values. To summarize, only configurations with little or no collectivity are predicted to be low enough in energy to be identified with the experimental levels 1.0–2.5 MeV above the fully aligned terminating states. This is consistent with the fact that no clear discrete collective band structures have been identified in ^{157}Er above the favored terminating states, although some evidence of a weak "$E2$ bump" [18,19] of unresolved collective decays at very high spin is observed.

The present case is the first that elucidates the feeding of these especially favored terminating states in the $N = 90$ region. These states lie in a deep minimum with no states close in energy at higher spin. Thus, no specific route to higher spin is preferred and the feeding intensity is highly fragmented. This behavior is very different to that observed in the lighter nucleus ^{154}Dy [20] where, the valence space terminating states (for example $I = 36^+$) are less favored, and a well delineated pathway to higher spin is observed through weakly collective configurations lying close in energy.

The experimental and theoretical levels in ^{157}Er above the terminating states are shown in Fig. 4. The gap in the experimental level density above the terminating states is directly related to the $Z = 64$ shell gap and the present results show that this gap is still important at very high spin (40–$50\hbar$). The dense groups of calculated levels above the favored terminating states are complete up to 700–800 keV above the lowest state in the respective group, i.e., they include all configurations which enter this energy range.

Experimentally, the lowest-energy feeding transitions of the terminating states tend to be $\Delta I = 1$ transitions. For example, the fully aligned $87/2^-$ state of band 2 is fed by a 1017 keV $E1$ transition from band 3 and by 1264, 1429, and 1538 keV $M1/E2$ transitions from $89/2^-$ states. By comparison with the calculations it is possible to suggest theoretical counterparts to these $89/2^-$ states. Thus the four lowest core-excited $89/2^-$ states are predicted to be built from configurations with one proton excited into the $d_{3/2}$ orbital of favored signature, followed by configurations with one proton excited into

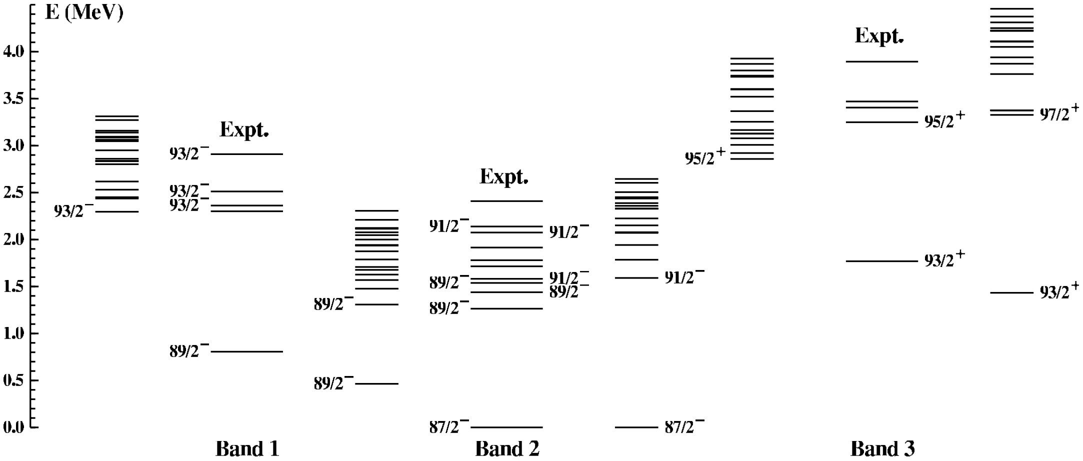

FIG. 4. Experimental (wide) and theoretical (narrow) levels above the three terminating states. The energies are normalized to the $87/2^-$ state of band 2 (excitation energy = 14.044 MeV). Experimental spins and parities are shown for levels where available, while the theoretical groups of levels, of the same spin and parity, are only labeled at the lowest level.

the $d_{3/2}$ unfavored and favored $h_{11/2}$ orbitals, respectively. At slightly higher energy configurations with two protons excited to either $d_{3/2}$ or $h_{11/2}$ orbitals are predicted. These configurations are then combined with the favored neutron $(i_{13/2})^2$ or $(i_{13/2})^3$ configurations to obtain negative parity. They all terminate in the spin range $I^\pi = 93/2^- - 101/2^-$ and are thus triaxial and slightly collective at $89/2^-$. The fourth lowest experimental level, decaying by the 1582 keV $\Delta I = 2$ transition, could then correspond to the lowest-energy $91/2^-$ theoretical level, which is the terminating state of the $\pi[(d_{3/2})^1(h_{11/2})^3] \otimes \nu[(i_{13/2})^3(h_{9/2}, f_{7/2})^4]$ valence-space configuration. This closed-core state is somewhat unique and is followed by states built from similar proton configurations as for the $89/2^-$ states. The same kind of proton configurations are also responsible for the lowest states in the other groups of levels shown in Fig. 4.

In summary, the feeding of the special favored band terminating states in ^{157}Er has been investigated and found to comprise a large number of weak transitions of energies 1.0–2.5 MeV. Cranked Nilsson-Strutinsky calculations indicate that the levels from which they originate mainly correspond to weakly collective (with deformations $\varepsilon_2 = 0.10$–0.15 and $\gamma = 30°$–$45°$) configurations involving core-breaking proton particle-hole excitations across the semimagic $Z = 64$ shell gap.

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[1] A. Bohr and B. R. Mottelson, *Nuclear Structure* (W. A. Benjamin Inc., New York, 1975), Vol. II.
[2] I. Ragnarsson, Z. Xing, T. Bengtsson, and M. A. Riley, Phys. Scr. **34**, 651 (1986).
[3] J. Dudek and W. Nazarewicz, Phys. Rev. C **31**, 298 (1985).
[4] T. Bengtsson and I. Ragnarsson, Phys. Scr. **T5**, 165 (1983).
[5] F. S. Stephens *et al.*, Phys. Rev. Lett. **54**, 2584 (1985).
[6] J. Simpson *et al.*, Phys. Lett. B **327**, 187 (1994).
[7] S. J. Gale *et al.*, J. Phys. G **21**, 193 (1995).
[8] A. V. Afanasjev, D. B. Fossan, G. J. Lane, and I. Ragnarsson, Phys. Rep. **322**, 1 (1999).
[9] M. Piiparinen *et al.*, Phys. Lett. B **194**, 468 (1987).
[10] M. A. Deleplanque *et al.*, Phys. Lett. B **195**, 17 (1987).
[11] K. Heyde, *Basic Ideas and Concepts in Nuclear Physics* (IOP Publishing, Bristol, 1999), p. 53.
[12] S. G. Nilsson and I. Ragnarsson, *Shapes and Shells in Nuclear Structure* (Cambridge University Press, Cambridge, 1995), p. 230.
[13] I. Y. Lee, Nucl. Phys. **A520**, 641c (1990).
[14] D. C. Radford, Nucl. Instrum. Methods Phys. Res., Sect. A **361**, 297 (1995).
[15] T. Bengtsson and I. Ragnarsson, Nucl. Phys. **A436**, 14 (1985).
[16] F. Sarić, Master's thesis, Lund Institute of Technology, 2000 (Lund-MPh-00/07).
[17] C. Andreoiu *et al.*, Phys. Rev. Lett. **91**, 232502 (2003).
[18] J. O. Newton, J. C. Lisle, G. D. Dracoulis, J. R. Leigh, and D. C. Weisser, Phys. Rev. Lett. **34**, 99 (1975).
[19] R. S. Simon, M. V. Banaschik, P. Colombani, D. P. Soroka, F. S. Stephens, and R. M. Diamond, Phys. Rev. Lett. **36**, 359 (1976).
[20] W. C. Ma *et al.*, Phys. Rev. C **65**, 034312 (2002).