Beyond Band Termination: Ultra-High Spin Spectroscopy of Light Erbium Nuclei

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(Dated: February 27, 2009)

The observation of high-energy γ rays beyond the band terminating states in ^{157,158}Er have suggested a return to collectivity at ultra-high (50-60$\hbar$) spin, fuelling debate on how nuclei generate angular momentum at such extremes of spin. This data resulted from a highly successful Gammasphere experiment at Lawrence Berkeley National Laboratory. Further analysis of the same data set reveals similar structures in ^{156}Er, with the γ-ray decay of energetically expensive core-breaking states observed. To extend the systematic studies of the erbium isotopes, a further Gammasphere experiment has been performed at Argonne National Laboratory. A beam of ^{48}Ca was used to bombard a target of ^{114}Cd at 215 MeV, populating high-spin states in ^{159,160,161}Er. Results from both experiments are discussed.

I. INTRODUCTION

How nuclei generate angular momentum at very high spins is still a topic of great interest to both experimental and theoretical nuclear physicists. A deformed prolate nucleus can increase its spin by collective rotation about an axis perpendicular to its symmetry axis leading to discrete energy levels that approximate quantum-rotor behaviour, i.e. $E(I) \propto I(I+1)$, and consequently the observation of regular rotational bands in γ-ray emission spectra. As the angular momentum is increased, nuclei exhibit Coriolis-induced alignments where nucleonic pairs are broken by the fictive Coriolis force in a rotating frame of reference. As more and more valence nucleons align with the axis of rotation, a larger fraction of the nuclear spin is generated by single-particle non-collective contributions. Eventually, the angular momentum is wholly generated by the single-particle contributions of a finite number of valence nucleons in equatorial orbits outside a closed spherical (doubly magic) core. In the N$\sim$90 nuclei, this fully aligned state results in an oblate nuclear shape.

The light erbium nuclei can be thought of as valence nucleons coupled to a semi-magic $^{146}_{64}$Gd$_{82}$ core. For the lightest isotope considered in this work, ^{156}Er, it is easy to see how as the valance nucleons align with the core, the collective behaviour of the nucleus breaks down and a single-particle structure is observed. This change of spin generation from collective to non-collective manifests itself experimentally as band termination [1, 2].

The textbook example is in ^{158}Er, which was one of the first nuclei in which Coriolis-induced pair-breaking (backbending) was discovered [3] and the first nucleus in which the second alignment was observed. The evolution of the structure of ^{158}Er is shown in the schematic diagram in Fig. 1. At spin 38$\hbar$, there is a dramatic change in the structure as the less-collective band structures become favoured. Here, the valence single-particle angular momenta are aligned outside of the ^{146}Gd doubly magic core, driving the nucleus towards an oblate shape. Band termination occurs in ^{158}Er at 46-49$\hbar$ when all of the twelve valence particle spins are maximally aligned in specific configurations. In order to generate further angular momentum, the Z=64 core has to be broken, which is energetically expensive. Similar behaviour in shape evolution is seen in the neighbouring Er isotopes and this presentation gives a brief overview of recent analysis which extends the ultra-high-spin studies of light erbium isotopes from ^{156}Er to ^{161}Er.

II. EXPERIMENTAL DETAILS AND RESULTS

The high-spin structures of ^{156,157,158}Er were studied at the 88 Inch Cyclotron of the Lawrence Berkeley National Laboratory, using the Gammasphere γ-ray spectrometer [4] containing 102 HPGe detectors. A

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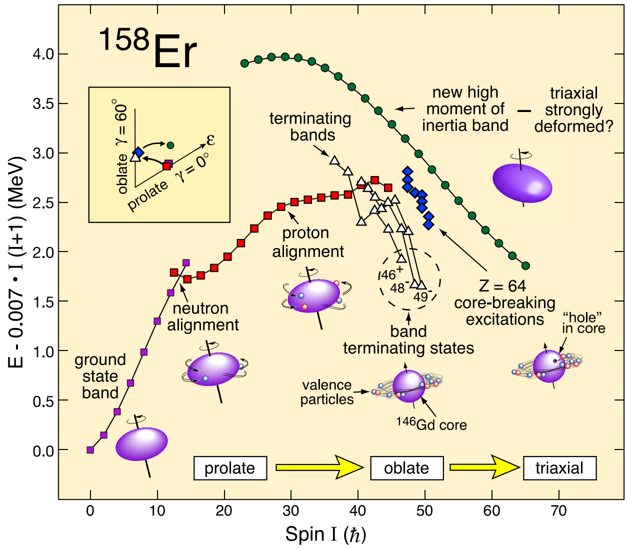

FIG. 1: Schematic showing the evolution of the nuclear structure of ^{158}Er with spin, taken from Ref. [9]. Excitation energies of a variety of the observed structures are plotted with respect to a rigid-rotor reference. The high moment of inertia band is included but its exact excitation energy is not known.

^{48}Ca beam of energy 215 MeV was used to bombard two stacked thin self-supporting foils of ^{114}Cd, of total thickness 1.1 mg/cm^2, producing $^{162-x}$Er through the ^{114}Cd(^{48}Ca,xnγ) reaction. A total of 1.2×10^9 events were collected when at least seven Compton-suppressed HPGe detectors fired in prompt time coincidence.

In the off-line analysis, approximately 6.5×10^{10} quadruple (γ^4) coincident events were unfolded from the data and replayed into a Radware-format four-dimensional hypercube [5, 6], with a non-linear gain compression, for subsequent analysis. The nuclei ^{156}Er (6n), ^{157}Er (5n), and ^{158}Er (4n) were measured to be populated in the ratio 0.4:1.0:1.0, approximately, in the hypercube. Analysis of these data showed that the terminating states in ^{157,158}Er were populated by a series of weak, high-energy transitions [7–9]. The interpretation of the nature of these feeding states was based on calculations using a configuration-dependent, cranked Nilsson-Strutinsky formalism without pairing [10, 11]. These calculations indicate that these states beyond the band termination come from weakly collective configurations involving core-breaking proton particle-hole excitations across the Z=64 shell gap [7]. This represented the first observation of the characteristic highly fragmented decay of these core-excited states.

The high-fold nature of the Gammasphere data allows one dimensional spectra gated on multiple transitions to be produced, using the technique of [12]. This sort of analysis proved pivotal in extracting the weak, high-spin transitions and bands in the ^{157,158}Er analysis. Recently, we have applied this technique to the ^{156}Er data from the same data set, revealing a number of previously unobserved transitions [13], shown in the partial level scheme,

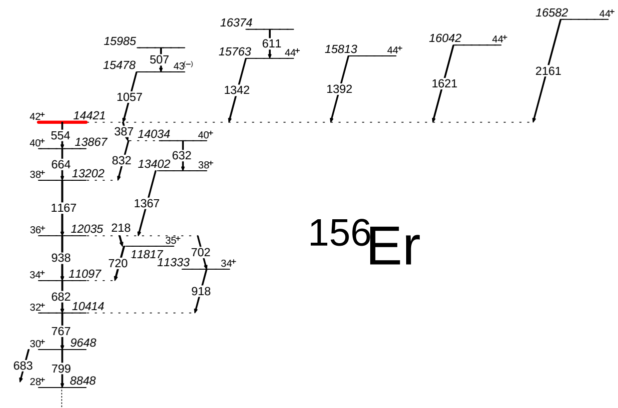

FIG. 2: Partial level scheme diagram showing the high-spin states feeding the terminating state at $I^\pi = 42^+$ in the yrast structure of ^{156}Er. The terminating state is highlighted in red. The spins have been inferred from angular distribution analysis.

Fig. 2. Spectra unfolded directly from the data up to fold eight (γ^8) were produced from the raw data. An example of the high-fold spectra in shown in Fig. 3. This technique has been extended to produce spectra corresponding to the detectors in the different rings of the Gammasphere array, at a fixed angle to the beam direction and hence it has been possible to perform angular distribution analysis.

Detailed study of the ^{156}Er data reveals several previously unknown, high-energy γ rays (1342, 1392, 1621 and 2161 keV) feeding the well-established 42^+ band-terminating state [13], in addition to the known 1057-keV transition. Angular distribution analysis has confirmed that the 1057-keV γ ray is dipole in nature and the other four transitions are of stretched quadrupole (E2) character.

However, these new states beyond band termination only advance the spectroscopy by a further one or two units of spin. The question of what happens at higher spin before the fission point is reached is still open. Careful, high-fold, detailed searches were performed on ^{157,158}Er data and four rotational sequences were found, two in ^{158}Er and two in ^{157}Er [9]. These bands were estimated to be carrying only 10^{-4} of the respective channel intensity and consequently are very hard to pick out. These bands by-pass the terminating states and the weakly collective regime and extend to spins of around $50\hbar$ and above. Cranked Nilsson-Strutinsky calculations indicate that these structures are most likely to be associated with a new shape minimum for strongly deformed, triaxial structures ($\varepsilon_2 \sim 0.37, \gamma \sim 25^o$). The sequences show a high moment of inertia and similar structures, interpreted as Triaxial Strongly Deformed (TSD) bands, are observed in nearby Tm [14, 15], Yb [16] and Lu nuclei. This includes the classic case of ^{163}Lu [17] which provides the best evidence of triaxiality with the observation of a "wobbling" mode.

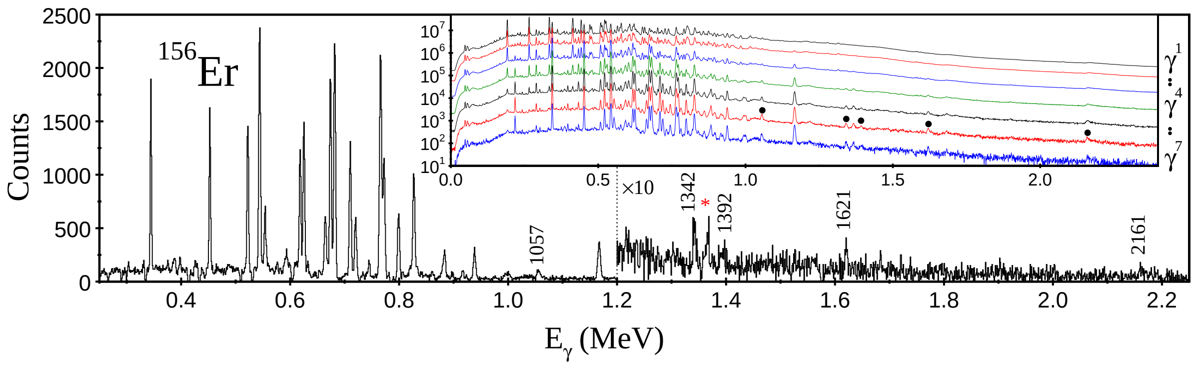

FIG. 3: Multiply gated γ-ray spectra obtained from a high-fold analysis of the data for the positive-parity bands in ^{156}Er. The main spectrum represents a γ^6-gated spectrum (i.e. γ^7 analysis) where a corresponding γ^4-gated spectrum (γ^5) has been used as a background spectrum. Note that above 1.2 MeV, the y axis has been scaled by a factor of ten. The inset shows the raw multiply gated spectra from γ^1 (i.e. no gates) up to γ^7 (6 gates), plotted logarithmically. The five transitions that directly feed the terminating $I^\pi = 42^+$ state are labelled by their energies in keV in the main diagram and denoted by solid circles in the γ^6 inset spectrum.

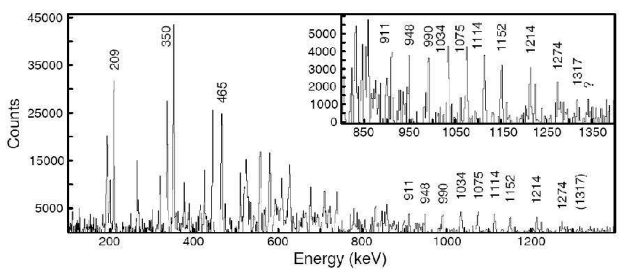

FIG. 4: Sample spectrum showing candidate TSD band in ^{160}Er. The band shows similar properties to the high moment of inertia bands seen in ^{157,158}Er. Full details in [18]. Spectrum by J. Ollier.

The studies of the light erbium nuclei have been extended to ^{159,160,161}Er with a recent experiment. The high-spin states were populated by using a 215 MeV ^{48}Ca beam, produced by the ATLAS accelerator at Argonne National Laboratory, to bombard two stacked, thin, self-supporting foils of ^{116}Cd of total thickness 1.3mg/cm^2. The resulting γ rays were detected by the 101 HPGe detectors of the Gammasphere array and a total of 1.9×10^9 events were collected with the condition that at least seven of the detectors had fired in prompt coincidence. The data were replayed off-line into Radware-format three-dimensional cubes and four-dimensional hypercubes for analysis. Multiply-gated high-fold singles spectra have also been generated as in the previous analysis.

Two candidate TSD bands have been identified in ^{160}Er and a further band in ^{159}Er [18], one of which is shown in Fig. 4. All three bands show the high moment of inertia characteristic of the other TSD candidate bands in the region and initial comparison with theoretical calculations support the triaxial interpretation. Detailed comparisons with theoretical calculations and the finalisation of this analysis is still ongoing and will be reported in full in [18].

The previous work of [19] has been verified and the $(+,+\frac{1}{2})$ band has been extended to $117/2\hbar$. This appears to remain yrast at this spin and no evidence of competing structures with enhanced deformation as observed.

III. SUMMARY

Transitions originating above the energetically favoured band-terminating state have been observed in several of the light erbium nuclei, most recently in ^{156}Er. Following band termination, high spin can be only be generated by core-excited configurations, involving particle-hole excitations from the spherical semi-magic nuclear core. Identifying these states has been of great interest but only provides a mechanism for creating one or two units of spin more, which does not reach the fission limit, hence, the question of what happens in this regime remained.

The observation of weakly populated rotational structures with a high moment of inertia in ^{157,158}Er provides a possible solution for this, as these bands appear to bypass the terminating states. The highly fragmented feeding of a favoured state from single-particle levels is observed in the same nuclei as these collective rotational bands, seemingly in the same spin regime. The fully aligned terminating states are oblate in nature, whereas the new high moment of inertia bands appear to be stable triaxial structures, as comparison to Cranked Nilsson-Strutinsky calculations suggests that these sequences are most likely to be associated with a new triaxial strongly deformed shape minimum. This gives another example of shape coexistence in the nuclear landscape. The TSD minimum becomes yrast at close to spin $60\hbar$, and candidate TSD bands have been observed in Er, Tm, Yb, and Lu isotopes in the N$\sim$90-96 area.

A recent experiment to study high-spin states in ^{159,160,161}Er has extended both the number of favoured terminating states and candidate TSD bands known in the erbium nuclei, and recent analysis of ^{156}Er has also

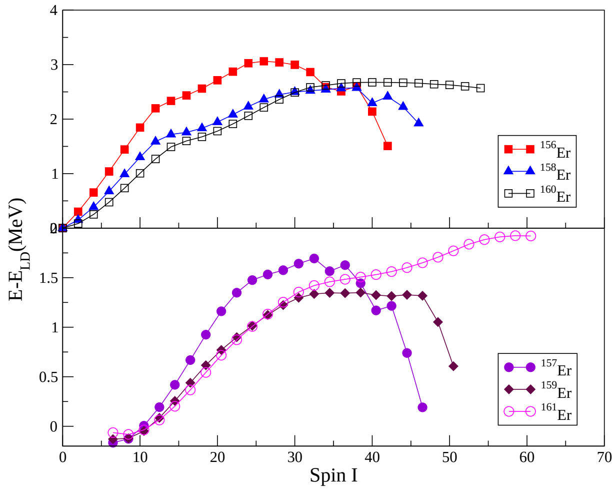

FIG. 5: Rigid-rotor plots comparing the ground-state rotational bands for (top)even-mass erbium isotopes and (bottom) odd-mass erbium isotopes around N≈90. ^{156}Er (filled squares) shows the "classic" band termination behaviour with a sudden decrease at high spin, showing a highly favoured state at $42\hbar$. A similar pattern finishing with an energetically favoured state is seen for ^{157}Er (filled circles) and ^{158}Er (triangles). The latest analysis confirms band termination in ^{159}Er (diamonds) and hints of fragmentation are seen in ^{160}Er (open squares). ^{161}Er, with 5 more valence particles available than ^{156}Er, generates yet more angular momentum and the ground-state band is observed up to I^{π} =117/2^{+}.

added to this knowledge. The abrupt, relatively low-energy termination seen in ^{156}Er at $42\hbar$ is dramatic in contrast with the continuation of the $(+,+\frac{1}{2})$ band in ^{161}Er, which is observed up to 117/2 $\hbar$. A comparison of the yrast bands of $^{156-161}$Er is shown in the rigid rotor plot in Fig. 5, where the favoured band terminating states in $^{156-159}$Er are clearly contrasted against the unpaired band crossing observed in ^{161}Er. Data analysis from the most recent experiment is continuing with results being finalised. A further experiment to investigate the quadrupole moment of the TSD bands in ^{157,158}Er through DSAM lifetime measurements is scheduled to be carried out shortly and will add valuable information to our understanding of these ultra-high spin structures.

Acknowledgments

This work was supported in part by the United Kingdom Engineering and Physical Sciences Research Council (EPSRC) and Science and Technology Facilities Council (STFC), the U.S. Department of Energy under Contract No. AC03-76SF00098, the National Science Foundation, the State of Florida, and the Swedish Science Research Council. Thanks to Dr. D. C. Radford for providing the Radware analysis codes and to the accelerator staff at the Lawrence Berkeley National Laboratory and at Argonne National Laboratory, and to all those involved in the continued upkeep of the Gammasphere array.

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