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STRONGLY DEFORMED NUCLEAR SHAPES AT ULTRA-HIGH SPIN AND SHAPE COEXISTENCE IN $N \sim 90$ NUCLEI*

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The $N \sim 90$ region of the nuclear chart has featured prominently as the spectroscopy of nuclei at extreme spin has progressed. This talk will present recent discoveries from investigations of high spin behavior in the $N \sim 90$ Er, Tm and Yb nuclei utilizing the Gammasphere gamma-ray spectrometer. In particular it will include discussion of the beautiful shape evolution and coexistence observed in these nuclei along with the identification of a remarkable new family of band structures. The latter are very weakly populated rotational sequences with high moment of inertia that bypass the classic terminating configurations near spin 40–50$\hbar$, marking a return to collectivity that extends discrete γ-ray spectroscopy to well over 60$\hbar$. Establishing the nature of the yrast states in these nuclei beyond the oblate band-termination states has been a major goal for the past two decades. Cranking calculations suggest that these new structures most likely represent stable triaxial strongly deformed bands that lie in a valley of favored shell energy in deformation and particle-number space.

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1. Introduction

Fascinating discoveries of new nuclear-structure phenomena at high spin continue to be made in concert with the development of increasingly sensitive multidetector γ-ray arrays [1]. In the rare-earth region of the nuclear landscape nuclei can accommodate the highest values of angular momentum and some central topics have included the spectroscopy of *(i)* superdeformed (SD) nuclei around ^{152}Dy [2]; *(ii)* triaxial strongly deformed (TSD) bands and associated "wobbling" motion in nuclei around ^{163}Lu [3]; *(iii)* highly deformed structures in $A \approx 174$ Hf nuclei [4,5]; and *(iv)* band termination in $N \approx 90$ nuclei [6–13].

This talk will discuss recent discoveries at ultra-high spin from investigations of $N \sim 90$ Er, Tm and Yb nuclei utilizing the Gammasphere gamma-ray spectrometer. The coexistence of a variety of nuclear shapes and their evolution with spin will be discussed along with the identification of a remarkable new family of band structures. The latter are very weakly populated high moment of inertia rotational sequences that bypass the classic terminating configurations near spin 40–50$\hbar$, marking a return to collectivity that extends discrete γ-ray spectroscopy to well over 60$\hbar$. It has been a holy grail over the last two decades to establish the nature of the yrast states in these nuclei beyond the special oblate band-termination states. We have performed cranking calculations that suggest that these new structures most likely represent stable triaxial strongly deformed bands that lie in a valley of favored shell energy in deformation and particle-number space.

The $N \approx 90$ Er isotopes have featured prominently as the spectroscopy of nuclei at extreme spin has progressed. A schematic diagram of the structural evolution with spin in the nucleus ^{158}Er is shown in Fig. 1 where the interplay of numerous co-existing structures near the yrast line is illustrated. The behavior of the shape evolution of this nucleus is given as an example and is typical of nuclei in this region. ^{158}Er was one of the initial nuclei in which Coriolis-induced pair-breaking (backbending) was discovered [14] and the first nucleus in which the second alignment was observed [15]. At spin 38$\hbar$ a dramatic change of structure occurs along the yrast line when less-collective band structures become energetically favored [10,16]. These sequences reach higher spin by aligning their valence single-particle angular momenta, outside the $^{146}_{64}$Gd$_{82}$ doubly magic core, causing the shape of the nucleus to become oblate. The bands then terminate at the maximum value of spin available to the valence particles. In ^{158}Er, band termination occurs at spin 46–49$\hbar$, depending on spin and parity [12] when all of the twelve valence-particle spins are maximally aligned in specific nucleonic configurations. Indeed, this nucleus provides the textbook example of the phenomenon of band termination in heavy nuclei [17, 18].

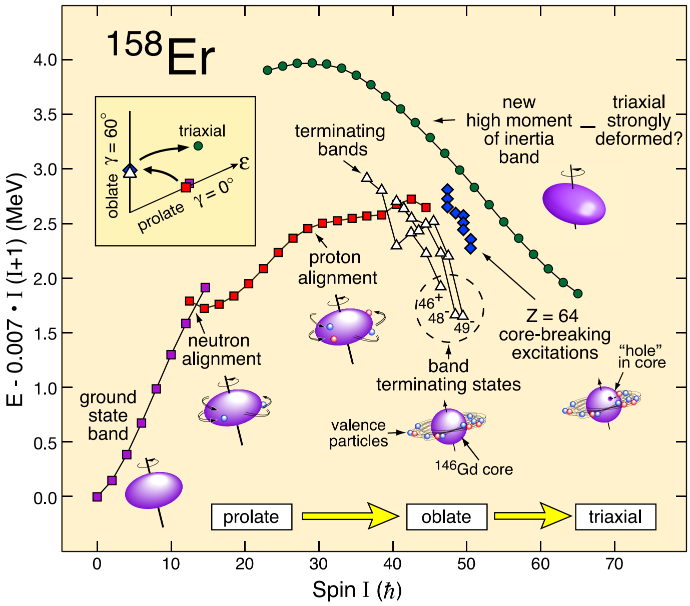

Fig. 1. Evolution of the nuclear structure of ^{158}Er [26]. Excitation energies of a variety of observed structures are plotted with respect to a rigid-rotor reference in order to emphasize the changes that occur along and close to the yrast line as a function of spin. The strongest new high moment-of-inertia band is included, but its exact excitation energy is not known. The insert illustrates the changing shape of ^{158}Er with increasing spin within the standard (ε, γ) deformation plane.

2. Experimental details, results and discussion

It has been a goal for many years to establish the nature of the yrast states in these nuclei in the spin range from 50 to 70$\hbar$, well beyond the very favored band-termination states. An experiment was therefore performed to observe the ultra-high spin structure in ^{156,157,158}Er. The magnificent Gammasphere gamma-ray spectrometer [19] was used, which at the time was located at the 88 Inch Cyclotron accelerator at the Lawrence Berkeley National Laboratory. Ultra-high spin states were populated using a 215 MeV ^{48}Ca beam which bombarded two stacked thin self-supporting 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 of the 102 Compton-suppressed HPGe detectors fired in prompt coincidence. In the analysis, $\approx 6.5 \times 10^{10}$ quadruples (γ^4) were unfolded from the data set and replayed into a Radware-format [20] four-dimensional hypercube for γ-ray coincidence analysis.

Analysis of these data showed that the classic band terminating states in ^{156,157,158}Er were populated by a series of weak high energy transitions [21–24]. In order to interpret the nature of the feeding states calculations were performed in the framework of the configuration-dependent, cranked Nilsson–Strutinsky formalism without pairing [13,25]. These calculations indicated that the feeding states originate mainly from weakly collective (with $\varepsilon_2 = 0.10$–0.15 and $\gamma = 30°$–$45°$) configurations involving core-breaking proton particle-hole excitations across the semi magic $Z = 64$ shell gap [21].

These new states only advanced discrete γ-ray spectroscopy by a further one or two units of spin and the puzzle of the missing spin regime from $50\hbar$ to fission remained. However, after further painstaking searches within the data set four rotational sequences, two in ^{158}Er and two in ^{157}Er, were established which extended discrete levels in ^{157,158}Er to beyond $60\hbar$ [26].

Fig. 2 shows spectra of the most intense rotational bands in ^{157,158}Er that by-pass the terminating states and the weakly collective regime in each of these nuclei. The four bands identified in ^{157,158}Er were estimated to carry at maximum only 10^{-4} of the respective channel intensity, *i.e.* two orders of magnitude lower than the yrast SD band in ^{152}Dy [2]. A high-fold analysis of the intensity profiles at the bottom of the most intense band in ^{158}Er, see insert in Fig. 2, in comparison to feeding intensities into the known normal deformed states allowed an estimation of the highest spin reached by this band of $65\hbar$.

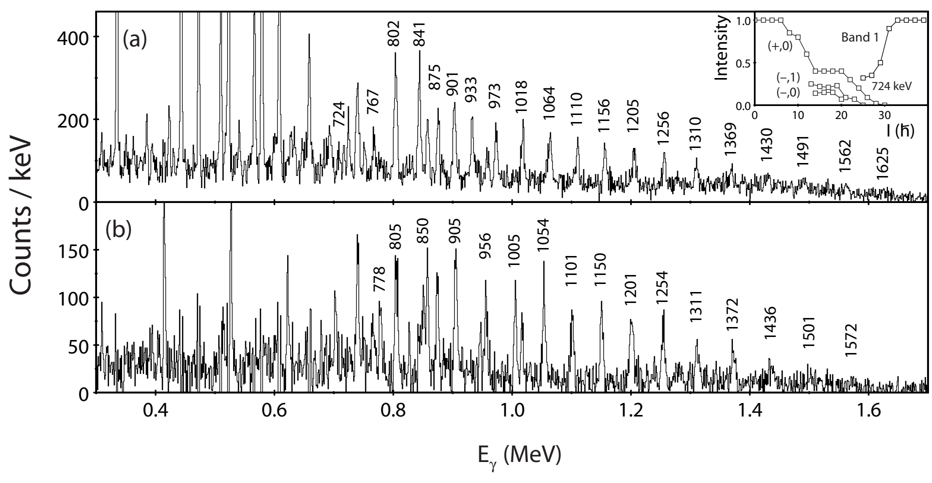

Fig. 2. Background-subtracted coincident γ^5 spectra illustrating the two strongest sequences observed in (a) ^{158}Er and (b) ^{157}Er [26]. The strong unlabeled peaks represent the low-spin yrast structures in these nuclei. The relative intensity profiles of the new (Band 1) sequence in ^{158}Er and known structures around the feedout region are shown in the inset of (a). The latter intensity analysis was important in estimating the spin range of the band.

Cranked Nilsson–Strutinsky calculations were again used to interpret the nature of these bands. Comparison with the calculations suggest that these high moment of inertia sequences are most likely associated with a new shape minimum for strongly deformed ($\varepsilon_2 \sim 0.37$) triaxial ($\gamma \sim 25°$) structures, which is illustrated in Fig. 3. It is suggested that they have a common configuration component involving two neutron holes in the $h_{11/2}[505]_{11/2}$ orbital and two neutron holes in the highest $N_{\rm osc} = 4$ orbital (along with the well known triaxial driving $i_{13/2}$ proton). A valley of favoured shell energy in deformation and particle-number space is formed below these neutron orbitals at triaxial shape. It can be traced through collective bands in Dy nuclei, over the new bands in ^{157,158}Er to TSD bands in Lu nuclei [26].

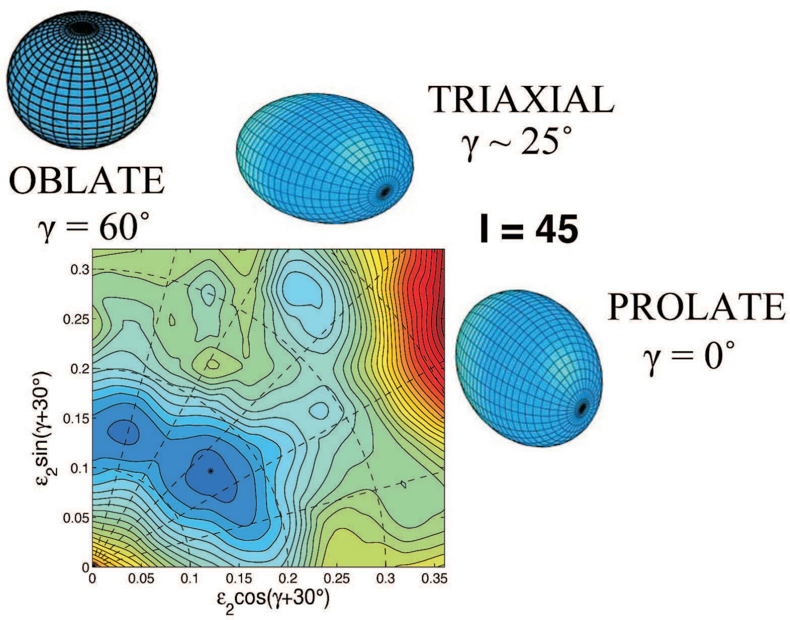

Fig. 3. Calculated potential energy surfaces versus quadrupole deformation ε_2 and triaxiality parameter γ for spin $I = 45$ for (parity, signature) = $(\pi, \alpha) = (-, 1)$ in ^{158}Er. Energy contours are 0.2 MeV. Note the coexistence of competing nuclear shape minima for *(i)* near prolate, *(ii)* near oblate and *(iii)* triaxial strongly deformed. It is the latter which we suggest may be associated with the experimental sequences displayed in Fig. 1.

Fig. 3 displays a typical potential energy surface, which shows three coexisting minima at spin 45 for near prolate, near oblate and triaxial strongly deformed shapes. These shape minima coexist over a broad range of spin values with the TSD minimum coming yrast or close to yrast at spin $\sim 60\hbar$, see also Ref. [9].

The observation of structures with properties consistent with that of triaxial shape extends the region of triaxiality to lighter nuclei from the classic case of ^{163}Lu, see Fig. 4. This nucleus provides the best evidence for triaxial deformation with the observation of a "wobbling" mode, which is unique to a rotating asymmetric nucleus [3]. Whether stable triaxial deformation exists in neighboring nuclei and how far this TSD island extends is an open question. Observations of TSD structures have also been recently reported in ^{163}Tm [27, 28].

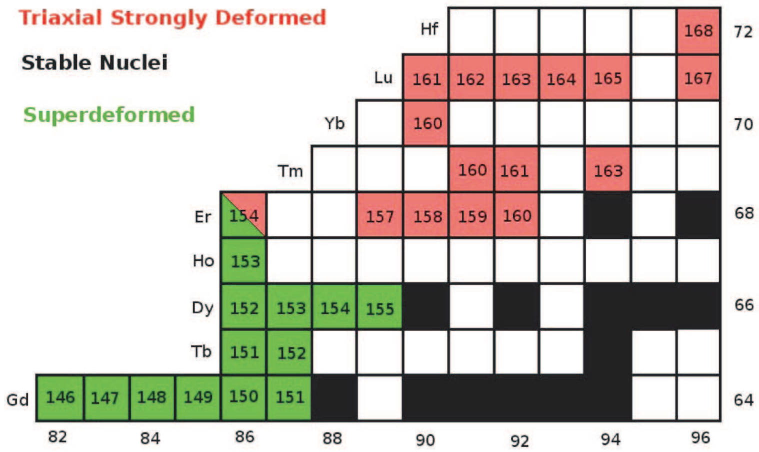

Fig. 4. Section of the nuclear chart showing nuclei that exhibit superdeformed and triaxial strongly deformed structures.

Two additional Gammasphere experiments have established structures, in ^{160}Yb [29] and ^{160,161}Tm [30] (the assignment in ^{161}Tm is tentative) with characteristics similar to the ^{157,158}Er bands discussed above as candidates for strongly deformed triaxial shapes. The results in ^{160}Yb came from a reaction employing a 210 MeV ^{44}Ca beam, provided by the 88-Inch Cyclotron accelerator at the Lawrence Berkeley National Laboratory, bombarding two stacked ^{120}Sn targets of total thickness 0.65 mg/cm^2. A total of 2.26×10^9 fivefold or higher coincidence γ-ray events were collected. A single weakly populated band in ^{160}Yb with a high moment of inertia was observed which exhibited a discontinuity at $\hbar\omega = 0.40$–0.45 MeV. The latter feature can be explained as a crossing between $i_{13/2}$ neutron levels at $\varepsilon_2 = 0.37$, $\gamma \sim 20^\circ$ in our cranking calculations, which lends support to the triaxial interpretation of this structure [29].

High-spin states in ^{160,161}Tm were populated by a 170 MeV ^{37}Cl beam provided by the ATLAS facility at Argonne National Laboratory. The ^{128}Te foils of various thicknesses ranging from 400 to 500 μg/cm^2 were mounted on a rotating target wheel. The side of the targets facing the beam was coated with a $\sim 75\mu$g/cm^2 thick gold foil. The target was also backed with 500 μg/cm^2 thick gold. In addition a beam "wobbling" device was utilized so that a higher beam intensity could be deposited ($\sim$ 2 pnA) on the Te target. A total of 3.5×10^9 fivefold or higher γ-ray coincidence events were collected. Spectra for two very weak rotational sequences are illustrated in Fig. 5. Of note is the fact that the dynamical moment of inertia for the band assigned to ^{161}Tm is identical to that of TSD Band 1 in ^{157}Er indicating a similar parentage of high-j particles in their respective configurations [30]. Also in Fig. 5 potential energy surfaces for ^{161}Tm as a function of spin are plotted. As in the case of ^{158}Er discussed earlier there is an evolution from prolate to oblate to triaxial strongly deformed shape with increasing spin.

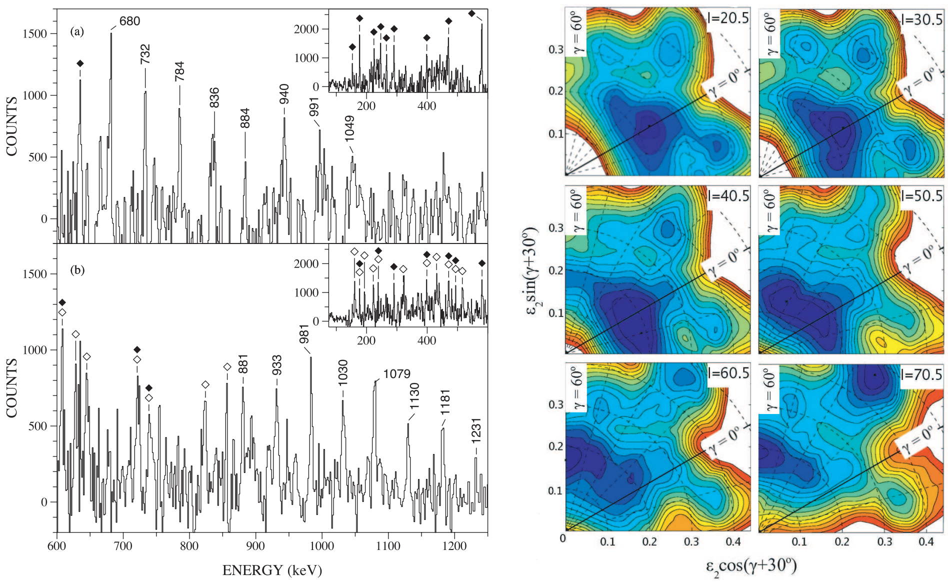

Fig. 5. Left: Background-subtracted spectra of γ rays resulting from summing all triple coincidences of in-band transitions in the TSD bands assigned to (a) ^{160}Tm and (b) ^{161}Tm [30]. The insets show the low-energy part of the spectra where the solid diamonds indicate γ rays associated with ^{160}Tm while the open diamonds indicate known γ ray transitions in ^{161}Tm. Right: Calculated potential energy surfaces versus quadrupole deformation ε_2 and triaxiality parameter γ for spins $I = 20.5$ to 70.5 for (parity, signature) $= (\pi, \alpha) = (+, 1/2)$ structures in ^{161}Tm. The other combinations of (π, α) in this nucleus show similar features.

In order to provide a more consistent picture of the nature of the bands in the Er nuclei we recently performed another experiment to search for possible TSD structures in ^{159,160}Er. This experiment again used Gammasphere at Argonne National Laboratory. High-spin states in ^{159,160}Er were populated by a 215 MeV ^{48}Ca beam bombarding two stacked thin self-supporting foils of ^{116}Cd of total thickness 1.3 mg/cm^2. A total of 1.9×10^9 events were collected when at least seven of the 101 Ge detectors fired in prompt coincidence.

Two candidate TSD band sequences in ^{160}Er and one in ^{159}Er have been identified [31] so far. Spectra for these bands are shown in Fig. 6. The moments of inertia of all TSD and SD bands in Er nuclei are plotted in Fig. 7. At the present time we are finalizing the analysis of these data and detailed comparisons with theoretical calculations are ongoing.

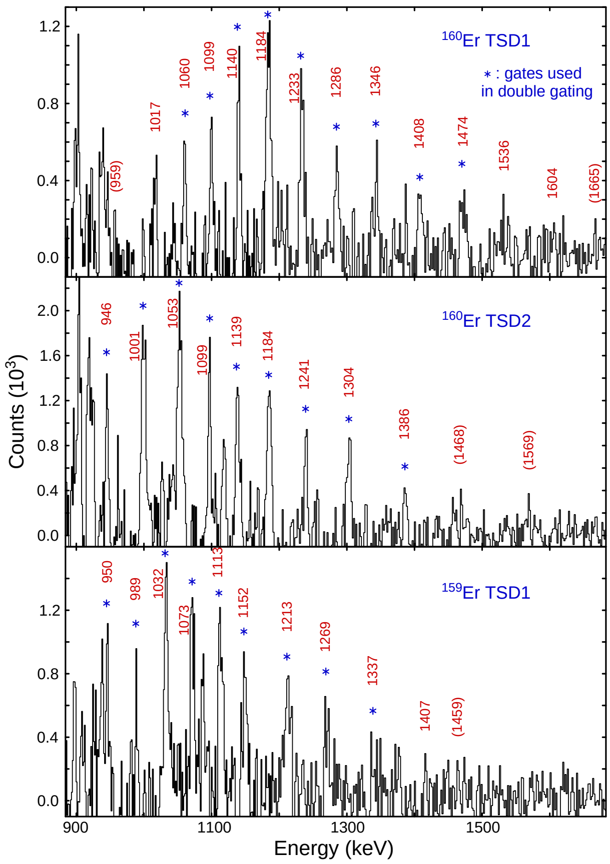

Fig. 6. Background-subtracted coincident γ^3 spectra illustrating the new high moment of inertia sequences observed in ^{160}Er and ^{159}Er.

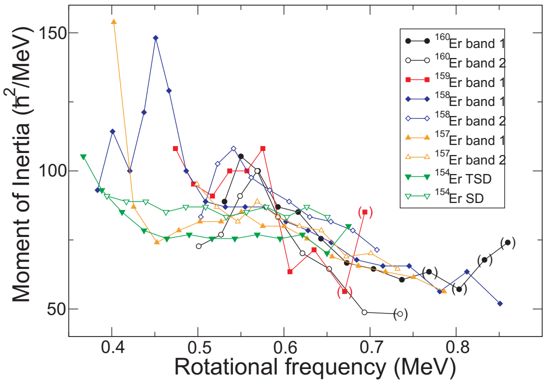

Fig. 7. Dynamical moments of inertia for SD and TSD candidate bands in the light Er nuclei [26,31,32].

3. Summary

After several decades, the answer to the question "What happens above band termination?" in $A \sim 160$ nuclei around $I = 45$–50 has been answered. Exquisite examples of shape coexistence have been identified and a new frontier at ultra-high spin in these nuclei has opened up with the discovery of a family of high moment of inertia collective sequences which extend as high as $I = 65$. These extremely weak intensity band structures have now been established in a number of $N \sim 90$ Er, Tm and Yb nuclei. It is suggested that they may correspond to strongly deformed triaxial shapes. Interestingly our quest to observe TSD structures in light Er nuclei goes back as far as 1989. Many connections and similarities are beginning to unfold between these new structures and the classic superdeformed (^{152}Dy), triaxial superdeformed (^{163}Lu) and strongly deformed (^{174}Hf) regions. Much work, both theoretical and experimental, of course remains to be done. A lifetime experiment using the Gammasphere spectrometer to measure the quadrupole moment of the ^{157,158}Er bands will be performed in the very near future.

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