# The fascinating nuclear structure world of Erbium-158

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| Abstract: | |
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# The fascinating nuclear structure world of Erbium-158

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***Key Words:***
Nuclear structure; Gamma-ray spectroscopy; Angular momentum/Spin; Excitation energy; Nuclear shape; Band termination; Transition quadrupole moment

The response of atomic nuclei to increasing angular momentum (or spin) and excitation energy is one of the most fundamental topics of nuclear structure research and is often studied through high resolution gamma-ray spectroscopy. Erbium-158 ($^{158}$Er) is widely considered as a classic nucleus in this field since it exhibits a number of beautiful structural changes as it evolves with increasing excitation energy and angular momentum. At low spin it behaves like a weakly deformed prolate quantum rotor, similar to many other rare earth nuclei. With increasing angular momentum it undergoes Coriolis induced alignments of high-j neutron or proton pairs until a dramatic prolate collective to oblate non-collective transition eventually takes place via the mechanism of band termination. At the highest spins, a spectacular return to collective rotation is observed in the form of triaxial strongly deformed structures. This latter suggestion is based on a comparison of energies, spins, and transition quadrupole moments (Qt) between experiment and theory. This observation confirms the long standing prediction that such heavy nuclei will possess non-axial shapes on their path towards fission.

## Nuclear structure physics and gamma-ray spectroscopy

Nuclear structure physics concentrates on understanding the structure, behavior and properties of atomic nuclei, which make up 99.9% of the mass of our everyday world. At the present time there are 118 known elements and over 3100 known isotopes of which approximately 270 are stable. The latter are plotted in Fig. 1. One of the great quests of nuclear structure physics is to reach out and discovery the limits of nuclear existence both in proton number **Z** and neutron number **N**. Large efforts worldwide are being undertaken to map out the so-called proton and neutron drip lines which define the limits of nuclear existence. Intense studies are also being conducted to understand the pathways far from the line of stability which are taken in the processes that create the heavy elements beyond Iron. This plot of **N** and **Z** is similar in many ways to the well known Periodic Table of Elements in chemistry. For example, certain nuclei exhibit "magic numbers" which represent especially favored or stable numbers of protons and neutrons akin to the noble gases. These special numbers and their periodicity arise from the underlying quantal shell structure in both atomic and nuclear systems. Note that the numbers are not the same in the two systems since in nuclei the spin-orbit interaction plays a dominant role. These numbers (2, 8, 20, 28, 50, 82, and 126) correspond to closed shells and are indicated in Fig. 1. The colored shading in Fig 1 indicates the degree of the ground-state deformation or shape of nuclei. It can be seen that as one moves away from the magic numbers the deformation is strongly dependent on the number of "valence" nucleons (protons and neutrons). Again this is similar to atomic systems where the number of valence electrons determines an element's chemical properties.

Another great quest in nuclear structure physics is to explore the behavior of nuclei at the limits of angular momentum and excitation energy. This is shown in Fig. 1 by the third angular momentum/spin (**I**) axis. These studies give us deep insight into the many body nuclear problem and especially the role of the "intruder" orbitals which help define the magic numbers above and which play a dominant part in determining the properties (shapes, moments of inertia, pairing correlations, collectivity, etc.) of nuclei at high spin. In fact, it was as early as 1937 that Bohr and Kalckar proposed that we could learn about the evolving structure and shape of excited nuclei by detecting their gamma-ray emissions. Again this is similar to investigating atomic or molecular structure by the radiation emitted when these systems are excited. Indeed, to this day gamma-ray spectroscopic studies based on novel detector technologies continue to revolutionize our understanding of the atomic nucleus revealing an extremely rich system that displays a wealth of static and dynamical facets. For example, as shown in Fig. 2, the discoveries in $^{158}$Er have benefited enormously from the progression of detector technology. The next major step is to move towards the goal of a 4π Germanium ball utilizing the mechanism of gamma-ray energy tracking. This will bring yet another revolution to the field of gamma-ray spectroscopy and usher in a new era in nuclear structure physics.

## Level structures up to band termination in Erbium-158

In the field of high spin nuclear physics, the rare earth region has always been one of the most favored regions since nuclei here can accommodate the highest values of angular momentum. In particular, in the Erbium-158 ($^{158}$Er: Z = 68, N = 90) nucleus numerous fascinating phenomena have been observed with increasing excitation energy and angular momentum (see Fig. 2), and, it is widely acknowledged as a textbook example of the evolution of nuclear structure. For example, as the angular momentum increases, this nucleus exhibits Coriolis-induced rotational alignments of both neutron and proton pairs along the yrast line (the line that defines the lowest state in energy for a given angular momentum); see Figs. 2 and 3. Erbium-158 was among the first in which backbending, i.e., rotational alignment of a pair of high-j neutrons (see Fig. 3), was discovered (spin I ~ 14), and it was the first nucleus where a second alignment, of high-j protons, at I ~ 28 and a third anomaly at I ~ 38 in the moment of inertia along the yrast line were identified. When spin values reach 40 - 50hbar, a very different structure becomes most energetically favored (i.e., yrast), where this nucleus undergoes a dramatic shape transition from a collective prolate (American football shape) rotation to non-collective oblate (M&M candy shape) configurations. The latter terminates at an energetically favored state where the valence nucleons outside the Gadolinium-146 ($^{146}$Gd: Z = 64, N = 82) semi-magic spherical core all have their spins fully aligned in the same direction.

Band termination represents a clear manifestation of mesoscopic physics, since the underlying finite-particle basis of the nuclear angular momentum generation is revealed. In $^{158}$Er, three terminating states, $46^+$, $48^-$, and $49^-$, have been observed (see Figs. 2 and 3). Other neighboring nuclei were also found to exhibit similar fully aligned states.

## Level structures beyond band termination in Erbium-158

It had been a goal for several decades to establish the nature of the states in the rare earth nuclei well beyond the very favored band terminating states. Several years ago, a number of weak, individual transitions feeding into the terminating states were observed in $^{158}$Er (and its neighbor $^{157}$Er), but this only extended the highest spin by 1 - 2hbar. The related levels above band termination have been suggested to arise from weakly collective single-particle excitations that break the $^{146}$Gd core (see Fig. 2). More significantly, in 2007, two rotational structures, displaying high dynamic moments of inertia and possessing very low intensities (~ $10^{(-4)}$ of the respective channel intensity), in $^{158}$Er were identified; see Fig. 3. These structures bypass the well-known “band terminating” states and extend over a spin range of ~ 25 - 65hbar, marking a spectacular return to collectivity at spins beyond band termination. These sequences have properties, for example, moment of inertia values that are very different from the lower spin states (see Figs. 2 and 3). Thus, a new frontier of discrete-line gamma-ray spectroscopy towards spin ~ 70hbar (the so-called “ultrahigh-spin regime”) in $^{158}$Er was opened.

The new ultrahigh spin bands in $^{158}$Er were initially proposed to be triaxial strongly deformed (TSD) structures solely based on theoretical calculations. A triaxial nuclear shape has distinct short, intermediate, and long principal axes (see Fig. 3). At high spin, collective rotation about the short axis is expected to be energetically favored over rotation about the intermediate axis (and even more so over the long axis) based on moment of inertia considerations. In a later study using the Doppler Shift Attenuation Method (DSAM), the transition quadrupole moments (Qt) of the ultrahigh spin bands in $^{158}$Er were experimentally determined to be ~ 9 - 11 eb. As the low spin collective yrast band in $^{158}$Er has a measured Qt of ~ 6 eb, this result demonstrates that the ultrahigh spin bands in $^{158}$Er are all associated with strongly deformed shapes. However, the measured Qt values appear to be too large for the calculated energetically favored TSD shape (rotating about the short axis and with a calculated Qt ~ 7.4 eb). This puzzling discrepancy has attracted much attention and has motivated more sophisticated theoretical calculations which allow the angular momentum vector to “tilt” between the two minor axes. However, a fully coherent understanding has not yet emerged.

A large number of questions arise from the striking observation of the return of collectivity and unusual nuclear shapes beyond band termination in $^{158}$Er. An extended systematic study of ultrahigh spin phenomenon in nuclei around $^{158}$Er is in progress from which we hope to find answers to the mysteries of the evolution of nuclear structure at the limits of angular momentum and excitation energy.

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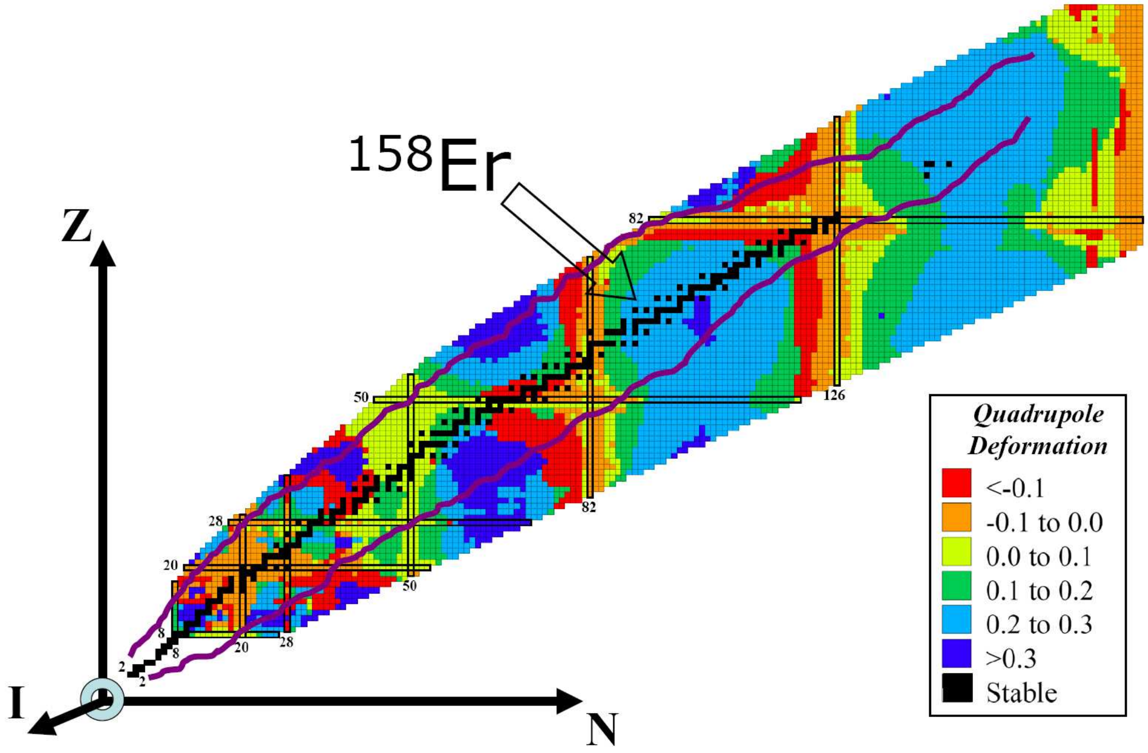

Fig. 1. Chart of nuclei and their calculated ground state quadrupole deformations as a function of neutron number (**N**) and proton number (**Z**). “Magic numbers” (2, 8, 20, 28, 50, 82, and 126) which correspond to closed shells are labeled. The present limits of experimental known nuclei are between the two thick violet lines above and below the stable nuclei (black squares). A third axis of angular momentum or spin (**I**) is also shown and it is the evolution of nuclear structure along this axis that this article addresses. The location of the $^{158}$Er nucleus is marked.

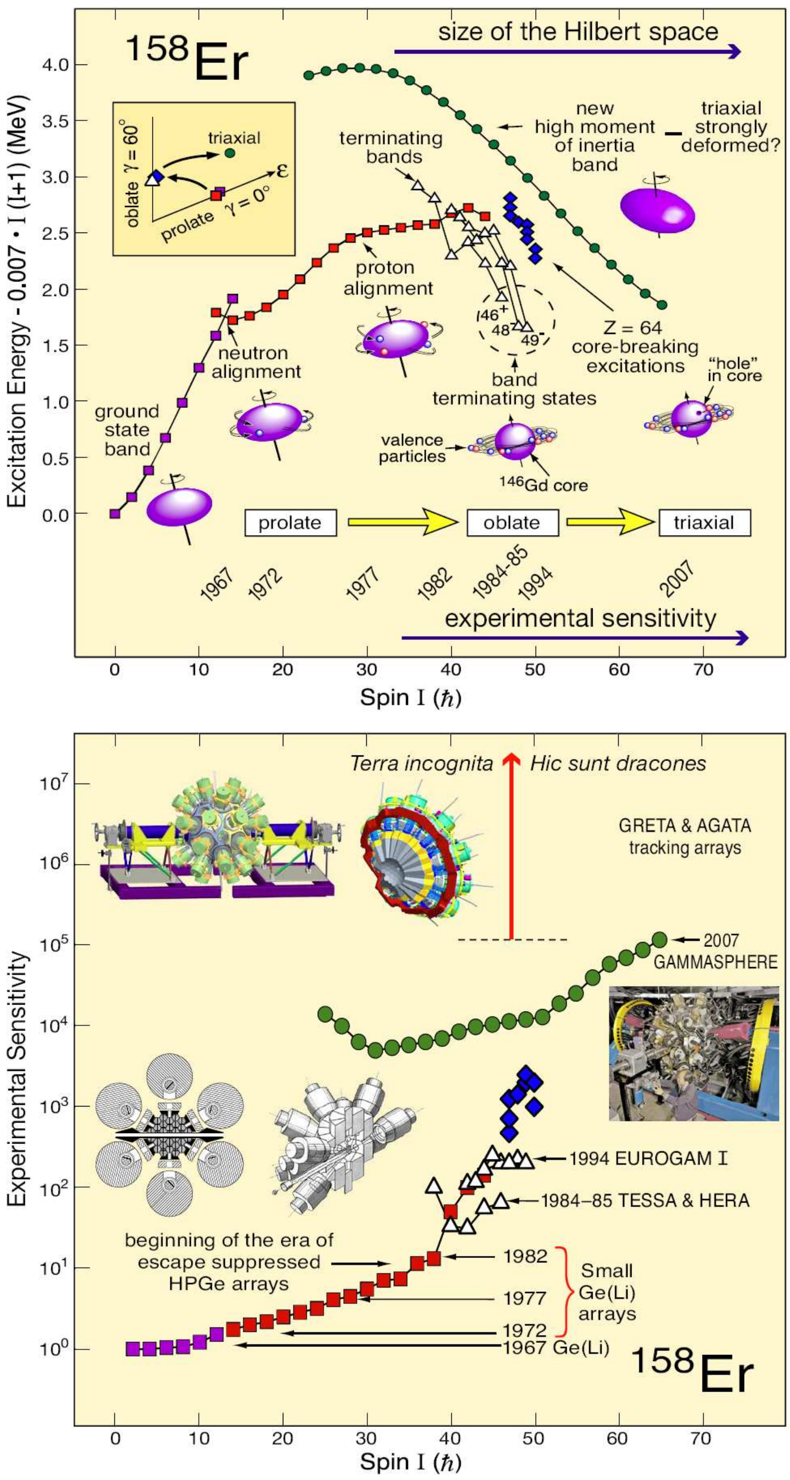

Fig. 2. Top: the evolution of nuclear structure in $^{158}$Er with excitation energy and angular momentum (spin). The inset illustrates the changing shape of $^{158}$Er with increasing spin within the standard (ε, γ) deformation plane. Bottom: the experimental sensitivity of detection (proportional to the inverse of the observed gamma-ray intensity) is plotted as a function of spin showing the progression of gamma-ray detector technology with time that are associated with nuclear structure phenomena in $^{158}$Er.

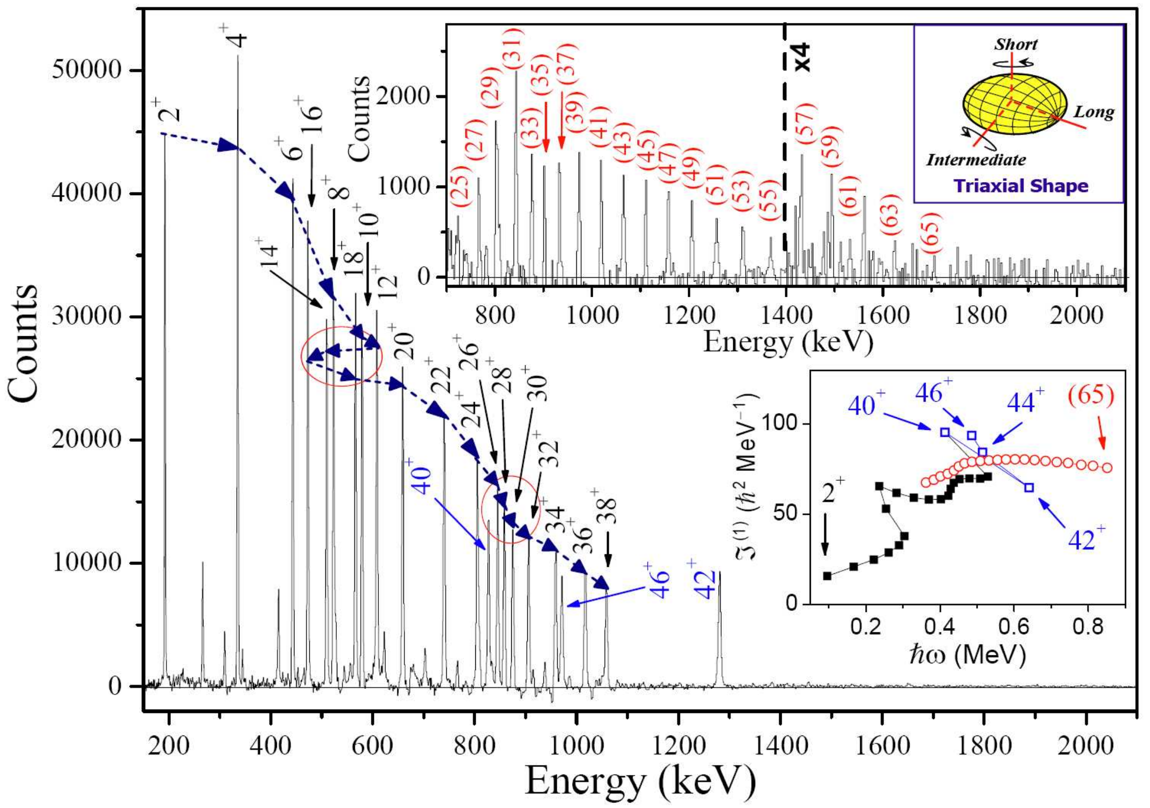

Fig. 3. Coincidence gamma-ray spectrum representative of the yrast band in $^{158}$Er (in coincidence with the $44^+ \rightarrow 42^+$ transition). The observed neutron (Energy ~ 550 keV, spin I ~ 14) and proton (Energy ~ 850 keV, I ~ 28) rotational alignments are marked in red circles. Upper inset: coincidence spectrum representative of the most intense collective band at ultrahigh spin (band 1) observed in $^{158}$Er. The portion of this spectrum above 1400 keV has been magnified by a factor of 4. The spins assigned are tentative and the parity of the sequence is not known. Transitions are all labeled with the states (spin$^{\text{parity}}$) which they decay from. Triaxial nuclear shape that the ultrahigh spin bands are associated with is schematically illustrated at the upper-right corner. Lower inset: moments of inertia, $\Im^{(1)}$, as a function of rotational frequency, hbar*ω, for the yrast sequence and band 1 in $^{158}$Er. Note that the $\Im^{(1)}$ line bends back (towards lower rotational frequency) with increasing spin when the neutron alignment occurs (hbar*ω ~ 0.25 MeV), hence the name "backbending". The $40^+$, $42^+$, $44^+$, and $46^+$ states are based on a configuration that terminates at the $46^+$ non-collective oblate state. The triaxial collective band shown extends up to a spin of ~ 65hbar.