The fascinating γ-ray world of the atomic nucleus: The evolution of nuclear structure in ^{158}Er and the future of γ-ray spectroscopy

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Abstract The rare-earth nucleus ^{158}Er exhibits a number of beautiful structural changes as it evolves with increasing excitation energy and angular momentum. After undergoing Coriolis induced alignments of high-j neutron and proton pairs, a dramatic prolate collective to oblate non-collective transition 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 bands. This latter suggestion is based on a comparison of transition quadrupole moments (Q_t) between experiment and theory, and long standing predictions that such heavy nuclei will possess nonaxial shapes on their path towards fission. These exciting discoveries in ^{158}Er have benefited greatly from the progression of γ-ray detector developments through recent decades. The new γ-ray energy tracking technique and the next generation detector arrays utilizing this technique, *e.g.*, GRETINA (1π) and GRETA (4π), are briefly discussed.

1 The evolution of nuclear structure in ^{158}Er

In 1937 Bohr and Kalckar [1] proposed that we could learn about the structure of nuclei by detecting their γ-ray emissions. Indeed, to this day γ-ray spectroscopic studies continue to revolutionize our understanding of the atomic nucleus revealing an extremely rich system that displays a wealth of static and dynamical facets. One of the most fundamental and fascinating topics of research in γ-ray spectroscopy

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is the response of atomic nuclei to increasing angular momentum and excitation energy [2], often referred to as high spin nuclear physics.

In the field of high spin nuclear physics, the rare-earth region has always been one of the most favored domains since nuclei here can accommodate the highest values of angular momentum. The ^{158}Er ($N = 90$) nucleus has become a textbook example in terms of the evolution of nuclear structure with increasing excitation energy and angular momentum [3, 4, 5]. The discoveries in ^{158}Er illustrated in Fig. 1 have benefited much from the progression of detector techniques. On the other hand, the excitement generated by these observations and discoveries in other nuclei have also pushed the advancement of γ-ray detector systems.

As displayed in Fig. 1, many fascinating phenomena have been observed in ^{158}Er. For example, as the angular momentum increases, this nucleus exhibits Coriolis-induced alignments of both neutron and proton pairs along the yrast line (see Fig. 2). It was among the first in which backbending was discovered [6] ($I{\sim}14$), but it was also the first nucleus where the second ($I{\sim}28$) and third ($I{\sim}38$) discontinuities along the yrast line were identified [7, 8]. At spins $40-50\hbar$, the yrast line is crossed by a very different structure, where the ^{158}Er nucleus undergoes a dramatic shape transition from a prolate collective rotation to non-collective oblate configurations [9, 10, 11]. This transition manifests itself as favored, fully aligned band termination. In ^{158}Er, three terminating states, 46^+, 48^-, and 49^-, have been observed [11]. Band termination occurs when the valence nucleons outside the ^{146}Gd spherical core are fully aligned with the axis of collective rotation [12, 13, 14]. A schematical illustration of band termination is shown in Fig. 3. It represents a clear manifestation of mesoscopic physics, since the underlying finite-particle basis of the nuclear angular momentum generation is revealed [4, 5]. Experimentally there is a huge drop in intensity of γ rays above the terminating state. For example, relative to the decay from the 46^+ terminating state in ^{158}Er, the feeding transitions above this state observed in the $1300-2000$ keV energy range are lower in intensity by at least one order of magnitude, see Fig. 4 (a).

2 The return of collective rotational band structures at spins beyond band termination in ^{158}Er

It had been a goal for decades to establish the nature of the states in the rare earth nuclei well beyond the very favored band-termination states (in the spin range of $40-50\hbar$). In 2007, a new frontier of discrete-line γ-ray spectroscopy in the spin $50-70\hbar$ range (the so-called "ultrahigh-spin regime") was opened. Four rotational structures in ^{158}Er and ^{157}Er (two in each nucleus), displaying high dynamic moments of inertia and possessing very low intensities ($\sim 10^{-4}$ of the respective channel intensity), were identified and extended up to spin $\sim 65\hbar$ [15]. These structures bypass the well-known "band-terminating" states, marking a return to collectivity at spins beyond band termination. As shown in Figs. 1 and 4, the ultrahigh spin bands have properties significantly different from the low-lying collective prolate

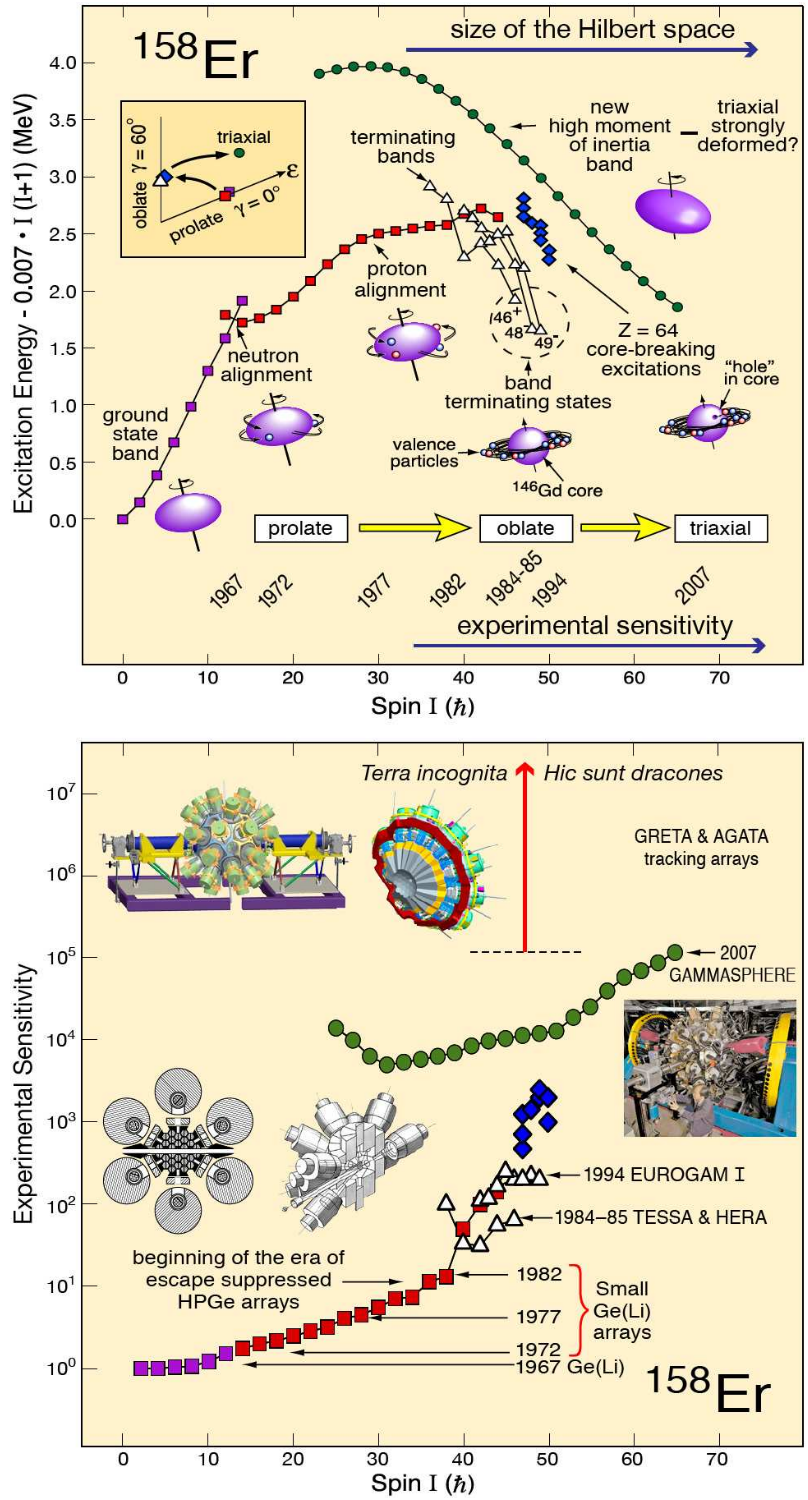


Fig. 1 (Color online) Top: the evolution of nuclear structure in ^{158}Er with excitation energy and angular momentum (spin). The inset illustrates the changing shape of ^{158}Er with increasing spin within the standard (ε, γ) deformation plane. Bottom: the experimental sensitivity of detection is plotted as a function of spin showing the progression of γ-ray detector techniques with time that are associated with nuclear structure phenomena in ^{158}Er.

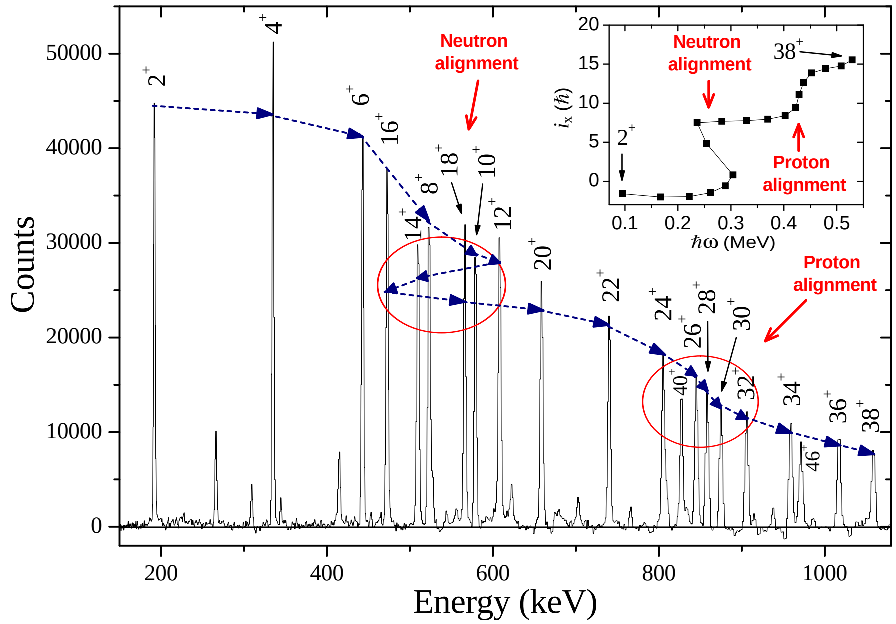


Fig. 2 (Color online) Coincidence γ-ray spectrum representative of the yrast band in ^{158}Er. Inset: experimental aligned spin (*i.e.*, angular momentum in the intrinsic reference frame of a nucleus), i_x, as a function of the rotational frequency, $\hbar\omega$, for the same band. The observed neutron and proton alignments are marked in both the spectrum and the aligned spin plot. Note that the i_x line bends back (towards lower rotational frequency) with increasing spin when the neutron alignment occurs, hence the name "backbending".

bands (normal deformed) or the non-collective oblate states. These bands were proposed to be triaxial strongly deformed (TSD) structures [15], consistent with the predictions of the early cranking calculations of Bengtsson and Ragnarsson [12] and Dudek and Nazarewicz [13]. Thus, a new chapter in the story of ^{158}Er began.

It is worth mentioning that a triaxial nuclear shape has distinct short, intermediate, and long principal axes, as shown in Fig. 5. This shape is commonly described using the parameters (ε_2, γ) of the Lund convention [16], where ε_2 and γ represent the eccentricity from sphericity and triaxiality, respectively. At high spin, collective rotation about the short axis, corresponding to a positive γ value ($0^\circ < \gamma < 60^\circ$), usually has the lowest excitation energy based on moment of inertia considerations [17, 18]. Thus, this mode is expected to be favored over rotation about the intermediate axis ($-60^\circ < \gamma < 0^\circ$). In ^{158}Er, configurations with $\varepsilon_2 \sim 0.34$ and a positive value of $\gamma = 20^\circ - 25^\circ$ were predicted to be low in energy theoretically and, were thus initially adopted to interpret the collective bands at ultrahigh spin [15]. However, it was imperative to determine their deformation experimentally in order to elucidate their character further and to test the above predictions.

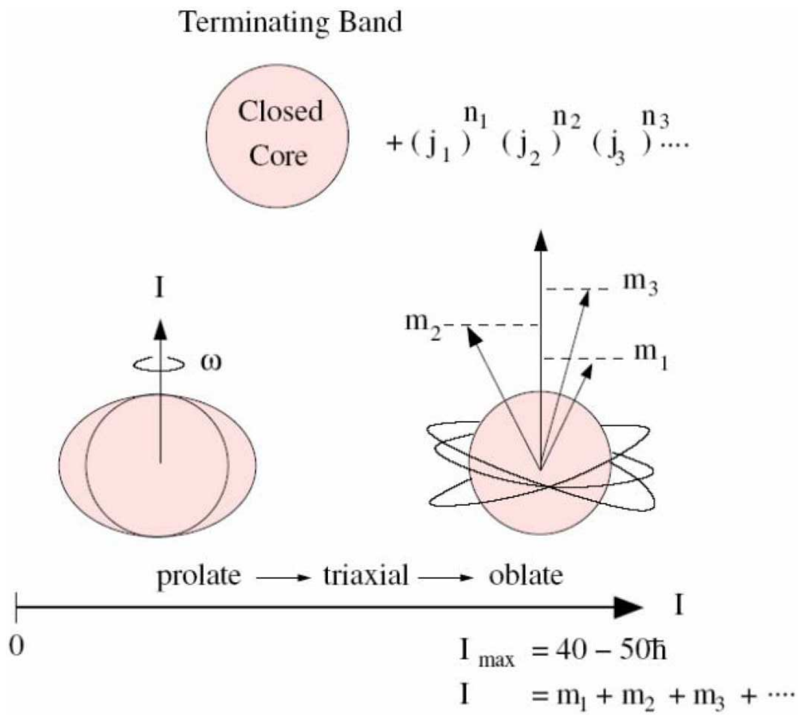


Fig. 3 (Color online) A schematical illustration of the band termination phenomenon. See text for details. Adopted from Ref. [14].

A follow-up experiment to measure the transition quadrupole moments was carried out using the Doppler Shift Attenuation Method (DSAM) [19]. A 215 MeV ^{48}Ca beam was delivered by the ATLAS facility at Argonne National Laboratory in the USA and bombarded a 1 mg/cm^2 ^{114}Cd target backed by a 13 mg/cm^2 ^{197}Au layer. A 0.07 mg/cm^2 ^{27}Al layer between Cd and Au was used to prevent the migration of the target material into the backing. The emitted γ rays were detected by the Gammasphere spectrometer [20]. More details of this DSAM experiment can be found in Refs. [21, 22]. Compared with the previous thin-target experiment [15], the enhanced statistics of the DSAM experiment allowed the observation of a new collective band at ultrahigh spin in ^{158}Er (band 3), which was estimated to carry an intensity of only $\sim$10% of the strongest collective band at ultrahigh spin (band 1). In spite of their extremely low intensities, an analysis of fractional Doppler shifts $F(\tau)$ was conducted for the three bands in ^{158}Er (see Ref. [21] for details). The transition quadrupole moments (Q_t) of bands 1 and 2 in ^{158}Er have been published in Ref. [21], while the preliminary result for band 3 was reported in Ref. [22].

The transition quadrupole moments Q_t of the three collective bands at ultrahigh spin in ^{158}Er have been experimently determined to be $\sim 9-11$ eb, as shown in Fig. 6. This result demonstrates that they are all associated with strongly deformed

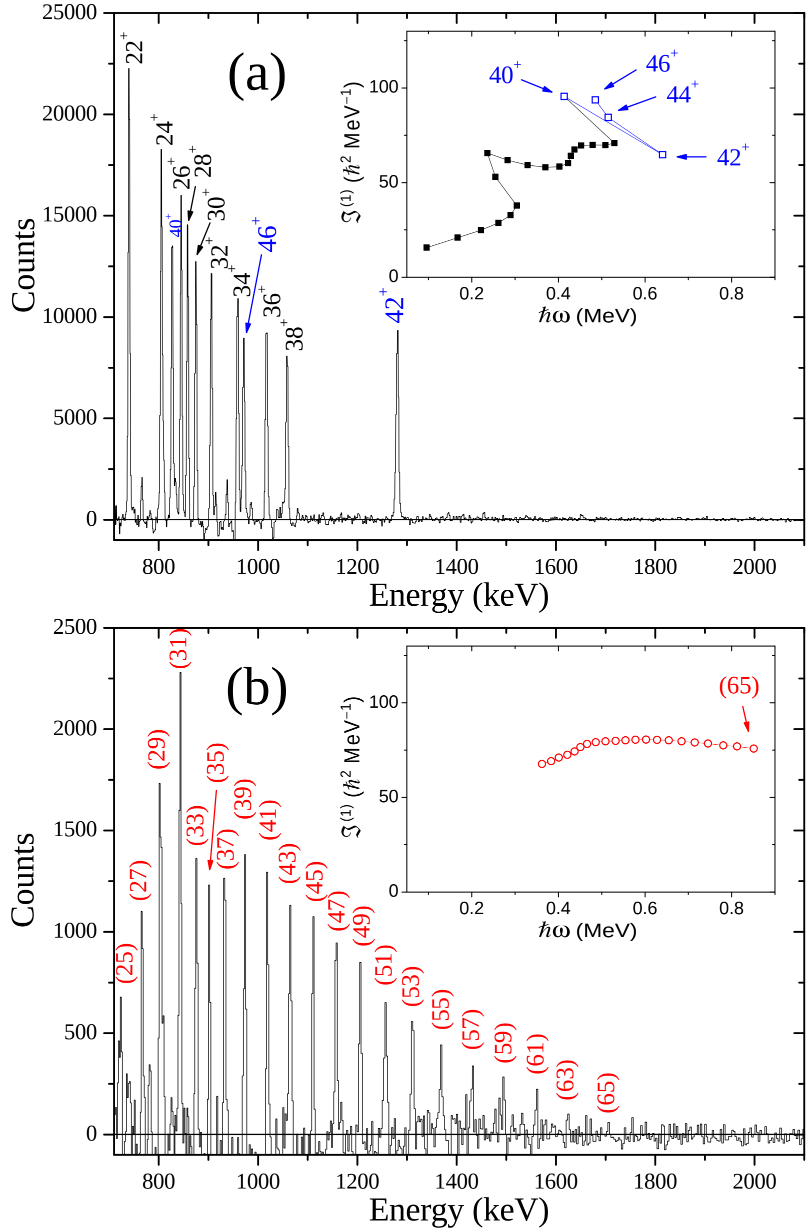


Fig. 4 (Color online) (a): Sample spectrum highlighting the high spin γ-ray transitions of the yrast band in ^{158}Er from the thin target data [15] (in coincidence with the $44^+ \rightarrow 42^+$ transition and any one of the transitions between the 38^+ and the 22^+ states in the yrast band). The huge drop in intensity of γ rays above the 46^+ terminating state (marked in blue) is evident, see text for details. (b): Coincidence spectrum representative of the strongest collective band at ultrahigh spin (band 1) observed in ^{158}Er from the same data as (a). The spins assigned are tentative and the parity is not known for band 1. In both (a) and (b), transitions are marked with the states (spin$^{\text{parity}}$) which they decay from. Insets: kinematic moments of inertia, $\Im^{(1)}$, as a function of rotational frequency, $\hbar\omega$, for the yrast sequence and band 1 (see also Sec. 2) in ^{158}Er. The 40^+, 42^+, 44^+, and 46^+ states are based on a configuration that terminates at the 46^+ non-collective oblate state, while band 1 (collective) extends up to a spin of $65\hbar$. Note that the collective band beyond band termination has a behavior of $\Im^{(1)}$ significantly different from the structures shown in (a).

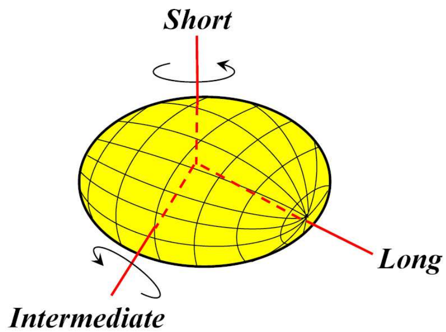


Fig. 5 (Color online) A schematical illustration of a triaxial nuclear shape. The distinct short, intermediate, and long principal axes are marked.

shapes, since the low spin yrast band in ^{158}Er has a measured Q_t of $\sim$ 6 eb [23]. However, the measured Q_t values appear too large for the energetically favored positive-γ (rotation about the short axis) triaxial shape (TSD1: $\varepsilon_2{\sim}0.34$). Rather, they are more compatible with a negative-γ (rotation about the intermediate axis) triaxial deformed minimum (TSD2: $\varepsilon_2 \sim 0.34$) or a positive-γ minimum with larger deformation (TSD3: $\varepsilon_2{\sim}0.43$) within the current cranked Nilsson-Strutinsky (CNS) theoretical framework [24].

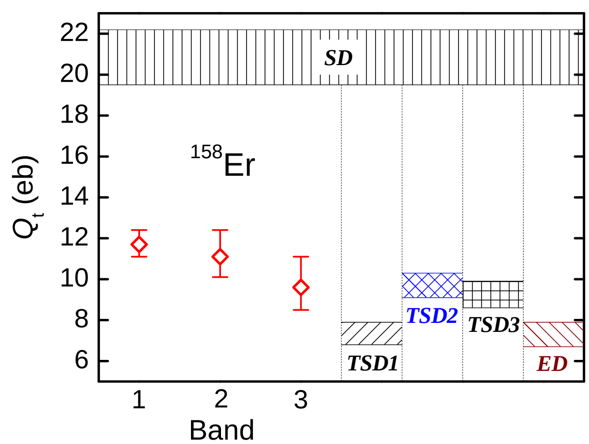


Fig. 6 (Color online) Measured transition quadrupole moments Q_t (plotted with diamonds) of the three bands at ultrahigh spin in ^{158}Er, compared with the theoretical Q_t values (horizontal shaded areas) associated with the minima of interest calculated in the CNS model [21] (ED: enhanced deformed; SD: superdeformed). See text for the definitions of the three TSD minima.

This puzzling discrepancy in our Er work has recently motivated another theoretical study in which calculations using the 2-dimensional tilted axis cranking

(TAC) method [25] based on a self-consistent Skyrme-Hartree-Fock (SHF) model were conducted for configurations associated with triaxial shapes at ultrahigh spin in ^{158}Er [26]. In this TAC/SHF work, it is shown that the negative-γ minimum (rotation about the intermediate axis) becomes only a saddle point when titled cranking is considered and, thus, the previously mentioned TSD2 minimum may be removed from consideration. The calculated Q_t value for a candidate positive-γ triaxial minimum with large deformation ($\sim$ 10.5 eb) also agrees well with the experimental values, nevertheless, this minimum does not become yrast until spin $\sim 70\hbar$. Thus, the question "where are the band structures associated with the most energetically favored TSD minimum?" still remains open.

3 An extended study of collective bands at spins beyond band termination in the rare earth region

Several questions naturally arise from the above striking observations of collective band at spins beyond band termination in ^{158}Er. For example, is observation of such structures a general feature of the light rare-earth nuclei? How do properties of these minima with exotic shapes change with Z and N? In fact, the recent discoveries in ^{158}Er have triggered a comprehensive project to explore this phenomenon in the light rare earth nuclei with a mass of $150-165$. The primary aim of this ongoing project is to bridge our physics understanding of the evolution of nuclear structure between the well known SD (superdeformed) domain of the Gd, Tb, and Dy nuclei (^{152}Dy [27], for example) and the lower spin TSD/Wobbling regime of the Lu nuclei (^{163}Lu [28], for example) and the neighbors (^{167}Ta [29], for example) in the nuclear landscape, as illustrated in Fig. 7.

Our research plan for this project is currently conducted along two directions: in the Er isotopes and in the $N = 90$ isotones. So far, collective bands with similar characteristics to the ^{158}Er case have also been found in the Er isotopes, *e.g.*, ^{154}Er [30, 31] and ^{160}Er [32], as well as in the $N = 90$ isotones, *e.g.*, ^{160}Yb [33] and ^{157}Ho [22]. A new DSAM experiment of ^{160}Yb has been approved and is expected to be performed soon at the ATLAS facility at Argonne National Laboratory.

4 The γ-ray tracking technique and the new generation of detector arrays

Every major advance in γ-ray detector techniques and systems has resulted in significant progress in studying the nuclear structure of rapidly rotating nuclei, as illustrated, for example, in ^{158}Er (Fig. 1). The current state-of-the-art 4π γ-ray detector arrays, for example, Gammasphere at Argonne National Laboratory (ANL) in the USA [20] which consists of more than 100 large volume HPGe detectors each surrounded by a Compton-suppression shield, have pushed this particular detector

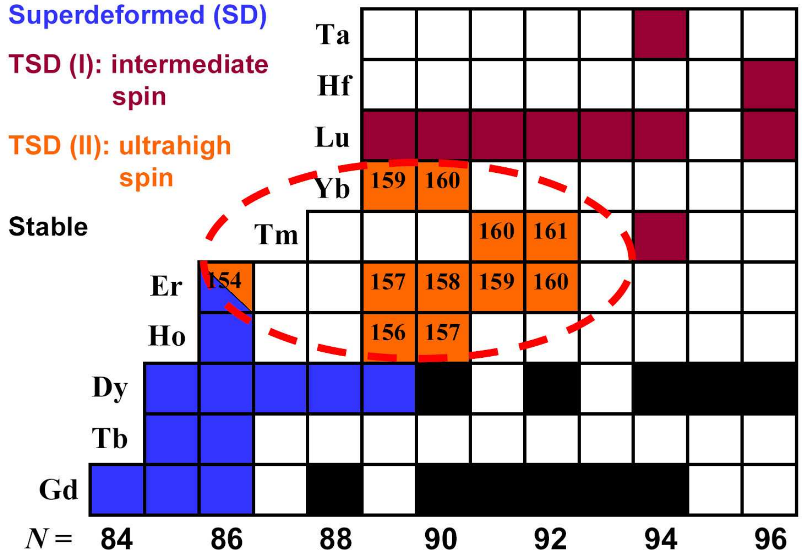


Fig. 7 (Color online) Section of the nuclear landscape highlighting nuclei in the SD domain of Gd, Tb, and Dy and the TSD/Wobbling (TSD: triaxial strongly deformed) regime of Lu and its neighbors as well as those covered by the present project. Nuclei in the thickened, dashed circle are covered by the present project. See text for details.

technology to its limit, with an efficiency for a 1 MeV γ ray of about 10% and a peak-to-total ratio of 55% [34, 20].

Current generation radioactive beam facilities in the USA, Europe, and Japan are beginning to offer tantalizing glimpses of new physics in the terra-incognita of rare isotopes with extreme proton to neutron ratios, while a new generation of high-intensity radioactive beam facilities, for example, FRIB at Michigan State University (MSU), are being constructed or planned worldwide. To fully exploit the scientific discovery potential of these facilities a new generation of high-efficiency detectors with improved position resolution is required. The next major step in γ-ray spectroscopy is to abandon the concept of a physical suppression shield, which greatly reduces the overall possible efficiency, and to move towards the goal of a 4π Ge ball utilizing the technique of γ-ray energy tracking in electrically segmented Ge crystals [35, 36].

With the new tracking technique, the position and energy of γ-ray interaction points are identified in the detector segments. Since most γ rays interact more than once within the crystal, the energy-angle relationship of the Compton scattering formula is used to track the path of a given γ ray. The full γ-ray energy is obtained by summing only the interactions belonging to that particular γ ray. In this way, there are no vetoed Compton scatters in the suppression shields and scattered γ rays between crystals are recovered. Thus, a 4π γ-ray energy tracking array, for example, GRETA [35, 36] in the USA (see Fig. 8), will have a high overall efficiency, $\sim$

60% for a single 1 MeV γ ray. Other key benefits of a tracking array include good peak-to-total ratio ($\sim$ 85%), high counting rate ($\sim$ 50 kHz) capability per crystal, excellent position resolution ($\sim$ 2 mm), the ability to handle high multiplicities without summing, the ability to pick out low-multiplicity events hidden in a high background environment, and high sensitivity for linear polarization measurements. A back-to-back comparison of GRETA with Gammasphere on several key technical parameters is given in Fig. 9. During the last few years, γ-ray energy tracking technology has been shown to be feasible. GRETINA [37], a 1π detector system, has been constructed in the USA, while the AGATA [38, 39, 40] demonstrator has been constructed in Europe. We will focus on GRETINA and GRETA below.

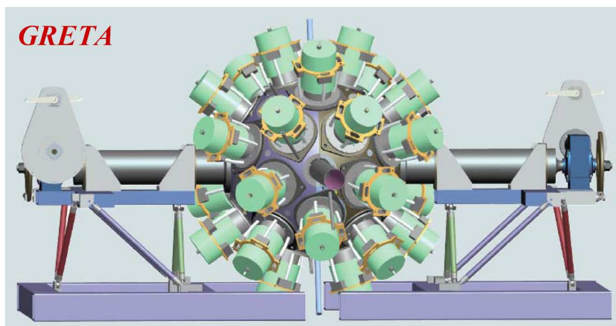
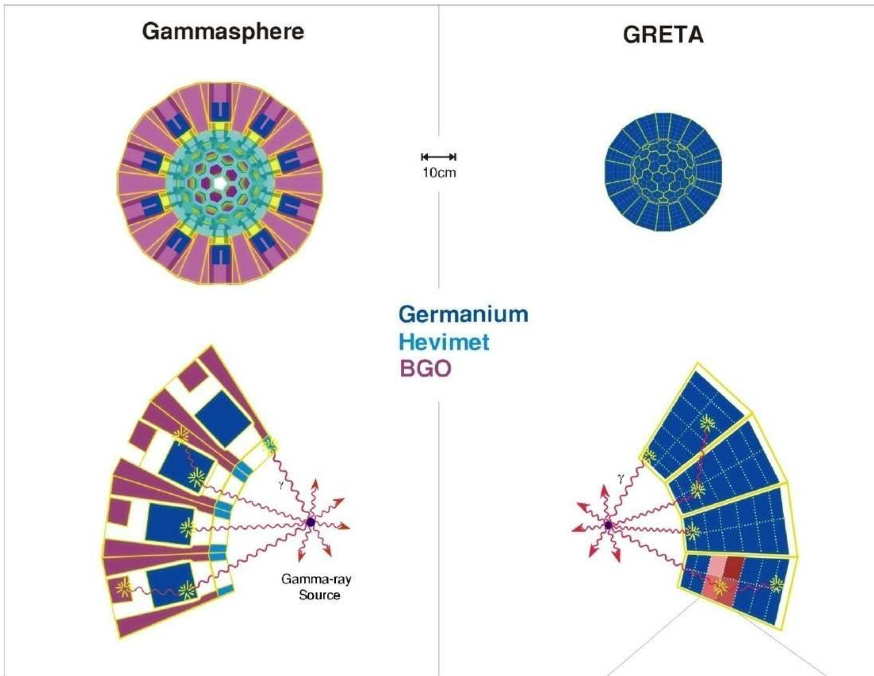


Fig. 8 (Color online) The planned 4π GRETA (Gamma Ray Energy Tracking Array) spectrometer. Adapted from Ref. [41]. Note that a very similar system, AGATA, is planned in Europe.

In March 2011, the construction of GRETINA was completed at Lawrence Berkeley National Laboratory (LBNL). From April to July in 2011, a series of engineering runs, in-beam tests of GRETINA, were carried out to help with the debugging, characterization, and initial optimization of GRETINA. Some photos and results from the first engineering run, of which the primary aim was to test GRETINA under high multiplicity conditions using a reaction populating high spin states in ^{158}Er, are displayed in Fig. 10. From the fall of 2011 to present, a series of commissioning runs with GRETINA coupled to the Berkeley Gas Separator (BGS) have been conducted. It is hoped that these runs will provide the opportunity both to obtain physics results on the spectroscopy of super heavy elements (SHE) and to test GRETINA under "battle conditions".

In the summer of 2012, the first scientific campaign of GRETINA will begin. It is first to be stationed at the NSCL facility at MSU for about one year and then will move to the ATLAS facility at ANL. The GRETINA detector array is thus about to enter its operations phase. However, the momentum in developing the γ-ray energy tracking technology to its ultimate potential must continue towards GRETA which is a full 4π spectrometer. As addressed in the 2007 NSAC Long Range Plan [41], GRETA will improve the power of GRETINA by a factor of $10-100$ for most experiments. This 4π γ-ray energy tracking spectrometer (along with AGATA in



Efficiency (1 MeV):	~ 10%	~ 60%
Efficiency (15 MeV):	~ 0.5%	~ 12%
Peak/Total (1 MeV):	~ 55%	~ 85%
Position resolution:	~ 20 mm	~ 2 mm

Fig. 9 (Color online) Comparison of GRETA with Gammasphere, demonstrating the advantages of a new generation γ-ray detector array utilizing the energy tracking technique. Adapted from Ref. [42].

Europe) will revolutionize γ-ray spectroscopy in the same way that Gammasphere and Euroball [44] did. These next generation γ-ray spectrometers in conjunction with a suite of specially designed auxiliary detector systems will be essential to fully exploit the compelling scientific opportunities of the new radioactive beam facilities and will bring nuclear physics into a new era.

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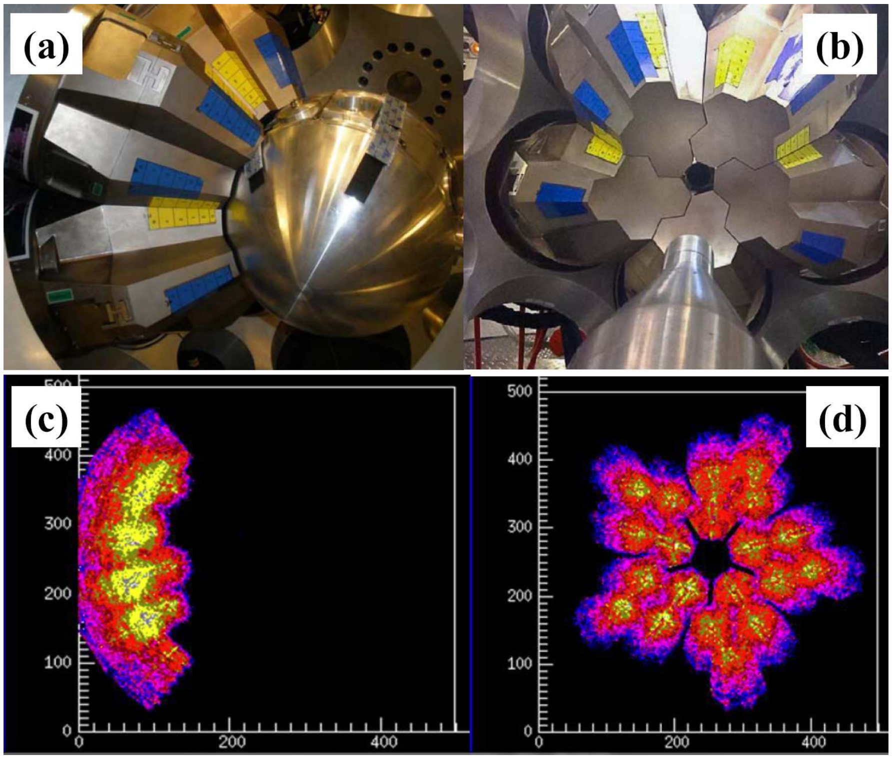

Fig. 10 (Color online) Photos and images from the first engineering run of GRETINA in April 2011 at LBNL where reactions leading to ^{158}Er were used to test the new GRETINA system. (a): Side view photo of GRETINA; (b): Front view photo of GRETINA; (c): Interaction points analysis side view; and (d): Interaction points analysis front view. Adopted from Ref. [43].

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