Collective structures up to spin $\sim 65\hbar$ in the $N = 90$ isotones ^{158}Er and ^{157}Ho

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Abstract. A new collective band with high dynamic moment of inertia in ^{158}Er at spins beyond band termination has been found in addition to the two previously reported ones. The measured transition quadrupole moments (Q_{t}) of these three bands are very similar. These three bands have been suggested to possess a triaxial strongly deformed shape, based on comparisons with calculations using the cranked Nilsson-Strutinsky model and with tilted axis cranking calculations using the Skyrme-Hartree-Fock model. In addition, three collective bands with similar high dynamic moments of inertia, tentatively assigned to ^{157}Ho, have been observed. Thus, it is suggested that all these structures share a common underlying character and that they are most likely associated with triaxial strongly deformed minima which are predicted to be close to the yrast line at spin $50 - 70\hbar$.

1. Introduction

The ^{158}Er nucleus has been a textbook example for high-spin nuclear physics [1, 2, 3]. It was among the first in which backbending was discovered [4], and it was also the first nucleus where the second and third discontinuities along the yrast line were identified [5, 6]. Near a spin of $45\hbar$,
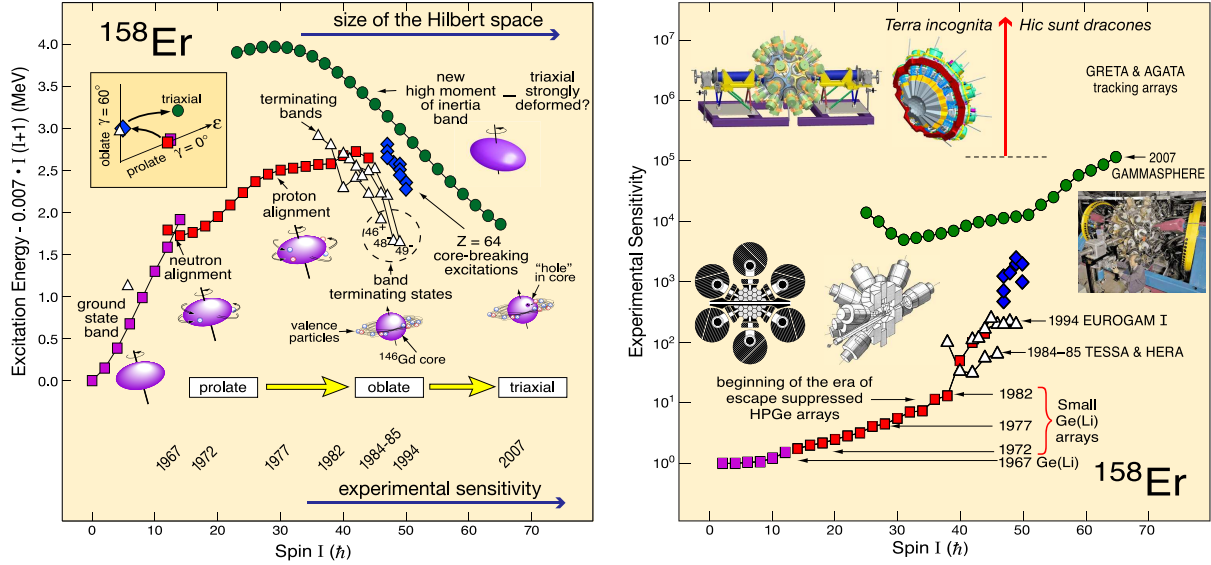
Figure 1. (Colour online) Left: the evolution of nuclear structure in ^{158}Er with excitation energy and angular momentum. The inset illustrates the changing shape of ^{158}Er with increasing spin within the standard (ε, γ) deformation plane. Right: the experimental sensitivity of detection is plotted as a function of spin showing the progression of γ-ray detector techniques with time that are associated with the nuclear structure phenomena in ^{158}Er.

the yrast line undergoes a dramatic shape transition from a prolate shaped state of collective rotation to a non-collective oblate shaped configuration [7, 8, 9] via the mechanism of band termination [10, 11].

In 2007, a new frontier of discrete-line γ-ray spectroscopy at spin $50 - 70\hbar$ (the so-called "ultrahigh-spin regime") was opened. Four rotational structures in ^{158}Er and ^{157}Er, displaying high dynamic moments of inertia, were identified. These extended up to spin $\sim 65\hbar$ and bypassed the band terminating states [12]. A follow-up DSAM experiment has comfirmed that these collective bands at ultrahigh spin are associated with strongly deformed shapes [13]. In fact, the ^{158}Er nucleus has featured as an outstanding example for the evolution of nuclear structure with excitation energy and angular momentum (see Fig. 1). The discoveries in ^{158}Er illustrated here have benefited much from the progression of detector techniques. On the other hand, the exploration of nuclear behavior at the limits of angular momentum and excitation energy has also pushed the advancement of γ-ray detector systems.

Transition quadrupole moments (Q_t) of the two collective bands with high moments of inertia, bands 1 and 2, in ^{158}Er (as well as of two similar bands in ^{157}Er) have been reported in Ref. [13]. A new collective band with high dynamic moment of inertia in ^{158}Er, band 3, and its measured Q_t moment are reported in the present manuscript. In addition, three new collective bands tentatively assigned to ^{157}Ho, an odd-Z isotone of ^{158}Er, which have been observed in a recent experiment using the Gammasphere spectrometer [14] are also presented and discussed. They have similar dynamic moments of inertia with the three bands in ^{158}Er and are, therefore, assumed to be of similar character.

2. Experimental details

The ^{158}Er and ^{157}Ho experiments were carried out at the ATLAS facility in Argonne National Laboratory, USA. The emitted γ rays were detected by the Gammasphere spectrometer, which
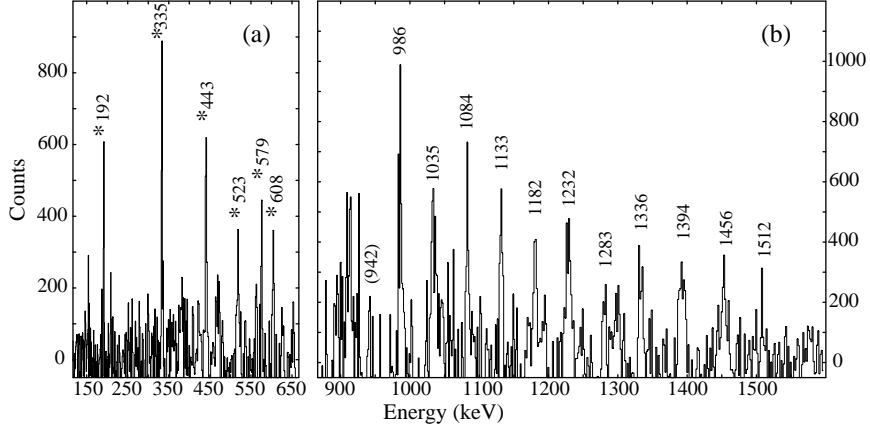
Figure 2. Coincidence spectra for the new band (band 3) in ^{158}Er. The triple-gated spectrum from the thin-target data [12] in (a) has been selected by transitions in the new band initially identified in the thick-target data. The known low-lying yrast transitions in ^{158}Er are marked in $*$. This demonstrates that the new band belongs to ^{158}Er. A double-gated spectrum from the thick-target data is displayed in (b). The inband transitions of band 3 are marked with their energies in keV.

consisted of 101 Compton-suppressed HPGe detectors. For the ^{158}Er experiment, a 215 MeV ^{48}Ca beam and a 1 mg/cm^2 ^{114}Cd target backed by 13 mg/cm^2 of ^{197}Au were used. A total of 9.9×10^9 coincidence events with fold ≥ 4 were acquired. For the ^{157}Ho experiment, a ^{37}Cl beam of 177 MeV energy bombarded a ^{124}Sn target. In the first 15 shifts of beam time, a stack of two 0.5 mg/cm^2 self-supporting ^{124}Sn foils was used, while, in the last 3 shifts, a 1 mg/cm^2 ^{124}Sn target backed by a 15-mg/cm^2 layer of ^{197}Au was used. A total of about 3×10^9 and about 0.6×10^9 coincidence events were accumulated in the thin- and the thick-target runs, respectively, each event containing at least 4 coincident γ rays. The subsequent offline analyses of both data sets were performed with the RadWare software package [15] as well as the BLUE database [16].

3. Results and Discussion

Bands 1 and 2 in ^{158}Er were discovered in a thin-target experiment by the same collaboration [12]. In the follow-up, thick-target experiment, the primary purpose was to measure their quadrupole moments [13]. Compared to the previous thin-target experiment, the enhanced statistics of the latter allowed the observation of a new collective band in ^{158}Er (labelled as band 3), which is estimated to carry an intensity of $\sim$10% of band 1. Sample spectra representative of band 3 in ^{158}Er are given in Fig. 2.

In spite of the corresponding weak intensity, an analysis of fractional Doppler shifts $F(\tau)$, using the same method as that employed for bands 1 and 2 [13], was conducted for band 3. As a result, the $F(\tau)$ values of 8 of the 12 transitions in band 3 and the relevant errors were extracted. The Q_t value of band 3 has been determined experimentally to be $9.6^{+1.5}_{-1.1}$ eb, while the resulting side-feeding quadrupole moment, Q_{sf}, is very close to Q_t (see Fig. 3).

The transition quadrupole moments of the three ^{158}Er bands up to spin $\sim 65\hbar$ have been measured to be $\sim 10 - 11$ eb. This result demonstrates that they are all associated with strongly deformed shapes. As illustrated in Fig. 4 (and also pointed out in Ref. [13]), the measured Q_t values appear to be most compatible with a negative-γ (rotation about the intermediate axis) triaxial deformed minimum (TSD2: $\varepsilon_2 \sim 0.34$) or a positive-γ (rotation
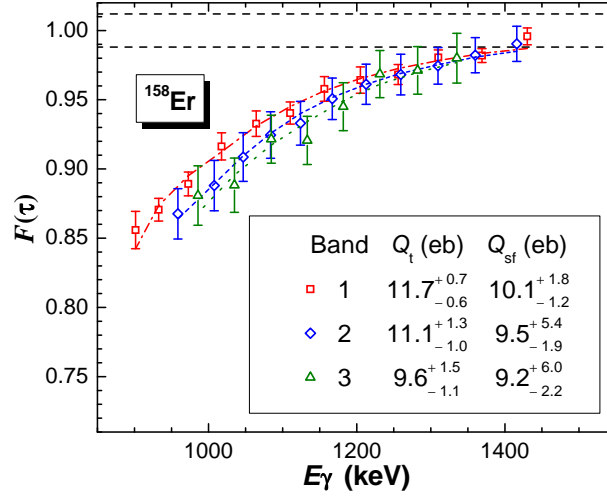
Figure 3. (Colour online) Measured $F(\tau)$ values as a function of the γ-ray energy with best-fit curves for the three bands in ^{158}Er. The two horizontal dashed lines show the range of initial recoil velocities of the Er nuclei within the ^{114}Cd target layer. The insets summarize the measured transition quadrupole moments. The error bars are statistical only, *i.e.*, they do not include the $\sim$15% error associated with the systematic uncertainty in the stopping powers [17]. However, an experiment to help "calibrate" these Q_t values was performed and is discussed in Ref. [13] and in the contribution by Revill *et al.* to the present proceedings.

about the short axis) minimum with larger deformation (TSD3: $\varepsilon_2 \sim 0.43$), rather than with the energetically favoured positive-γ triaxial shape (TSD1: $\varepsilon_2 \sim 0.34$), within the current cranked Nilsson-Strutinsky (CNS) theoretical framework [18]. Calculations using the 2-dimensional tilted axis cranking (TAC) method [19] based on a self-consistent Skyrme-Hartree-Fock (SHF) model have also been performed by Shi *et al.* for configurations associated with triaxial shape at ultrahigh spin in ^{158}Er [20]. In this work, it is claimed that the negative-γ minimum becomes only a saddle point when titled cranking is considered. In addition, the calculated Q_t value for the candidate positive-γ triaxial minimum (~ 10.5 eb) agrees well with the experimental values.

Several questions naturally arise from these discoveries 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? Our plan of exploring these questions are currently carried out along two directions: in the Er isotopes [21] and in the $N = 90$ isotones [22].

An experiment with the focus on ^{157}Ho has been carried out to further explore the latter. Preliminary results have revealed observation of three new collective bands with high moments of inertia tentatively assigned to ^{157}Ho. These three bands correspond to a similar rotational frequency range as in the ^{158}Er bands (and, hence, a similar spin range). They appear to bypass and extend beyond the band terminating states $87/2^-$ and $75/2^-$ established in ^{157}Ho [9]. A representative spectrum of the strongest new band tentatively assigned to ^{157}Ho is displayed in Fig. 5. Both CNS and Woods-Saxon calculations [11] have predicted that triaxial strongly deformed minima also exist over a wide range of spin in ^{157}Ho in a manner very similar to ^{158}Er. A comparison of dynamic moments of inertia between the three bands at ultrahigh spin in ^{158}Er and the ones in ^{157}Ho exhibits strong similarities, as displayed in Fig. 6. This indicates that all these structures have a similar underlying character and are most likely associated with a triaxial strongly deformed shape.
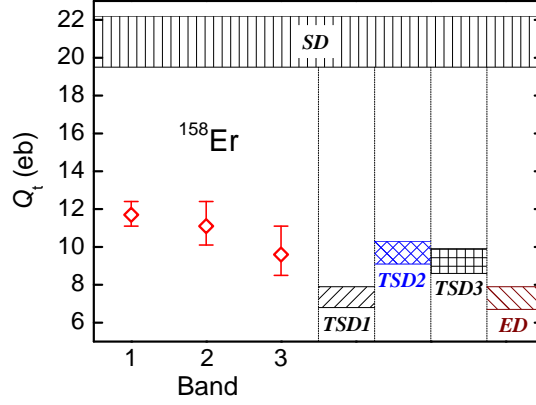
Figure 4. (Colour online) Measured transition quadrupole moments Q_t (plotted with diamonds) of the three bands in ^{158}Er, compared with the theoretical Q_t values (horizontal shaded areas) associated with the minima of interest calculated in the CNS model [13] (ED: enhanced deformed; SD: superdeformed). See text for the definitions of the three TSD minima.
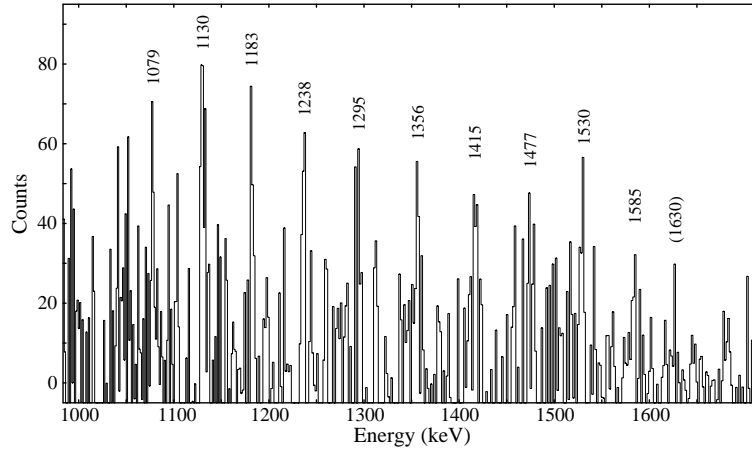

Figure 5. Triple-gated, summed coincidence spectrum from the thin-target data for the strongest new collective band tentatively assigned to ^{157}Ho. The energies of the inband transitions are given in keV.

4. Summary and perspective

A third high moment of inertia collective band at ultrahigh spin in ^{158}Er and its measured transition quadrupole moment are presented for the first time. It has been suggested that the three bands possess a triaxial strongly deformed shape, based on a comparison between data and calculations in the CNS model and those using the TAC method with a SHF model. In addition, three collective bands beyond the spin regime of band termination in ^{157}Ho have been observed for the first time. These three new bands seem to be associated with predicted triaxial strongly deformed minima as well. However, a dedicated DSAM experiment is required to confirm their strong similarity with the ultrahigh spin bands in ^{158}Er.
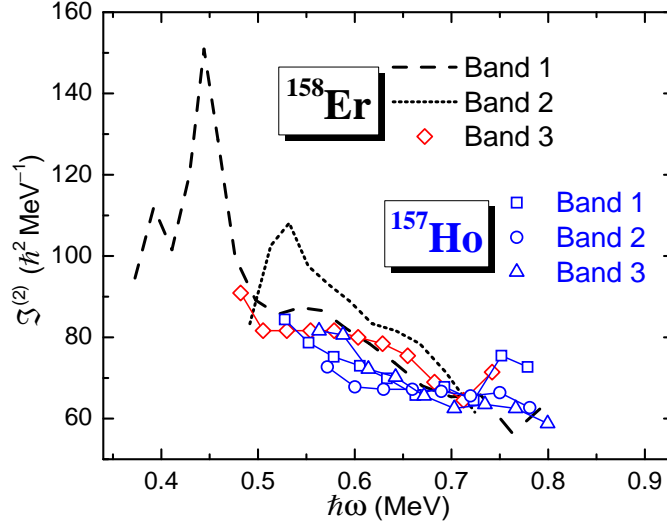
Figure 6. (Colour online) Dynamic moments of inertia ($\Im^{(2)}$) as a function of rotational frequency ($\hbar\omega$) for the three ultrahigh spin bands in ^{158}Er and those tentatively assigned to ^{157}Ho.

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