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Phys. Scr. **T125** (2006) 123–126 doi:10.1088/0031-8949/2006/T125/028

Observation of states beyond band termination in ^{156,157,158}Er and strongly deformed structures in ^{173,174,175}Hf

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Received 9 August 2005
Accepted for publication 1 September 2005
Published 28 June 2006
Online at stacks.iop.org/PhysScr/T125/123

Abstract

High-spin terminating bands in heavy nuclei were first identified in nuclei around ^{158}Er$_{90}$. While examples of terminating states have been identified in a number of erbium isotopes, almost nothing is known about the states lying beyond band termination. In the present work, the high-spin structure of ^{156,157,158}Er has been studied using the Gammasphere spectrometer. The subject of triaxial superdeformation and 'wobbling' modes in Lu nuclei has rightly attracted a great deal of attention. Very recently four strongly or superdeformed (SD) sequences have been observed in ^{174}Hf, and cranking calculations using the Ultimate Cranker code predict that such structures may have significant triaxial deformation. We have performed two experiments in an attempt to verify the possible triaxial nature of these bands. A lifetime measurement was performed to confirm the large (and similar) deformation of the bands. In addition, a high-statistics, thin-target experiment took place to search for linking transitions between the SD bands, possible wobbling modes, and new SD band structures.

PACS numbers: 27.70+q, 21.10.Re, 23.20.Lv, 23.20.En

1. Observation of states beyond band termination in ^{156,157,158}Er

High-spin terminating bands [1] in heavy nuclei were first identified in nuclei around $^{158}_{68}\mathrm{Er}_{90}$; see [1–6] and references therein, also see [7] for a recent summary of the field. At termination, this nucleus can be considered as a spherical core ($^{146}_{64}\mathrm{Gd}_{82}$) plus 12 (four protons and eight neutrons) aligned valence particles which can generate a maximum spin of around 46$\hbar$ at an excitation energy of ≈20 MeV, depending on the specific configuration. To produce higher-spin states, particle–hole excitations of the core are required and the question arises whether these excitations induce collective deformation or whether the nucleus remains oblate or near-oblate. While clear examples of the special terminating states have been identified in a number of erbium isotopes, almost nothing is known about the specific states lying above band termination in isotopes close to the textbook example of ^{158}Er [8, 9]. The purity of high-spin terminating states has recently been used to great advantage in differentiating among the many Skyrme force parametrizations [10].

In this regard, the high-spin structure of ^{156}Er, ^{157}Er [11] and ^{158}Er have been studied using the Gammasphere spectrometer [12, 13], containing 102 Ge detectors. A 215 MeV ^{48}Ca beam, provided by the 88 inch Cyclotron accelerator at the Lawrence Berkeley National Laboratory, was used to bombard 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 Compton-suppressed Ge detectors fired in prompt coincidence. Approximately 6.5×10^{10} quadruples (γ^4) were unfolded from the data set and replayed into a Radware-format [14] four-dimensional hypercube for coincidence analysis.

The high-spin level scheme of ^{157}Er deduced from this work is shown in figure 1 and greatly extends the previous work [5]. Bands 1 and 2 were previously established up to the band terminating states at $89/2^-$ and $87/2^-$, while Band 3 has been extended from the $85/2^+$ state up to the new terminating state at spin $93/2^+$. A large number of weak high-energy γ rays feeding these terminating states have been observed in the present data. The multipolarity for a number of these transitions has been measured.

In order to understand the nature of the states above band termination, calculations have been performed in the framework of the configuration-dependent, cranked Nilsson–Strutinsky formalism without pairing [7, 11] which is able to treat collective and non-collective states on the same footing.

In ^{157}Er, the three fully aligned terminating states at $87/2^-$, $89/2^-$ and $93/2^+$ are formed by coupling the $\pi[(\mathrm{h}_{11/2})^4]_{16^+}$ proton configuration to the three neutron configurations, $\nu[(\mathrm{i}_{13/2})^2(\mathrm{h}_{9/2},\mathrm{f}_{7/2})^5]_{55/2^-,57/2^-}$ and $\nu[(\mathrm{i}_{13/2})^3(\mathrm{h}_{9/2},\mathrm{f}_{7/2})^4]_{61/2^+}$, respectively. The favoured way to make higher-spin states for $I = 45$–$55\hbar$ is to excite protons from the $\mathrm{g}_{7/2}$ and $\mathrm{d}_{5/2}$ orbitals below the $Z = 64$ shell gap into the fifth and sixth $\mathrm{h}_{11/2}$ orbitals and into the two lowest $\mathrm{d}_{3/2}$ orbitals. A systematic investigation was carried out for 'core-excited' proton configurations with 1–4 particles excited across the $Z = 64$ gap. The lowest 25 proton configurations were then combined with the three favoured neutron configurations given above to generate 75 possible high-spin configurations in ^{157}Er.

The resulting structures are predicted to build the yrast states in ^{157}Er up to $I \approx 55\hbar$. These configurations show little collectivity and terminate at a small oblate deformation $\varepsilon_2 \sim -0.15$. From detailed comparisons between experiment and theory, we conclude that only configurations with little or no collectivity are predicted to be low enough in energy to be identified with the experimental levels 1.5–2.5 MeV above the fully aligned terminating states. This is consistent with the fact that no clear discrete collective band structures have yet been identified in ^{157}Er, which is very different to the behaviour of ^{154}Dy at high-spin, see [15] and references therein.

In ^{158}Er similar high-energy transitions have now been identified feeding the favoured terminating states at 46^+ (1997 keV, 1454 keV and 1382 keV), and 48^- (2078 keV, 1593 keV, 1528 keV and 1460 keV). A 1655 keV gamma-ray is observed to decay to the 44^+ yrast level. Figure 2 shows the spectrum in coincidence with the 1030 keV ($44^+ \rightarrow 42^+$) transition which illustrates the huge drop in intensity of individual transitions above the terminating state. The large 971 keV peak shows the decay from the 46^+ state while the extremely weak nature of the feeding transitions to this level in the 1300 keV–2100 keV range (each less than 10% of the 971 keV intensity) are clearly evident.

In ^{156}Er transitions of energies 2165 keV, 1621 keV and 1342 keV, and tentatively 2320 keV, 1786 keV and 1682 keV, have been observed feeding the favoured terminating state at 42^+.

2. Strongly deformed (SD) structures in ^{173,174,175}Hf: are they triaxial?

Although triaxial deformation may play a role in describing various nuclear structure phenomena, establishing experimental evidence of stable triaxiality remains a challenge. The best evidence of triaxial deformation is the observation of a 'wobbling' mode since it is unique to a rotating asymmetric nucleus [1]. Indeed, wobbling excitations have been confirmed in ^{163}Lu [16, 17] for structures based on an $\mathrm{i}_{13/2}$ proton configuration. These bands have been labelled triaxial strongly deformed (TSD).

In ^{174}Hf four bands with large moments of inertia were identified, suggesting that they were SD [18]. Ultimate cranker (UC) calculations indicate that such structures may exist in TSD minima. Two experiments have been performed in an attempt to verify the possible triaxial nature of these bands. A lifetime measurement was performed to confirm the large (and similar) deformation of the bands. In addition, a high-statistics, thin-target experiment was run to search for linking transitions between the SD bands to provide evidence that some of the bands may be associated with wobbling excitations. The experimental details of these experiments can be found in [19].

The experimental fractional Doppler shift was extracted from a centroid shift analysis [19]. In order to determine the quadrupole moment Q_t, computer simulations of the population and decay of the levels was performed with the code FITFTAU [20].

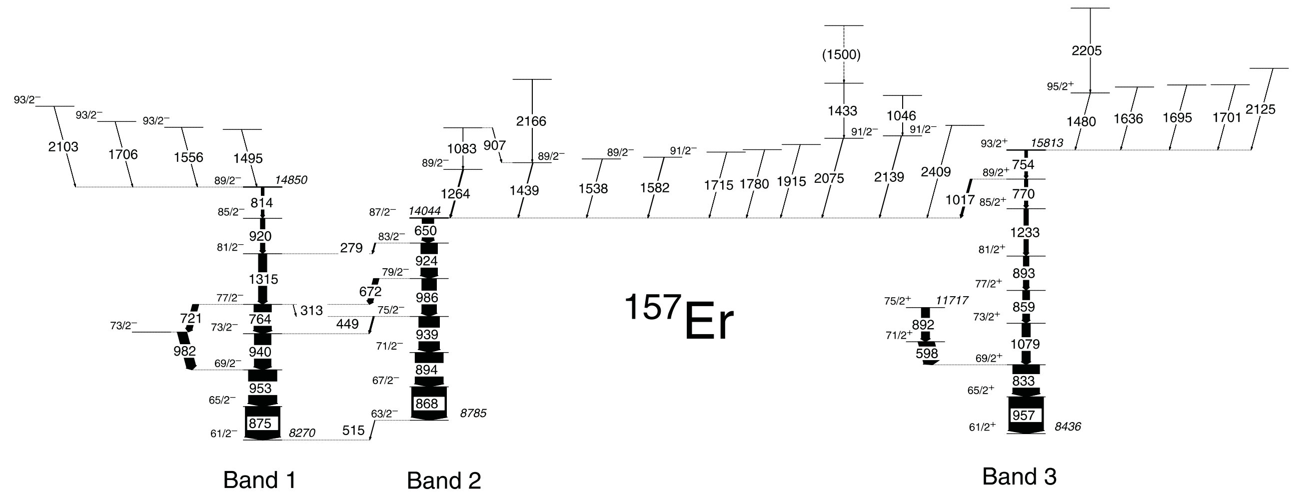

Figure 1. Partial level scheme of ^{157}Er above $30\hbar$ showing the many transitions feeding the special terminating states at $87/2^-$, $89/2^-$ and $93/2^+$.

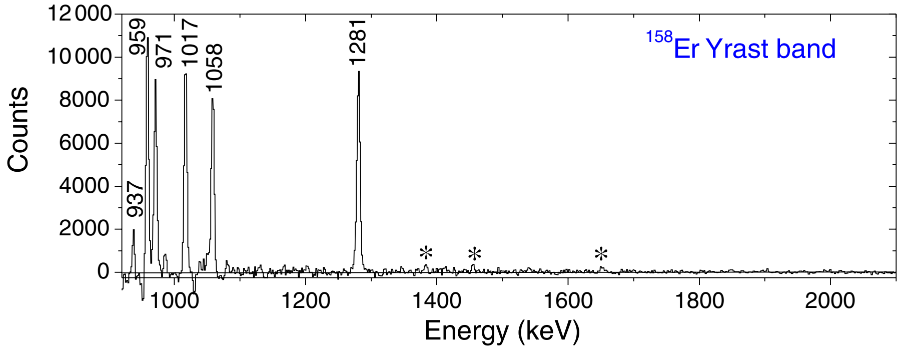

Figure 2. Double-gated triple-coincidence spectra generated for the yrast band in ^{158}Er. The spectrum is the coincidence of the 1030 keV (yrast $44^+ \rightarrow 42^+$ transition) gamma ray with a list of transitions in the yrast band above spin 30. Transition energies of previously known decays [4] are labelled in keV. The huge drop in intensity of individual transitions above the terminating fully aligned terminating state is evident. The large 971 keV peak shows the intensity of the decay from the terminating 46^+ state while the extremely weak nature of the high-spin feeding transitions (marked by an asterisk) in the 1300–2100 keV range are clearly evident.

Large deformation has been established for all four bands with quadrupole moments ranging from $Q_t = 12.6$ to 13.8 b. A new SD band in ^{173}Hf was observed in the thin-target experiment. A value of $Q_t = 14.5^{+0.7}_{-0.7}$ b was determined for this ^{173}Hf sequence. Normal deformed structures are expected to have $Q_t \approx 7$ b, therefore, these measurements confirm that all of these bands are SD and have larger deformation than the Lu TSD bands.

Despite the higher level of statistics compared with our previous thin target experiment [18], linking transitions between SD bands (which would indicate wobbling) in ^{174}Hf could not be identified. Four new, presumably SD, bands were also found in ^{174}Hf but once again no linking transitions between the bands were observed. It was furthermore not possible to link any of the eight SD bands to the normal deformed states. However, the fact that SD 1 is isospectral with the SD band in ^{175}Hf [21] (which has been linked to known states) has allowed us to conclude that the bands in ^{174}Hf are likely based on six or eight quasi-particles [19]. Therefore, the SD structures in the Hf nuclei seem to be part of a different 'class' of SD bands than the Lu TSD sequences.

If the SD sequences in ^{174}Hf are triaxial (as suggested by UC calculations), a family of bands with nearly identical moments of inertia are expected to be observed which have different wobbling quanta. It is indeed possible to group the bands in ^{174}Hf into two families based on their moment of inertia, see figure 3. However, the presence of SD bands displaying similar moments of inertia is not unique to wobbling.

Not only do the present experimental data not prove stable triaxial deformation for ^{174}Hf, but they also result in some inconsistencies. One inconsistency is that UC calculations predict a lower quadrupole moment ($\sim$9.9 b) for the TSD minimum than what was measured. Another problem is the fact that only a single SD band exists in ^{173}Hf and ^{175}Hf. If a TSD minimum were present, a family of bands would be expected in all the Hf nuclei, even if the bands could not be linked. The fact that families have not been observed in the odd-A nuclei raises questions of whether stable triaxial deformation exists in the $N \approx 100$ nuclei. However, the sharp contrast of the multiplicity of bands seen in ^{174}Hf compared with the single bands in its odd-A neighbours is certainly surprising and raises further questions even if wobbling excitations cannot be associated with some of the ^{174}Hf bands.

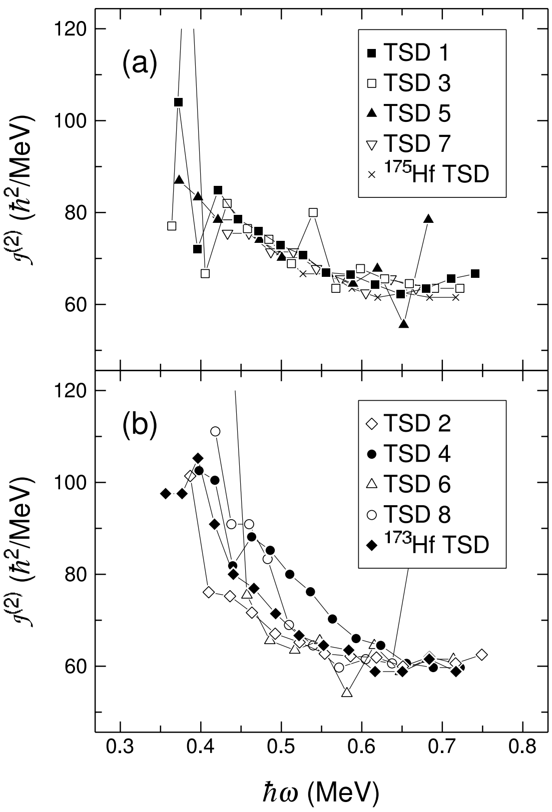

Figure 3. The dynamic moments of inertia for the eight SD or TSD bands in ^{174}Hf, and the bands in ^{173}Hf and ^{175}Hf. The ^{174}Hf bands are split into possible families of bands based on the similarity of their moments of inertia.

3. Conclusion

Recent work in two areas has been presented. The first study involved the quest to observe excited structures beyond the favoured band termination states in ^{156,157,158}Er. A large number of weak transitions of energies 1.0–2.5 MeV feeding the 'valence-space' terminating states have been identified. Cranked Nilsson–Strutinsky calculations indicate that the levels from which they originate mainly correspond to weakly deformed ($\varepsilon_2 = 0.10$–0.15 with $\gamma = 45$–$60°$) configurations involving core-breaking proton particle–hole excitations across the semi-magic $Z = 64$ shell gap. These new data combined with results on ^{155}Er [22] constitute a beautiful set of systematics in Er nuclei for the transition from prolate collective to oblate non-collective rotation with increasing angular momentum, and of the excitations occurring directly above the fully aligned non-collective terminating states.

The second study involved the investigation of candidate superdeformed triaxial bands in ^{174}Hf [19]. The measurement of quadrupole moments confirms the large deformation of the four previously known SD bands in ^{174}Hf. Four additional, presumably SD, bands were observed in ^{174}Hf, as well as one in ^{173}Hf. However, the non-observation of linking transitions between the SD bands in ^{174}Hf, the discrepancy between experimental and theoretical Q_t moments, and the absence of comparable families of bands in ^{173,175}Hf raise serious questions about an interpretation in terms of triaxiality. In addition, the fact that eight bands are seen in the even–even nucleus, while only one band is seen in each of the neighbouring odd-N systems, is a fascinating puzzle. These new results constitute a considerable challenge for the interpretation of the behaviour of Hf nuclei.

Acknowledgments

The authors wish to thank the staff at the 88-Inch and ATLAS accelerator facilities for their support during the experiments. Software support by D C Radford and H Jin is gratefully acknowledged. This work was supported by the National Science Foundation under grant numbers PHY-0300673 (USNA) and PHY-0139950 (FSU), as well as the Department of Energy, office of Nuclear Physics, under contract numbers DE-FG02-96ER40983 (UT), W-31-109-ENG-38 (ANL), DE-FG02-94ER40848 (UML), and the UK EPSRC. D M C acknowledges the receipt of an EPSRC Advanced Fellowship AF/100225.

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