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# Beyond band termination in $^{157}$Er and the search for wobbling excitations in strongly deformed $^{174}$Hf

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**Abstract**

High-spin terminating bands in heavy nuclei were first identified in nuclei around $^{158}$Er$_{90}$. While examples of special 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 $^{157}$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 ultimate cranker calculations predict 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 was run to search for linking transitions between the SD bands and possible wobbling modes.

## 1. Beyond band termination in $^{157}$Er

High-spin terminating bands [1] in heavy nuclei were first identified in nuclei around $^{158}_{68}$Er$_{90}$; see [2–5] and references therein, also see [6] for a recent summary of the field. At termination, this nucleus can be considered as a spherical core $\left(^{146}_{64}\mathrm{Gd}_{82}\right)$ plus 12 (4 protons and 8 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 [7, 8].

In this regard, the high-spin structure of $^{157}$Er [9] has been studied using the Gammasphere spectrometer [10, 11], 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 $1.2 \times 10^9$ events were collected when at least seven Compton-suppressed Ge detectors fired in prompt coincidence. Approximately $6.5 \times 10^{10}$ quadruples ($\gamma^4$) were unfolded from the data set and replayed into a Radware-format [12] four-dimensional hypercube for coincidence analysis to establish the level scheme.

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 have been extended from the $85/2^+$ state up to the new terminating state at spin $93/2^+$. A large number of weak high-energy $\gamma$ rays feeding these terminating states has been observed in the present data. The multipolarity for a number of these transitions have 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 [6, 9] 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 $\pi[(h_{11/2})^4]_{16^+}$ proton configuration to the three neutron configurations, $\nu[(i_{13/2})^2(h_{9/2}, f_{7/2})^5]_{55/2^-,57/2^-}$ and $\nu[(i_{13/2})^3(h_{9/2}, f_{7/2})^4]_{61/2^+}$, respectively. The favoured way to make higher-spin states for $I = 45$–$55\hbar$ is to excite protons from the $g_{7/2}$ and $d_{5/2}$ orbitals below the $Z = 64$ shell gap into the 5th and 6th $h_{11/2}$ orbitals and into the two lowest $d_{3/2}$ 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 only configurations

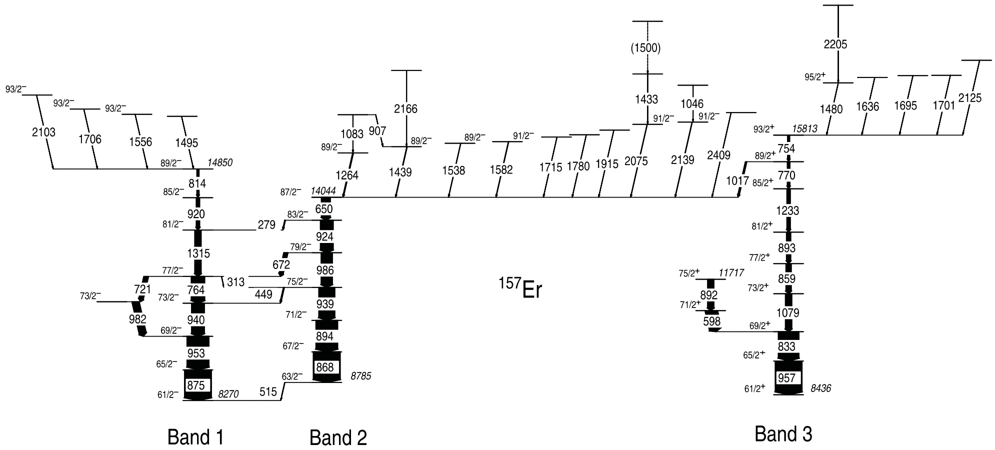


**Figure 1.** Partial level scheme of $^{157}$Er above $30\hbar$ showing the many transitions feeding the special terminating states at $87/2^-$, $89/2^-$ and $93/2^+$.

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 been identified in $^{157}$Er which is very different to the very high-spin behaviour of $^{154}$Dy, see [13] and references therein.

## 2. The search for wobbling excitations in strongly deformed $^{174}$Hf

Although triaxial deformation may play a role in describing various nuclear structure phenomena, establishing experimental evidence of stable triaxiality remains a challenge. Perhaps 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 [14, 15] for structures based on an $i_{13/2}$ proton. 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 strongly deformed (SD) [16]. Ultimate cranker (UC) calculations indicated 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 [17].

The experimental fractional Doppler shift was extracted from a centroid shift analysis [17]. In order to determine the quadrupole moment $Q_t$, computer simulations of the actual decay of the levels with the bands and their sidefeeding were performed with the code FITFTAU [19].

Figure 2 displays the $F(\tau)$ data for the four previously known SD bands in $^{174}$Hf along with the fits generated by FITFTAU. Large deformation has been established for all four bands with quadrupole moments ranging from $Q_t = 12.6$ to $13.8\ e$b, see figures 2(a)–(d). The quoted errors are based solely on the uncertainty of determining the centroid energy of the peaks. An additional systematic error of 15–20% should be added to account for the uncertainties in the stopping powers. A new SD band in $^{173}$Hf was observed in the thin-target experiment.

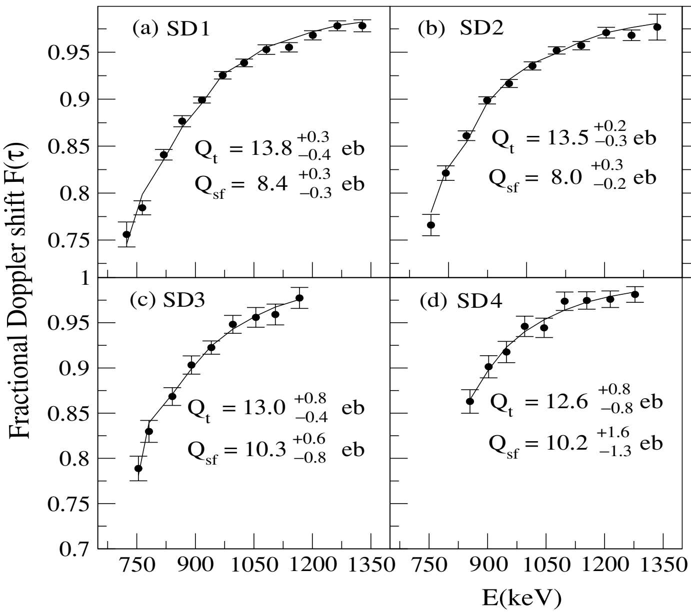


**Figure 2.** The data points [17] represent the measured fractional Doppler shifts of transitions in the four candidate SD bands in $^{174}$Hf [16] and the SD band in $^{173}$Hf. Results from the FITFTAU code are shown as solid lines, and the transition quadrupole $Q_t$ and sidefeeding $Q_{sf}$ moments from the fitting routine are given for each band.

A value of $Q_t = 14.5^{+0.7}_{-0.7}$ *e*b was determined for this $^{173}$Hf sequence, see figure 2(e). Normal deformed structures are expected to have $Q_t \approx 7$ *e*b; therefore, these measurements clearly indicate that all of these bands are, indeed, strongly deformed and have larger deformation than the Lu TSD bands.

Despite the higher level of statistics compared with our previous thin target experiment [16], linking transitions between SD bands (which would be indicative of wobbling) in $^{174}$Hf could not be identified. Four new, presumably strongly deformed, bands were also found in $^{174}$Hf but once again no linking transitions between the bands were observed. In addition, it was 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 [20] (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 quasiparticles [17]. 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 strongly deformed 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 behaviour. 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 ultimate cranker calculations predict a lower quadrupole moment (∼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 in all the Hf nuclei would be expected, 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.

## 3. Summary

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 $^{157}$Er [9]. 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.

The second study involved the investigation of candidate superdeformed triaxial bands in $^{174}$Hf [17]. The measurement of quadrupole moments confirms the large deformation of the four previously known SD bands in $^{174}$Hf. Four additional, presumably strongly deformed, bands were also observed in $^{174}$Hf, as well as one in $^{173}$Hf. However, the non-observation of linking transitions, 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.

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