Coexistence of Superdeformed Shapes in ^{154}Er

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A new superdeformed rotational band has been observed in ^{154}Er using the Euroball Ge detector array. The new band and the one previously observed can be understood as based on coexisting superdeformed structures at prolate and triaxial shapes, respectively. The observation resolves long-standing difficulties in the theoretical interpretation of superdeformed states in ^{154}Er.

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Superdeformed (SD) atomic nuclei with very elongated shapes (major to minor axis ratio ≈ 2) are, in addition to the fission isomers in actinide nuclei, now known to exist in several regions of the nuclear chart [1–6]. The existence of nuclei with such extreme deformations is explained by the occurrence of pronounced quantal level bunchings, "shells," and consequently large shell gaps which compensate for the increased deformation energy. Theoretical models have successfully predicted the existence of such shell gaps; even the simple deformed harmonic oscillator model is able to produce shell gaps at SD shapes. However, the positions of the theoretically predicted shell gaps, in terms of deformation, neutron number, and proton number, depend on the detailed features of the model. The boundaries of superdeformation in the nuclear chart as well as the detailed properties of SD bands are therefore important to establish experimentally since they provide critical tests for nuclear models. Several types of model calculations, e.g., cranked Strutinsky calculations [7–10] based on the Woods-Saxon potential and cranked relativistic mean field calculations [11], predict pronounced shell gaps for $N = 86$ and $Z = 66$ at a prolate shape and a quadrupole deformation around $\beta_2 = 0.6$. By extending the concept used for spherical nuclei, the nucleus ^{152}Dy is therefore predicted to be "doubly magic" in the SD regime. Important aspects of the microscopic structure of SD bands have been explained [12] in terms of the occupation of high-N (N is the major oscillator shell quantum number), high-j intruder orbitals, which are brought down in energy close to the Fermi level at large deformation and high rotational frequency. Experimentally, the behavior of the dynamic $\mathcal{J}^{(2)}$ moments of inertia is known to follow well the predicted intruder occupation of the particle configurations. With the exception of the nucleus ^{154}Er, addressed in this Letter, there has generally been reasonable agreement between the experimentally determined properties of SD states and the theoretical predictions. It was expected that for the nucleus ^{154}Er, the yrast SD band should correspond to the same occupation of intruder orbitals as in the doubly magic yrast SD band in ^{152}Dy. The two additional protons are, at a SD shape, predicted to occupy deformation aligned orbitals which are relatively unaffected by the rotation of the ^{152}Dy core. The first experimental observation of SD states in ^{154}Er [13] indicated, however, a rather different result. Ever since this experimental observation various theoretical studies (see, e.g., [14,15]) have failed to convincingly interpret the data. Primarily, there was a striking disagreement between the $\mathcal{J}^{(2)}$ moment of inertia of the observed band and the one predicted. Recently, it was suggested [15] that the SD band in ^{154}Er might be explained as based on a triaxial configuration.

Shape coexistence and shape polarization are phenomena which are known to occur in various regions of the nuclear chart [16,17]. The most notable examples are perhaps the nuclei exhibiting coexisting superdeformed and moderately deformed shapes as well as "spherical" single-particle-excited structures [1,2,18]. However, the question whether nuclei may support different coexisting shapes at extreme deformations has up to now been open. In this Letter we present new experimental data and theoretical calculations which resolve the earlier conundrum concerning the interpretation of the SD structure of ^{154}Er and a picture of shape coexisting SD states emerges.

Excited states in ^{154}Er were populated using the reaction ^{110}Pd(^{48}Ti, 4n)^{154}Er, at a beam energy of 215 MeV. The target consisted of a stack of two self-supporting metallic foils with thickness 2×500 μg/cm^2 and an isotopic purity of 98.64%. The emitted γ rays were detected using the Euroball [19] Ge detector array, then placed at Legnaro National Laboratories, Italy. Euroball consisted of 13 clusters, 25 clovers, and 26 tapered escape-suppressed detectors. The cluster and clover detectors are composite detectors comprising seven and four large germanium crystals, respectively. With a trigger condition requiring at least seven unsuppressed Ge detectors to have fired, 1.3×10^9 raw γ-ray coincidence events were collected by the data acquisition system. After add back, i.e., adding the energies from Compton scattering between crystals of a composite detector, and Compton suppression, a total of 2.9×10^8 three- and higher-fold events resulted. The data were sorted off-line into a symmetrized $E_\gamma - E_\gamma - E_\gamma$ coincidence cube and analyzed using the RADWARE [20] software package.

A careful search of the data resulted in the identification of two cascades, each of mutually coincident γ-ray transitions with SD band characteristics. One of these structures has been observed previously by Bernstein *et al.* [13]. In Fig. 1, coincidence spectra for the previously known band (band 1) and the new band (band 2) are shown. These spectra were produced using sums of selected double gates on the bands. The gate selections are based on the degree of contamination for each gate combination. The transitions belonging to band 1, which were previously reported in [13], have been confirmed in this work, and a 1350 keV transition has been placed at the top of the band. The 1368 and 1425 keV transitions, which were previously assigned to be in coincidence with band 1 [13] (but assumed not to belong to the band), have not been confirmed in this work. The uppermost transition in band 2 is tentative. The assignment of the bands to ^{154}Er is based on the coincidence relationships between the transitions in the band and transitions known from the decay of low-lying yrast states in ^{154}Er [21]. The bands are most strongly in coincidence with the normal deformed (ND) negative parity band which becomes yrast above 3 MeV in excitation energy. Band 1 appears to feed into the ND band between the $I^\pi = 19^-$ and $I^\pi = 25^-$ states (with the feeding intensity divided between several of these states). Band 2 has a similar feeding pattern, although it may feed in slightly higher up in the ND band. The intensity of the strongest SD band relative to the population of the ND states is estimated to be approximately 0.5%, in agreement with the ratio given by Bernstein *et al.* [13]. Band 2 is populated at about one-third of the intensity of band 1.

Figure 2(b) compares the dynamic moment of inertia, $\mathcal{J}^{(2)}$, for the two SD bands in ^{154}Er with that of the yrast SD

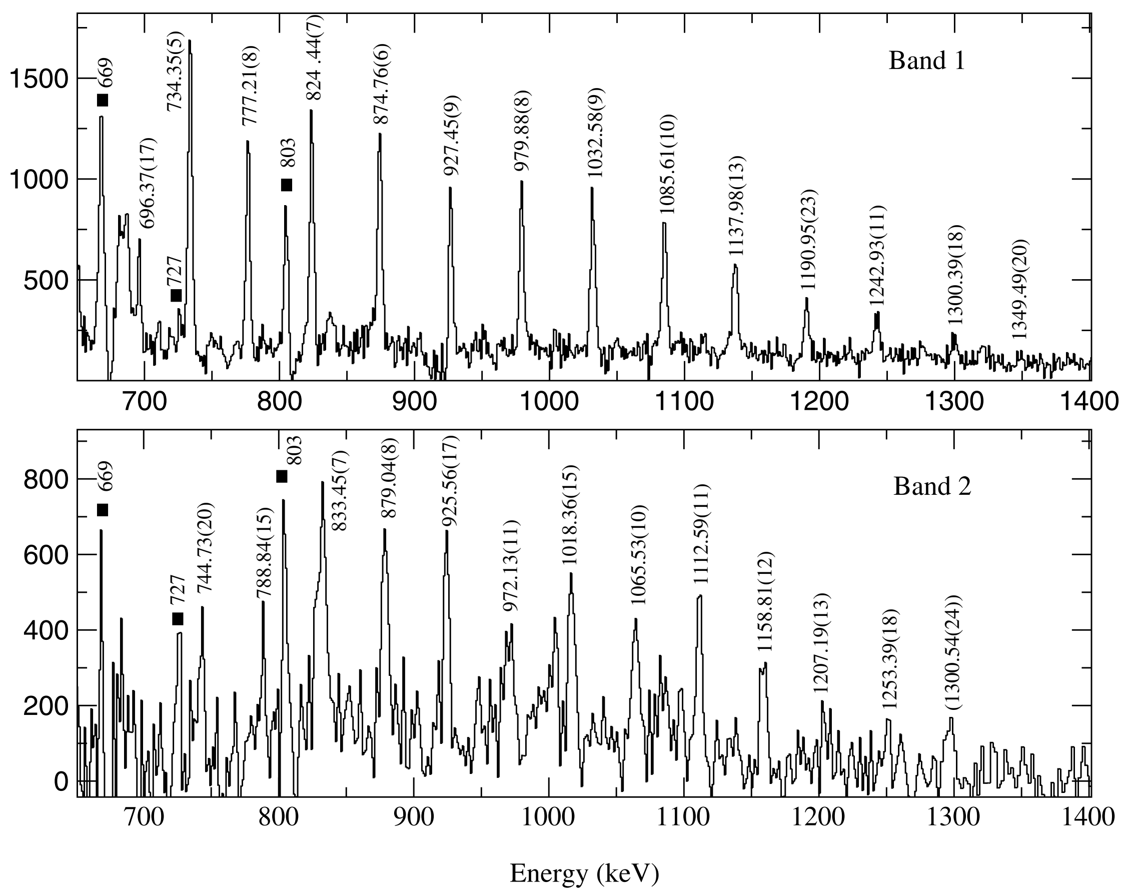

FIG. 1. Coincidence γ-ray spectra obtained by double gating on selected pairs of in-band transitions for the previously known (top panel) and new SD band (bottom panel) in ^{154}Er. Previously reported transitions between low-lying negative parity states (filled squares) appear in coincidence with the bands. Relevant background contributions have been subtracted. The energies of the transitions in the superdeformed bands are given in the figure, with uncertainties in the least significant digits in parentheses.

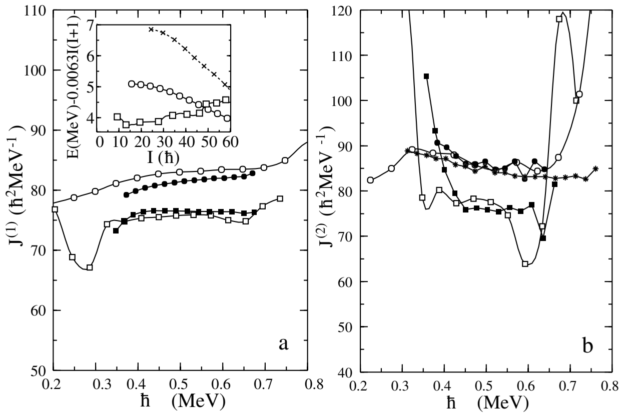

FIG. 2. Panel (a) shows the calculated and experimental values for the $\mathcal{J}^{(1)}$ moment of inertia versus rotational frequency. A bandhead spin of 24^+ and 26^+, respectively, is assumed for bands 1 and 2. Panel (b) shows the dynamic moment of inertia, $\mathcal{J}^{(2)}$, as a function of rotational frequency. In both figures, open squares and open circles mark the theoretically predicted values for bands 1 and 2, respectively, and filled squares and filled circles show the experimental values for bands 1 and 2, respectively. The inset shows theoretical excitation energies as a function of angular momentum for bands 1 and 2, as well as for the first excited SD band (crosses). In the $\mathcal{J}^{(2)}$ plot, the yrast superdeformed band in ^{152}Dy (stars) is also included. The rise in the calculated $\mathcal{J}^{(2)}$ moments of inertia at $\hbar\omega \approx 0.65$ is due to rotational alignment of a pair of high-j particles.

band in ^{152}Dy [18], as a function of rotational frequency. The $\mathcal{J}^{(2)}$ values of band 2 follow rather closely those of the yrast band in ^{152}Dy while band 1 exhibits $\mathcal{J}^{(2)}$ values which are significantly lower and feature a pronounced irregularity at low rotational frequencies. The observed differences between the $\mathcal{J}^{(2)}$ moments of inertia of the two SD bands of ^{154}Er accentuate the need to measure the transition quadrupole moments, Q_t, as a means to assess their deformations. This can, for thin-target data, be achieved by applying a residual Doppler shift technique [22]. Because of large collective E2 transition strengths, lifetimes of SD states are generally short as compared to the lifetimes of low-lying yrast states in a nucleus. Consequently, the SD states predominantly decay inside even a thin target foil while the nucleus is still slowing down. The velocity of the nucleus will then vary as a function of excitation energy in the SD band and can be calculated from the Doppler shifts of emitted gamma rays. The nuclear velocities together with known stopping power parameters [23] provide estimates of the lifetimes of the in-band states, from which the Q_t can be deduced. However, since a stack of self-supporting target foils was used in the present experiment the conditions were not optimal for measuring the lifetimes. The SD character of bands 1 and 2 is, however, confirmed by the fact that the nucleus is moving with a significantly higher velocity for superdeformed transitions than for the ND transitions as seen by comparing the Doppler shifts of gamma rays emitted in different directions. Furthermore, the average residual Doppler shift of gamma rays belonging to band 2 is seen to be about 30% larger than for band 1 (relative to the ND band). This indicates that the Q_t of band 2 is larger than that of band 1, following the trends of the $\mathcal{J}^{(2)}$ moments of inertia.

The pronounced differences between the moments of inertia of the two SD bands in ^{154}Er imply a significant difference between the underlying structures. In order to investigate this theoretically, cranked Strutinsky calculations based on a Woods-Saxon potential [24] were performed. Pairing correlations were taken into account by means of a seniority and double stretched quadrupole pairing force [25], approximate particle number projection was performed via the Lipkin-Nogami method [26,27], and each quasiparticle configuration was blocked self-consistently. The energy in the rotating frame of reference was minimized with respect to the deformation parameters β_2, β_4, and γ. The two most favored SD configurations are shown in the total Routhian surface plots of Fig. 3. One of these configurations is calculated to be based on four $i_{13/2}$ $(N = 6)$ protons and two $j_{15/2}$ $(N = 7)$ neutrons at a prolate SD shape, due to the presence of the large shell gap at $Z = 66$, $N = 86$. This configuration is similar to that of the yrast SD band in ^{152}Dy and develops a deformation of ($\beta_2 = 0.61$, $\beta_4 = 0.13$, $\gamma = 0°$). Adopting the convention in [12], it is denoted as $\pi 6^4 \nu 7^2$, reflecting the number of particles occupying high-N orbits. However, the energetically most favored SD configuration is calculated to be based on a triaxial SD shape, with deformation parameters ($\beta_2 = 0.40$,

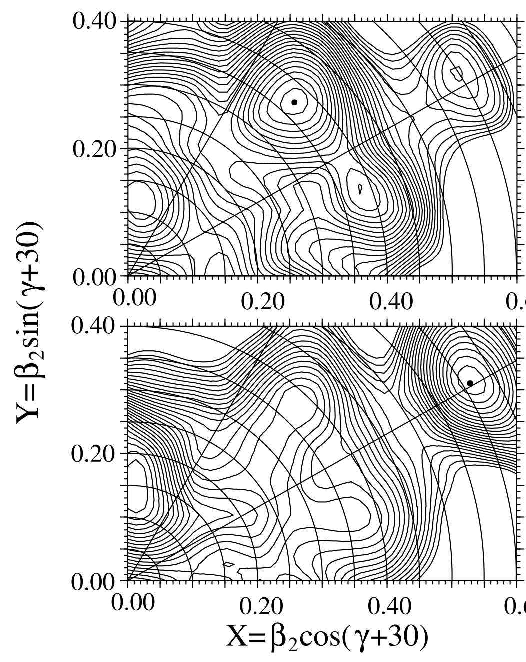

FIG. 3. Calculated total Routhian surfaces for the triaxial (top panel) and prolate (bottom panel) SD configurations in ^{154}Er. The surfaces are calculated for rotational frequencies $\hbar\omega = 0.53$ MeV and $\hbar\omega = 0.61$ MeV for the triaxial and prolate bands, respectively. The filled circle indicates the position of the SD minimum in each case.

$\beta_4 = 0.07$, $\gamma = 12°$). At the triaxial SD shape, the configuration is based on a single proton $N = 6$ intruder orbital, similarly to those of the triaxial SD bands observed in the $A = 165$ mass region [28–31]. The calculated $\mathcal{J}^{(1)}$ and $\mathcal{J}^{(2)}$ moments of inertia for these configurations are compared with the experimental values for bands 1 and 2 in Fig. 2(a) and 2(b), respectively. Since the transitions linking the SD structures to the low-lying yrast states are unobserved, the experimental $\mathcal{J}^{(1)}$ moments of inertia are based on spin assignments deduced from the decay-out patterns and in the case of band 2 on comparison with the yrast SD band in ^{152}Dy. Note that our tentative spin assignments for band 1 differ by two units of $\hbar$ from the previous assignment [13]. In the inset in Fig. 2(a) are also shown the excitation energies as a function of angular momentum for the two configurations, confirming the favored character of the triaxial SD structure. This is consistent with the fact that band 1 is more strongly populated in the experiment. Furthermore, according to our calculations, the first excited prolate SD band lies about 1 MeV higher in excitation energy in the angular momentum regime of $(45–55)\hbar$ where the bands are fed.

In summary a new SD band has been identified in the nucleus ^{154}Er. The observation resolves the long-standing difficulties in the theoretical interpretation of the previously observed band. The new SD band exhibits excellent agreement with the properties predicted for a prolate deformed SD band whereas the previously observed band may now be understood as a SD band based on a triaxial shape. Thus, our interpretation suggests the first observation of coexisting SD structures at prolate and triaxial shapes, respectively.

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