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Superdeformation in ^{154}Er

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A superdeformed (SD) band consisting of 13 γ-ray transitions has been observed in ^{154}Er, an isotone of $^{152}_{66}$Dy. The experiment was performed using the ^{118}Sn(^{40}Ar,4n) reaction at E(^{40}Ar)=185 MeV and the early implementation of GAMMASPHERE. This is an observation of a SD band in the $A\approx150$ region with a proton number greater than 66. The $\mathscr{J}^{(2)}$ moment of inertia of the band is constant above $\hbar\omega$=0.45 MeV and shows a sharp rise below this value suggesting a paired band crossing. These results suggest that total Routhian surface calculations fail to accurately predict the deformation of the band.

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Since the discovery of superdeformation in ^{152}Dy [1] an extensive effort has led to an increased understanding of nuclear structure of the states in the second minimum of the potential energy in the $A\approx$ 150 region. Discrete line superdeformation has been identified in nuclei between La (Z=57) and Dy (Z=66). However, no SD bands have been observed in the $A\approx150$ mass region with proton number greater than 66. Theoretically, total Routhian surface (TRS) and cranked-Hartree-Fock calculations [2] predict a well-developed second minimum at a rotational frequency of $\hbar\omega\approx$ 0.5 MeV with a deformation of $\beta_2\approx$ 0.61 for ^{154}Er (Z=68). Earlier work by de Voigt *et al.* [3] reported a ridge-like structure in a γ-γ-correlation matrix. However, no discrete γ-ray transitions were observed. In this work we report the first observation of a superdeformed (SD) band in ^{154}Er (Z=68), an isotone of ^{152}Dy. The band consists of 13 γ rays with an average ΔE_γ = 50.7(5) keV between $\hbar\omega$ = 0.45 and 0.65 MeV.

The experiment was performed at the 88-in. Cyclotron at Lawrence Berkeley Laboratory. The ^{118}Sn(^{40}Ar,4n) reaction at E(^{40}Ar) = 185 MeV was used to populate ^{154}Er. Two self-supporting (0.5 mg/cm^2) targets were used. Spectroscopy was done using the early implementation of GAMMASPHERE, consisting of 36 Compton-suppressed Ge detectors, 15 at forward, 15 at backward, and 6 at 90° angles with respect to the beam. Approximately 1.5×10^9 events were recorded onto magnetic tape with a trigger condition of at least 3 suppressed, coincident Ge signals. The data consisted of approximately 60% triples, 27% quadruples, and 10% quintuples. This resulted in a total of 6×10^9 unfolded triples events. The most intensely populated channel in the experiment ($\approx$ 80% of the total evaporation residue cross section) was ^{154}Er. Energy and efficiency calibrations were performed using ^{152}Eu, ^{60}Co, ^{207}Bi, and ^{56}Co sources.

Data were sorted into a symmetrized cube [$600<E_\gamma$ (keV)<1500] which was searched for coincident, equally spaced γ-ray transitions with SD band characteristics using the search algorithm of Hughes *et al.* [4]. A single cascade of 13 mutually coincident γ-ray transitions was identified. A matrix double gated on these transitions was sorted and a generalized background subtraction [5] was done. The spectrum, shown in Fig. 1, was obtained by gating on the SD transitions in this matrix and subtracting a spectrum of selected background gates. The lowest energy transition, 695 keV, is very weak and its assignment to the band is uncertain. Energies and relative intensities for the transitions obtained from this spectrum are presented in Table I.

Two γ rays are visible in the spectrum above the highest of the 13 SD γ rays, with E_γ = 1368 and 1425 keV. The 1368-keV line has a width and an intensity consistent with a high energy SD transition. However, there is an yrast γ-ray transition in ^{154}Er with nearly the same energy [6], the 1369-keV ($29^-\rightarrow27^-$; 9475 $\rightarrow$ 8106 keV). Although the decay pattern of the SD band into states in the first well (see below) suggests that this transition should not be visible in this spectrum, there is some chance of contamination due to residual background counts. The width of the 1425-keV line is not consistent with the other members of the SD band. The energies and intensities of these transitions are listed in Table I, even though they are not considered part of the band for purposes of determining the $\mathscr{J}^{(2)}$. Additional statistics will be necessary in order to determine unambiguously whether these transitions are members of the SD band.

Multipolarity of the transitions was established through the use of an empirical asymmetry ratio, $R_{\rm asym}$ =[I_γ(forward+backward)/I_γ(90°)]. Two single-SD-gated matrices were sorted; (i) forward+backward vs all angle and (ii) 90° vs all angle. Summed, double-gated spectra normalized to the numbers of detectors at 90° and forward +backward angles, respectively, were obtained from the matrices. The $R_{\rm asym}$ for a γ ray was determined from the peak area ratios. Known stretched transitions in ^{154}Er yielded the value $R_{\rm asym}$ = 1.59(25) for stretched quadrupoles and $R_{\rm asym}$ = 0.82(24) for stretched dipoles. The large errors are due to the small number of detectors at 90° and the resulting limited statistics. The value of $R_{\rm asym}$ is listed in Table I for several transitions in the SD band. The average value of $R_{\rm asym}$ for the SD band transitions is 1.56(35), consistent with a stretched quadrupole and inconsistent with a stretched dipole assignment.

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TABLE I. Energies (in keV), intensities and angular asymmetry ratios of ^{154}Er SD transitions.

γ No.	Energy (keV)	Intensity	R_{asym}
1[a]	695.06±0.25	0.21±0.05	-
2	734.26±0.23	1.00±0.08	1.79±0.25
3	776.73±0.22	0.98±0.08	1.39±0.39
4	824.09±0.21	0.96±0.09	-
5	874.95±0.23	0.68±0.07	-
6	927.51±0.26	0.76±0.07	1.80±0.39
7	981.04±0.44	0.73±0.07	1.44±0.40
8	1032.14±0.20	0.71±0.09	1.40±0.47
9	1085.24±0.22	0.71±0.08	1.78±0.62
10	1137.88±0.30	0.63±0.07	1.27±0.52
11	1191.39±0.28	0.63±0.07	1.61±0.40
12	1243.84±0.34	0.41±0.07	-
13	1301.93±0.51	0.37±0.06	-
(14)[b]	1368.4±1.2	0.12±0.08	-
(15)[b]	1425.26±0.39	0.30±0.08	-

[a]The low intensity of this transition makes a definitive placement of it uncertain.

[b]Not placed in the SD band.

The assignment of the band to ^{154}Er is based on coincidences between SD γ rays and transitions known to be in ^{154}Er. Schuck *et al.* [6] have deduced the high-spin level scheme of ^{154}Er via the same reaction as used in this work. The only transitions visible in Fig. 1, other than the SD lines (marked by an asterisk), are transitions that are known to be in ^{154}Er (marked by $\triangle$).

The entry region of the SD band into the normal states can also be determined from the spectrum in Fig. 1. The SD band depopulates sharply ($\approx$ 80% of peak intensity) after the 734-keV transition. One of the largest peaks in Fig. 1 is the 319-keV ($25^- \rightarrow 23^-$; 7334 $\rightarrow$ 7015 keV) yrast transition. The intensity of this peak is approximately equal to that of 734-keV SD transition. The next higher yrast transition in ^{154}Er, the 772-keV ($27^- \rightarrow 25^-$; 8056 $\rightarrow$ 7334 keV) is not visible. This indicates that the likely entry region of the SD band into the normally deformed states in ^{154}Er is near $E_x >$ 7.4 MeV and 26 $\hbar$. Figure 2 shows this decay pattern. The widths of the arrows reflect the intensity of the γ ray in Fig. 1. This pattern of decay out of the SD band is similar to other nuclei in this region including ^{150}Gd, an isotone of ^{154}Er, where a likely entry level spin of 29$\hbar$ was reported [7].

A definitive assignment of the intensity of the SD band as a fraction of the total reaction cross section is difficult due to the weakness of the band. However, an estimate can be made based on the intensity of the known yrast transitions in ^{154}Er in Fig. 1. The ratio of the counts in the 319-keV transition in ^{154}Er gated by SD and normal deformed (ND) yrast transitions, respectively, yields a SD/ND ratio of 0.4%. This is weak in comparison with other yrast SD bands in the $A \approx 150$ region. For example, the intensity of the yrast SD band in ^{152}Dy is $\approx$ 1–2 % of the total evaporation residue channel intensity.

Figure 3 illustrates the experimental $\mathcal{J}^{(2)}$ values for the SD band in ^{154}Er (labeled by ●). The $\mathcal{J}^{(2)}$ for ^{154}Er is

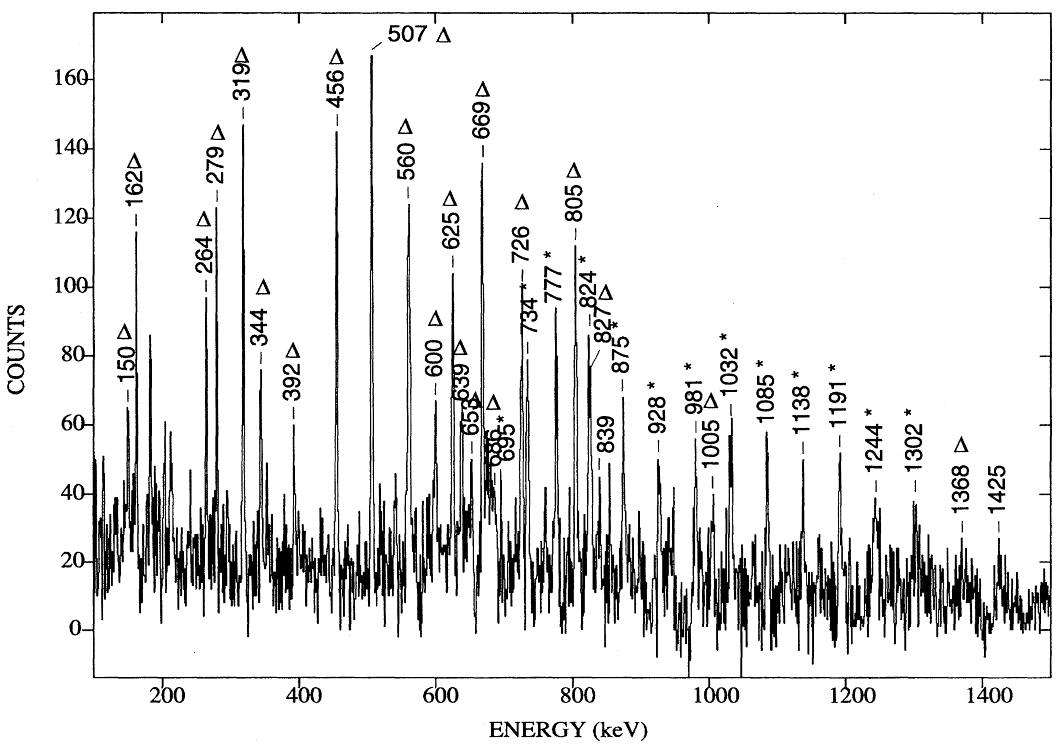

FIG. 1. Triple-gated quadruples spectrum of the superdeformed band in ^{154}Er. SD band γ rays are labeled by an asterisk and normal transitions in ^{154}Er by $\triangle$.

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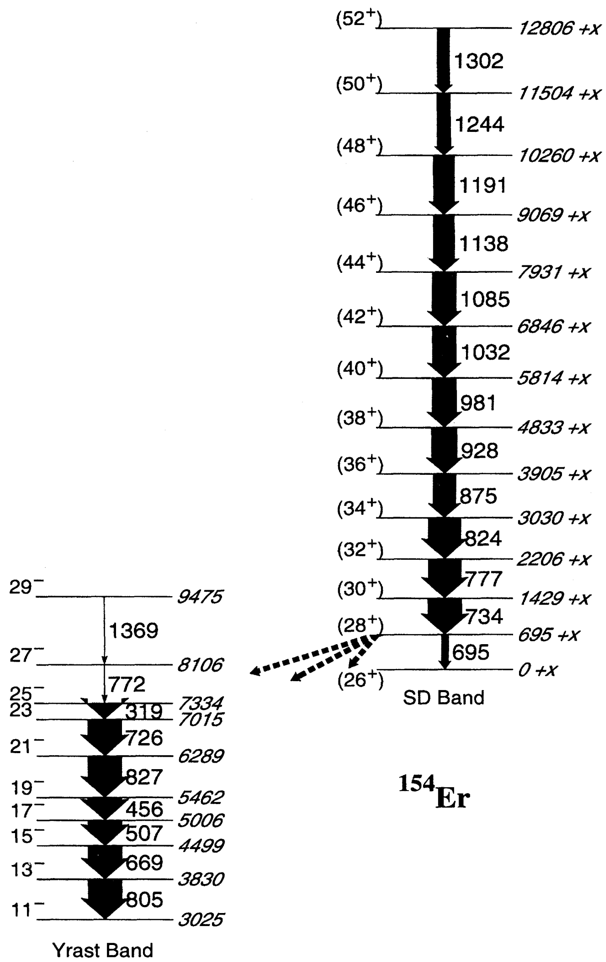

FIG. 2. The decay path of the SD band into the high-spin, normally deformed states in ^{154}Er. The partial level scheme is due to [6].

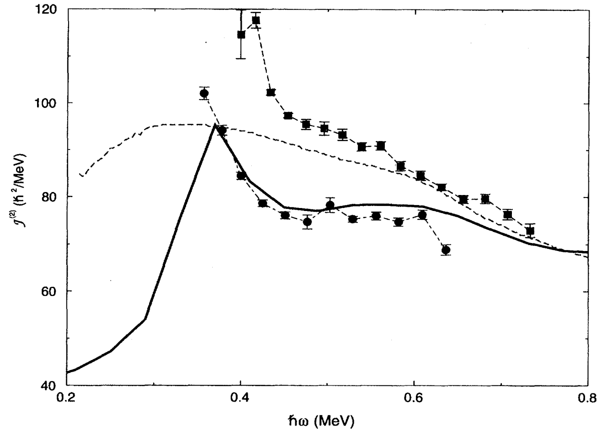

FIG. 3. $\mathcal{J}^{(2)}$ of the yrast SD bands in ^{154}Er (●) and ^{150}Gd (■) from experiment. Also shown are calculations for ^{154}Er with β_2 = 0.61 (- - -), and β_2 = 0.58 (—).

constant above $\hbar\omega \approx 0.45$ MeV with an average value of 75.4(10) $\hbar^2$/MeV. Below $\hbar\omega \approx 0.4$ MeV, the $\mathcal{J}^{(2)}$ rises rapidly with decreasing frequency to $\approx$ 100 $\hbar^2$/MeV. A change in $\mathcal{J}^{(2)}$ of this sort corresponds to a rapid gain in alignment (spin), which may occur following the rotation-induced alignment of a pair of particles (paired band crossing). The rapid rise of the $\mathcal{J}^{(2)}$ over only 4 transitions would imply a relatively weak interaction between the crossing orbitals. The nature of the observed alignment in ^{154}Er can be identified by examining the systematics of SD bands and their interpretation in neighboring nuclei. The $\mathcal{J}^{(2)}$ of the yrast SD band in ^{150}Gd [7], an isotone of ^{154}Er, is also shown in Fig. 3 (labeled by ■). We note that the ^{154}Er and ^{150}Gd $\mathcal{J}^{(2)}$ curves show a similar rise at low rotational frequency. In the following discussion we will use the data on ^{150}Gd to help understand our data in ^{154}Er.

Nazarewicz *et al.* [8] have assigned intruder configurations [9] to many SD bands in the $A \approx 150$ region using a combination of total Routhian surface (TRS) and cranked Wood-Saxon calculations that include pairing. These calculations are remarkably successful in predicting the $\mathcal{J}^{(2)}$ for the majority of the SD bands in this mass region and even reproduce the rapid rise in the ^{150}Gd band 1 $\mathcal{J}^{(2)}$. We note that calculations which do not include pair correlations fail to reproduce the low frequency rise in the ^{150}Gd band 1 $\mathcal{J}^{(2)}$. Consequently this rise in $\mathcal{J}^{(2)}$ is attributed to the alignment of the [770]1/2 quasineutron states. However, these same calculations fail to reproduce the behavior of the SD band in ^{154}Er. The dashed line in Fig. 3 shows the predicted [8] $\mathcal{J}^{(2)}$ for the yrast SD band in ^{154}Er which is $\approx$ 15–25 % larger than that observed and it does not show any rise in the moment of inertia at rotational frequencies near to $\hbar\omega \approx 0.4$ MeV.

The clear discrepancy between calculation and experiment may be due to the TRS calculations in Ref. [8] predicting too large a deformation for the yrast SD band in ^{154}Er (i.e., $\beta_2 \approx 0.61$). This deformation is very close to that of the ^{152}Dy band 1 [11,8]. The size of the $N=86$ SD shell gap is predicted [8] to be sensitive to small changes in deformation, and is a maximum at $\beta_2 \approx 0.6$. For the case of the ^{150}Gd yrast SD band, the deformation is smaller ($\beta_2 \approx 0.58$ [10]) and hence the $N=86$ SD gap is expected to be smaller. The reduced $N=86$ SD gap leads to a higher neutron level density, and therefore larger pairing correlations. In addition, the smaller deformation moves the [770]1/2 intruder closer to the Fermi surface. The net effect is the occurrence of a weakly interacting paired band crossing in ^{150}Gd band 1. We performed a cranked shell model calculation with pairing and a smaller deformation of $\beta_2 \approx 0.58$ (solid line in Fig. 3). This calculation not only predicts the same overall value as the experimental $\mathcal{J}^{(2)}$, but also succeeds in predicting the crossing at $\hbar\omega \approx 0.4$ MeV. In addition, the calculations yield spin values consistent with those shown in the level scheme (Fig. 2). Given that (i) ^{154}Er and ^{150}Gd are isotones ($N=86$), (ii) the similarity of the low frequency rise in $\mathcal{J}^{(2)}$ of ^{150}Gd band 1 and the ^{154}Er band, and (iii) the success of the calculations (at β_2 = 0.58) in predicting the $\mathcal{J}^{(2)}$, then it is likely that the rise in $\mathcal{J}^{(2)}$ at low $\hbar\omega$ can be associated with the $N=7$ quasineutron band crossing.

A final note needs to be made concerning the SD band in ^{154}Er. The transition energies, as presented in Table I, show a stagger in the ΔE_γ between $\Delta I=2$ states for transitions above the crossing frequency ($\hbar\omega$ = 0.45 MeV). This type of stagger in the spectrum of a SD band has been previously observed in ^{149}Gd [12] and ^{194}Hg [13] and has been associated with a C_4 symmetry. However, since the stagger exists over a shorter number of transitions its underlying cause is uncertain. This is the first observation, in the $A\approx$ 150 region, of a $\Delta I=2$ stagger in a SD band in an even-A nucleus.

In conclusion, a band consisting of 13 γ-ray transitions has been observed in ^{154}Er. This is the first observation of a SD band in the $A\approx$ 150 mass region with $Z>$ 66. The band is one of the weakest yrast SD bands in the $A\approx150$ region. The intensity profile and ΔE_γ of the transitions in the band are similar to other SD bands in the $A\approx$ 150 region. Angular asymmetry ratios for several of the transitions in the band are consistent with known stretched quadrupole transitions in ^{154}Er. The $\mathcal{J}^{(2)}$ shows a sharp increase below $\hbar\omega\approx0.4$ MeV which can be interpreted as a paired band crossing. Calculations [8] of the $\mathcal{J}^{(2)}$ fail to reproduce experiment. However, the similarity between the $\mathcal{J}^{(2)}$ of this band and the yrast band in ^{150}Gd [7], together with the success of calculations where the deformation is lowered by $\approx$ 5%, suggests that the rise in $\mathcal{J}^{(2)}$ corresponds to the alignment of two $N=7$ quasineutrons. Finally, at frequencies above $\hbar\omega=0.4$ MeV the ΔE_γ shows a stagger between states that differ by $\Delta I=2$.

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