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Superdeformed band in ^{154}Dy

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A superdeformed band has been found in the ^{154}Dy ($N=88$) nucleus. The dynamic moment of inertia is identical to that of the yrast superdeformed band of ^{152}Dy and the transition energies are similar to those of an excited superdeformed band in ^{153}Dy. It is proposed that the two valence neutrons above the $N=86$ shell gap occupy the deformation-driving [514]9/2 orbital.

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Over the years, the ^{154}Dy nucleus has proven to be a very interesting laboratory for the study of the dramatic structural changes that rapid rotation can induce. With $N=88$ neutrons, this nucleus bridges the sudden change in the ground state shape of Dy isotopes from oblate for $N \leqslant 86$ to prolate for $N \geqslant 90$. As spin increases along the ^{154}Dy yrast line, the level spacing characteristic of a rotational sequence associated with a moderate prolate deformation ($\beta_2 \sim 0.2$) gives way to a level structure (at $I \sim 30\hbar$) which is much more irregular in energy [1]. This sequence of states represents a gradual transition from a prolate to an oblate shape which theory describes in terms of band termination [2], a process where under the stress of rotation the spins of several pairs of nucleons gradually align with the nuclear symmetry axis until the maximally aligned, terminating state is reached. Surprisingly, a return to modest collectivity at spins in excess of $40\hbar$ was also inferred from lifetime measurements [1].

Here, we report on the discovery of yet another interesting collective phenomenon in ^{154}Dy. In an experiment exploiting the increased detection sensitivity provided by GAMMASPHERE, one of the new generation γ-ray spectrometers [3], a weakly populated superdeformed (SD) band has been found. This result can be viewed as somewhat of a surprise. To the best of our knowledge, none of the cranked mean field calculations, which have been so successful in predicting the existence of the island of superdeformation in the vicinity of ^{152}Dy [4–7], have suggested that a SD band would be observed in ^{154}Dy. There is no indication in the calculations for a pronounced SD minimum which would become yrast or near-yrast in the spin range 40–60 $\hbar$ where the known SD bands of this region are thought to be populated. Presumably, the absence of an yrast minimum in the calculations reflects the weakening of the shell effects as neutrons populate energy levels above the $N=86$ SD shell gap. Furthermore, the ^{154}Dy SD band has transition energies identical to those of an excited SD band in ^{153}Dy. This observation is another challenge for theory to explain.

States in ^{154}Dy were populated via the ^{122}Sn(^{36}S,4n) reaction with a 165 MeV beam from the Lawrence Berkeley 88 Inch Cyclotron. The target consisted of a stack of three 350 μg/cm^2 self-supporting foils. The decay γ rays were detected with the early implementation phase of the GAMMASPHERE spectrometer which consisted at that time of 36 Compton-suppressed Ge detectors. A total of 1.3×10^9 events was collected where three or more suppressed Ge detectors were required to fire in prompt coincidence. The data were analyzed by sorting all events into a three-dimensional histogram [8]. Double-gated one-dimensional histograms were created using full background subtraction and proper propagation of errors [9].

A systematic search through the coincidence cube uncovered the weak band presented in Fig. 1. The measured intensity in the band corresponds to $0.6 \pm 0.2\%$ of the total γ-ray flux feeding the ^{154}Dy ground state. This band displays many of the characteristics of known SD bands in the $A \sim 150$ region: i.e., (1) a long, regular sequence of 18 transitions in coincidence with one another (see Fig. 1); (2) energy spacings between transitions in the band (~ 48 keV) very similar to those of known SD bands in the $A \sim 150$ region [10]; (3) and an intensity pattern in the band (inset to Fig. 1) characteristic of other known SD bands, i.e., the γ-ray intensity increases with decreasing transition energy until a constant value is reached, and a sudden decay-out occurs over 2–3 transitions at the lowest energies. On the basis of these similarities, the band of Fig. 1 is interpreted as a SD band.

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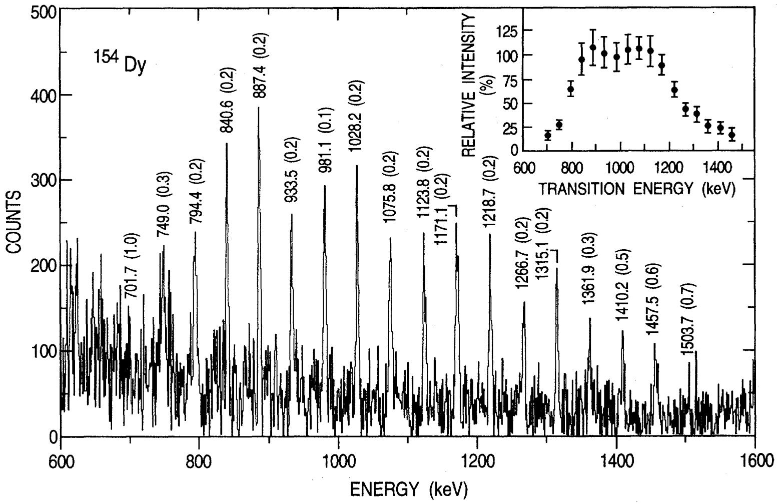

FIG. 1. The SD band of ^{154}Dy obtained from a sum of double coincidence gates. The energies of the transitions are given in keV, together with the errors (presented in parenthesis). The inset shows the intensity profile in the SD band.

The transitions in this SD band are close in energy to those of a SD band (band 3) in ^{153}Dy [11] and the assignment to ^{154}Dy has been carefully checked. As shown in Fig. 2, the strong γ rays observed in coincidence with the SD band all are known ^{154}Dy yrast and near-yrast transitions, and there can be no doubt that this SD band belongs to ^{154}Dy. In fact, levels up to a spin of $\sim 28\hbar$ are reached in the decay-out of the SD band. A search through the coincidence cube for the two other SD bands in ^{153}Dy (bands 1 and 2) revealed that band 1 is present in the data, but with an intensity lower by more than a factor of 2 than that of the band of Fig. 1. (Coincidence spectra gated on transitions in the latter ^{153}Dy band show the expected ^{153}Dy yrast transitions and not the ^{154}Dy γ rays seen in Fig. 2.) The data contain little evidence for band 2 in ^{153}Dy. This excited SD band is below the detection sensitivity of the present experiment. As bands 2 and 3 in ^{153}Dy are thought to be signature partner bands [11], any contribution from ^{153}Dy transitions to the band of Fig. 1 must be very weak. With the present report, ^{154}Dy becomes the heaviest Dy isotope where superdeformation has been observed thus far.

As mentioned above, recent mean field calculations do not predict the SD minimum in ^{154}Dy to become yrast in the spin 40–60 $\hbar$ range. For example, the cranked Strutinsky calculations of Werner and Dudek [6], which are representative of the theoretical situation, indicate that the SD band in ^{152}Dy becomes yrast at $I = 54\hbar$ and only at $I = 66\hbar$ in ^{154}Dy. At $I = 54\hbar$, the SD minimum in ^{154}Dy is calculated to lie 2.4 MeV above an yrast line associated with rotational structures of smaller prolate deformation. The higher excitation energy of the ^{154}Dy SD band may be expected to lead to a reduction of the population intensity with respect to that seen in ^{152}Dy [12]. Whether the calculated excitation energy can account for the observed reduction by a factor of $\sim$2–3 needs to be studied with a model describing the feeding of SD bands. Indeed, other parameters such as the height and width of the barrier separating SD and normal states also affect the intensity. The decay-out of the SD band in ^{154}Dy occurs at a higher transition energy than in ^{152}Dy, as expected if the band is located higher in excitation energy. The lowest transition to carry 100% of the in-band intensity in ^{154}Dy has an energy of 841 keV while the corresponding

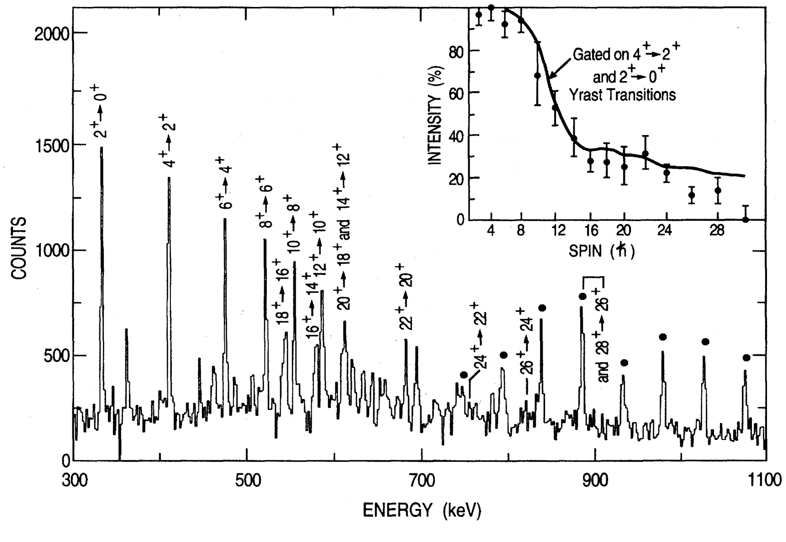

FIG. 2. Coincidence spectrum double gated on SD transitions showing that the yrast and near-yrast ^{154}Dy γ rays are in coincidence with the SD band. The yrast transitions are labeled; the SD γ rays are marked with dots. The inset compares the intensity of the yrast transitions measured in coincidence with the SD band (data points) normalized to the strongest SD transitions (100%) with the intensity profile measured in coincidence with the $2^+ \to 0^+$ and $4^+ \to 2^+$ yrast transitions (line) normalized to the $6^+ \to 4^+$ transition (100%).

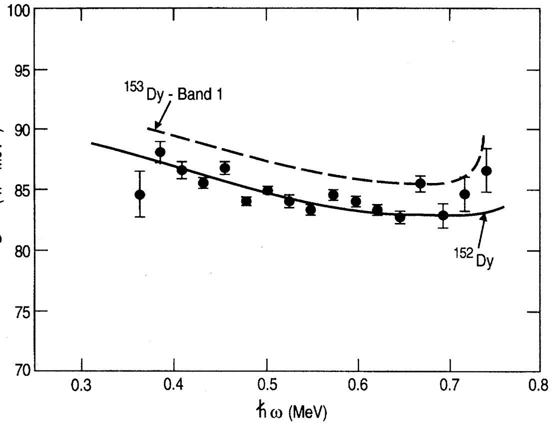

FIG. 3. Comparison of the $\mathfrak{I}^{(2)}$ dynamic moment of inertia as a function of the rotational frequency $\hbar\omega$ in ^{154}Dy (data points), ^{152}Dy (line) and ^{153}Dy-band 1 (dashed line). It should be noted that the $\mathfrak{I}^{(2)}$ values for bands 2 and 3 in ^{153}Dy are essentially identical to those of ^{152}Dy.

transition in ^{152}Dy is at 693 keV. Interestingly, the decay-out then proceeds over four transitions in ^{154}Dy and only over two in ^{152}Dy. Clearly, measurements of (i) energy and spin distributions leading to the SD states in ^{154}Dy and of (ii) the complete spectrum of γ rays connecting SD and "normal" states would allow some of the issues raised here to be addressed, as was shown in Refs. [13] and [14] for the case of the ^{192}Hg SD band.

The dynamic moment of inertia $\mathfrak{I}^{(2)}$ for the new SD band is presented as a function of the rotational frequency $\hbar\omega$ in Fig. 3. The same figure also provides a comparison with the $\mathfrak{I}^{(2)}$ values of band 1 in ^{153}Dy and of the yrast SD band in ^{152}Dy. As was first shown by Bengtsson *et al.* [15], the behavior of $\mathfrak{I}^{(2)}$ with respect to $\hbar\omega$ is mainly influenced by the number of high-N intruder orbitals occupied. Thus, differences in the $\mathfrak{I}^{(2)}$ moments between SD bands have been used to determine the occupation of specific high-N orbitals [10]. From a close inspection of Fig. 3, it is clear that the new SD band is characterized by $\mathfrak{I}^{(2)}$ values which are essentially *the same* at all frequencies as those seen in ^{152}Dy and in bands 2 and 3 of ^{153}Dy. On the other hand, the $\mathfrak{I}^{(2)}$ values for ^{153}Dy-band 1 are markedly higher (the average $\mathfrak{I}^{(2)}$ values for band 1 in ^{153}Dy and for the ^{154}Dy SD band are 87 and 84 $\hbar^2$ MeV^{-1}, respectively). These comparisons then suggest that the SD band in ^{154}Dy has the same high-N configuration as the yrast SD band in ^{152}Dy, i.e., in the language of Ref. [15] a $\pi 6^4 \nu 7^2$ intruder configuration, where four $i_{13/2}$ proton and two $j_{15/2}$ neutron intruder orbitals are occupied. The implication of this assignment is that the additional $j_{15/2}$ orbital, which is believed to be occupied in ^{153}Dy-band 1 [11], is not occupied in ^{154}Dy and that the two valence neutrons occupy instead an orbital which has little effect on the $\mathfrak{I}^{(2)}$ moment of inertia.

As discussed in Refs. [5] and [11], four orbitals lie close in energy above the $N=86$ shell gap in the neutron single-particle spectrum. These are the third $j_{15/2}$ (7^3) high-N intruder, $h_{11/2}$[514]9/2, $h_{9/2}$[521]3/2, and $d_{5/2}$[402]5/2 orbitals. The relative energies of these four configurations with respect to each other depend not only on the rotational frequency, but also on the deformation. The three SD bands in ^{153}Dy have been interpreted [11] as follows: band 1 has been assigned to the $\pi 6^4 \nu 7^3$ configuration which is calculated to be yrast for frequencies $\hbar\omega > 0.8$ MeV, where the SD band is fed. Bands 2 and 3 are signature partner SD bands which have been associated with the [514]9/2 $\otimes$ $\pi 6^4 \nu 7^2$ configuration, i.e., the valence neutron occupies either of the signature partner bands associated with the [514]9/2 orbital. This assignment was used in Ref. [16] within the framework of strong coupling to account for the observations that consecutive transitions in bands 2 and 3 (a) lie at the 1/4 and 3/4 point of the interval spanned by consecutive transitions in ^{152}Dy, and (b) have an average equal to the energies of the yrast SD band in ^{152}Dy.

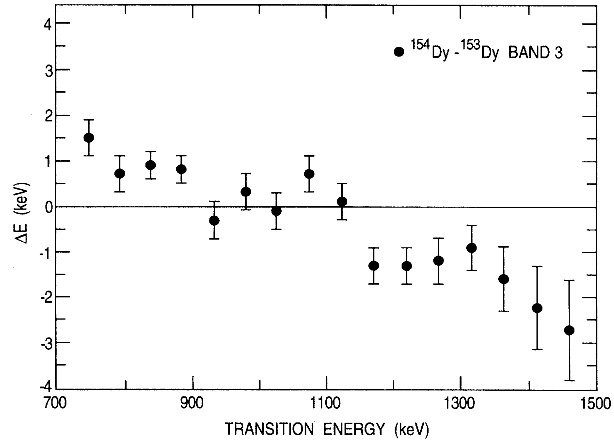

FIG. 4. Difference in the transition energies measured in the SD bands of ^{154}Dy and ^{153}Dy-band 3.

In ^{154}Dy, the comparison of $\mathfrak{I}^{(2)}$ values presented above suggests that the two valence neutrons are located in the [514]9/2, [521]3/2, or [402]5/2 orbitals. In the frequency range where the SD band is fed, these orbitals lie lower than the $j_{15/2}$ intruder when the β_2 deformation decreases slightly with respect to ^{152,153}Dy. It is possible that the change in mass between $A=152$ and $A=154$ is compensated by a small change in deformation and that the identical moments of inertia for the two SD nuclei are the result of the delicate cancellation between the two contributions, as suggested originally by Ragnarsson [17] to account for the identical SD bands phenomenon in nuclei around ^{152}Dy. Such a decrease is indicated by TRS calculations [5]. The choice of the ([514]9/2)^2 $\otimes$ $\pi 6^4 \nu 7^2$ configuration for the SD band is motivated by the fact that this orbital is lowest above the $N=86$ gap. This orbital is upsloping in an energy vs deformation diagram and its occupation tends to decrease the deformation, as mentioned above. Furthermore, the observation that the transition energies in the band are very close (Fig. 4) to those of band 3 in ^{153}Dy, which is assigned to this [514]9/2 orbital, can be regarded as an additional hint favoring this assignment.

As already noted, the transition energies in the new SD band lie close to the 3/4 points relative to those in the yrast SD band of ^{152}Dy. Assuming that transitions of similar energies link states with the same spin values, this observation implies that the new SD band is characterized by half-integer alignment with respect to the ^{152}Dy SD band. This is clearly an unexpected feature and the half-integer relative alignment may well be accidental. Nevertheless, the possibility should not be ruled out that there may be a more profound explanation, which could account not only for the presence of so many SD bands with identical $\mathfrak{J}^{(2)}$ moments of inertia in neighboring nuclei, but also for the measured alignment values.

Finally, it is worth noting that after the decay-out of the SD band, the feeding of the known yrast states is similar to that achieved by the deexcitation from the ensemble of all entry states produced in the reaction. This is shown in the inset of Fig. 2, where the normalized intensity (see figure caption for details) along the yrast line measured in coincidence with the SD band is compared with that obtained from a coincidence spectrum gated on the $2^+ \rightarrow 0^+$ and $4^+ \rightarrow 2^+$ transitions. As can be seen, states up to 28^+ are reached in the decay-out of the SD band. The band also feeds other near-yrast states (e.g., states in the negative parity and in the yrare positive parity bands) with intensities which are proportionally the same as those with which these levels are fed in the reaction. These observations emphasize the statistical nature of the decay-out process as proposed by Vigezzi *et al.* [18] and confirmed recently in Ref. [14]. This is the first time that a SD band has been observed to decay to collective, prolate yrast states of normal deformation. In all other SD nuclei near $A = 150$ and 190, the decay proceeds towards either oblate single-particle ($A \sim 150$) or weakly collective oblate ($A \sim 190$) states. As a consequence, the feeding pattern to the normal states in ^{154}Dy spans a much broader range in spin than in other SD nuclei. Thus, we predict that the spectrum of γ rays connecting superdeformed and normal states should exhibit more features than that measured in ^{192}Hg [14], e.g., the presence of a new $E2$ component.

In summary, a SD band has been found in ^{154}Dy, making this the first $N = 88$ nucleus in which superdeformation has been shown to occur. The $\mathfrak{J}^{(2)}$ moment of inertia of the new band is identical to that of the yrast SD band in ^{152}Dy and of an excited band in ^{153}Dy. The transition energies in this excited ^{153}Dy band and in the new SD band are very similar. A configuration of $(\nu[514]9/2)^2 \otimes \pi 6^4 \nu 7^2$ is proposed.

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