Observation of Identical Superdeformed Bands in $N=86$ Nuclei

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Excited superdeformed bands have been observed in the $N=86$ isotones ^{150}Gd and ^{151}Tb. The properties of these bands were found to closely resemble those of the yrast superdeformed bands in their $Z+1$ $N=86$ isotones (^{151}Tb and ^{152}Dy) such that, on average, the transition energies are identical to an accuracy of 1:1000. It is proposed that these excited superdeformed bands are based on single-proton excitations from the $[301]\frac{1}{2}$ orbital into the $[651]\frac{3}{2}$ intruder orbital and thus they are the first observation of proton excitations in superdeformed nuclei.

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The first discrete-line superdeformed states in the mass $A\approx150$ region were found in ^{152}Dy.[1] This confirmed many years of calculations[2-5] predicting the occurrence of exotic nuclear shapes with large prolate deformations ($\beta_2\approx0.6$) stabilized by microscopic shell effects. With the discovery of several other examples of superdeformation in neighboring nuclei[6-11] it soon became apparent that some properties of these bands differed considerably. In particular, the dynamic moments of inertia $\mathcal{J}^{(2)}$ and the deexcitation frequencies were seen to vary from one example to the next. Bengtsson *et al.* proposed[12] that the properties of the superdeformed bands would be influenced by the occupation of high-N intruders. Indeed they calculated the contribution to the total $\mathcal{J}^{(2)}$ from the intruder orbitals and found that over the frequency range of interest each intruder orbital contributed almost uniquely to $\mathcal{J}^{(2)}$. More recently, total-Routhian-surface (TRS) calculations[13] have confirmed these results. Thus, from the slopes of the $\mathcal{J}^{(2)}(\omega)$ curves it is possible to assign configurations to the superdeformed bands in terms of the high-N intruder occupation scheme. It is expected that excited superdeformed bands would be built on particle-hole excitations and it is not clear how these particle excitations should affect the properties of the superdeformed bands. In this Letter we report on the observation of excited superdeformed bands in ^{150}Gd and ^{151}Tb. These new bands are essentially identical to the yrast superdeformed bands in their $Z+1$ $N=86$ isotones. We propose that they are single-proton excitations into high-N intruder orbitals and are thus the first observations of proton excitations in superdeformed nuclei.

The experiments were carried out on the tandem Van de Graaff accelerator at Daresbury Laboratory using the TESSA3 γ-ray spectrometer.[14] High-spin states in ^{150}Gd were populated by the reaction ^{130}Te(^{26}Mg, $6n$)^{150}Gd at a beam energy of 145 MeV while the states in ^{151}Tb were populated by the reaction ^{130}Te(^{27}Al, $6n$)^{151}Tb at a beam energy of 150 MeV. The targets consisted of two self-supporting, isotopically enriched 400-μg cm^{-2} tellurium foils. The reaction conditions were chosen so that the final nucleus was formed near to yrast and at high angular momentum. The total number of Ge-Ge-BGO coincidence events recorded was around 230×10^6 in each experiment. For each data set E_γ-E_γ correlation matrices were produced with sum-energy and fold conditions in the BGO ball which maximized the relative yield of superdeformed compared to normal-deformed γ rays. In general, this corresponded to events where more than 17 BGO ball elements registered.

The energetically favored superdeformed bands (yrast superdeformed) have already been reported[9] and were found to each carry around 1% of the ^{150}Gd and ^{151}Tb reaction-channel intensity. In this work an extra band sequence in each nucleus has been observed with γ-ray energy spacings consistent with a superdeformed structure. These superdeformed bands (Fig. 1) are a factor of 3 weaker than the yrast bands, and assuming that yrast states are usually fed more intensively than excited states, for rotational band structures, we conclude that the new bands are energetically unfavored (excited superdeformed). The bands were seen to be in coincidence with known γ rays in ^{150}Gd and ^{151}Tb. However, the entry point of the superdeformed band into the yrast states could not be clearly identified and hence no definite spin assignments to the superdeformed levels could be made. The excited superdeformed bands are seen to have similar properties to the previously observed yrast superdeformed bands in their $Z+1$ isotones. In particular, the transition energies are almost identical. However, one may rule out the possibility of these identical (twin) bands being one and the same, as the $Z+1$ isotones can-

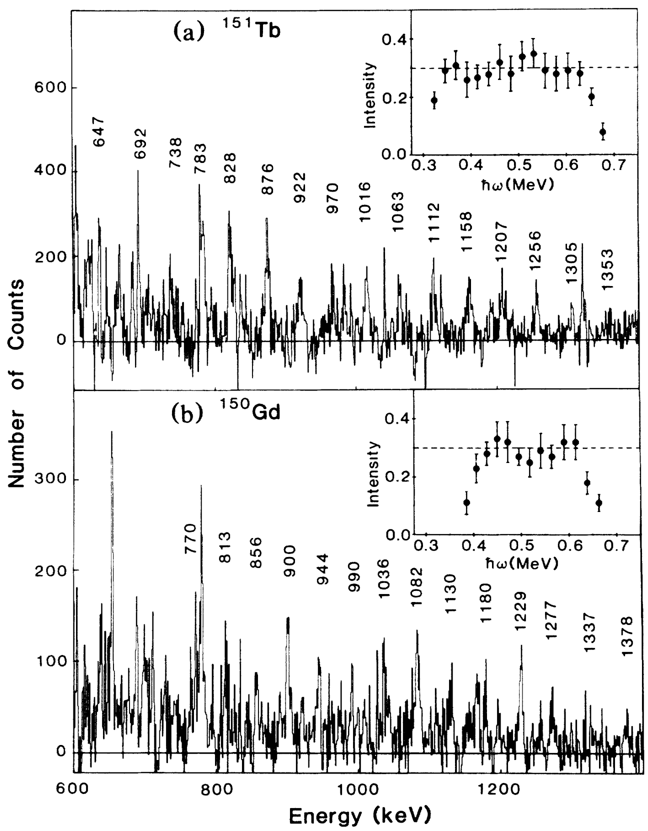

FIG. 1. Sum of spectra in coincidence with transitions in the non-yrast-superdeformed bands in the $N=86$ nuclei (a) ^{151}Tb and (b) ^{150}Gd. The γ-ray energies of the bands are given in the figure. Other γ rays are associated with normal-deformation yrast decays following the deexcitation of the bands. Insets: The excited superdeformed band intensities relative to the maximum intensity of the yrast superdeformed bands in ^{151}Tb and ^{150}Gd, respectively.

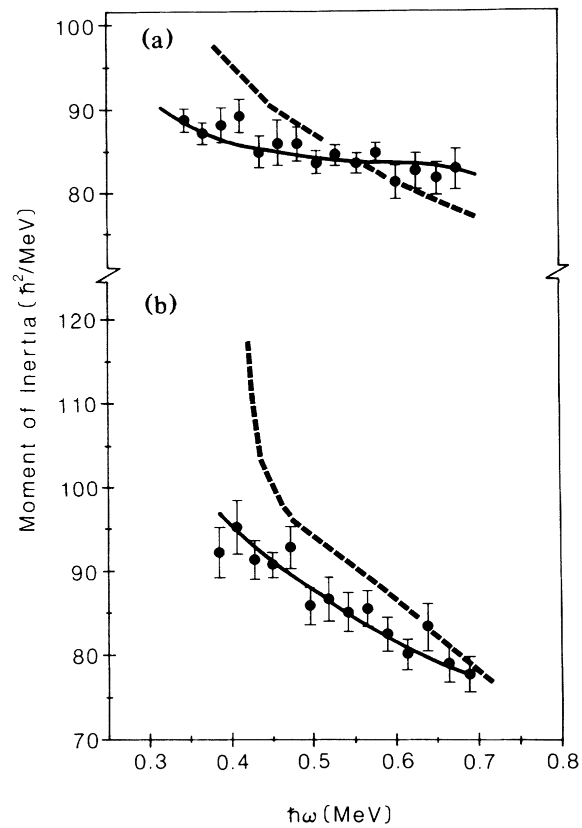

FIG. 2. The dynamic moment of inertia $\mathcal{J}^{(2)}$ as a function of rotational frequency for (a) the excited superdeformed band in ^{151}Tb (circles) together with the $\mathcal{J}^{(2)}$ curves for the yrast superdeformed band in ^{151}Tb (dashed line) and the yrast superdeformed band in ^{152}Dy (solid line) and (b) the excited band in ^{150}Gd (circles) and the yrast bands in ^{150}Gd and ^{151}Tb (dashed and solid lines, respectively). Clearly the $\mathcal{J}^{(2)}$ values for the excited superdeformed bands are very similar to the yrast superdeformed bands in their $Z+1$ $N=86$ isotones. This implies similar high-N intruder configurations.

not be produced in the reactions used.

The properties of the superdeformed bands are mainly influenced by the number of the high-N intruder orbitals occupied.[12,13] For example, it is proposed[9] that the large slopes on $\mathcal{J}^{(2)}(\omega)$ in ^{150}Gd and ^{151}Tb are due to the occupation of the $\pi 6_2, \nu 7_2$ orbitals while in ^{152}Dy the $\pi 6_4$ level is also occupied and this leads to a more constant $\mathcal{J}^{(2)}(\omega)$. A plot of $\mathcal{J}^{(2)}(\omega)$ for the excited superdeformed band in ^{151}Tb [Fig. 2(a)] gives a curve that is practically constant and which closely follows the $\mathcal{J}^{(2)}$ curve traced out by the yrast superdeformed band in ^{152}Dy (solid line) but which is very different from the yrast superdeformed band in ^{151}Tb (dashed line). Similarly, the ^{150}Gd excited superdeformed band [Fig. 2(b)] has $\mathcal{J}^{(2)}$ values which resemble those observed in the ^{151}Tb yrast superdeformed band (solid line). It is concluded from these comparisons that the excited superdeformed bands in ^{151}Tb and ^{150}Gd have the same high-N orbitals occupied as the yrast superdeformed bands observed in ^{152}Dy and ^{151}Tb, respectively.

The occurrence of superdeformed bands in neighboring nuclei, apparently having the same intruder orbitals occupied, can be understood in terms of particle-hole excitations, in particular, proton excitations. In Fig. 3 the calculated[13] single-particle levels for protons are shown as a function of deformation β_2. At $\beta_2 \approx 0.6$ a strongly prolate-deformation-driving intruder orbital originating from the $N=6$ shell is crossed by the equally deformation-sensitive but oblate-driving orbital labeled $[301]\frac{1}{2}$. It is therefore possible to excite a proton from the $[301]\frac{1}{2}$ orbital into the $[651]\frac{3}{2}$ intruder orbital, and hence the excited superdeformed band in ^{151}Tb can be associated with the configuration $\pi 6_4([301]\frac{1}{2})^{-1} \otimes \nu 7_2$ and the excited band in ^{150}Gd can be associated with the configuration $\pi 6_3([301]\frac{1}{2})^{-1} \otimes \nu 7_2$. The occupation of only one $[301]\frac{1}{2}$ orbital leads to the bands possessing odd parity. The slopes of the $[301]\frac{1}{2}$ orbitals are insensitive to the rotation[13] and hence they do not contribute to

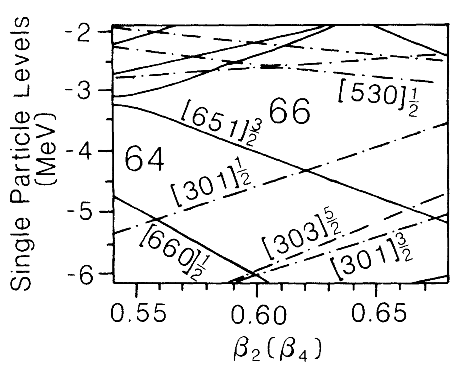

FIG. 3. A section of the proton single-particle levels as a function of deformation $\beta_2(\beta_4)$. At $\beta_2 \approx 0.6$ the oblate-driving $[301]\frac{1}{2}$ orbital and the prolate-driving $[651]\frac{3}{2}$ intruder orbital cross each other. A proton excitation from the $[301]\frac{1}{2}$ to the $[651]\frac{3}{2}$ level is therefore energetically favorable. The occupation of an extra intruder orbital results in the nucleus having an increased deformation.

$\mathcal{J}^{(2)}$.

The remarkable similarities between the excited superdeformed bands and the previously observed yrast superdeformed bands in the $Z+1$ isotones are further illustrated when direct comparisons of the γ-ray energies are made. Figure 4 shows the differences between the γ-ray energies observed in the identical bands in the pairs of nuclei ^{151}Tb-^{152}Dy and ^{150}Gd-^{151}Tb. It can be seen that on the average the deviation is less than 1 keV for the ^{151}Tb-^{152}Dy pair and slightly larger for the ^{150}Gd-^{151}Tb pair. Since the γ-ray energy for a given spin (angular momentum) is dependent on the kinematic moment of inertia $\mathcal{J}^{(1)}$, a 1-part-in-1000 difference in the γ-ray energies corresponds to a difference in $\mathcal{J}^{(1)}$ of the same order. This very small difference is extremely surprising since a simple $A^{5/3}$ scaling ($\mathcal{J} \propto MR^2$) would imply differences in γ-ray energies of the order of $\Delta E \approx 10$ keV for $E_\gamma \approx 1$ MeV. Moreover, when one views the excited superdeformed bands as being a proton hole in either the ^{152}Dy or ^{151}Tb superdeformed core, then the removal of a particle (in a strongly oblate-driving orbital) from the core appears to have a negligible effect on the properties of the core.

As with all the other observed superdeformed bands in this region the present examples deexcite extremely rapidly. However, several interesting points emerge from the depopulation of these excited bands. In particular, the rate and the frequency range over which the bands deexcite follows closely the decay patterns observed for their twin bands (superdeformed yrast). This is clearly seen by considering both superdeformed bands in ^{151}Tb. The yrast band deexcites at a rotational frequency $\hbar\omega \approx 0.4$ MeV while the excited band extends to lower frequencies and is seen to deexcite at $\hbar\omega \approx 0.32$ MeV, identical to its twin band in ^{152}Dy. Since the two bands in the same nucleus have different structures, this implies that the frequency and pattern of decay from the super-

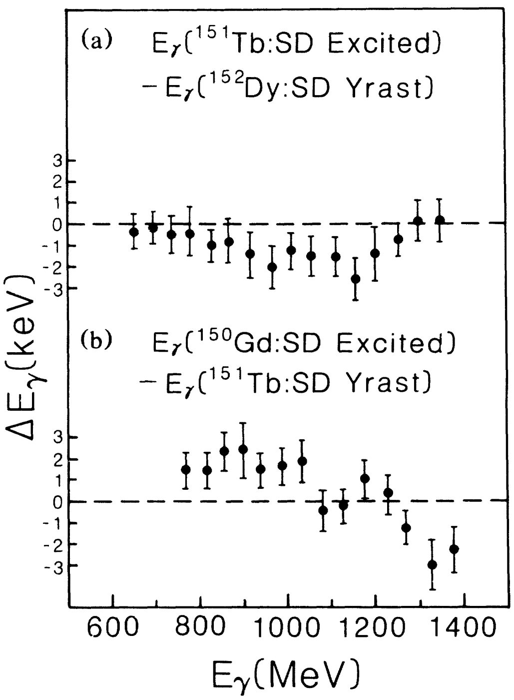

FIG. 4. The differences in the γ-ray energies between the bands in (a) ^{151}Tb (excited superdeformed) and ^{152}Dy (yrast superdeformed) and (b) ^{150}Gd (excited superdeformed) and ^{151}Tb (yrast superdeformed). For the ^{151}Tb-^{152}Dy pair the difference is, on average, less than 1 keV while for the ^{150}Gd-^{151}Tb pair the difference is slightly larger.

deformed band into the normal yrast states is dependent on the structure of the superdeformed band. Moreover, for a decay mechanism in which pair correlations play a role,[15] one may consider the number of occupied high-N intruders to influence (through differences in the deformations of the superdeformed bands[13]) the onset of static pair correlations.

In summary, excited superdeformed bands have been observed in both ^{150}Gd and ^{151}Tb. They are seen to extend to high spins, to carry around 0.3% of the $6n$ reaction-channel intensity, and to follow an in-band intensity pattern similar to the other superdeformed bands around $A \sim 150$. The dynamic moments of inertia $\mathcal{J}^{(2)}$, the feeding and decay patterns, and indeed the transition energies for the bands were found to be remarkably close to those observed in the yrast superdeformed bands in their $Z+1$ $N=86$ isotones. The similarities can be understood in terms of single-proton excitations from the $[301]\frac{1}{2}$ orbital into the $[651]\frac{3}{2}$ intruder orbital and this approach is discussed[16] in detail in the following paper. The observed decay patterns indicate that the deexcitation of the superdeformed bands is dependent on the structure of the superdeformed nucleus. This first observation of proton excitations in superdeformed nuclei highlights the stability of the superdeformed cores at $N=86$. Indeed it is seen that even removing a proton from a strongly oblate-driving orbital has essentially no effect on the moments of inertia of the core.

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