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Superdeformation in the odd-odd nucleus ^{150}Tb: Experimental search for superdeformed configurations

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A superdeformed band was found in the nucleus ^{150}Tb following the reaction ^{31}P+^{124}Sn at 160 MeV. This is the first odd-odd nucleus in the mass 150 region where such a band has been found. Its observed properties do not differ significantly from those of other cases in this mass region. From a systematic study of this region, we have determined experimentally the contribution to the moment of inertia $\mathcal{J}^{(2)}$ of each of the last particles in these nuclei. At present, this seems to us the best way to identify the orbitals occupied by these particles.

Since the discovery[1,2] of the first two discrete superdeformed bands at high spins in the ^{152}Dy and ^{132}Ce nuclei, several more have been found in these two mass regions. In addition, two more mass regions of high-spin superdeformation have been proposed, namely the region[3] around $A=105$, and the region[4,5] around $A=180$. However, lifetime measurements[6-9] have shown that the largest deformations found so far are in the mass 150 region. The deformation $\epsilon \sim 0.56$ found there corresponds to that of an ellipsoid having a ratio of axes around 2:1:1, for which the nucleus is expected to have a special stability. This stability at large deformation is the result of shell effects, which are gaps in the single-particle spectrum due to particular properties of the orbitals. Therefore, considerable progress in understanding superdeformation could be achieved if these orbits could be identified and their evolution followed in a set of neighboring nuclei, especially in the mass 150 region where these deformations are largest. Six[1,7,10-13] superdeformed (SD) nuclei were known in that mass region. We report the discovery of a discrete SD band in the nucleus ^{150}Tb, the first one in an odd-odd nucleus in that mass region. By subtracting the moments of inertia $\mathcal{J}^{(2)}$ between neighboring nuclei, we have tried to find the contribution to that moment of inertia from individual SD orbits and to identify these orbits.

The nucleus ^{150}Tb was produced at the 88-inch cyclotron of the Lawrence Berkeley Laboratory in the reaction ^{31}P+^{124}Sn at 160 MeV. Two thin targets, ~ 0.5 mg/cm^2 thick, were used so that the product nuclei recoiled out of the targets with nearly full velocity. The γ rays were detected in the HERA (high-energy-resolution array) of 21 Compton-suppressed Ge detectors. The γ rays were Doppler shifted and the gain of each detector was therefore adjusted (on line) according to its angle so that the spectra from all detectors had the same energy calibration and could be added together. Only threefold and higher-fold events were stored on magnetic tape; twofold events were stored directly in a two-dimensional matrix of a histogramming memory.

The approximately 180×10^6 threefold and higher-fold events were first broken into pairs of γ rays which were accumulated into a two-dimensional matrix. No ridges, which (with the proper spacing) would be indicative of a SD band, were observed. However, a detailed analysis revealed a set of regularly spaced transitions in coincidence, of order 50 keV apart. In order to see this band more clearly, a triple-coincidence spectrum was constructed by adding spectra gated by any combination of two out of the ten strongest SD lines. This is shown in Fig. 1, and only the SD lines and some known lines in the ^{150}Tb nucleus appear. The individual double-gated spectra and their sum (Fig. 1) show that the SD lines form a band and belong to the nucleus ^{150}Tb. Additional evidence for identifying the nucleus generating this band was obtained by another triple-coincidence sort. In this analysis, one gate was set on any SD line and the other on some known line of each product nucleus in the reaction, namely ^{151,150,149}Tb. The SD band was seen only in the spectra where one gate was in the nucleus ^{150}Tb.

The angular correlation method described in Ref. 14 was used to determine the multipolarity of the transitions. Since there is a factor of 8 less statistics than in the full matrix (due to angle selection) and only one line (at 902 keV) could be used as a gate, the statistics are not very good. The 36°/79° ratios for the SD band are shown in Table I and are consistent with those of stretched quadrupole transitions.

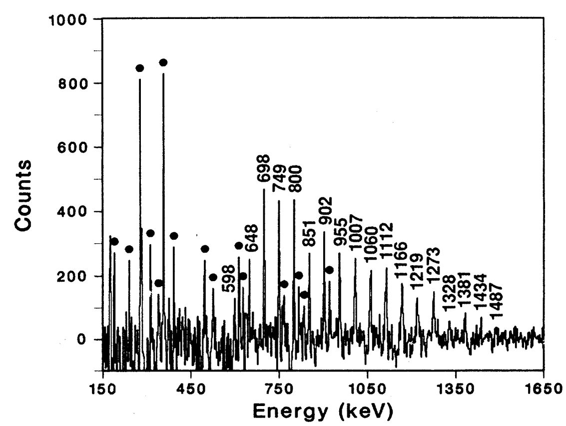

FIG. 1. Triple coincidence spectrum summed for all double-gate combinations of ten SD lines (698–1166 keV) in ^{150}Tb. The full dots indicate known lines of ^{150}Tb in coincidence with the SD band.

TABLE I. Relative intensities of the SD band transitions, and some angular correlation data.

E_γ (keV)	I^a	R^b (36°/79°)
310[c]		0.77±0.09
355[d]		1.19±0.12
598	0.25±0.10	
648	0.45±0.10	
698	0.92±0.11	1.2±0.3
749	1.07±0.11	1.4±0.4
800	0.96±0.11	0.6±0.3
851	0.86±0.11	1.2±0.3
902	1.00±0.11	1.1±0.3
955	0.87±0.11	1.15±0.3
1007	1.05±0.11	
1060	1.11±0.11	
1112	1.12±0.11	
1166	0.95±0.11	
1219	0.72±0.11	
1273	0.76±0.11	
1328	0.38±0.10	
1381	0.43±0.10	
1434	0.30±0.10	

[a]Normalized to the average intensity of the SD lines from 749 to 1166 keV as unity.
[b]R is the ratio of the intensity in the ~36° detectors for E_γ (for a 902-keV gate at ~79°) to the intensity in the ~79° detectors for E_γ (for the 902 keV gate at ~36°). Assuming that the 902 keV gate has an $E2$ character, R is 1 for a stretched quadrupole transition and is close to 0.6 for a stretched dipole transition. The error bars indicated here are only statistical.
[c]A known dipole transition.
[d]A known quadrupole transition.

The average intensity of the SD band was obtained by comparing intensities of the SD lines and of known lines in triple-coincidence spectra. For the SD band, the quoted intensity is that averaged over the 10 most intense lines (from 749 to 1273 keV) in a spectrum of all double-gate combinations of 15 lines (from 648 to 1381 keV). For the low-lying part of the ^{150}Tb nucleus, intensities were obtained from the 355-765 keV double-gated spectrum which represents the strongest branch,[15] and this was corrected for the other branches. We found an intensity of about 1% of the total cross-section for the nucleus ^{150}Tb. The relative intensity of the SD lines (see Table I) is roughly constant between γ-ray energies of 0.7 and 1.2 MeV, and drops above and below these values, in a manner similar to that of the other cases known in that region (except[12] for ^{150}Gd).

The spins were tentatively determined, using triple-coincidence spectra gated on the SD band, in a method similar to that of Refs. 1, 7, and 10. All the lines up to spin 21 in ^{150}Tb are seen,[15] and in addition, the new lines at 188, 338, 526, and probably 496 keV, which belong to this nucleus. The level scheme above spin 21 appears complicated and has not been completely worked out yet, but we found from the intensities and the coincidence spectra that these lines lie above the known spin-21 level. The 526-keV line is the crossover of the 188 and 338 keV lines which are both of stretched dipole character. The 496-keV line has also a stretched dipole character. The spin at the top of these lines is then assumed to be at least 24. Based on these assignments and the intensity of these lines in the decay spectrum of the SD band, the average entry spin in the yrast line was found to be $21\hbar$. Assuming $(1.5-2)\hbar$ of angular momentum carried by a few statistical-type γ rays out of the SD band, the average decay spin of the SD band is then $23\hbar$. From the intensity of the lower SD lines, this average spin is assigned to the state decaying by the 598-keV transition, and a value of $21\hbar$ for the spin of the lowest SD state is deduced. No linking transition has been found between the SD states and the low-deformation states.

The nucleus ^{150}Tb is the first odd-odd nucleus in the 150 mass region in which a discrete SD band has been observed. In contrast to the mass 130 region where the SD bands were more heavily populated[16,17] in the odd than in the even-even nuclei, there does not seem to be large differences in the population of the SD bands of the mass 150 region.

The properties of the SD bands in this mass region are rather similar. Their moments of inertia are equal within 10%, and the deformations, where measured, are equally close. However, when compared in detail, both the dynamic moment of inertia $\mathcal{J}^{(2)}$ and the kinematic moment of inertia $\mathcal{J}^{(1)}$ behave differently from nucleus to nucleus, as shown in Fig. 2. Some of the variations in absolute values of $\mathcal{J}^{(1)}$ are probably due to uncertainties in spin assignments, but the values of $\mathcal{J}^{(2)}$ are well determined since they only depend on the transition energies. If the

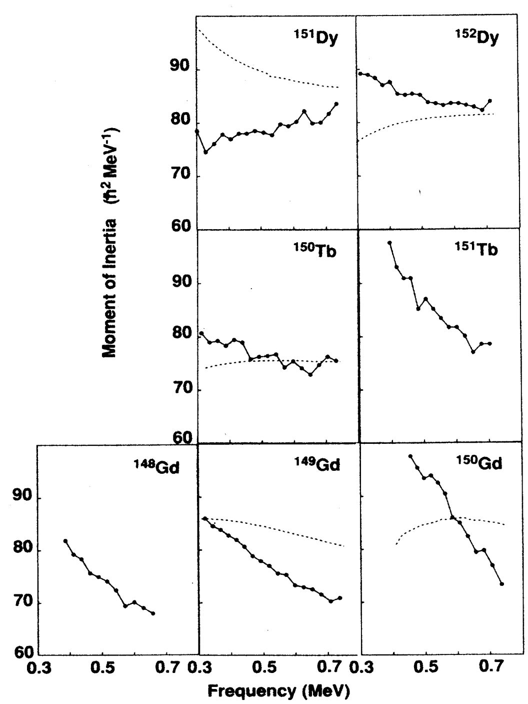

FIG. 2. Moments of inertia $\mathcal{J}^{(2)}$ (solid) and $\mathcal{J}^{(1)}$ (dashed) for the seven known SD nuclei in the mass 150 region.

contributions to that moment of inertia are additive, as is implied by the cranking model, then the difference in moments of inertia between two adjacent nuclei should come from the additional nucleon. Since various individual orbitals (especially orbits from unique-parity high-j shells) have different contributions,[18] these differences in moment of inertia can, in principle, be used to identify them.

The observation of the SD band in ^{150}Tb is especially interesting as it makes possible a more systematic investigation of these properties of individual orbitals. We can obtain the contribution to the $\mathcal{J}^{(2)}$ moment of inertia for the neutron orbital $N=86$ in three independent ways by subtracting the experimental values of $\mathcal{J}^{(2)}$ for ^{151}Dy from those for ^{152}Dy, or for ^{150}Tb from those for ^{151}Tb, or for ^{149}Gd from those for ^{150}Gd. These differences are shown as solid lines in Fig. 3(a) and can be compared to theoretical values plotted in Fig. 3(c). Figure 3(c) represents the contribution to the moment of inertia $\mathcal{J}^{(2)}$ from each of the first four individual (proton) orbitals in the $i_{13/2}$ shell. Since their behavior is rather similar[18] for any unique-parity shell, we shall use this plot for comparison with both neutron and proton experimental values.

Calculations[19] suggest that the $N=86$ neutron orbital should correspond to the second $j_{15/2}$ orbital and therefore would correspond to the curve labeled 2 in Fig. 3(c). The general variation with frequency of the experimental curves is in agreement with the theory. However, the absolute values of the experimental curves differ, which should not be the case if everything was identical in the three nuclei ^{152}Dy, ^{151}Tb, and ^{150}Gd. The contribution to the moment of inertia $\mathcal{J}^{(2)}$ for the $N=86$ orbital is systematically larger in lighter nuclei. Pairing effects are not expected to be important, at least for the higher spins, so that deformation effects are the most probable cause of these differences. Although these may be changes in deformation between Dy and Tb nuclei, for example, they should tend to subtract out in the above differences of moments of inertia. However, the polarization of the core by the additional orbital would be different for different cores and this will not subtract out. Since such changes affect all the orbitals in the nucleus, it may not be unreasonable to observe variations for different cases amounting to $\pm 5\%$ (of the total moment of inertia) in the contributions to the moments of inertia of Fig. 3(a). Very recent calculations[20] including small changes in deformation and pairing look promising. The moments of inertia of the $N=86$ orbital are consistent with their identification as the second $j_{15/2}$ orbital. The contribution of the $N=85$ neutron orbital is obtained by subtracting the moments of inertia for ^{148}Gd from those for ^{149}Gd and is shown as a dashed line in Fig. 3(a). The calculations[19] suggest that the $N=85$ orbital is a low-j orbital, which would indeed give a flat contribution, but the first $j_{15/2}$ orbital would also give a flat contribution in the frequency range observed. A flat contribution, therefore, is not very definitive, and one cannot conclude anything about the configuration of the $N=85$ neutron orbit.

For the protons, there are two ways to obtain experimentally the contribution of the $Z=66$ orbital, and also two ways to obtain that of the $Z=65$ orbital and the results are plotted in Fig. 3(b). The calculations of Ref. 19 suggest that these should be the fourth and third orbitals in the $i_{13/2}$ shell, respectively. However, the experimental contributions increase with frequency for both $Z=66$ and 65, whereas only the fourth orbit [Fig. 3(c)] is predicted to increase. Thus, the $Z=66$ contribution varies as expected, whereas the $Z=65$ does not. (The very recent cal-

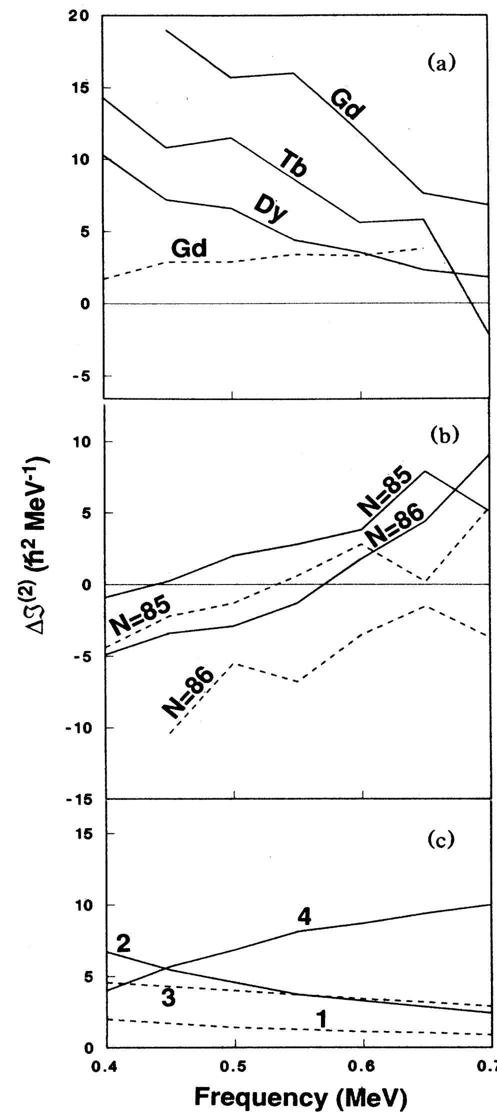

FIG. 3. (a) Contribution to the moment of inertia $\mathcal{J}^{(2)}$ for $N=86$ (solid lines) and $N=85$ (dashed line) obtained from the differences in the experimental moments of inertia: ^{152}Dy $-$ ^{151}Dy (Dy), ^{151}Tb $-$ ^{150}Tb (Tb), ^{150}Gd $-$ ^{149}Gd (Gd), and ^{149}Gd $-$ ^{148}Gd (Gd), respectively. (b) Same as (a) for the protons $Z=66$ (solid lines) and $Z=65$ (dashed lines). The $Z=66$ values were obtained from the experimental moment of inertia differences for ^{152}Dy $-$ ^{151}Tb ($N=86$) and ^{151}Dy $-$ ^{150}Tb ($N=85$), and the $Z=65$ values from the differences for ^{151}Tb $-$ ^{150}Gd ($N=86$) and ^{150}Tb $-$ ^{149}Gd ($N=85$). (c) Calculated (Ref. 19) contributions to the moment of inertia $\mathcal{J}^{(2)}$ for the four lowest protons in the $N=6$ shell (labeled 1,2,3,4). The deformation parameters were $\epsilon=0.556$, $\epsilon_4=0.029$, and $\gamma=0°$.

culations[20] including deformation and pairing changes can reproduce the $Z=65$ slope, but this is the only case calculated to our knowledge and it is not clear how significant this agreement is.) A more detailed theoretical investigation, as well as more systematic experimental data, will be necessary to clarify the different factors influencing the values of the moments of inertia. For the proton contributions [for example $Z=66$, see Fig. 3(b)], the absolute values of the moment of inertia are again systematically larger in lighter nuclei, as was found for the neutron orbitals.

In conclusion, the properties of the discrete SD band found in the (first) odd-odd nucleus in the mass 150 region ^{150}Tb are not significantly different from those of other nuclei in that region (see Fig. 2). Using the seven known SD nuclei of that mass region, we subtracted the moments of inertia $\mathcal{J}^{(2)}$ from adjacent nuclei to determine the contribution to that moment of inertia of the last particle and tried to identify it with a particular configuration (orbit). Although not perfect, this seems to us the only way at present to determine configurations in superdeformed nuclei. We found that the variations with frequency for a given nucleon number are consistent, at least in the trend, for different mass numbers. These trends for the neutron numbers $N=85,86$ and for the proton number $Z=66$ are consistent with the theoretical expectations. For the proton orbital $Z=65$, however, the experimental trend does not follow the simple theoretical one, and this needs further study.

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[1]P. Twin *et al.*, Phys. Rev. Lett. **57**, 811 (1986).

[2]P. Nolan *et al.*, J. Phys. G **11**, L17 (1985).

[3]A. O. Macchiavelli *et al.*, Phys. Rev. C **38**, 1088 (1988).

[4]J. Burde *et al.*, Phys. Rev. C **38**, 2470 (1988).

[5]T. Rzaca-Urban *et al.*, in Proceedings of the Conference on High-Spin Nuclear Structure and Novel Nuclear Shapes, Argonne, 1988 (Report No. ANL-Phy-88-2, unpublished), p. 46.

[6]M. A. Bentley *et al.*, Phys. Rev. Lett. **59**, 2141 (1987).

[7]B. Haas *et al.*, Phys. Rev. Lett. **60**, 503 (1988).

[8]A. J. Kirwan *et al.*, Phys. Rev. Lett. **58**, 467 (1988).

[9]R. M. Diamond *et al.* (unpublished).

[10]R. F. V. Janssens *et al.*, in Ref. 5; G. E. Rathke *et al.*, Phys. Lett. B **209**, 177 (1988).

[11]P. Fallon *et al.*, in Proceedings of the Workshop on Nuclear Structure, Copenhagen, 1988 (unpublished).

[12]P. Twin *et al.*, in Ref. 5.

[13]M. A. Deleplanque *et al.*, Phys. Rev. Lett. **60**, 1626 (1988).

[14]F. S. Stephens *et al.*, Phys. Rev. Lett. **54**, 2584 (1985).

[15]R. Broda *et al.*, in Proceedings of the Symposium on High-Spin Phenomena in Nuclei, Argonne, 1979 (Report No. ANL-Phys-79-4, unpublished), p. 401.

[16]E. M. Beck *et al.*, Phys. Rev. Lett. **58**, 2182 (1987).

[17]E. M. Beck *et al.*, Phys. Lett. B **195**, 531 (1987).

[18]T. Bengtsson *et al.*, Phys. Lett. B **208**, 39 (1988).

[19]S. Aberg *et al.*, in *Proceedings of the Twenty-Sixth International Winter Meeting on Nuclear Physics, Bormio, Italy, 1988,* edited by I. Iori (Ricerca Scientifica ed Educazione Permanente, Milano, 1988).

[20]W. Nazarewicz (private communication).