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Unfavoured signature partner superdeformed bands associated with proton excitations in ^{151}Tb

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Abstract

Candidates for two excited superdeformed (SD) bands based on unfavoured signature partners of proton particle-hole excitations in the ^{152}Dy core have been observed in the ^{151}Tb nucleus with the EUROGAM spectrometer. In the framework of cranked shell model calculations, one of these bands is interpreted as the signature partner of the ^{151}Tb yrast band. It is suggested that the second band is either the signature partner of the ^{151}Tb first excited band with a proton $\pi[301]1/2$ configuration or is an excitation from the $\pi[303]5/2$ into the $[651]3/2$ intruder orbitals. There is a disagreement between the data and the predictions of self-consistent relativistic Hartree-Fock calculations.

The quantum structure effects related to nuclear superdeformation (corresponding to an ellipsoidal nucleus with a 2:1 axis ratio) have seen a resurgence in activity with the advent of the new generation of γ-ray spectrometer, such as EUROGAM, due to their ability to obtain data on very weakly populated superdeformed (SD) structures. The observation of the first excited SD band in ^{151}Tb [1] has suggested the important role played by the quantal pseudo-SU(3) symmetry and its pseudo-spin subsymmetry at high spin and large deformation; indeed this symmetry has been used to explain the remarkable transition energy degeneracy between the first excited SD band in ^{151}Tb based on a hole in the $[301]1/2$ $\alpha = -1/2$ proton orbit and the ^{152}Dy yrast SD band giving a decoupling parameter $a = 1$ in agreement with experiment [2]. An alternative approach using fully self-consistent relativistic calculations [3] have predicted the energies of proton excited SD bands in the nucleus ^{151}Tb by removing one proton from the ^{152}Dy core. In particular, they have been able to reproduce the degeneracy observed between the first excited SD band in ^{151}Tb and the yrast SD band in ^{152}Dy. The purpose of the present work was to search for the signature partners

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of the yrast and first excited SD bands in ^{151}Tb in order to establish experimentally the lowest SD proton particle-hole excitations.

This letter reports the discovery of two excited SD bands in ^{151}Tb corresponding to proton particle-hole excitations. The first new band has been identified as the signature partner of the yrast SD band which is based on the [651]3/2 ($\alpha = +1/2$) intruder orbital configuration. The calculated signature splitting gives an estimate of the relative excitation energy of this excited band compared to the yrast band. The second new band is a candidate for the signature partner of the original identical SD band based on a hole in the [301]1/2 ($\alpha = -1/2$) orbit, and it has features which do not follow the expected pseudo-spin interpretation. However the configuration of this band may be based on a different proton orbital and this leads to the strong probability that the two signature partners have identical γ-ray transitions, as expected from the simple pseudo-spin picture. The data on the new bands also show that there is a quantitative disagreement with some of the predictions of recent relativistic self-consistent calculations [3].

The experiment was carried out at the Daresbury Nuclear Structure Facility. The SD bands in ^{151}Tb were populated using the ^{27}Al + ^{130}Te reaction at a bombarding energy of 154 MeV. The ^{130}Te target of 550 μg cm^{-2} thickness,was evaporated onto a 440 μg cm^{-2} gold film and positioned so that the nuclei recoiled into vacuum. In the present experiment the EUROGAM spectrometer [4] had 42 operational Ge detectors surrounded by BGO anti-Compton shields. The average suppressed peak to total ratio for detecting γ-rays from a ^{60}Co source was 55 %. The counting rate in the individual Ge detectors was $\sim$ 8 kHz. The trigger level was set to accept unsuppressed events with a γ-ray multiplicity greater or equal to seven which corresponded to an average number of coincident detectors of $\sim$ 3.9 after the Compton suppression requirement had been applied. A total data set of 5.5×10^8 suppressed events with Ge fold ≥ 3 has been obtained. The unpacking of high fold events led to 3.1×10^9 γ^4 coincidences. The final spectra were obtained by summing combinations of 3 dimensional gates set on SD transitions in a 4-dimensional analysis [5].

In this analysis, apart from the two previously reported SD bands in ^{151}Tb [1,6], six new SD bands have been assigned to this nucleus. These excited bands have been labelled from 3 to 8 generally according to their intensities relative to the yrast band (band 1). The assignment to a given isotope is based on the unambiguous observation of known γ-ray transitions of the normal deformed scheme which are in coincidence with the SD band members. The intensities (with uncertainties) of the various bands relative to the yrast band are 50 (5)% (band 2), 35 (5)% (band 3), 6 (2)% (band 4), 10 (2)% (band 5), 9 (2)% (band 6), 11 (2)% (band 7), 7 (3)% (band 8). Bands labelled 5 to 8 have been interpreted in terms of single neutron excitations accross the $N = 86$ shell gap [7] and will not be discussed here. The γ-ray transition energies of bands 1 to 4 are listed in Table 1.

Table 1
Measured gamma-ray energies in keV of SD bands 1 to 4 in ^{151}Tb. The errors on the energies are given in parenthesis. The assumed spins for the transitions marked * are given at the end of the table.

Band 1	Band 2	Band 3	Band 4
	602.1 (8)		
	646.4 (5)		
	691.9 (5)	681.5 (10)	
726.5 (5)	737.4 (3)	727.7 (8)	
769.3 (5)	783.4 (3)	773.9 (5)	768.6 (5)
811.2 (3)	828.7 (3)	821.2 (8)	816.3 (10)
854.0 (3)	874.8 (3)	867.8 (8)	865.3 (6)
897.5 (3)	921.6 (4)	915.8 (5)	913.9 (5)
942.7 (3)	968.1 (4)	963.6 (10)	961.9 (6)
988.2 (3)	1015.7 (4)	1013.3 (5)	1009.4 (6)
1034.2 (3)	1063.0 (5)	1061.8 (5)	1056.6 (5)
1082.0 (3)	1110.5 (6)	1111.4 (5)	1103.8 (8)
1130.0 (4)	1158.6 (6)	1160.8 (5)	1152.5 (6)
1178.0 (3)	1206.9 (8)	1209.6 (5)	1201.1 (7)
1227.9 (3)	1254.8 (6)	1258.8 (5)	1248.5 (6)
1277.9 (3)	1303.2 (8)	1309.6 (7)	1296.5 (7)
1328.2 (8)	1352.0 (8)	1357.7 (7)	1344.8 (7)
1379.3 (5)	1339.5 (9)	1408.2 (8)	1392.9 (10)
1431.7 (7)*	1448.3 (9)*	1456.8 (9)*	1439.3 (10)*
1483.0 (7)	1495.0 (11)	1504.8 (10)	1485.5 (10)
1535.2 (10)			
$60.5^+ \rightarrow 58.5^+$	$62.5^- \rightarrow 60.5^-$	$61.5^+ \rightarrow 59.5^+$	$61.5^- \rightarrow 59.5^-$

The dynamical moments of inertia $\mathrm{Im}^{(2)} = 4\hbar^2/\Delta E_\gamma$ (where ΔE_γ is the energy spacing between two consecutive transitions) of band 4 and the yrast band of the ^{152}Dy isotone are very similar indicating that band 4 has the same high-N proton configuration as ^{152}Dy with four $N = 6$ proton intruder orbitals oc-

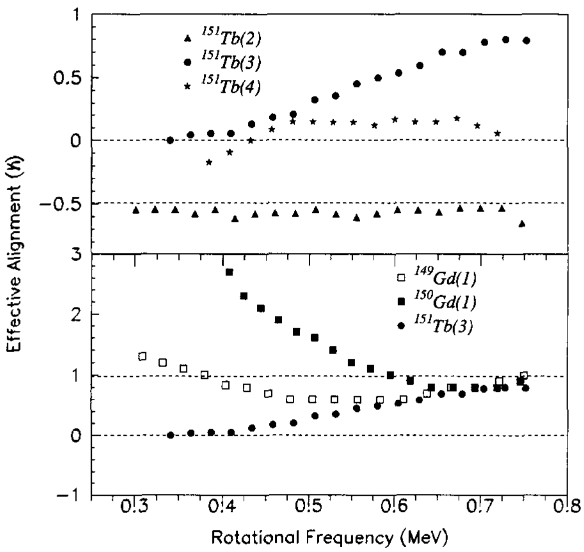

Fig. 1. (Upper panel) Measured effective alignments as a function of rotational frequency for bands 2, 3 and 4. The chosen reference is the SD ^{152}Dy yrast band. (Lower panel) The measured effective alignment as a function of rotational frequency of band 3 is compared with those of the superderformed yrast bands of ^{149}Gd and ^{150}Gd for which the reference bands are the yrast SD bands of isotones ^{150}Tb and ^{151}Tb, respectively.

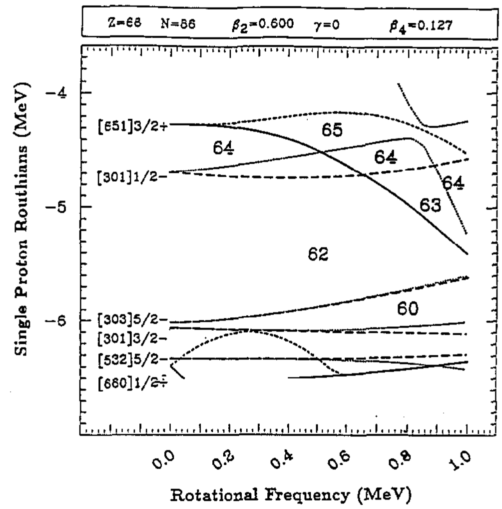

Fig. 2. Calculated proton routhians as a function of rotational frequency using the Woods-Saxon potential [9]. The orbitals with parity and signature $(\pi,\alpha) = (+,+1/2),(+,-1/2),(-,+1/2)$ and $(-,-1/2)$ are indicated by solid, dashed-dotted, dashed and dotted lines, respectively.

cupied. Band 3 has the similar variation of the Im$^{(2)}$ moment of inertia with that of the ^{152}Dy yrast SD band but its magnitude is slightly smaller. It is dissimilar to the dynamical moments of inertia associated with other high-N configurations (yrast SD bands of ^{151}Dy, ^{150,151}Tb, ^{149,150}Gd). These observations suggest that the deformation associated with band 3 is large like that of ^{152}Dy, and that one orbital whose energy varies linearly with frequency is unoccupied.

In assigning the most probable configurations of SD bands 3 and 4, it is useful to extract the effective alignments of these bands relative to the yrast SD band in ^{152}Dy, assuming the spin values proposed in Ref. [8]. The effective alignment between a given SD band and the reference band is defined by their difference in spin at a given γ-ray energy. These alignments together, with those of band 2, are plotted as a function of rotational frequency in Fig. 1 (upper panel). In discussing the configurations of these bands we first focus on the previously known band 2. With the high quality data set obtained in the present experiment it has been possible to extend band 2 (see Table 1) both to higher and lower γ-ray energies, and to measure the transition energies very accurately. The data show that the identity with the γ-ray transition energies of the ^{152}Dy yrast SD band is maintained, on average, to less than than 1.5 keV over 20 transitions yielding an effective alignment of $-0.55\hbar$ relative to the ^{152}Dy yrast SD band (Fig. 1). Band 2 has been associated with a hole in the ($\alpha = -1/2$) signature member of the [301]1/2 proton orbital of the SD ^{152}Dy core configuration. The concept of pseudo-SU(3) asymptotic limit has been introduced [2] in order to explain the observed similarities between the yrast SD band in ^{152}Dy ($Z = 66$) and band 2 in ^{151}Tb ($Z = 65$). It gives the correct value of the decoupling parameter ($a = +1$) for the [301]1/2 hole in the ^{152}Dy core, equivalent to an effective alignment of $-0.5\hbar$. However the cranked shell model calculations also give good agreement with band 2 as the effective alignment varies between $-0.3\hbar$ for anharmonic oscillator [8] and $-0.5\hbar$ for Woods-Saxon [9] potentials.

The next two most favourable proton excitations are the signature partners of bands 1 and 2 and they are expected to have similar large deformations. First we consider the signature partner of band 1, an excitation from the [651]3/2, $\alpha = -1/2$ ($\pi 6_3$) to the [651]3/2, $\alpha = +1/2$ ($\pi 6_4$) intruder orbitals (Fig. 2), and we associate band 3 with this excitation. The alignment as a function of rotational frequency for the $\pi 6_3$ active orbital can be extracted (Fig. 1, upper panel) from the differences in spin between band 3 and the yrast SD band in ^{152}Dy which has both $\pi 6_3$ and $\pi 6_4$ occupied. The comparison with the effective alignments calculated for the same orbital [8] indicates a reasonable agreement with theory. The figure also shows (Fig. 1, lower panel) other experimental alignments of the $\pi 6_3$ orbital obtained by comparing the yrast SD bands of ^{149}Gd and ^{150}Gd to the yrast SD bands of the isotones ^{150}Tb and ^{151}Tb respectively. In these two cases there is also reasonable agreement with calculated values for high rotational frequencies, but large differences occur for lower frequencies. As suggested in Refs. [7,8] the discrepancies are probably due to pairing correlations which have not been taken into account in the calculations, and which are important in these two nuclei as evidenced, for example, by the large increase in $\mathrm{Im}^{(2)}$ at low frequency in the case of the yrast SD band of ^{150}Gd. We propose that band 3 corresponds to the promotion of the last proton from the [651]3/2 ($\alpha = 1/2$) intruder orbital into its signature partner, and we have therefore identified, in the same nucleus, two bands corresponding to both signatures of the [651] intruder level. It is worth noting that their signature splitting is rather insensitive to small changes in the deformation parameters. It turns out that in Woods-Saxon calculations this splitting corresponds to $\sim$ 650 keV at a frequency of $\sim$ 0.7 MeV (Fig. 2). As a consequence, we suggest that band 3 lies 600–700 keV above the yrast SD band in the feeding region and that this amount of excitation energy is responsible for the factor $\sim$ 3 loss in intensity of the corresponding ^{151}Tb excited band compared to the yrast band. Furthermore an estimate can be made of the average excitation energy of the final state feeding the SD states. Using the data on the two [651]3/2 signature proton bands (an energy separation of 650 keV and a relative intensity of 35%), and assuming the intensities of γ-ray decays vary as E_γ^4 [10], this excitation energy is 2.7 MeV. These arguments allow us to estimate the relative excitation energy in the feeding region of excited SD bands in ^{151}Tb.

We now consider the possible configurations for band 4. One possibility is that it is the excitation from the other signature of the [301]1/2 orbital. The $\mathrm{Im}^{(2)}$ moment of inertia has the correct variation with frequency. The experimental effective alignment is $\sim$ 0.2$\hbar$ (Fig. 1), close to the values predicted by cranked shell model calculations. However the intensity of the band is $\sim$12% of that of the other signature partner [301]1/2 band, which from cranked shell model calculations are separeted in energy by approximately 0.3 MeV. This is much smaller than a separation of $\sim$0.8 MeV expected from a comparison with the above discussion on the [651]3/2 signature partners. This raises some doubts about this interpretation of band 4, but it could also indicate that changes in deformation are causing large differences to the excitation energy of signature partners. A second possibility for band 4 is that it is associated with an excitation from the next proton orbital [303]5/2 (Fig. 2) wich could explain its low relative intensity. However in this case there should be a signature partner [303]5/2 band with no signature splitting and thus have γ-ray transition energies at the half point energies of band 4. It is not possible to confirm or deny the existence of such a signature partner band as the expected γ-ray transitions are very close in energy to those of the yrast band (for 0.47 MeV $\leq \hbar\omega \leq$ 0.66 MeV) and identical to those of band 6 at the lowest frequencies. If this second explanation of band 4 is correct it raises the question of the missing [301]1/2 signature partner. We note that in the simple pseudo-SU(3) limit with a decoupling parameter of $a = +1$ the missing [301]1/2 band would have identical γ-ray energies with band 2 and thus the spectrum of band 2 would be the sum of both [301]1/2 signature partners. This scenario would confirm that the simple pseudo-SU(3) limit is correct but be at variance with the cranked shell model predictions which have given a good description of the first excited band in ^{151}Tb and the neutron particle-hole SD excitations in the A = 150 mass region [7,9].

Recently the problem of identical bands in SD nuclei has been investigated using a relativistic self-consistent cranking theory [3]. In particular, bands in ^{151}Tb have been calculated by removing one proton from the ^{152}Dy core. Taking particles out of the orbits directly below the large Z = 66 proton gap (the orbits with approximate Nilsson quantum numbers [651]3/2 and [301]1/2) produces four bands in ^{151}Tb which are associated, respectively, with bands 1, 3, 2 and possibly 4 discussed previously. The energy differences $\Delta E_\gamma = E_\gamma(\mathrm{Tb}) - E_\gamma(\mathrm{Dy})$ between the transition energies of the above four bands in ^{151}Tb

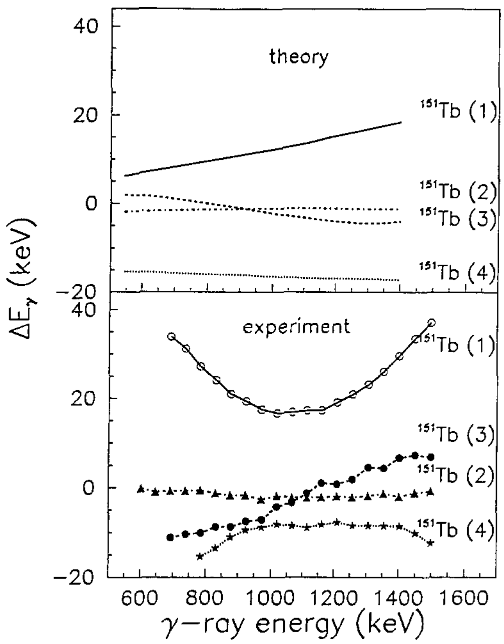

Fig. 3. Gamma-ray energy differences $\Delta E_\gamma = E_\gamma(^{151}\text{Tb}) - E_\gamma(^{152}\text{Dy})$ as a function of γ-ray energy; lower panel, the experimental values for bands 1 to 4; upper panel, calculated values in a relativistic fully self-consistent description [3] for the lowest four proton excitations from the [651]3/2 and [301]1/2 orbitals.

and the yrast SD band in ^{152}Dy have been calculated in the framework of that model [3]. The corresponding experimental quantities are shown in the lower panel of Fig. 3 whereas the theoretical calculations are presented in the upper panel. Although the observed degeneracy between band 2 of ^{151}Tb and the yrast band of ^{152}Dy is nicely reproduced (the calculated ΔE_γ values are of the order of 1 keV over the whole energy range), the predicted energy differences for bands 1, 3 and 4 are in disagreement with the data.

In summary, with the use of high fold γ-ray coincidences, we have discovered two new proton excited SD bands in the nucleus ^{151}Tb. We propose that band 3 is the expected signature partner of the yrast SD band. The proposed configurations for the other band have implications on our understanding of excited SD bands. Either the intensity of signature partners is not simply linked to their energy splitting or the cranked shell model calculations are not correctly predicting the alignment of the [301]1/2 unfavoured signature orbital whereas the simple pseudo-spin limit is giving a good description. The resolution of these problems may not be solved by further data on ^{151}Tb but probably requires a systematic study of proton-hole excited SD bands in neighbouring $A = 150$ nuclei. Finally, although the relativistic fully self-consistent calculations give good agreement for the first excited band of ^{151}Tb they do not reproduce the energy variations with frequency of the other proton excited bands.

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