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Discrete decay of the yrast superdeformed band in the ^{151}Tb nucleus

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The Euroball array has been used to search for linking transitions between the superdeformed (SD) and the normal deformed (ND) wells in ^{151}Tb. Many γ rays in the energy range 2–4 MeV have been observed in coincidence with the yrast SD band. It is proposed that the highest energy transition of 3748 keV and the strongest line (2818 keV) of the previously observed transitions both decay from the same SD level as their links with the ND states have been identified. The current spectra have insufficient statistics to completely identify the decay point in the SD band. Theoretical calculations covering SD bands in the $A \approx 150$ region enable the two possible spin assignments to be compared with experimental data on proposed links in ^{149}Gd and ^{152}Dy. It is concluded that the energy of the lowest SD band member in ^{151}Tb has an excitation energy of 12861 keV and a spin of $65/2^+$.

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I. INTRODUCTION

Since the first observation in the ^{152}Dy nucleus in 1986 [1] more than ∼250 superdeformed (SD) bands have been identified in various mass regions extending from $A \approx 30$ to $A \approx 190$ [2]. Many of the new SD bands found in the $A \approx 40$, 60, 80, and 130 mass regions were easily connected to normally deformed states because of a smaller change in deformation between the SD and ND states and due to a lower level density in the ND well. However, in the $A \approx 150$ and $A \approx 190$ mass regions the decay is dominated by its statistical aspects. This results in the decay-out contribution to the spectrum being dominated by a quasicontinuum with very weak discrete linking transitions between SD and ND wells. So, despite the large number of SD bands discovered in the $A \approx 150$ and $A \approx 190$ mass regions only few linking transitions connecting SD bands to normally deformed (ND) states have been found. First evidence of such linking transitions were reported in ^{194}Hg [3] and ^{192,193,194}Pb isotopes [4–6]. In the $A \approx 150$ region there have only been two reports of links; a weak two-step decay in ^{149}Gd [7] and a single-step transition in ^{152}Dy [8]. There have been many theoretical calculations of SD bands in the $A \approx 150$ region and, in particular, calculations [9] of the relative alignments enable a comparison of spins in different nuclei. These indicate that the ^{149}Gd and ^{152}Dy experimental spin assignments from the links are inconsistent. This paper reports the search for links between SD and ND states in another $A \approx 150$ nucleus, namely ^{151}Tb.

Both ND [10,11] and SD [12–16] states in the ^{151}Tb nucleus have been studied in considerable detail. Several studies on the decay-out from the yrast SD band in the ^{151}Tb nucleus have been reported [17,18] and the first identification of a possible SD to ND linking transition (2818 keV) was found in the analysis of an experiment performed on

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EUROBALL IV [19,20]. However the statistics collected during 4.8 d was insufficient to fit the 2818 keV transition into the decay scheme. Therefore a much longer experiment was performed in which many candidates for linking transitions were identified. Two of the strongest candidates, the 2818 keV and the 3748 keV gamma rays, have been shown to be single step decays from a level in the SD band to two ND levels with spins of $71/2^-$ and $75/2^-$ in ^{151}Tb.

II. EXPERIMENTAL CONDITIONS

The ^{151}Tb nuclei were produced via the ^{130}Te (^{27}Al, xn) reaction at a beam energy of 155 MeV. A stack of two self-supporting ^{130}Te foils ~500 μg cm^{-2} thick were bombarded by an ^{27}Al beam produced at the Vivitron accelerator of the Institut de Recherches Subatomiques of Strasbourg, France. The γ-ray decays of the residual nuclei were measured using the Euroball IV array which consisted of 30 tapered Ge detectors (forward quadrant), 26 clover Ge detectors (around 90°) and 15 cluster Ge detectors (backward angles). Each Ge detector was surrounded by a BGO suppression shield. There was also an inner ball of BGO detectors (210 crystals), which was analysed by forming 164 groups of ‘equivalent’ detectors of approximately equal solid angle and efficiency, thus enabling a measurement of the multiplicity and the sum energy of γ-rays emitted in the nuclear reaction.

The data collection trigger for high-multiplicity events was that at least six unsuppressed (equivalent to four suppressed) Ge detectors and at least ten BGO ball elements fired. A total yield of 8.7×10^9 fourfold and higher-fold events was obtained with a mean fold of five. A nonspiked database according to the procedure described in Ref. [21] was used for the analysis of the large data set.

III. RESULTS

A triple-gated spectrum, shown in Fig. 1, was obtained using only clean ^{151}Tb yrast SD band transitions and an advanced background subtraction process [22]. The strongest high energy candidate for a linking transition is at 3748 keV which has an intensity of ~0.9% relative to the yrast SD band intensity. At this high energy the 3748 keV transition is expected to be a single-step link. No statistically significant transitions were present above 3748 keV. However, many other candidates were observed in the 1.9–3.7 MeV range and the energies of the stronger lines are indicated on Fig. 1.

The next step is to identify the ND states to which the 3748 keV transition decays. The relevant spectrum was obtained by adding a third single gate on the 3748 keV γ-ray to the multiple two gates on SD band transitions and part of the resulting spectrum is shown in Fig. 2(b). Figure 2(a) shows part of the spectrum arising from just two gates on the SD band transitions. In this spectrum the 3748 gate area contains 1300 counts in the 3748 γ-ray itself but this is only 7% of the total counts in the gate. Therefore the background to be subtracted from the 2SD+3748 spectrum is large and it is difficult to identify the appropriate background spectrum. The technique used above [22] is inappropriate as we are interested in the

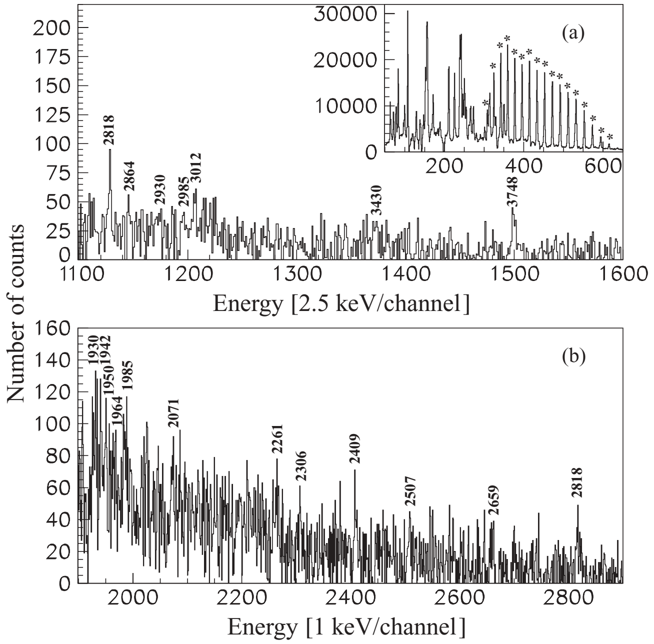

FIG. 1. (a) Parts of the 0–20 MeV spectrum in coincidence with three gates on the ^{151}Tb SD transitions. In inset is displayed the low-energy part of the 0–20 MeV spectrum showing the SD transitions (indicated by stars) and ND transitions fed by the yrast SD band. (b) Part of the 0–4 MeV spectrum in coincidence with three gates on the ^{151}Tb SD transitions.

intensities of the ND transitions at high spin into which the 3748 transition decays. The intensities of these gamma-rays decrease rapidly with each addition of another SD gate as they are not fed in the majority of SD band decays. So the method of [22] would produce too much subtraction for these high spin ND transitions and result in negative peaks. It was concluded that it was preferable to base the analysis on the spectra without any background subtraction correction as it is the change in the individual high spin ND γ-ray intensities between the 2SD gated spectrum and the 2SD+3748 gated spectrum that provides information on those transitions that are associated with the additional gate on the 3748 keV transition. The intensities of the transitions between the ND states at the entry regime from the SD band were normalised to the low spin transitions at the bottom of the ND structure for the SD+SD spectrum, the SD+SD+3748 spectrum and the SD+SD+SD spectrum. The relative change in intensity when a third gate (either another SD gate or the 3748 gate) was added to the SD+SD spectrum provide the data for identifying the entry point into the ND states.

The 1096 keV and 381 keV ND transitions show a small increase as the relative intensity is 1.2(1) with the 3748 additional condition. The relative intensity is larger still at 1.4(2) for the higher spin 371 keV and 1041 keV transitions and then drops to 0.4(2) for the 934 keV transition. The spectrum produced with the extra SD gate (SD+SD+SD) shows a different behavior as the relative intensity commences at 0.95(15) for the 381 keV transition, drops to just over 0.6 for the 1096 keV and 371 keV transitions and then to 0.5(1) for both the 1041 keV and 934 keV transitions. This reduction

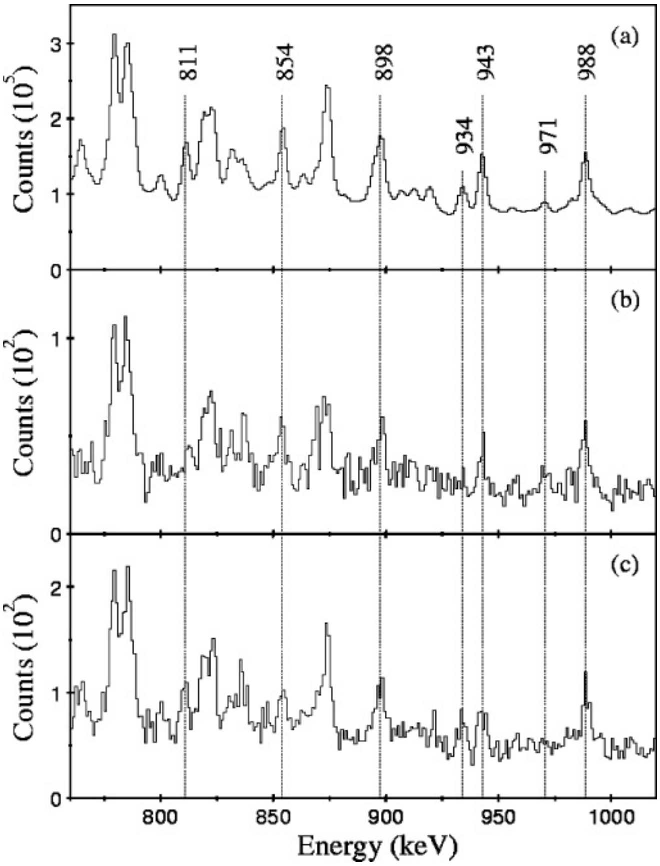

FIG. 2. (a) Spectrum obtained by setting pairwise gates on an SD transition. (b) Spectrum obtained from setting pairwise gates on an SD transition (above 854 keV) and an additional gate on the 3748 keV transition. (c) Spectrum obtained from setting pairwise gates on an SD transition (above 854 keV) and an additional gate on the 2818 keV transition.

in the intensities for the extra SD gate is because the majority of the decay paths from the SD band feed into the ND states at or below the 381 keV transition. Indeed, in the spectrum generated from 4 SD gates the relative intensities of the 371 keV and 1041 keV transitions are less than 0.1 and so this means that relative intensities of around 0.5 for the 1041 keV and 934 keV γ-rays in the SD+SD+SD spectrum are entirely due to background coincidences. Thus the figure of 0.4(2) for the 934 keV transition in the spectrum of SD+SD+3748 is consistent with this transition not being in the decay path of the 3748 keV link. As the relative intensities of the 1096 keV, 371 keV, and 1041 keV transitions are larger than unity it is concluded that these are in the decay path of the 3748 keV link. Therefore the data clearly indicate that the 3748 keV link decays into the ND states below the 934 keV transition and into the 10690 keV ($71/2^-$) state. This assignment means that the energy of the SD state from which the 3748 keV γ-ray originates is 14440 keV.

Information was obtained on the multipolarity of the 3748 keV linking transition from measurements of the angle-dependent intensity $I_\gamma(\theta)$ ratios using a method derived from directional correlations of decays from oriented nuclear states (DCO ratio). An asymmetry ratio is defined as

$$R_{\text{asym}} = \frac{I_\gamma(\text{cluster} + \text{tapered})}{I_\gamma(\text{clover})} \approx \frac{I_\gamma(\text{cluster})}{I_\gamma(\text{clover})} \approx \frac{I_\gamma(\text{backward})}{I_\gamma(90^\circ)}, \qquad (1)$$

where I_γ is the efficiency corrected intensity of the γ-ray detected with the cluster and clover detectors respectively. For comparison R_{asym} values of known stretched $E1$ (or $M1$) transitions in the ND level scheme and $E2$ transitions from the SD yrast band of the ^{151}Tb nucleus have also been extracted; the mean values obtained are 0.58(2) and 1.11(2) for $E1$ (or $M1$) and $E2$ multipolarities, respectively. The value measured for the 3748 keV transition is 0.52(0.11) which indicates a most probable dipole character for this transition. Without a linear polarization measurement, it is not possible to distinguish between magnetic or electric radiation. However, based on $E1$-$M1$ probabilities and also on similarities in the $A \approx 150$ mass region [7,8], together with theoretical calculations that predict the yrast SD band has positive parity, we assume an $E1$ character for this transition. Thus the 14440 keV SD state from which the 3748 keV transition originates has a spin of either ($73/2^+$) or ($69/2^+$).

One approach to selecting the correct alternative between these two spin assignments is to identify other links between the SD band and the ND states. A link between the 14440 keV SD state and the 9649 keV ($67/2^-$) ND state (a 4791 keV γ-ray) would establish the spin at the lower value of ($69/2^+$). However no evidence was found for any γ-rays above 4 MeV. On the other hand, a link between the 14440 keV SD state and the 11624 keV ($75/2^-$) ND state (a 2816 keV γ-ray) would establish the spin as ($73/2^+$). As reported above a 2818(3) keV γ-ray (intensity $\sim$0.7% relative to the yrast SD band intensity) was observed in the spectrum obtained from triple SD band gates as shown in Fig. 1.

In order to confirm that this 2818 keV γ-ray is the transition to the 11624 keV ND state, the spectrum obtained by setting SD+SD+2818 gates (Fig. 2(c)) should show evidence of the 934 keV transition from the 11624 keV ND state. In the 2SD spectrum the 2818 gate contains 3200 counts in the 2818 γ-ray peak which is 4% of the total counts in the gate. In the 2SD+2818 spectrum the 934 keV γ-ray is clearly present and its intensity relative to that of the same transition in the SD+SD spectrum is 2.1(4). This figure is larger than the 1.3(2) observed for the subsequent 1041 keV and 371 keV transitions and 1.1(1) for the 1096 keV and 371 keV transitions. It is also very much larger than the relative intensity of 0.4(4) for the 934 keV γ-ray in the SD+SD+3748 spectrum. These data are strong evidence that the 2818 keV link feeds the 11624 keV ND state. Thus it is concluded that the 2818 keV and 3748 keV γ-rays originate from the same SD level which has a spin of ($73/2^+$) and an energy of 14440 keV.

We now have to determine the SD state from which the 2818 keV and 3748 keV transitions decay. The spectra in Fig. 2(b) and 2(c) were produced in an analysis using SD band transition gates which did not include gates on the 811 keV and 854 keV SD γ-rays. Figure 2(b) (SD+SD+3748) shows the SD transitions down to the 854 keV are clearly present with

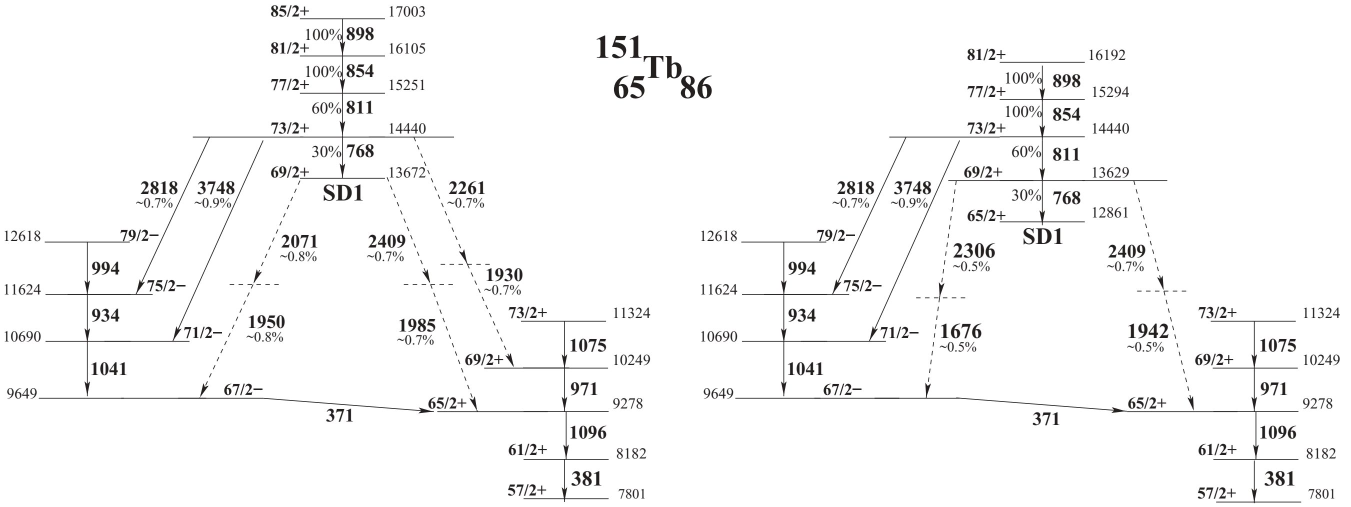

FIG. 3. Partial decay scheme of ^{151}Tb showing the lowest part of the yrast SD band and ND states to which the SD band mainly decays for both of the decay scenarii.

the intensity of the 854 keV transition 0.9(2) that of the higher energy SD transitions. There is a peak around 811 keV and its intensity is only 0.4(3) relative to that of the high-energy SD transitions and this is consistent with the random background level as discussed above for the 934 keV transition. Thus this spectrum indicates that the links decay out above the 811 keV SD transition. Figure 2(c) (SD+SD+2818) shows a much stronger 811 keV γ-ray with an intensity relative to the higher energy SD transitions of 0.9(3) which is statistically consistent with it being in the decay path. Thus the 3748 gated spectrum apparently indicates that the link is before the 811 keV SD transition whereas the 2818 gated spectrum indicates the link is after the 811 keV transition. One difference between the backgrounds in the linking transition gates in the 2SD spectrum is that the higher background in the 2818 gate contains other γ-rays associated with the overall decay-out from the SD band whereas it is less likely that there are other single step γ-rays around 3748 keV. This effect could account for some of the intensity in the 811 keV peak in the 2SD+2818 spectrum. However the statistical uncertainties in both measurements are large and both data points are within 2 standard deviations of them being consistent with the opposite conclusion about the 811 keV γ-ray. Therefore it is concluded that an unambiguous assignment of the decay out point is not possible with the current data set and the two possibilities for the spin of the SD band head are $69/2^+$ if the 811 keV γ-ray is in the linking path, and $65/2^+$ if it is not in the path.

An attempt was made to see if any of the other γ-rays identified as possible links in the spectrum of Fig. 1 had the appropriate energies to create two-step decays from the SD band to the known ND states. From theoretical calculations and previous data the intensity of the second-step γ-ray is expected to be much weaker than the first-step due to the large number of possible final states. No combinations could be found with these conditions. However, there is a pair of equal intensity γ-rays (1930 keV + 2261 keV) which have the correct sum energy to fit the energy difference between the 14440 keV SD level ($73/2^+$) and the 10249 keV ND level ($69/2^+$). Both transitions would be of $E1$ character. As this possible branch decays from the same SD level as the 2818 keV and 3748 keV links it does not add any further information about the decay-out point in the SD band. That requires a decay branch from another SD level. If the SD band head has the higher spin of $69/2^+$ there is a 2409 keV and 1985 keV combination that fits a link to the 9278 keV ($69/2^+$) ND level. However there is also a 2409 keV and 1942 keV combination that fits the related link, from the 13629 keV ($69/2^+$) SD level to the 9278 keV ($69/2^+$) ND level, if the SD band head has the lower spin. These two-step links, together with others to the 9649 keV ($67/2^-$) ND level, are shown in Fig. 3. As none of these two-step paths could be confirmed by coincidence relationships it is concluded that these two-step links do not assist in fixing the spins of the SD band.

IV. COMPARISON WITH ASSIGNMENTS IN ^{152}Dy AND ^{149}Gd

The observation of γ-rays linking the yrast SD band in ^{151}Tb ($\pi[651]3/2(r=+i)^{-1}\nu 7^2$) with the ND states is the third case in the $A \approx 150$ region. It is important to establish whether either of the resulting proposed assignments in ^{151}Tb are consistent with those previously proposed for the yrast SD bands in ^{149}Gd ($(\pi[651]3/2)^{-2}\nu[770]1/2(r=-i)^{-1}$) and ^{152}Dy ($\pi 6^4\nu 7^2$) and whether they are in agreement with theoretical predictions.

Two major theoretical studies of the spins of SD bands in Gd, Tb, and Dy nuclei are the cranked relativistic mean field calculations (CRMF) by Afanasjev *et al.* [9] and the cranking calculations based on a Woods-Saxon potential (CWS) by El Aouad *et al.* [23] who also carried out Hartree-Fock calculations with Skyrme SkM* interactions. These studies together with earlier cranked Nilsson model calculations of Ragnarsson *et al.* [24] are in complete agreement on the high-N proton and neutron orbital configurations of the yrast bands and they provide an excellent comparison of the relative spin assignments between the yrast SD bands based on their relative effective spin alignments as shown in Table 2 of Afanasjev *et al.* The initial disagreement with Ragnarsson *et al.* on the spins in the Dy nuclei was not due to the theoretical calculations but the selection of the best set of spins for the experimental data. These spin sets differ by $2\hbar$ and the difficulty was related to the influence of pairing which is large at low frequencies. It is now agreed that the lower spin choice of Afanasjev *et al.* [9] is correct.

The calculations also give predictions for the specific spin assignments and these are easier to discuss by using the example of the yrast SD band in ^{152}Dy. Both Afanasjev *et al.* and El Aouad *et al.* do not include pairing effects and, in that scenario, they predict that the lowest energy state observed in the yrast SD band in ^{152}Dy should be $26\hbar$. However when El Aouad *et al.* include pairing in the CWS approach the spin is lowered to $24\hbar$. It is this lower spin assignment which agrees with the experimental assignment of Lauritsen *et al.* [8]. It is also the spin assignment taken as the basis by Afanasjev *et al.* (Table 2) for the set of consistent spin assignments for the various high-N proton and neutron configurations in the SD bands of Gd, Tb, and Dy nuclei.

Based on the $24\hbar$ spin for the band head in ^{152}Dy it follows that the predicted spin assignment for the band head of the yrast SD band in ^{151}Tb (the state fed by the 768 keV gamma ray) is $65/2^+$. This prediction corresponds to the case in which the linking γ-rays arise from above the 811 keV SD transition and it is the lower of the two possible spin assignments (see discussion in the previous section). It is important to consider whether the experimental spin assignment in the yrast SD band in ^{152}Dy could be $2\hbar$ higher as this would equate to the other spin option from the data on ^{151}Tb. The ^{152}Dy experiment of Lauritsen *et al.* [8] was not only much longer than the current experiment thus producing better statistics, but it was able to use an efficient isomer trigger which greatly reduced the background from other reaction channels. These advantages produced spectra which clearly demonstrate that the 4011 keV link in ^{152}Dy can be unambiguously placed in the ^{152}Dy level scheme. This link by itself does allow a second spin option which was rejected by the observation of much weaker candidates for other links. However this second spin option is $2\hbar$ lower and not $2\hbar$ higher as required to be consistent with the ^{151}Tb links arising below the 811 keV SD transition. Therefore we conclude that the overall evidence points to the SD band head in ^{151}Tb being $65/2^+$. The ^{151}Tb data also confirms the conclusion of Lauritsen *et al.* [8] from spectra of other links with poorer statistics that the 4011 keV link in ^{152}Dy cannot be associated with the second spin option which is $2\hbar$ lower.

Afanasjev *et al.* predicted that the spin assignment for the yrast SD band head in ^{149}Gd is $51/2^-$. However Finck *et al.* [7] proposed that it is $2\hbar$ lower which is inconsistent with the predicted value. In ^{149}Gd the link is not a single step but involves two γ-rays and assumes a spin change of $3\hbar$ with the first 2188 keV γ-ray of $E1$ character and the second 2585 keV γ-ray of $E2$ character. As $M2$, $E3$ and other higher multipole transitions are extremely unlikely it is concluded that there can be no further increase in the spin change of $3\hbar$ assumed for the two-step link. The stronger first-step γ-ray has a much larger intensity and its link with the SD band was clearly identified whereas the link into the ND states of the weaker second-step was not established but inferred from the overall linkage of the first-step 2188 keV γ-ray into the ND states. This spectrum showed only weak feeding into the 49/2 state which has a mean lifetime of 4 ns and decays with a 186 keV $E2$ transition. On this evidence Finck *et al.* [7] proposed that the 2585 keV second step fed into the ND states below the 186 keV transition. However a second possibility is consistent with the experimental data. The weak 186 keV line observed in Ref. [7] could have been due to the very short flight time for the recoiling nuclei (<0.5 ns) before they were blocked by the Ge-detector collimator which meant that only about ~5% of the emitted 186 keV transitions were detected. In this scenario the 2585 keV γ-ray is the weak feeding of the strong 2188 keV first-step link into the 49/2 isomer state and thus the spin assignments of the SD band head in ^{149}Gd would be $2\hbar$ higher making them consistent with the predicted values.

The relative energies of the ND and SD structures as a function of spin is a critical input to calculations which attempt to model the feeding of the SD bands at high spins. In particular the spin at which the energies of the yrast ND and yrast SD are equal has been used as a useful parameter. In the case of ^{152}Dy this was considered to be around a spin of $54\hbar$ [25,26]. The relative energies of the yrast superdeformed and low deformation bands plus the yrast single-particle states are shown in Fig. 4 for ^{151}Tb and ^{152}Dy. The situation is unique in ^{152}Dy as three structures have been observed and the low deformation band, which is proposed to have a triaxial shape [27], does cross the SD band. The crossing spin is low at $42\hbar$. Experimentally the single-particle states in ^{152}Dy have only been observed up to $36\hbar$ but theoretical calculations [28] predict that their relative energies will increase by over 1 MeV around $40\hbar$ due to excitations across the 82 shell gap. An increase of only 0.5 MeV would bring the crossing point with the SD band to below $50\hbar$ and at 1 MeV it would be at $46\hbar$. This latter value would be consistent with the observation that the low deformation band is strongly fed between 40–$46\hbar$ as its excitation energy relative to the single-particle states would then be around 1 MeV. Thus it is concluded that at high spins

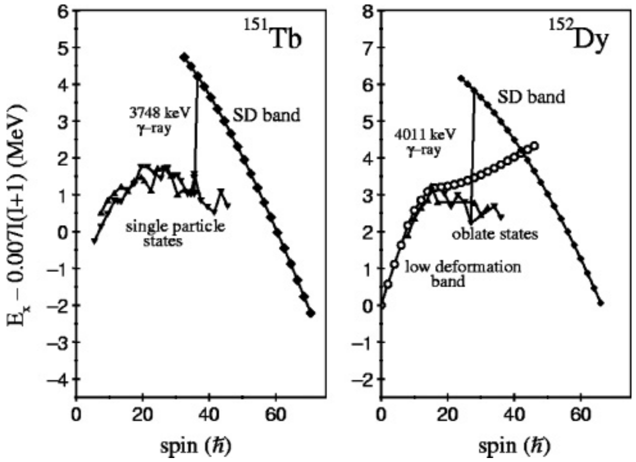

FIG. 4. Relative energies of the yrast superdeformed (squares) and low deformation (circles) bands in ^{151}Tb and ^{152}Dy. The yrast single-particle states (triangles) are also indicated.

the yrast SD band in ^{152}Dy is much lower in energy relative to the ND states than predicted.

In ^{151}Tb the single-particle states are known up to a higher spin of over $45\hbar$. Assuming an increase of 1 MeV due to excitations across the shell gap, the single-particle states would cross the SD band at around $52\hbar$ which is $6\hbar$ higher than in ^{152}Dy. This spin increase is replicated in theoretical calculations [26] as the crossing point goes from $54\hbar$ in ^{152}Dy to $58\hbar$ in ^{151}Tb and it underlines the role of large shell gaps in both protons and neutrons in ^{152}Dy.

In summary, two transitions have been identified that link a state in the yrast SD band to two specific ND states in ^{151}Tb. Current experimental evidence cannot unambiguously determine between the two possible alternatives for the SD state. However based on theoretical relative spin predictions of yrast SD bands in the $A \approx 150$ region it was concluded that the alternative that resulted in a lower spin for the SD band head in ^{151}Tb was consistent with assignments in other nuclei. An order of magnitude increase in statistics will be needed to confirm this assignment directly from an experiment on ^{151}Tb and this should be feasible using the next generation of gamma-ray spectrometers currently under development.

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