Direct Decay from the Superdeformed Band to the Yrast Line in $^{152}_{66}Dy_{86}$

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The excitation energy, spin, and parity of the yrast superdeformed band in ^{152}Dy have been firmly established. The evidence comes mainly from the measured properties of a 4011 keV single-step transition connecting the yrast superdeformed level fed by the 693 keV transition to the 27^- yrast state. Four additional, weaker, linking γ rays have been placed as well. The excitation energy of the lowest superdeformed band member is 10 644 keV and its spin and parity are determined to be 24^+.

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The first superdeformed (SD) band was observed in 1986 in the nucleus ^{152}Dy [1]. A sequence of nineteen almost equally spaced γ rays revealed the presence of a SD nucleus with an axis ratio of nearly 2:1. Since then, $\sim$175 SD bands have been found in the $A = 150$ and $A = 190$ SD mass regions. However, the energy, spin, and parity of only a handful of these SD bands have been established from discrete transitions which connect SD and normal yrast states in one step. The first such single-step linking transitions were found in ^{194}Hg [2], and linking transitions were reported in ^{194}Pb shortly thereafter [3,4]. Since then, very few links have been found [5,6] and there has been only one report of weak two-step decays in the $A = 150$ mass region [7]. Several attempts have been made to search for the single-step decays out of the yrast SD band in ^{152}Dy [8]. Obviously, even with modern γ-ray detector arrays such as Gammasphere [9] and Euroball [10], it is very difficult to find the weak, single-step transitions that allow for an unambiguous determination of the spin, parity, and excitation energy of SD bands. It is necessary to determine some or all of those quantities for as many SD bands as possible in order to address such issues as (i) the magnitude of shell corrections at large deformation, (ii) the particle configuration of the bands, (iii) the origin of identical SD bands [11], and (iv) the mechanisms responsible for the sudden decay-out of the SD bands. A number of new SD nuclei have been found in the $A = 60$, 40, 80, and 130 [12–15] mass regions, where it has proven easier to connect the SD bands to normally deformed states because the lower level densities result in predominantly discrete decay-out lines. However, in the $A = 190$ and $A = 150$ SD mass regions, the decay is dominated by quasicontinuum γ rays and sharp lines are very weak [16].

The first experimental evidence for a 4011 keV linking transition in ^{152}Dy, as well as hints of others, was found in a Gammasphere experiment performed at Argonne National Laboratory. The SD band in ^{152}Dy was populated with the nearly symmetric reaction ^{76}Ge(^{80}Se, $4n$)^{152}Dy. Beams were delivered by the ATLAS accelerator at an energy of 311 MeV (at midtarget). Data were collected for 4.5 days. Because of the low intensities of the observed linking transitions, another much longer experiment (12 days) was performed with Gammasphere at Lawrence Berkeley National Laboratory. This time the ^{152}Dy SD band was populated with the reaction ^{108}Pd(^{48}Ca, $4n$)^{152}Dy. Beams were delivered by the 88 inch cyclotron at an energy of 191 MeV (at midtarget). The target consisted of a stack of two 0.4 mg/cm^2 self-supporting ^{108}Pd foils. Gammasphere contained 100 Compton suppressed germanium detectors.

The ^{152}Dy yrast SD band is known to decay almost entirely through an 86 ns isomer [8]. This feature was exploited for clean channel selection by tagging on isomers, which were emitted from residues caught on a 28 mg/cm^2 Pb stopper foil, $\sim$35 cm downstream from the target, among the forward bismuth germanate (BGO) Compton shield detectors. The efficiency for isomer detection in ^{152}Dy was measured to be $\sim$80%. The energy and time signals of the forward ring of BGO detectors were written on tape only if the event satisfied a high-multiplicity ($M \geq 5$) condition. A total of 4.6×10^9 (after prompt time requirements) triple-or higher-fold coincidence events were collected. With the requirement of delayed γ rays in the forward BGO detectors (between 12.5 and 185 ns after the reaction), 1.6×10^9 events remained which were almost exclusively from ^{152}Dy.

Figure 1a shows the spectrum obtained by placing pairwise coincidence gates on transitions in the yrast SD band in ^{152}Dy. At higher γ-ray energies, shown in Fig. 2a, several candidates for decay-out transitions are clearly seen. In particular, γ rays at 2713 and 4011 keV are prominent while a number of other, weaker, candidates are visible as well. No transitions above 4011 keV are observed.

The coincidence spectrum obtained by placing pairwise gates on SD lines and on the 4011 keV transition is presented in Fig. 1b. It is clearly seen that the 647 and 602 SD lines (see Fig. 3) are not in coincidence with the 4011 keV γ ray, whereas the 693 keV and higher SD lines are. This unambiguously establishes that the 4011 keV transition originates from the SD level fed by the 693 keV line. Of the normal yrast transitions in the spectrum [17], the 221 and 541 keV γ rays have the full intensity of the SD band [0.8(3) and 0.9(2), respectively], whereas there is no indication of the normal 967 keV transition [the intensity is 0.3(3)], which should be detectable despite the proximity of the 970 keV SD γ ray. A comparison with the spectrum in Fig. 1a shows no new peaks with an area larger than three standard deviations. This strongly suggests that the 4011 keV γ ray feeds directly into the 27^- yrast state in a single step. This establishes the excitation energy of the SD level fed by the 693 SD line as 11 893 keV—as shown in the partial level scheme of Fig. 3.

To determine the spin of the 11 893 keV SD level, an angular distribution analysis of the 4011 keV transition was performed. The intensity of this γ ray, as a function of polar angle, is presented in Fig. 2b. Using the functional form $W(\theta) = A_0[1 + A_2P_2(\cos\theta) + A_4P_4(\cos\theta)]$ [18], the angular distribution coefficients were determined

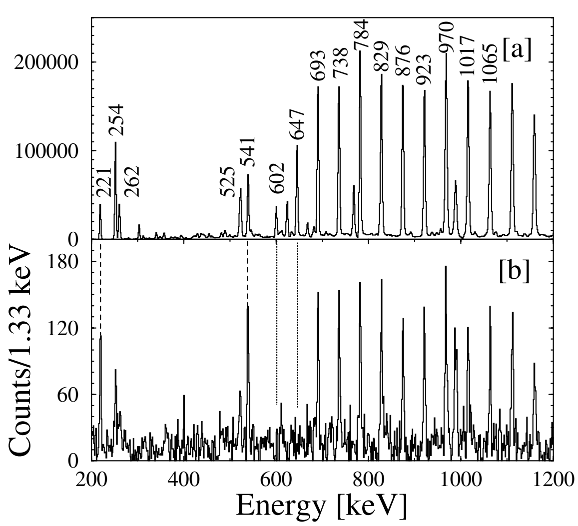

FIG. 1. (a) Spectrum from pairwise coincidence gates in the yrast SD band of ^{152}Dy. The 94 cleanest combinations of the following SD transitions were used: 647, 693, 738, 784, 829, 876, 923, 1017, 1065, 1161, 1209, 1257, 1305, 1353, 1402, and 1449 keV. (b) Spectrum obtained from setting pairwise gates on a SD line and the 4011 keV transition. All SD transitions listed above (except that of 647 keV) were used as gates.

to be $A_2 = -0.35(12)$ and $A_4 = -0.02(16)$—consistent only with a stretched or antistretched dipole character [18]. Thus, based on the 4011 keV transition, the feeding SD level must have a spin of either $26\hbar$ or $28\hbar$.

Based on Weisskopf estimates [19], transitions of $E1$ character are expected to be nearly 2 orders of magnitude faster than those with $M1$ multipolarity. In neutron capture experiments, indeed, the $E1$ transitions have been shown to dominate [20]. Therefore, it is most likely that the 4011 keV transition is of $E1$ character and, thus, a positive parity is assigned to the SD band. This assignment is also supported by theoretical expectations [21].

With the energy of the SD band determined by the 4011 keV line, four additional γ rays in the 3 MeV region of Fig. 2 can be placed in the level scheme as direct links between the SD band and the normal states. They are included in Fig. 3. All four of these additional links are very weak and, thus, it is difficult to place coincidence gates on them. However, in a spectrum of pairwise gates placed on the 693 keV line and on clean SD transitions above it, the 2895, 3044, 3364, and 3585 keV γ rays are clearly present, whereas a similar spectrum with a gate on the 647 keV line shows only the two transitions with the highest energies, i.e., the 2895 and 3044 keV γ rays are absent. Thus, the latter two transitions emanate from the 11 893 keV SD level, and the two others are associated with the deexcitation of the SD state directly below it at 11 246 keV. These weaker one-step linking transitions also resolve any remaining ambiguity concerning the spins of the SD band members. Only when 28^+ is assigned to the 11 893 SD level are the multipolarities of the 2895 and 3364 keV lines reasonable: $M1$ and $E1$, respectively. A 26^+ assignment would result in respective $M3$ and $E3$ multipolarities which are improbable, if only because of the competition with the in-band, highly collective 602 keV γ ray. Finally, for the strong 2713 keV transition mentioned above, it was possible to determine that it also

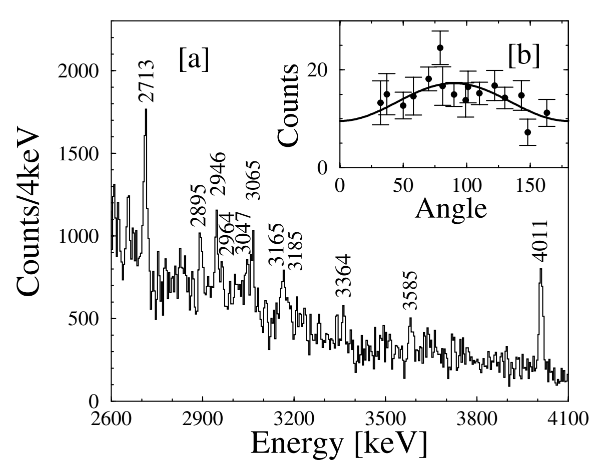

FIG. 2. (a) High-energy portion of the spectrum in coincidence with ^{152}Dy SD transitions. (b) Angular distribution of the 4011 keV transition.

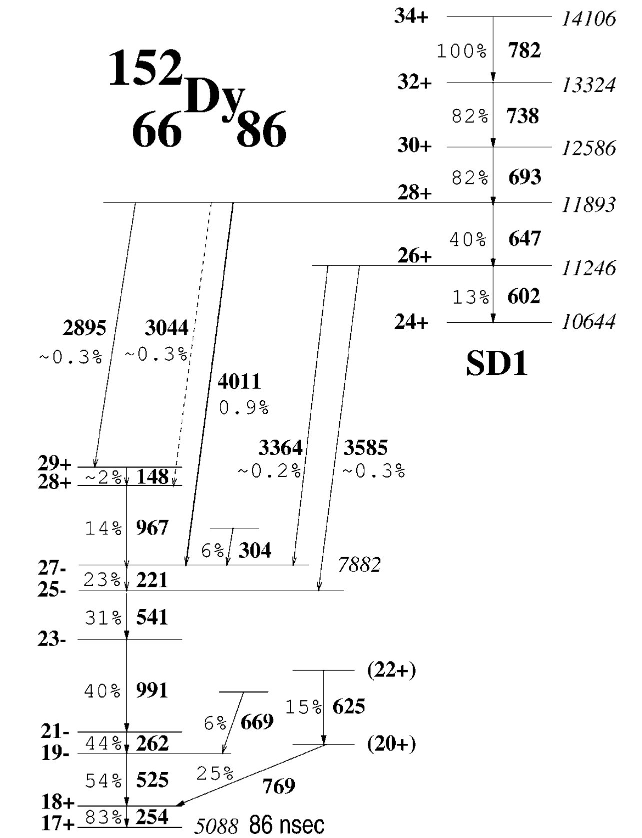

FIG. 3. Partial level scheme of ^{152}Dy showing the lowest part of the yrast SD band and normal states to which the SD band mainly decays. The transition intensities, given in %, reflect the requirement of the isomer tag.

originates from the 11 893 keV SD level. However, in this case the decay could not be traced all the way into the yrast or near yrast states, as the deexcitation fragments after the first transition into several paths involving γ rays with intensities below the detection threshold.

It is worth pointing out that the SD band spin values firmly assigned here are two units higher than those proposed by Twin *et al.* [1] following the discovery of the band. Several systematic theoretical investigations of all SD bands in the $A = 140-150$ region are also available. For ^{152}Dy, cranked Nilsson-Strutinsky calculations by Ragnarsson [22], and relativistic mean field calculations by Afanasjev *et al.* [23] suggested spins of either $28\hbar$ or $30\hbar$ for the 11 893-keV level, while the cranking calculations with a Woods-Saxon potential of Dudek *et al.* [24] propose a spin of $26\hbar$.

A solid understanding of superdeformed rotational motion requires data on both the kinematic and dynamic moments of inertia ($\Im^{(1)}, \Im^{(2)}$), which reflect the first and the second derivatives of the energy as a function of spin. In the mass 150 region, $\Im^{(1)}$ values have not been available since spins have not been firmly established. With the spins now assigned in ^{152}Dy, $\Im^{(1)}$ can be determined: It varies from $84.8\hbar$ to $85.7\hbar^2$ MeV^{-1} between spin $24\hbar$ and $38\hbar$ before decreasing smoothly back to $84.8\hbar^2$ MeV^{-1} at the highest spin of $68\hbar$. Results of calculations without pairing [25] are higher by 7%–5%, suggesting some persistence of pairing at the lower spins. The inclusion of pairing improves the agreement (see, e.g., [24,26,27]), but a simultaneous reproduction of $\Im^{(1)}$ and $\Im^{(2)}$ still has not been achieved.

Extrapolated to zero spin, the excitation energy of the SD band is $E^{\rm SD}(0^+) = 7.5$ MeV. The extrapolation was performed with a functional form of the excitation energy written as $E^{\rm SD}(I) = E^{\rm SD}(0^+) + a[I(I+1)] + b[I(I+1)]^2$, where $E^{\rm SD}(I)$ is the energy of the SD level at spin I. This procedure is less accurate here than in the $A = 190$ mass region because the spin of the lowest observed SD level is $24\hbar$ rather than $10\hbar$. The extrapolated zero spin energy is slightly higher than the values found in ^{192,194}Hg: 5.3(5) and 6.0 MeV [2,16]. For ^{152}Dy, a relativistic mean field prediction of the excitation energy is 8.32 MeV [28], while the cranked Strutinsky calculation of [21] obtains a value of $\sim$8.8 MeV. A recent Hartree-Fock-Bogoliubov calculation estimates the excitation energy to be $\sim$7 MeV [29].

The 4011 keV one-step decay line carries only 0.9(2)% of the intensity of the SD band. The quadrupole moment of the SD band in ^{152}Dy, 17.5(2) e b [30], gives a partial lifetime of the 647 keV in-band transition of 66 fs and a partial lifetime of the 4011 keV transition of 2.9 ps, equivalent to a strength in Weisskopf units (W.u.) of $\approx 2 \times 10^{-6}$. Just as in the $A = 190$ mass region [2], the decay-out transition is very retarded. This retardation can be understood [2] in terms of the decay mechanism out of the SD state first proposed by Vigezzi *et al.* [31]. In their interpretation, the SD level mixes with one (or a few) of the adjacent closely spaced levels in the normal well, on the other side of the SD barrier, and the decay occurs through the admixed component of the normal state in the wave function.

The model of Vigezzi *et al.* [31,32] was used to fit the SD transition intensities (i.e., decay-out profiles) in ^{152}Dy and ^{194}Hg, where the SD excitation energies are known. In this model, the probability for decay of a SD state to the normal well depends on the gamma decay widths Γ_s and Γ_n, the average separation D_n between excited normal-deformed states, and the width Γ for tunneling across the barrier. Γ_s, the decay width within a SD band, is obtained from the measured transition quadrupole moments; Γ_n, the $E1$ width for statistical decay from an excited ND state, and D_n are estimated by scaling [33] values obtained from neutron spectroscopy [34]. Values of the one free parameter Γ, which reproduce the measured SD transition intensities, are given in Table I. In both ^{152}Dy and ^{194}Hg, the SD transition intensities drop suddenly at the point of decay. This feature is reproduced by having Γ increase rapidly as the spin becomes smaller. The barrier heights E_b, which are deduced from Γ using expressions given in Refs. [31,32], show a corresponding decrease with spin (Table I). Alternative

TABLE I. Tunneling widths Γ and barrier heights E_b, extracted using the model of Vigezzi *et al.* [31,32], for two SD levels in ^{152}Dy and ^{194}Hg. The decay-out probabilities P_{out}, as well as the γ widths (Γ_s, Γ_n) and normal-deformed level spacing D_n, are given.

	I ($\hbar$)	P_{out}	Γ_s (meV)	Γ_n (meV)	D_n (eV)	Γ (eV)	E_b (MeV)
^{152}Dy	28	0.40	10.0	17	220	41	0.74
	26	0.81	7.0	17	194	220	0.58
^{194}Hg	12	0.40	0.108	21	344	0.56	1.15
	10	0.97	0.046	20	493	37	0.75

formalisms for calculating the decay out of SD bands have recently been published [35,36]. For cases encountered in experiments, their results agree with those obtained with the model of Vigezzi *et al.* [31,32,37]. Indeed, Γ values similar to those in Table I are obtained with the empirical expression given in Ref. [35]. A good approximation of the decay-out probability from the SD band is given by $P_{\text{out}} \sim \sqrt{\pi/2(\Gamma_n/\Gamma_s)(\Gamma/D_n)}$ [31,35]. At the point of decay, Table I shows that, compared to ^{194}Hg, ^{152}Dy has a smaller value of Γ_n/Γ_s (due to the larger SD transition energies). Consequently, Γ/D_n, which is a measure of the coupling between SD and ND states, is significantly larger (0.3 vs 0.002 when $P_{\text{out}} \sim 0.5$), indicating a stronger coupling in ^{152}Dy, although the coupling is still weak.

In summary, a number of single-step linking transitions have been observed in ^{152}Dy. Fifteen years after its discovery, the first superdeformed band is finally linked to the normal yrast states, and its spin, parity, and excitation energy have been firmly established.

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