Population and Decay of the Superdeformed Rotational Band of ^{152}Dy

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The observed pattern of the population and decay of the superdeformed band of ^{152}Dy is related to the large splitting of the giant dipole resonance based on the superdeformed minimum as well as to the low level density associated with it, and to the sudden onset of static pairing correlations taking place at the rotational frequency $\hbar\omega \approx 0.3$ MeV. A new method for spectroscopic studies of superdeformed nuclei is suggested.

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The recent discovery[1] of a superdeformed band in ^{152}Dy constitutes a major breakthrough in the study of nuclei at high spin, and confirms theoretical predictions.[2-5] However, the finding that the observed discrete band is populated with 0.2% probability at spin $I=60\hbar$, close to the angular momentum limit which nuclei can accommodate, implies the existence of a new process able to cool the compound nucleus an order of magnitude faster than previously observed. Furthermore, the sudden termination of the superdeformed band at $I=24\hbar$ requires a mechanism that within a narrow range of 2–4 units of $\hbar$ can change the tunneling probability between the superdeformed and normal minima by orders of magnitude. In the present paper, a simple model for these phenomena is proposed.

The feeding pattern of the superdeformed yrast band is intimately related to the competition between statistical dipole transitions that cool the nucleus without much changing its angular momentum and the collective rotational transitions that take place at constant temperature. The strong population of the superdeformed band then suggests an unusually enhanced $E1$ transition rate, more so because the collective $E2$ transition probabilities observed[6] are a few times larger than those found in normal deformed rotational bands. This implies that the $E1$ cooling leading to the superdeformed yrast band must be enhanced by more than an order of magnitude above standard cooling rates.

The integrated $E1$ transition probability $T(E1;U_i)$ associated with a state at energy U_i above yrast can be calculated in terms of the strength function f_{GDR} of the gi-

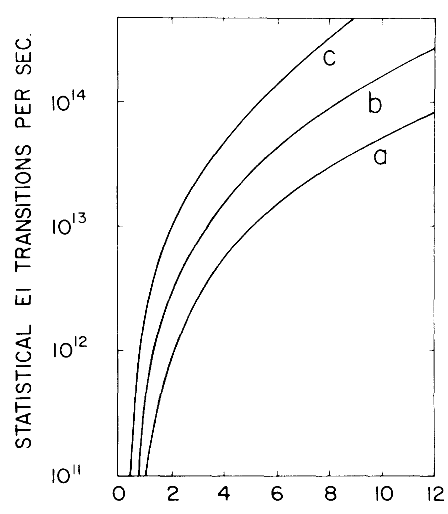

FIG. 1. Calculation of $E1$ transition probabilities. Curve a shows the probability calculated with the level density ρ_N and with the position of the GDR related to a normal deformed state. In curve b the superdeformed level density ρ_S is used and in curve c the splitting of the GDR in an average field of deformation $\beta=0.6$ is also taken into account.

ant dipole resonance (GDR) as

$$T(E1;U_i)=\text{const}\times\int_0^{U_i}\frac{\rho(U)}{\rho(U_i)}f_{\text{GDR}}(U_i-U)\times(U_i-U)^3dU, \quad (1)$$

where the level density

$$\rho(U)\propto(U+U')^{-2}\exp[2(aU)^{1/2}]$$

and f_{GDR} is as given by Bartholomew *et al.*[7] The constant is chosen to reproduce approximately the $T(E1, 6.44\text{ MeV})$ from neutron capture and the observed feeding to normal states in Dy.

The large increase in $E1$ transition probability $T(E1;U_i)$ needed to explain the population of the $60\hbar$ member of the superdeformed band arises from the product of two effects. The GDR built on a superdeformed state splits into two major components,[8] the lower expected around 8 MeV of excitation, and leads to an increase of $T(E1;U_i)$ by a large factor, as shown in Fig. 1.

The second effect, also illustrated in Fig. 1, is connected with the low level density expected in the superdeformed minimum, where $a(S)=A/10$ and $U'=0.7$ reproduce the calculations of Ragnarsson *et al.* and Aberg,[9] as compared to the normal deformed minimum where $a(N)=A/7$ is adapted from Holzmann *et al.*,[10] A being the mass number. At a few megaelectronvolts above the yrast line, the ratio $\rho(U)/\rho(U_i)$ in Eq. (1) leads to a further enhancement of the decay probability into the superdeformed minimum.

Once the superdeformed yrast band is populated, the nucleus remains in it through eighteen collective $E2$ transitions, ending up at about 5 MeV above the yrast line at spin $I=24\hbar$. Although the barrier (taken from Ref. 4) between the superdeformed and normal minima changes with spin, earlier calculations[9] predict a smooth depopulation over a range of more than 20 units of $\hbar$, starting at $I=40\hbar$.

We calculated the penetrability across the barrier between the two minima, making use of the WKB approximation and a simple model to describe the dynamics of nuclear deformation,[11] which recently has been applied to the study of exotic decay.[12]

In the tunneling process, the system evolves from one Hartree-Fock configuration to another by a jump (level crossing) of a pair of particles. The Hamiltonian connecting the configurations is governed by the pairing interaction, which is strongly renormalized by the presence of the pairing condensate, leading to matrix elements of the order of the pairing gap Δ. Because the superdeformed configuration is very different from the normal, about seven neutron crossings and four proton crossings are needed to change the deformation from $\beta_S=0.6$ to $\beta_N=0.25$, implying that about 22 ($=2n$) particles have to be rearranged. Results of Refs. 11 and 12 lead to a simple expression for the mass parameter

$$D=-\frac{\hbar^2}{V}\left(\frac{n}{\beta_N-\beta_S}\right)^2, \quad (2)$$

where $V=-\Delta^2/4G$ is an average transition matrix element and G the pairing coupling constant.

The sudden transition out of the superdeformed band at $I=24\hbar$ can be related to the onset of pairing caused by the dealignment of the lowest pair of high-j particles,[13,14] taking place when the rotational frequency is decreased to $\hbar\omega=0.3$ MeV. This leads to a large increase of the tunneling probability $P(I)$ (Fig. 2).

To test the ideas discussed above, statistical Monte Carlo simulations have been performed. The code uses two types of rotational states (N,S) associated with the normal and superdeformed minima. An yrast line is ascribed to each deformation. The S and N states are connected by tunneling as discussed above with the barrier

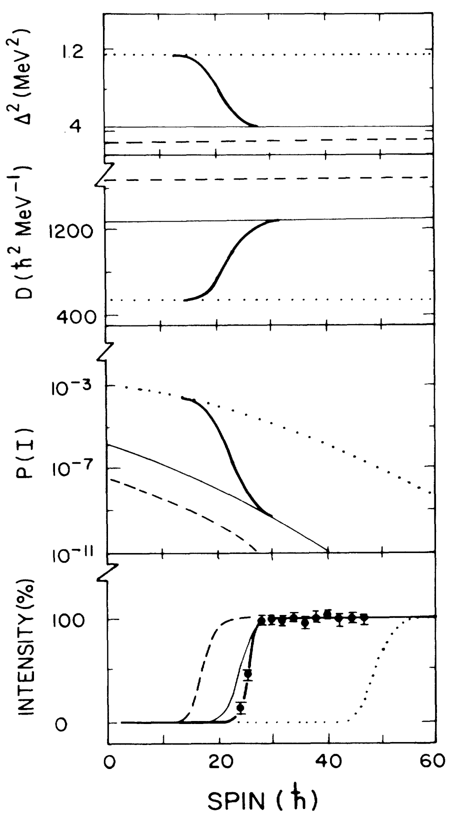

FIG. 2. Four different possibilities for the variation of the square of the pairing gap with spin are considered (upper part). Shown in the graphs below is the associated variation of the inertial mass D and of the penetrability $P(I)$. In the lowest part the relative intensity of the superdeformed band is displayed as a function of spin for comparison with the experimental data (Ref. 1).

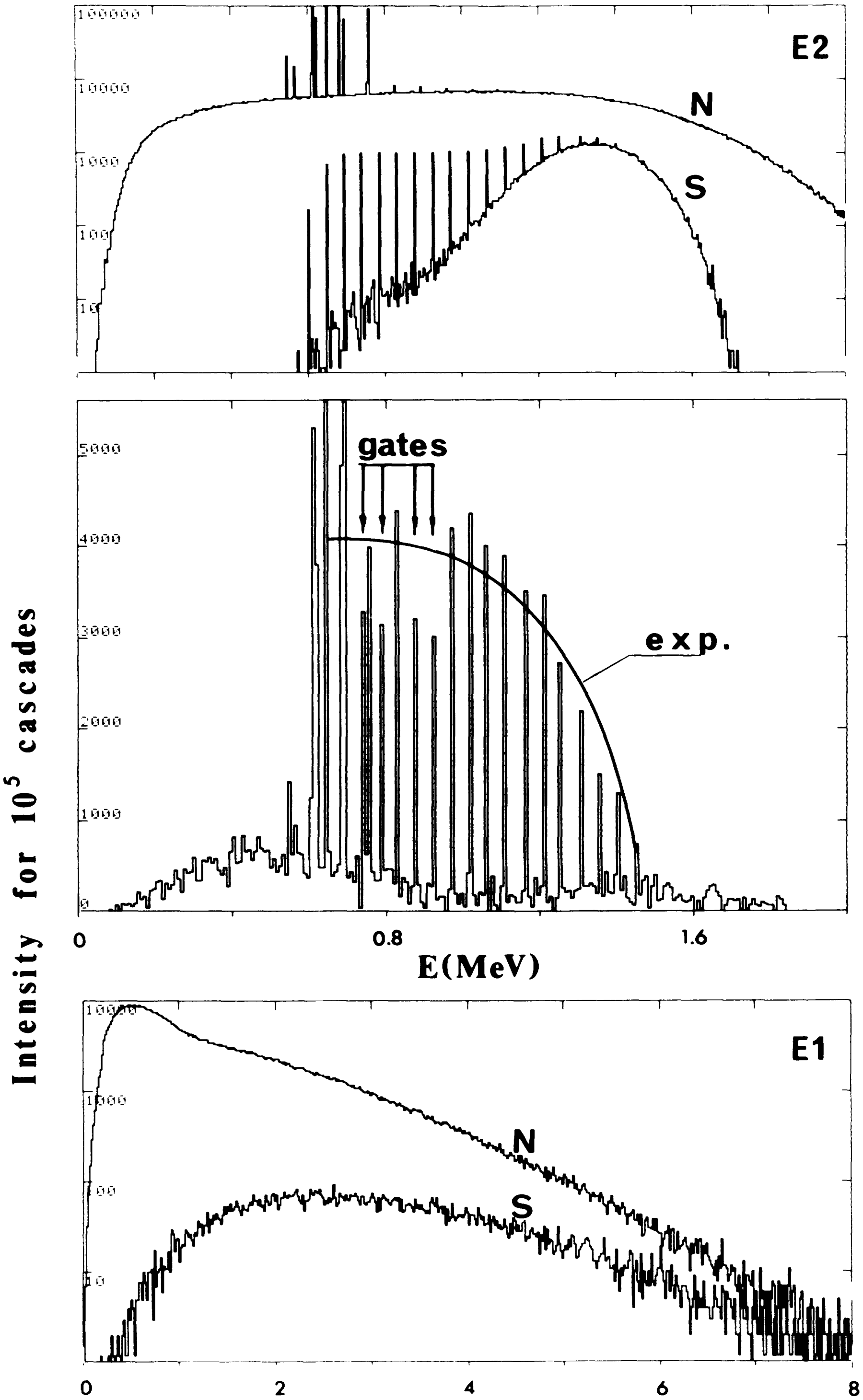

FIG. 3. Top: Spectra of the collective $E2$ transitions within superdeformed (S) and normal states (N). Similar spectra are shown in the bottom part for the statistical $E1$ transitions. The most significant parameters used in the present calculation are $a(N)=A/7.0$, $U'(N)=1.0$, $a(S)=A/10$, $U'(S)=0.7$, $B(E2,N)=100$ W.u., $B(E2,S)=2500$ W.u., $\langle I_i \rangle = 55\hbar$, $\sigma_{Ii}=5\hbar$, $\Delta^2_{max}=1.14$ MeV, $\Delta^2_{min}=0.44$ MeV, $E_{GDR}(N)=15$ MeV (100% energy-weighted sum rule), $E_{GDR}(S)=8$ MeV (30% energy-weighted sum rule). In the middle spectrum we show a simulated coincidence spectrum, gated with transitions corresponding to $I \rightarrow I-2$ for $I=30$, 32, 36, 38. The continuous curve corresponds to the experimental observations of Refs. 1 and 6.

parameters obtained from the results of Ref. 3. The γ decay on both sides of the barrier consists of competing collective $E2$ and statistical $E1$ transitions. The entry point is selected from an entry probability distribution of Gaussian shape with respect to both energy above yrast U_i and spin I_i. A moment of inertia and a $B(E2)$ distribution according to the damping picture of rotational motion[15] were used. Examples of γ spectra from the simulation are shown in Fig. 3. The upper part shows the rotational spectrum associated with the decay of superdeformed and normal states. In the lower part, the statistical decays are shown. It is recognized that the shapes of the $E1$ spectra are very different, which suggests a new powerful tool for the isolation of the decay through superdeformed states. In fact, if all cascades which contain a high-energy γ transition ($E_\gamma > 5$ MeV) are selected, the transitions through superdeformed states can be enhanced by a factor of 3.

In the middle part of Fig. 3, a spectrum is shown where gates have been set on four transitions of the superdeformed yrast sequence. This treatment of the spectra resembles closely that used in reducing the experimental data in Ref. 1. The calculated intensities, even with the restriction that $I_{\max} \leq 60\hbar$, reproduce the experimental findings quite accurately. However, since the parameters are correlated, the data used in the present analysis were found insufficient to determine the parameters uniquely. It is expected that when systematic information eventually becomes available on, e.g., $E1$ statistical tails, ridge intensities, etc., more specific model parameters can be deduced.

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