Feeding of Superdeformed Bands: The Mechanism and Constraints on Band Energies and the Well Depth

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(Received 22 July 1992)

Energy distributions leading to normal and superdeformed (SD) states in ^{192}Hg have been measured. A model, based on Monte Carlo simulations of γ cascades, successfully reproduces the entry distribution for SD states, as well as all other known observables connected with the population of SD states. Comparison of experimental and model results, together with the measured SD entry distribution, suggest that the SD band lies 3.3–4.3 MeV above the normal yrast line when it decays around spin 10 and the SD well depth is 3.5–4.5 MeV at spin 40.

PACS numbers: 21.10.Re, 21.60.Ka, 23.20.Lv, 27.80.+w

Bands with nearly twenty consecutive regularly spaced transitions have recently been discovered [1,2] in highly deformed nuclei with axis ratios of around 2:1. These superdeformed (SD) bands, which represent some of the most exciting recent developments in nuclear structure physics, are built on the ground state or low-lying excitations of a secondary minimum in the potential energy surface. The secondary minimum represents a false vacuum which lies above the normal (low deformation) ground state at low spin, but probably becomes the true vacuum at high spin.

This Letter explores how, following fusion, the compound nucleus is trapped in the false vacuum. SD bands are populated with surprisingly large cross sections —more than a factor of 10 larger than might be expected from extrapolation to high spin of the intensities of normal states. We provide in this Letter an explanation for this surprisingly large intensity. We also show which portion of the initial states for a given nucleus results in the formation of SD bands, and suggest that the decision on whether a γ cascade is trapped in the SD minimum is not made until the γ cascade gets below the barrier separating SD and normal states. Finally, we place constraints on the SD band excitation energy and on the barrier energy, for which no other direct information exists despite the observation of over forty SD bands in the $A=150$ and 190 nuclei [1,2].

The experimental observables which allow us to study the feeding of SD bands include the intensities of the SD bands, the variation of these intensities with spin, entry distributions, quasicontinuum spectra, and E_γ-E_γ correlation matrices. In this Letter we report on the first measurements of two-dimensional (I,E) entry distributions which lead to the population of both normal and SD states in ^{192}Hg (Ref. [3]). The entry distribution is the population distribution in spin and excitation energy following neutron evaporation, from which γ decay starts. We have also developed a model which describes the population of SD bands through Monte Carlo simulation of the γ-decay process. The model is able to reproduce all the observables mentioned above.

We have used the ^{160}Gd(^{36}S,4n) reaction to populate the SD band in ^{192}Hg, using beams of 159 MeV (at mid target) from ATLAS, the Argonne accelerator system. γ emission was detected with the Argonne–Notre Dame γ-ray facility consisting of twelve Compton-suppressed Ge detectors and a fifty-element BGO hexagonal array, which provided data on the number of detectors firing (fold,K) and the detected sum energy (H). Gates were set on particular pairs of coincident γ lines in the Ge detectors to obtain the (K,H) matrix associated with feeding of either SD or normal states. Use of clean pairwise gates, with background subtraction, provided a sufficiently high peak/background ratio to extract reliable (K,H) distributions for the weak SD lines [3]. The (K,H) response of the BGO array to a given multiplicity M and sum energy E was calibrated using 898-keV ^{88}Y γ rays. Using this response, two-dimensional unfolding [4] of the (K,H) distribution was performed to give the (M,E) distribution. By converting M to spin I using the relation

$$I=\Delta I(M-n_{\rm stat})+0.5n_{\rm stat}\,,$$

the two-dimensional entry distribution (I,E) was obtained. ΔI represents the average spin removed per photon, and $n_{\rm stat}$ is the number of statistical γ rays, each assumed to remove $0.5\hbar$. Values of $\Delta I=1.73\hbar, 1.88\hbar$ and $n_{\rm stat}=3.2, 5.1$ for feeding of normal and SD states, respectively, were obtained from unfolded Ge spectra, in the manner described in Ref. [5]. Corrections for estimated neutron hits and for transitions missed because of discriminator thresholds and conversion electrons are also included.

Figures 1(a) and 1(b) show the entry distributions obtained by setting gates on normal and SD transitions in ^{192}Hg. Figure 1(a) is actually the entry distribution for the entire ^{192}Hg channel since the gates were on low-lying normal transitions through which the SD band also decays. Also shown in Fig. 1 are the yrast line for normal states, the SD band, and the barrier between SD and normal states. It is clear that the entry distribution associated with the SD band originates from the higher spin components of the total distribution in Fig. 1(a). A superposition of both distributions also reveals that the SD distribution originates from slightly lower energy at a given spin.

We have developed a model which follows, by Monte Carlo simulations, the γ cascades after neutron emission, in the manner described by Holzmann [5], but expanded to include decays in normal and SD wells. The calculations start with the *measured* entry distribution for ^{192}Hg [Fig. 1(a)], and entry states are assigned as SD or normal (defined as all non-SD states) with probabilities proportional to their level densities. Mixing between the two classes of states is taken into account in the manner given by Refs. [6] and [7]. The change from one class to the other occurs through this mixing, which is governed by their relative level densities and by the barrier separating them. The $E2$ and $E1$ γ-decay widths in each well are also required in order to follow the γ cascade. Parameters used in the calculations will be discussed below; the main ones are the energies of the SD band and of the barrier separating the normal and SD states. Details of the calculations will be published elsewhere [8].

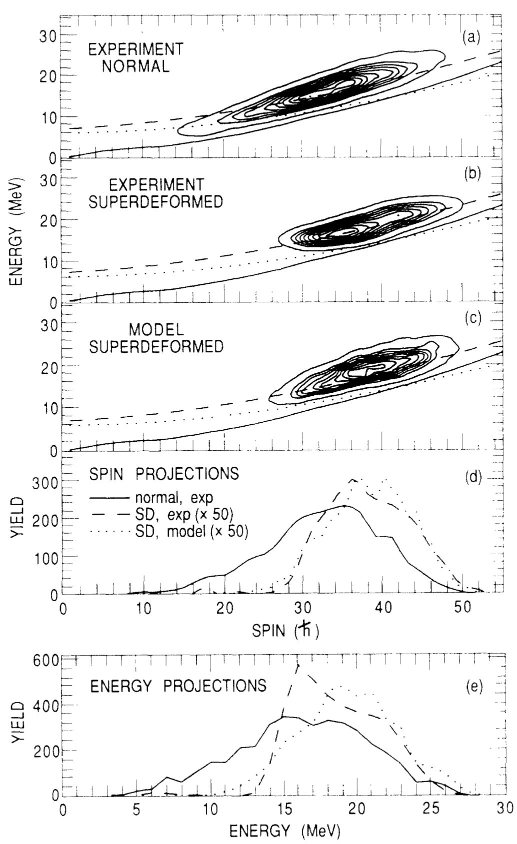

FIG. 1. Measured entry distributions leading to the population of (a) normal and (b) SD states in ^{192}Hg; contours represent changes of 10% of the maximum value. (c) Calculated entry distribution for SD states. (d) and (e) show the projections on the spin and energy axes, respectively, for the measured and calculated entry distributions; the SD distributions are multiplied by 50. Also shown in (a)-(c) are the normal (solid line) and SD (dotted line) yrast lines, and the barrier separating the two classes of states (dashed line). The SD band and barrier shown here give the best overall agreement between calculation and experiment.

The method is similar to that described by Schiffer and Herskind [9], who have pioneered the study of feeding of SD bands. Two improvements to their work have been added: (i) the treatment of the change from one class of states to the other (they consider the tunneling as a separate decay channel which competes with γ emission, and Vigezzi *et al.* [6] have pointed out that this is not justified); and (ii) starting the γ cascade from the measured entry distribution for the nucleus of interest (instead of a calculated one).

The calculated SD entry distribution is shown in Fig. 1(c) and the projections on the spin and sum-energy axes are given in Figs. 1(d) and 1(e). The calculated entry distribution reproduces the experimental one fairly well [cf. Figs. 1(b) and 1(c) with Figs. 1(d) and 1(e)]. The principal features, viz., that SD states originate from the higher spin portion of the channel distribution, emerges naturally from the calculation. This arises since it is only at the higher spins that the density of SD states, relative to that of the normal states, becomes sufficiently high to allow the former to be populated. This feature had been previously noted in Ref. [9].

The model gives a description of the feeding mechanism of SD bands and reveals how γ cascades become trapped in the SD minimum. Following neutron evaporation, the nucleus deexcites by emission of competing statistical and $E2$ γ rays. Initially there is little distinction between SD and normal states since large mixing occurs at high excitation energy, leading to jumps between the two classes of states (with about two jumps per cascade). However, when the cascade approaches the barrier in the SD well, the probability for trapping—resulting in the population of a SD band—begins to grow. On average, trapping occurs 1–2 MeV below the barrier. These points are illustrated in Fig. 2, which shows a sample of 25 cascades that result in trapping within the SD well. Cascades which occur when the nucleus has a SD shape are shown as thin lines and are observed to occur mainly below the barrier, primarily as $E2$ transitions.

Cascades which are trapped in the SD well are seen in Fig. 2 to contain early high-energy cooling transitions, which bring the decay pathway below the barrier. It is

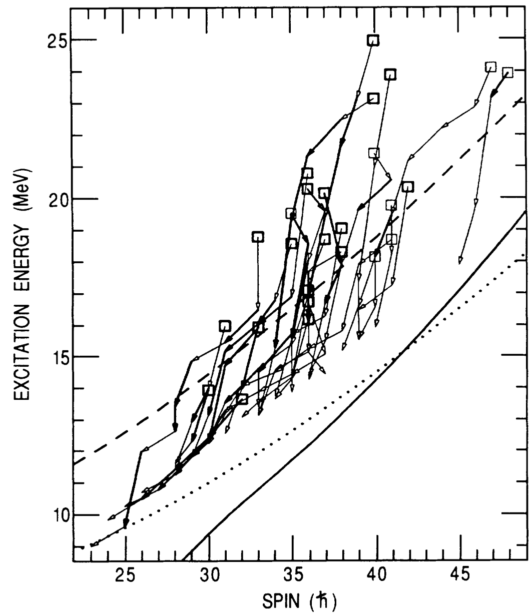

FIG. 2. Sample of 25 cascades which populate SD bands. Transitions are denoted by thick lines when the initial shape is normal deformed and by thin lines when it is SD. Thick or thin squares indicate either normal or SD shapes, respectively, at the starting point of a cascade. See the caption of Fig. 1 for a description of solid, dotted, and dashed lines.

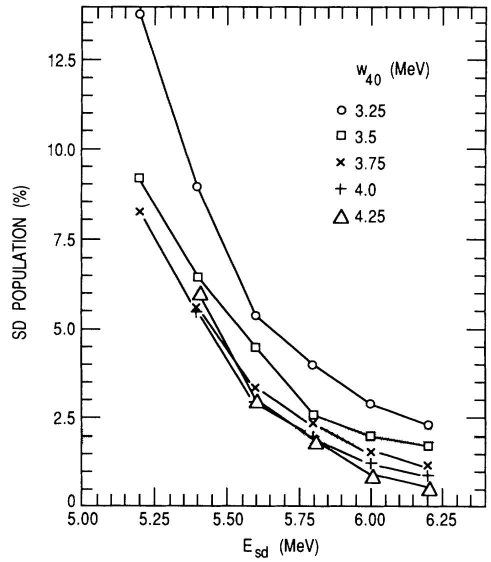

FIG. 3. Calculated intensity of the SD band (as a percentage of ^{192}Hg yield) as a function of SD energy E^0_{sd} for different values of SD well depth W_{40}. The measured [3] intensity of $(2\pm0.2)\%$ (shown in the shaded area) is obtained for only a narrow range of E^0_{sd}.

this rapid cooling which brings the deexcitation cascade down to the SD yrast line at high spin and, hence, is responsible for the unexpectedly large population of SD bands at very high spin. Thus, the unusual high spin population provides indirect evidence for the important role of the barrier.

Several parameters characterizing properties of the nucleus are used in the Monte Carlo simulations. Important parameters are the energies E^I_{sd} of the SD band levels (fixed by a parameter E^0_{sd}, the energy at zero spin) and the well depth, $W_I = E^I_{\rm barrier} - E^I_{sd}$. Other parameters describing properties of excited states are the barrier frequency $\hbar\omega$(0.6 MeV); moments of inertia $\mathcal{J}$ [(121,61) $\times\hbar^2$ MeV^{-1} for SD and normal states, respectively]; transition quadrupole moments Q_t (20,4 eb); level density parameters a [$A/(8-14)$,$A/8$]; the rotational damping width $\Gamma_{\rm rot}$ (200,200 keV); and the energy U_0($\sim$1.2,1.2 MeV) above the yrast line where the quasicontinuum cascade stops. Each parameter has a strong effect on only one or two observables: E^0_{sd} on the SD band intensity; W_I and $\hbar\omega$ on the entry distribution and the average $E2$ transition energy ($\overline{E2_\gamma}$); $\mathcal{J}$ on $\overline{E2_\gamma}$; Q_t on the Doppler shifts of quasicontinuum $E2$ peaks; a on statistical spectra; $\Gamma_{\rm rot}$ on the ridge intensity in a E_γ-E_γ matrix; and U_0 on the variation with spin of SD on normal yrast transition intensities. Thus, the observables provide strong constraints on the parameters, thereby yielding information on the nuclear properties. As an example, the calculated intensities are shown as a function of E^0_{sd} in Fig. 3 for various well depths at spin 40. The observed intensity [3] of $(2\pm0.2)\%$ can be reproduced in only a narrow range of E^0_{sd} for a spread of W_{40} values. (The change of SD band intensity with spin, not shown in Fig. 2, is also well reproduced.) Variation of other parameters, together with the requirement of simultaneously reproducing other observables, result in a larger uncertainty in E^0_{sd}. Good fits to all observables are obtained only for $E^0_{sd}=5.6$–6.2 MeV and $W_{40}=3.5$–4.5 MeV. Values of E^0_{sd} and W_{40} in this range give the best least-squares deviation ($\chi^2 \le 2\chi^2_{\rm min}$) with respect to the average values of (a) the SD band intensity, (b) the feeding spin of the band, (c) the entry spin, (d) the width of the entry spin distribution, (e) the entry energy, (f) the width of the entry energy distribution, and (g) the quasicontinuum $E2$ peak. Thus, we have exploited the model to place constraints on E^0_{sd} and W_{40}, in a manner reminiscent of that done for fission isomers [7].

The SD entry distribution is sensitively dependent on the well depth W_{40} mainly around spin 40. However, we assume that W_I increases linearly with spin, to take into account a theoretically expected variation with spin, with W_0 fixed at a calculated value [10] of 1 MeV. Tunneling through the barrier is governed by $(W_I - E)/\hbar\omega$ (see Ref. [7]), where E is the excitation energy in the SD well; we have used $\hbar\omega=0.6$ MeV, a somewhat arbitrary value adopted from Ref. [6].

Finally, another constraint on E^0_{sd}, which is independent of any comparison with the model, comes from the fact that the SD band must lie below its entire entry distribution, giving $E_{\mathrm{sd}}^{0} < 6.2$ MeV, consistent with the above model-dependent constraint, $E_{\mathrm{sd}}^{0} = 5.6-6.2$ MeV. The latter constraint has a further uncertainty of ± 0.4 MeV, since the yrast states of ^{192}Hg above spin 31 have not been established. By combining the two constraints, we obtain $E_{\mathrm{sd}}^{0} = 5.2-6.2$ MeV.

Several theoretical predictions for E_{sd}^{0} exist: 3.7, 4.2, 4.3, and 5.4 MeV are given in Refs. [10–13], respectively. The predicted well depths at $I=0$ in these calculations are 1.0, 1.3, and 1.6 MeV in Refs. [10–12], while at $I=14$ and 40 they are 2.1 (Ref. [14]) and 3.3 (Ref. [12]) MeV, respectively. The increase with spin of W_I is roughly consistent with that obtained from our analysis.

In summary, we report the first measurement of the entry distribution for a SD band. We have also performed Monte Carlo simulations to follow the history of the γ-ray cascade associated with the feeding of SD bands. The simulations correctly describe all observables simultaneously: They reproduce the SD entry distribution, the SD band intensity and its variation with spin, and the quasicontiuum $E2$ spectra, with well-defined ranges of the SD band energy and well depth. By combining constraints obtained from the model and from the measured SD entry distribution, we suggest that the SD band has an excitation energy between 5.2 and 6.2 MeV at spin 0. At the point of decay out of the SD band, estimated to occur at spin 10, these values correspond to an excitation energy of 3.3–4.3 MeV [15] above the normal yrast line. The SD well is suggested to be 3.5–4.5 MeV deep at spin 40.

We acknowledge helpful discussions with H. Esbensen, B. Herskind, W. Nazarewicz, K. Schiffer, and R. Wyss. This research was supported in part by the U.S. Department of Energy, Nuclear Physics Division, under Contracts No. W-31-109-ENG-38, No. DE-AC07-76ID01-570, and No. DE-FG02-87ER40346, and by the National Science Foundation under Grants No. PHY88-02279 and No. PHY91-00688.

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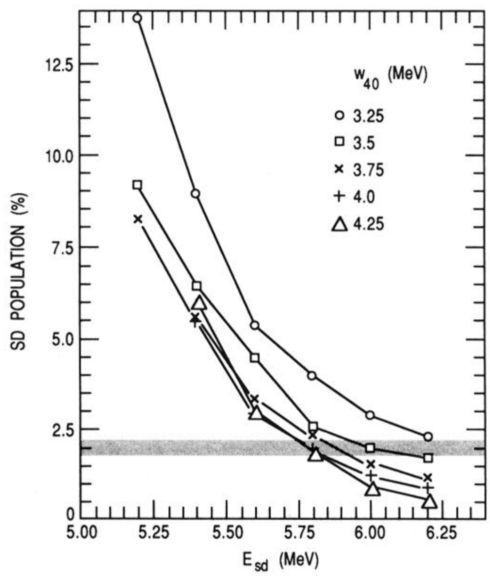

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