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Population of Superdeformed Bands and Competition with Fission

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Abstract. Average entry points for superdeformed (SD) and normal states have been measured in ^{191,192}Hg and in ^{152}Dy. Compared with normal states, the superdeformed states have entry spins ~10 $\hbar$ higher and internal excitation energies ($U = E^* - E_{yrast}$) at least 2 MeV lower for the Hg cases and about 8 MeV lower for ^{152}Dy. By comparison with calculated ℓ-distributions of evaporation residues (ER), using CASCADE to compute the fission competition, we find that the initial population of the SD band in ^{192}Hg originates from the tail of the ER spin distribution.

Following the discovery (Twin et al. 1986) of a discrete superdeformed (SD) band in ^{152}Dy, considerable experimental and theoretical interest has developed. Recently, a new region of superdeformation near A~190 has been discovered (Moore et al. 1989). The SD bands in both the A~150 and A~190 regions exhibit common features in their feeding patterns: they are populated to considerably higher spin than normal states and with much higher intensity (by more than an order of magnitude) than would be expected when compared to the population of states of ordinary deformation.

One question that naturally arises concerns the feeding mechanism of the SD bands and whether a common mechanism is responsible for the feeding of the SD bands in different regions of the periodic table. Information on the feeding of SD states gives insight into the structure of excited states and the dynamics of large shape changes in nuclei. The feeding of SD states also serves as an ideal probe of the very high-ℓ partial waves involved in reactions leading to the formation of evaporation residues. From a more practical standpoint, knowledge about the feeding of SD states provides valuable guidance on how best to populate SD bands in order to optimize experiments which investigate the structure of SD nuclei.

In this contribution, we report on the measurement of the entry points (defined as the average spin I_i and energy E_i of the starting point for the γ-cascade following particle emission) leading to the SD and normal bands in ^{191,192}Hg and in ^{152}Dy. The Hg measurements were carried out using ^{160}Gd(^{36}S,xn) reactions at several beam energies between 154 and

180 MeV, while the reaction $^{120}Sn(^{36}S,4n)$ at 172 MeV was used to populate states in ^{152}Dy. In all measurements, both self-supporting foils and backed targets were used; the latter are important to properly account for the presence short-lived isomeric states. The ^{36}S beams were supplied by the Argonne heavy-ion accelerator ATLAS. The γ-ray measurements were performed using the Argonne-Notre Dame BGO γ-ray facility which consists of 12 Compton suppressed Ge (CSG) spectrometers, surrounding an inner array of 50 hexagonal bismuth germanate (BGO) detectors. In addition to Ge singles and Ge-Ge coincidences, both the fold (K) and sum energy (H) measured in the array were recorded on an event-by-event basis.

In order to determine the average entry points from our data, we used two complementary approaches: (i) the total γ-ray spectrum in coincidence with gates in the cascades of interest was obtained from the Ge-Ge data; (ii) the fold and sum-energy distributions, measured in the BGO array, associated with the cascades of interest were obtained by gating on specific lines with a Ge detector. For the first approach, several steps were required in the analysis to obtain the "true" total γ-ray spectra: (i) a correction for coincidence summing was applied and the neutron-induced background was removed by subtracting an appropriately normalized, measured neutron induced spectrum (Holzmann et al., 1987); (ii) the background due to Compton scattering was unfolded (Radford et al., 1987) using measured CSG response functions; (iii) the resulting spectra were corrected for photopeak efficiency.

The procedure outlined above yields the total γ-ray spectrum in coincidence with the selected gate. The discrete lines associated with the selected gate were then subtracted from the spectra. After fitting the high energy ($2 < E_\gamma < 4$ MeV) portion of each spectrum with the usual formula for statistical γ-rays ($I_\gamma = E_\gamma^3 \exp(-E_\gamma/T)$) and subtracting the fitted spectrum out, we used angular correlation information to decompose the remaining quasi-continuum into components having dipole and quadrupole multipolarity (assuming stretched transitions). The average multiplicity of each component was then determined by normalizing the intensity to that of a transition with known multiplicity (e.g. the $2^+ \to 0^+$ γ-ray in the $4^+ \to 2^+$ gate in ^{192}Hg). Thus, the average spin removed (ΔI) and average energy removed (ΔE) by each component of a given cascade was obtained and the total spin and energy removed by the cascade was determined by summing each contribution.

In the second approach, the average entry points were determined from the fold and sum-energy information measured in the BGO array. In order to convert the measured distributions into spin and true energy, the following corrections were applied: (i) the measured fold was converted to true hits by using the response of the array (measured with radioactive sources); (ii) the number of hits was corrected for the bias in favor of higher multiplicity events introduced by the requirement of Ge-Ge coincidence in the event trigger and for the gating γ-ray; (iii) the neutron contribution to the multiplicity and sum energy was extracted by comparison with the results obtained from the Ge spectra described above. The average entry spin is then given by: $I = \Delta I(M_\gamma - n_{stat}) + 0.5 n_{stat}$, where ΔI is the average spin removed per photon and n_{stat} is the number of statistical transitions (both derived from the Ge analysis).

Figure 1 shows the total γ-ray spectra obtained by gating on SD and normal transitions in ^{192}Hg from the 159 MeV backed-target data. The

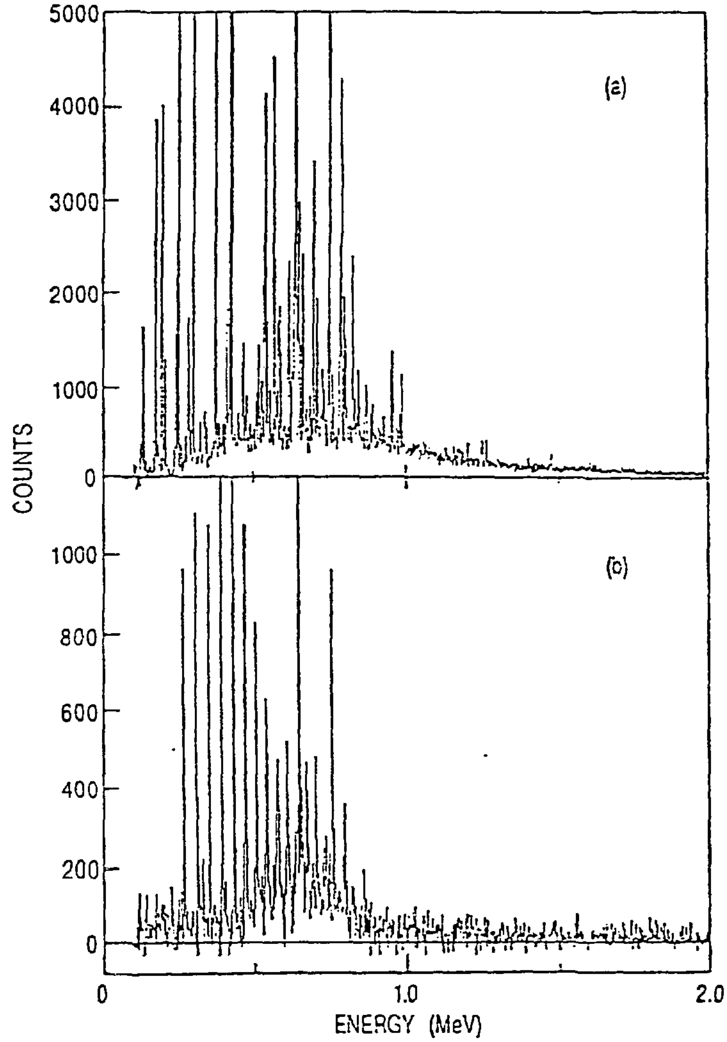

Fig. 1. Unfolded and efficiency corrected total γ-ray spectra obtained from the detectors at backward angles, gated on the $4^+ \to 2^+$ transition in ^{192}Hg (a) sum of spectra gated on SD transitions in ^{152}Dy (b).

average entry points into the two cascades have been determined from these data using the procedure outlined above and are shown in Fig. 2a. It should be mentioned that in order to obtain 'clean' spectra from the SD gates, a high multiplicity cut was applied to the data to remove unwanted background from fission products, etc. While this cut does introduce a small bias, the effect of the bias is smaller than the error bars shown in the figure. Clearly, the average entry into the superdeformed cascade originates from much higher spin (~10 $\hbar$) yet only moderately higher energy (~4 MeV) when compared to the normal entry point. Similar results were obtained from an analysis of ^{191}Hg data. This feature is even more pronounced for the ^{152}Dy case (Fig. 2b), where the SD entry point is on average higher by ~15 $\hbar$, yet the excitation energy is only about 1 MeV higher.

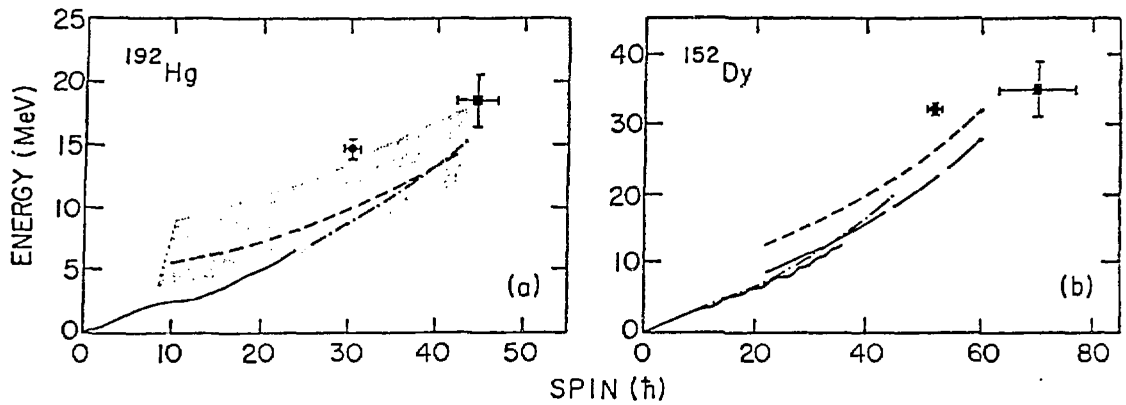

Fig. 2a. Entry points for normal (●) and SD (■) cascades in ^{192}Hg. The known yrast line (Hubel et al., 1986) is indicated by the solid line, the dashed-dot line represent the extrapolation to high spin. The dashed line shows the location of the SD band under the assumption that it becomes yrast at spin 40. The shaded area represents the experimental constraints on the location of the SD band (see text for details).

Fig. 2b. Normal (●) and SD (■) entry points in ^{152}Dy. The known single-particle (——) and moderately deformed prolate (—·—) bands are shown. The possible locations of the SD band are plotted under the assumption that at 55 ħ the band crosses the extrapolation of the single-particle band (— —) or the prolate (----) band.

The analysis outlined above allows one to place some constraints on the excitation energy of the superdeformed band (see Fig. 2a). In the case of ^{192}Hg, the spin at the bottom of the band is about 10 ħ and the SD band feeds into the normal states at about 8 ħ (Ye et al., 1990). The maximum energy that could be carried off in the ~ 2 ħ spin interval would be that carried by statistical transitions, giving an excitation of ~6 MeV for the SD band. On the other hand, if all of the statistical transitions were to preceed the entry into the SD band, then the bottom of the SD band would be located within 0.5 MeV of the yrast line at spin 10. The constraints mentioned above represent extreme limits for the location of the SD band and are illustrated by the shaded area in Fig. 2a. The location of the SD band, under the assumption that it becomes yrast at spin 40 (Chasman, 1989), is shown in Fig. 2a by the dashed line and is seen to be consistent with an excitation energy intermediate to the experimental constraints.

Similarly, some constraints may be placed on the location of the SD band in ^{152}Dy. If one assumes that this SD band becomes yrast (Twin et al., 1986) at about spin 55 (i.e. the spin at which the 50% feeding level is reached), then it is necessary to know where the normal yrast line sits when the two bands cross. If the single-particle oblate band is extrapolated to spin 55, then the location of the SD band is shown by the solid curve in Fig. 2b. If, however, the moderately deformed prolate band (Nyako et al., 1986) becomes yrast before spin 55, then the location of the SD band would be roughly given by the dashed curve in Fig. 2b. While the error bars on the SD entry point in ^{152}Dy are rather large, our results are more consistent with the lower placement of the SD band.

We have also measured the population of the SD and normal bands in $^{191,192}Hg$ at several beam energies (between 154 and 180 MeV). The population intensity results (Janssens et al.), normalized to integrated beam current, are presented in Fig. 3a. It is clear that the absolute intensity in the SD bands peaks at higher beam energy than that in the normal states, for a given channel. This result is consistent with the finding that the average entry points into the SD bands occur at higher spin. Figure 3b shows the relative intensity within the SD band in

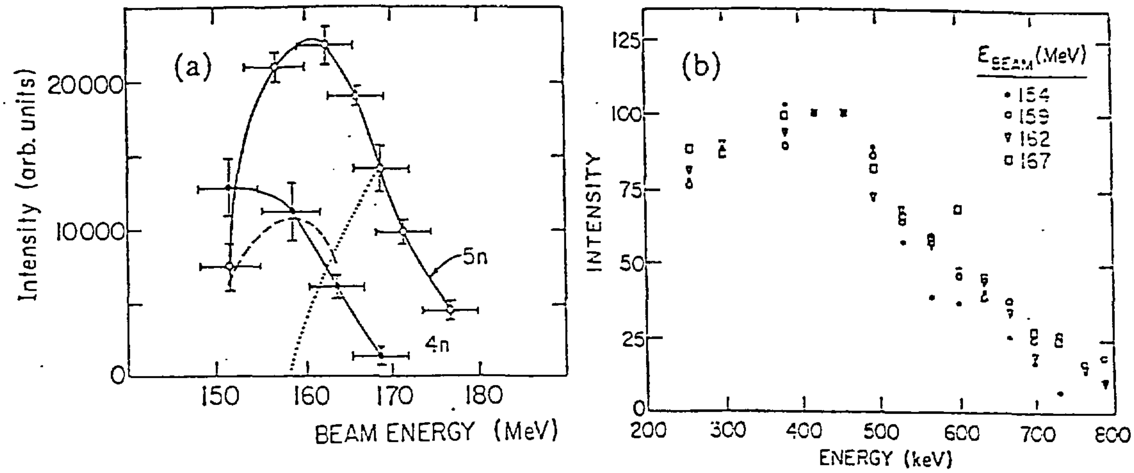

Fig. 3a: Population of the 4n (●) and 5n (○) channels (normal states) normalized to integrated beam current (the lines are to guide the eye). The superdeformed 4n (dashed line) and 5n (dotted line) intensities have been multiplied by a factor of 50 for the purpose of presentation.

Fig. 3b: Relative intensities of the members of the SD band in ^{192}Hg determined from a gate on the 340 keV transition. The intensities at all beam energies have been normalized to that of the 458 keV line.

^{192}Hg, gated on the 340 keV line and normalized to the 458 keV transition, over several beam energies. Although the estimated input ℓ_{max} varies from 27 $\hbar$ at 154 MeV to 46 $\hbar$ at 167 MeV, the relative intensities of the highest spin states in the band drop gradually with spin but are essentially independent of beam energy, except at the lowest energy measured where there is a noticeable decrease. The average feeding into the SD band occurs at about 27 $\hbar$ at 154 MeV and rises to about 30 $\hbar$ at the other beam energies. The saturation of the high spin feeding with increasing beam energy shows that increasing input angular momentum does not lead to increased feeding of the SD band at higher spin.

The fold (K) and sum-energy (H) distributions associated with the SD and normal bands in ^{192}Hg were obtained at several beam energies (154, 159, 162, and 167 MeV) by selecting the appropriate gates in a Ge detector. Figure 4 shows the K and H distributions gated on transitions in the SD and normal bands for three of the beam energies. While both distributions move towards higher values with increasing beam energy, those associated with the SD band are consistently higher than those for the normal band at all beam energies.

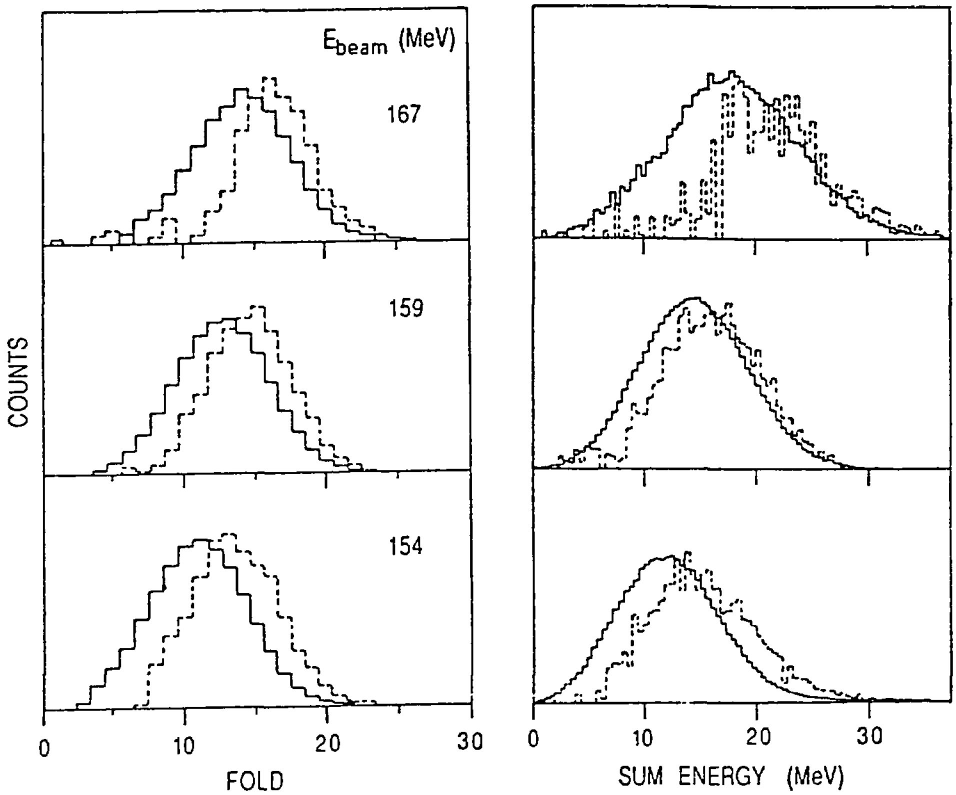

Fig. 4. Fold (K) and sum-energy (H) distributions measured in the array for the normal (——) and SD (----) cascades as a function of beam energy. The areas of the SD distributions have been scaled by arbitrary factors for clarity of presentation.

We have converted the K and H distributions into entry spin and energy using the procedure described above. The results are shown in Fig. 5a., where the energies have been scaled with the SD band as a reference. We have had to assume that the SD band crosses the extrapolation of the normal yrast line at spin 40, since the actual excitation is unknown (as is the case for all SD bands in this mass region). Several interesting features are illustrated in this figure: (i) the average entry into the SD band is consistently higher in spin than the normal entry points by about 10 ħ; (ii) the excitation energy of the entry points above the respective estimated yrast lines are significantly lower (i.e. cooler) by 1-3 MeV for the SD band; (iii) the average entry points into the SD band continue to move up in both spin and energy with increasing bombarding energy, yet the actual feeding into the discrete SD states saturates at about spin 30.

All of the data presented so far points out the need to include the role of fission competition when attempting to understand the population of SD bands. The estimated maximum angular momentum brought into the compound nucleus (CN) at the higher bombarding energies is significantly higher than the measured entry points into the SD band and suggests that there is a large depletion of the highest ℓ partial waves due to fission.

Figure 5b shows the estimated CN and ER cross-sections for beam energies

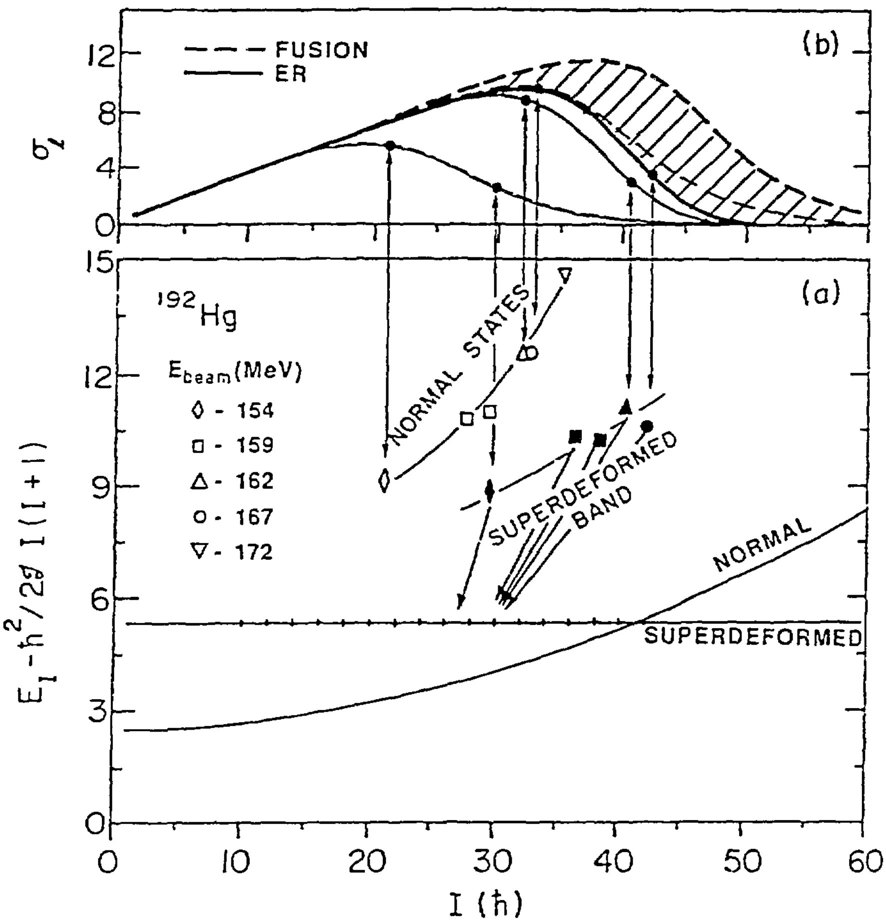

Fig. 5a: Average entry points into normal states (open symbols) and SD states (solid symbols) as a function of beam energy, determined from the array data. The excitation energies are shown relative to a rigid rotor reference (having the SD moment of inertia) under the assumption that the SD reference is yrast at spin 40. The extrapolation of the normal yrast line is also shown.

Fig. 5b: Calculated cross-sections for fusion (----) and evaporation residue formation (——). A diffuseness of $\Delta\ell = 4\hbar$ was used for the σ_ℓ (CN); the fission cross-sections were calculated with CASCADE. The cross-section for fission at E_{beam} = 167 MeV is illustrated by the hatched area.

of 154, 162, and 167 MeV. The fission cross-sections have been calculated with Sierk fission barriers using the code CASCADE (Puhlhofer, 1987). We have successfully reproduced fission excitation function yields in neighboring Hg and Pt nuclei (Reisdorf, et al., 1985; Lesko, et al., 1986) using the same prescription. It is clear that the highest partial waves in the reaction result in fission, leading to a saturation at high ℓ for the evaporation residues. In each case, the entry spin for the SD band corresponds to the high-ℓ tail of the ER spin distribution. Thus, the population of the SD bands represents successful competition against fission. The decrease of the feeding spin of the discrete SD states at the lowest beam energy is seen to be a result of the lower ℓ distribution at this energy. The increased entry spin at the higher beam energy is accompanied by a higher excitation energy U, and the resulting cooling towards the SD band is such that the feeding point into the band remains constant.

In summary, we have measured the average entry points into normal and superdeformed states in ^{191,192}Hg and in ^{152}Dy. We have found that the population of SD states consistently occurs at higher spin than that of normal states. Our data also shows that when the excitation energy of the SD entry points are calculated relative to the best estimate of the SD yrast line, the internal excitation energy U is considerably lower for SD states than for normal. The saturation in spin of the average feeding of discrete states in the SD band of ^{192}Hg was found to be consistent with a cutoff of the higher ℓ partial waves due to fission and an increase in internal excitation with the higher spin entry points. The average entry spins in ^{152}Dy are much higher than in the case of the Hg systems because the fission cutoff occurs at higher spin (~65 $\hbar$) in the former.

Our results suggest that in order to optimize the population of superdeformed bands, one must use relatively cool reactions (i.e. large input angular momentum and rather low excitation energy) and strike a delicate balance between bringing in sufficient angular momentum to populate the highest spin states in the bands, yet not so much that fission dominates and the γ-ray spectra become swamped by background due to fission products.

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