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POPULATION OF SUPERDEFORMED BANDS, THE COMPETITION WITH FISSION, AND THE BARRIER BETWEEN NORMAL AND SUPERDEFORMED STATES

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Superdeformed (SD) bands in both the Dy and Hg regions exhibit several common features in their feeding patterns: they are populated to higher spin than normal states, and with higher intensity (by more than one order of magnitude) than would be expected when compared to the intensities of lower spin states. The question naturally arises as to the feeding mechanism of the SD bands and whether a common mechanism is responsible for the feeding of these bands in the different regions of the periodic table. Some features in the feeding of SD bands in the Dy region have been reported[1,2], and Schiffer and Herskind[3] have performed statistical model calculations to explain a number of these features. However, there has been no direct measurement of the entry points leading to the population of SD bands. For the SD band in ^{149}Gd, Taras et al.[2] measured the fold K and sum energy H, which are closely related to the entry point, but did not convert these quantities to the entry spin and energy.

Information on the feeding gives insight into the structure of excited states and the dynamics of large shape changes in nuclei. It is also interesting to understand how the reaction strength ends up in a localized minimum in the potential energy surface. From a practical standpoint, knowledge about the feeding of SD bands provides guidance on how best to populate SD bands in experiments aimed at investigating their structure. An important starting point is the determination of the spin and energy region of the compound nucleus leading to the population of SD bands. This requires measuring the entry point (defined as the average spin I_i and energy E_i of the starting point for the γ cascade following neutron emission.) We suggest here that the entry point associated with the SD band is located near the peak of the barrier separating the SD and normal states and, thus, can provide a

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direct measure of the barrier height energy E_B;

$$E_i(I_i) \sim E_B(I_i) = E_{SD}(I_i) + W_D(I_i),$$

where E_{SD} is the energy of the SD minimum and W_D the well depth. The quantities E_{SD}, E_B and W_D are direct measures of the shell correction leading to the superdeformed secondary minimum. In this paper we report on the entry points leading to SD as well as normal bands. We find that, compared to normal bands, the entry spins for the SD bands are about 9 $\hbar$ higher, and the entry excitation energy 1-3 MeV colder. We also conclude that population of the SD bands represents successful competition against fission.

SD bands in ^{192}Hg were populated in the ^{160}Gd(^{36}S,4n) reaction, using ~1 mg cm^{-2} targets and beams with energies between 154 and 172 MeV from the Argonne heavy ion accelerator ATLAS. Ge-Ge coincidences and the associated γ multiplicity and sum-energy were measured using 12 Compton-suppressed Ge detectors and a 50 element BGO array of the Argonne-Notre Dame γ facility.

The fold (K) and sum-energy (H) distributions for SD and normal states were obtained by gating on specific lines with a Ge detector. Figure 1 shows the K and H distributions associated with normal and SD states in ^{192}Hg at several bombarding energies. It is apparent that both K and H are higher for

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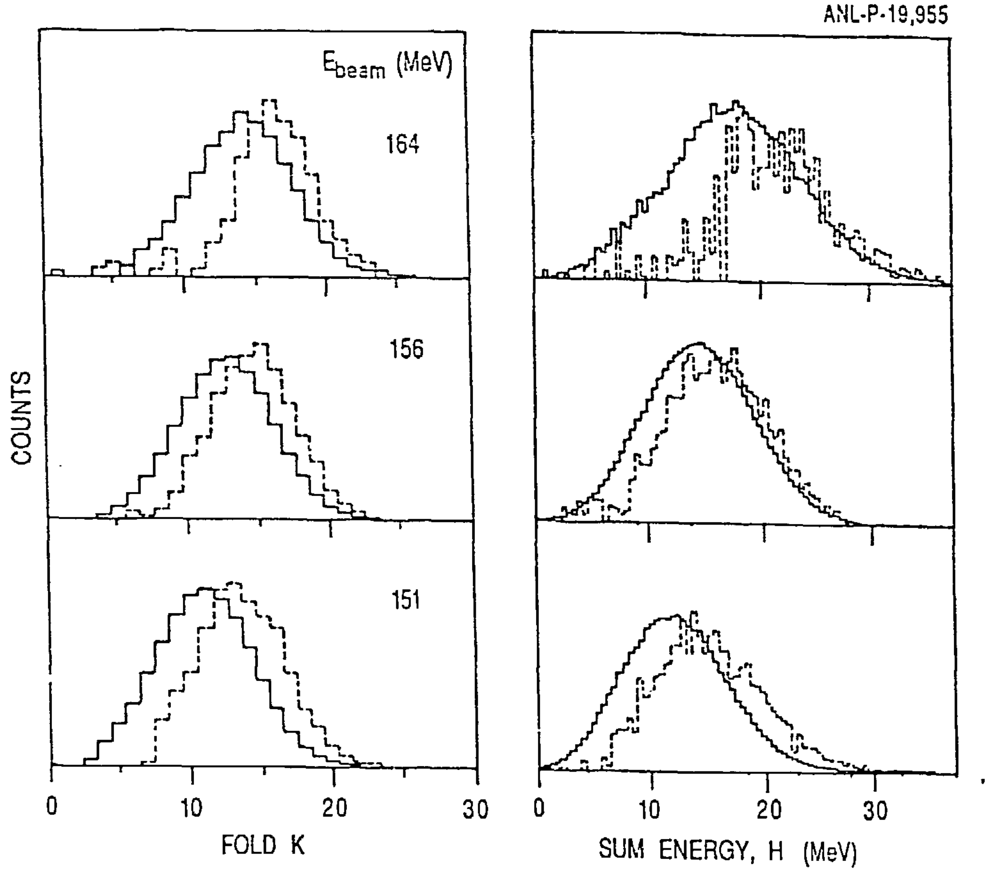

Fig. 1. Fold K and sum energy H associated with normal (sold lines) and SD (dashed lines) states of ^{192}Hg at the indicated beam energies.

the SD states. The corresponding average γ multiplicity m_γ and sum energy were determined after correcting for the response of the array (measured with radioactive sources). Corrections were also applied for the gating transition and for the bias in favor of higher multiplicity events introduced by the requirement of Ge-Ge coincidence in the event trigger. The neutron contribution to these quantities (m=0.64 and E=0.7 MeV per neutron) was extracted by comparing the average γ multiplicity and sum energy measured[4] using Ge detectors, as described in Ref. 5, with the same quantities measured using the BGO array. The average entry spin was given by

$$I = \Delta I(m_\gamma - n_{stat}) + 0.5n_{stat}$$

where ΔI is the average spin removed per photon and n_{stat} is the number of statistical transitions. We use ΔI=1.7 and 1.9 $\hbar$, n_{stat}=3 and 4.3 for normal and SD states, respectively, using values determined[4] from Ge spectra.

Figure 2(a) shows the entry points for normal and SD bands in ^{192}Hg for several beam energies. Also shown in Fig. 2(a) are the known yrast states and their extrapolation to higher spin, as well as the observed SD band. For the latter we take

$$E_{SD}(I) = 5.4 + (\hbar^2/2\mathcal{I})I(I+1),$$

where the moment of inertia is averaged over the known values[6]; the energy is taken from the assumption that the SD band becomes yrast at the calculated value of spin 40 [Ref. 7] since the actual excitation energy is not known (as for all SD bands). The entry point data are also shown in Fig. 3(a), in a

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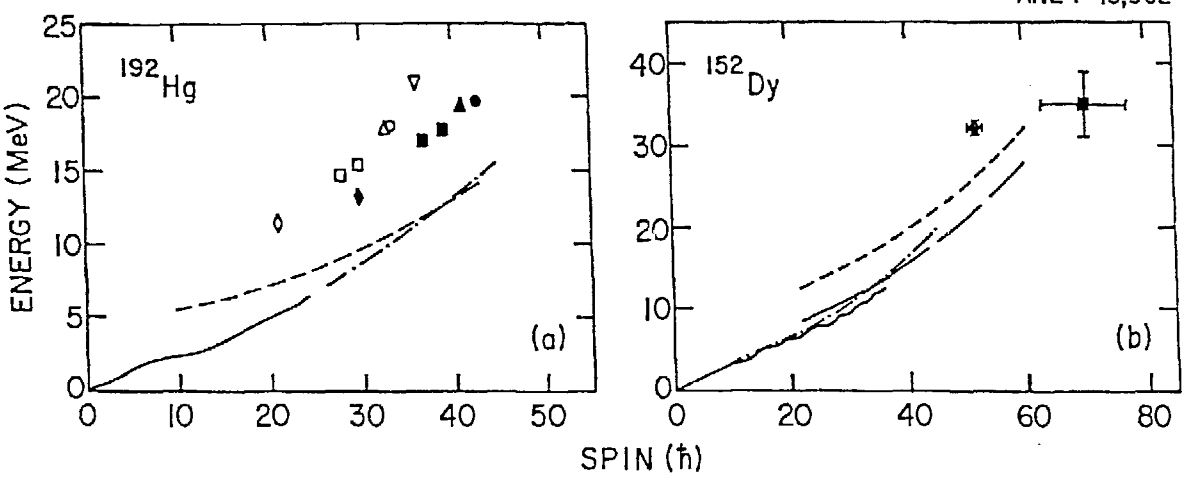

Fig. 2. Entry points associated with population of normal and SD states in (a) ^{192}Hg and (b) ^{152}Dy. The entry spins for the SD states are higher by >9 $\hbar$. The SD band energies (dashed lines) are given by the assumption that it crosses the extrapolation of the known yrast line at spin I=40 and 55 in ^{192}Hg and ^{152}Dy, respectively; two possibilities (short or long dashed lines) for the Dy SD band correspond to extrapolations of either the known oblate states or the weakly collectively band.[8]

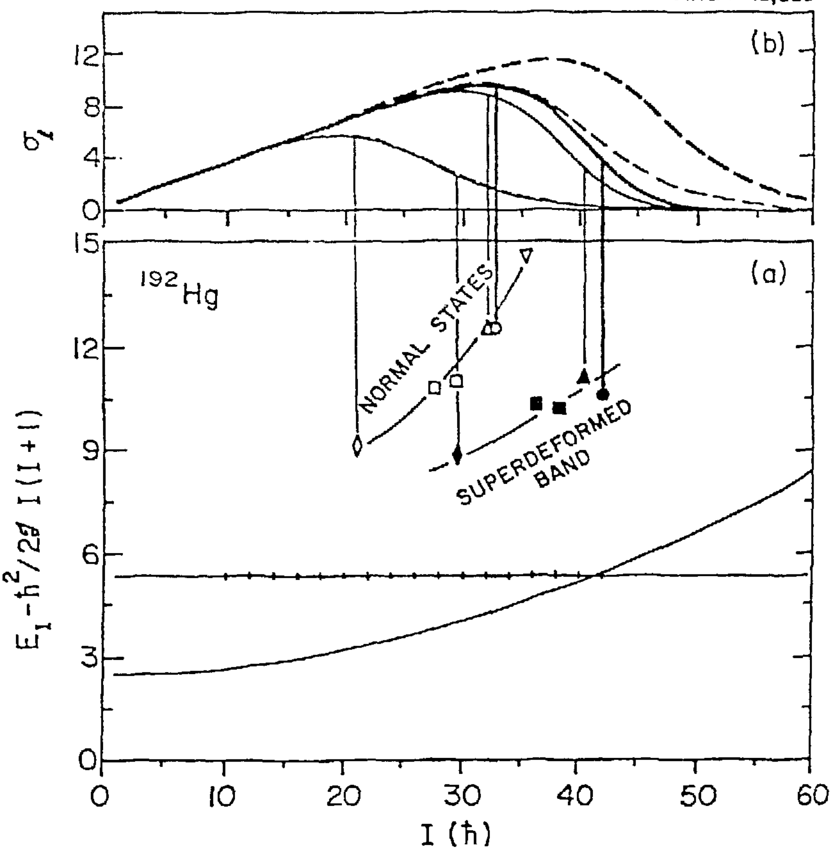

Fig. 3. Entry points for normal and SD states in ^{192}Hg at (mid-target) beam energies of 151 (diamonds), 156 (squares), 159 (triangles), 164 (circles) and 169 (inverted triangle) MeV. A term $(\hbar^2/2\mathcal{J}_{SD})\ I(I+1)$, is subtracted from all energies.

plot where $(\hbar^2/2\mathcal{J})I(I+1)$ is subtracted from the energy. Comparison of the entry points in Fig. 3(a) for the SD and normal states shows that the entry spin is ~9 ħ higher for the SD band, and the energy above the corresponding yrast lines, U, is 1-3 MeV lower (using the assumed SD energy).

The entry points for the normal and SD states in ^{152}Dy for the ^{120}Sn (^{36}S,4n) ^{152}Dy reaction at 170 MeV are shown in Fig. 2(b). The entry points in this case are obtained using Ge spectra obtained by gating on appropriate lines and using the methods described in Ref. 5. The uncertainties connected with the entry point for the SD band are quite large, due primarily to the low statistics and the choice of background subtraction in the gate. Nevertheless it is quite clear that the entry point for the SD band is significantly higher and the excitation energy U substantially lower.

Thus, the same feature is observed in both mass regions, viz. that the SD population originates from significantly higher spin events. Qualitatively this can be understood from the fact that only at high ℓ-values does the level density of SD states become larger than those of all other classes of states.

This is usually expected to occur when the SD band becomes yrast, i.e. when U for the SD states becomes larger than than the corresponding value for the normal states. However, this condition is only approximate, since in the Fermi gas model the level density ρ is proportional to $\exp[2(a(U-\Delta))^{1/2}]$, and Δ for normal and SD states could differ, perhaps by as much as 1 MeV. This is because Δ represents a correction due to pairing and other shell effects, and pairing is expected to be reduced for SD states. Thus, the spin where the SD band is fed (50% population point) may not necessarily be the same as that where the SD band crosses the normal yrast line, as is usually assumed[3].

Both the SD entry spin and feeding spin (point at which the band is fed) are significantly lower in ^{192}Hg than in ^{152}Dy. The estimated compound nucleus maximum angular momentum for Hg at the highest bombarding energies is significantly higher and suggests significant depletion of the highest partial waves due to fission. Figure 3(b) shows the estimated compound nucleus and evaporation residue (ER) partial wave cross-sections for E_b = 151, 161, 164 MeV (at the middle of the target). The differences at the highest ℓ are due to fission and have been calculated with Sierk fission barriers using the code CASCADE[9]. Our confidence in the fission calculations comes from the fact that we are able to reproduce fission excitation function cross-sections in neighboring Hg and Pt nuclei[10]. Since the highest partial waves result in fission, there is a saturation at high ℓ for the evaporation residues. The entry spin for normal states is near the peak of the ER partial wave distribution at each energy. On the other hand, the entry spin for the SD band corresponds to the high-ℓ tail of the ER spin distribution in each case. For these high partial waves there is a strong competition between ER survival and fission. Thus, population of the SD bands represents successful competition against fission, with a significant fraction of surviving ERs ending in the minimum of the SD well. In ^{152}Dy the entry spins are much larger than in ^{192}Hg because the fission cut-off occurs at higher spin (~65 $\hbar$) in the former.

At higher energies there is a small increase in the entry spin (Fig. 3(a)), although the feeding spin into the SD band remains constant. The increased entry spin is accompanied by a higher U, and the resulting cooling towards the SD band is such that the feeding point remains constant. The arrows in Fig. 3(a) connect the entry and feeding points for the SD band and very roughly indicate the γ decay pathway from the entry points into the SD band. The feeding point, where the band is fed on average, can be determined from the intensities of individual intraband transitions and generally corresponds to the point where the relative intensity is 50%. The intensities of the SD band transitions at several beam energies are shown in Fig. 4. It

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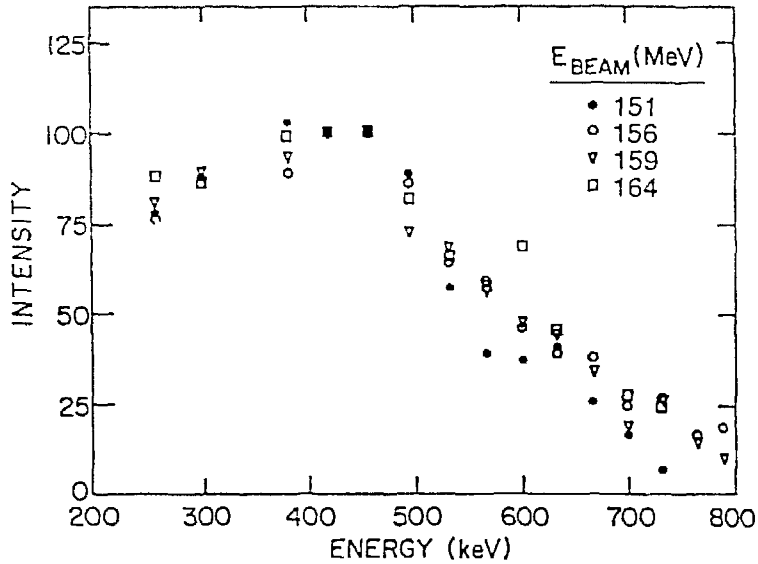

Fig. 4. Relative intensities of SD band transitions (normalized to 100 for the 381-keV transition) obtained by gating on the 341-keV line at the indicated beam energies (at mid-target).

is seen that the intensities of the highest spin states drop gradually with spin, but remain essentially constant at all beam energies, except at 151 MeV, where there is a noticeable decrease at the highest spins. The average feeding spin into the SD band is 27 $\hbar$ at 151 MeV and 30 $\hbar$ at the other beam energies. The saturation of the high spin feeding with increasing energy shows that increasing incoming angular momentum does not lead to increased feeding of the SD band at higher spin -- partly due to fission. The decrease of the feeding spin at 151 MeV is seen to be a result of the lower ℓ distribution at this energy.

Figure 5 summarizes the competing branches to be considered for population of SD bands. At high excitation energy neutron emission and fission are dominant, and excursions to other shapes occur because of thermal fluctuations. Below the neutron binding energy, fission and shape fluctuations cause excursions away from SD shapes, allowing the full family of shapes to be sampled. (It is not clear whether the Monte Carlo simulations of Ref. 3, which include only two classes of shapes -- normal and superdeformed -- properly include the full effect of the thermal shape fluctuations.) The impact of the SD minimum is felt only when the excitation energy becomes low. In particular, below the barrier separating the SD and normal minima, fluctuations away from the SD shape become suppressed, and gamma decay towards the SD minimum becomes increasingly the dominant decay branch. This could explain the lower U_{entry} associated with the SD bands and the empirical observation that it is best to populate SD bands cold[2].

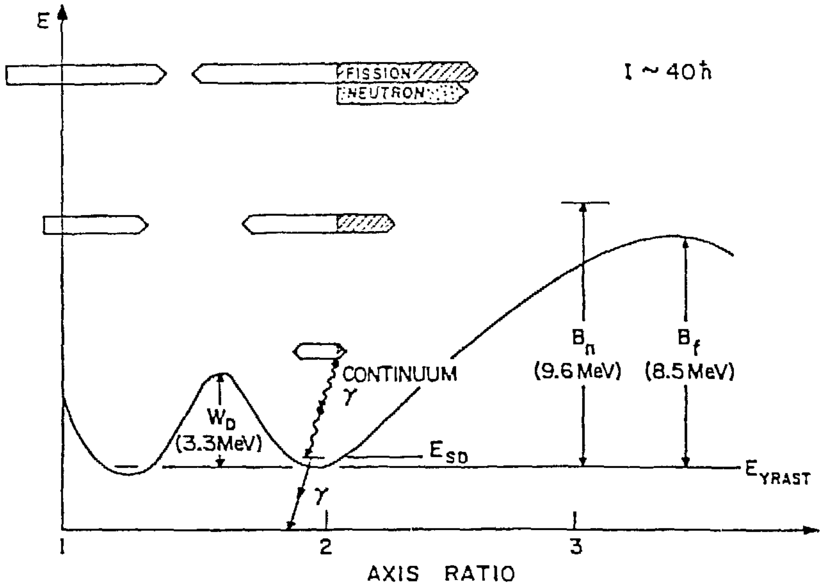

Fig. 5. Schematic representation of decay towards the SD secondary minimum. Shown are possible excursions from the SD shape by neutron and fission decay or thermal shape fluctuations (open arrows), and decay towards the SD minimum by γ emission.

Knowledge of the entry point for a SD band can give information not only on the population dynamics but also on the well depth W_D of the secondary minimum and the barrier E_B separating the SD band normal states. If after neutron evaporation the population ends up significantly above E_B the shape fluctuations at high temperature should result in little trapping into the well. On the other hand if the population is at or below the barrier then γ decay towards the minimum can compete against the fluctuation, resulting in a larger probability of being trapped. At I=30 and 40 $\hbar$ the calculated barriers[11] are 12.2 and 16.5 MeV, compared to entry energies of 13.5 and 19 MeV. This may be an indication that the calculated $E_B(I)$ is too low, but the hypothesis of equating E_i with E_B also needs to be verified.

Figure 6 provides a convenient summary of this talk. For the SD bands of ^{192}Hg and ^{152}Dy the figure shows the entry spins, and the feeding and decay regions. The two nuclei are representative of other cases in their respective mass regions. Also shown are the qualitative ℓ-dependence of evaporation residue survival, and the locations of known normal and SD states. The entry spins for ^{192}Hg are significantly lower than for ^{152}Dy primarily because fission depletes the highest ℓ-waves in Hg. The higher Z of Hg contributes towards a relative lowering not only of the SD minimum energy at large deformation, but also of the fission barrier. The feeding into the SD bands occur at spin values slightly lower than the entry spins, suggesting some

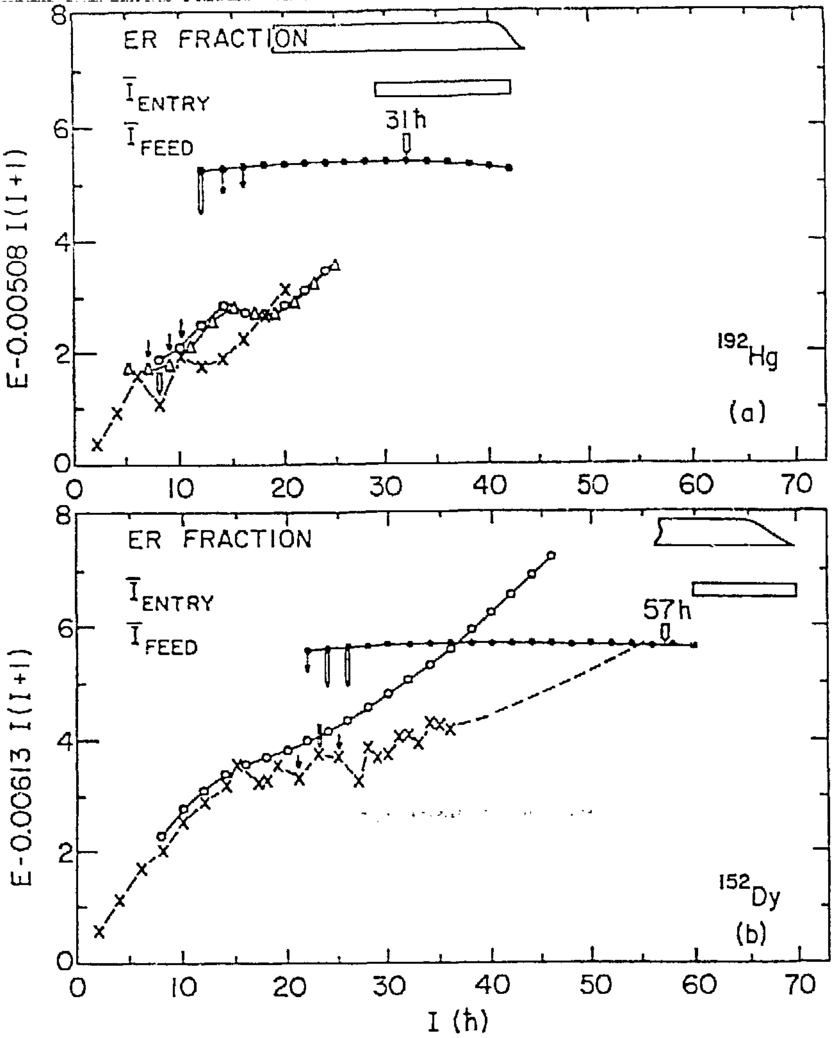

Fig. 6. Comparison of entry, feeding and decay spins of the SD bands in (a) ^{192}Hg and (b) ^{152}Dy. Evaporation residue survival fractions are also shown. The relative energies of the SD bands are not known, but are drawn using assumptions described in text.

removal of angular momentum as the γ cascade cools toward the SD band. Finally, the SD band continue to lower spin in ^{192}Hg, probably due in part to a larger SD well-depth W_D.

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