SUPERDEFORMATION: AN EXPERIMENTAL REVIEW

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INTRODUCTION

The discovery of a superdeformed (SD) band of 19 discrete transitions in the nucleus $^{152}\text{Dy}^1$ is at the origin of the formidable experimental and theoretical effort which has allowed for much progress in the unraveling of the main properties of superdeformation. Over the last five years, many unexpected features have been discovered. In fact, just as soon as a new feature has been explained invariably the next observation has highlighted another surprising phenomenon. The net result of all the activity has been a dramatic increase of our understanding of rapidly rotating nuclei.

The organizers of this conference have asked me to review the present status of the field: this is clearly an impossible task within the allowed space and time. Fortunately, the subject has recently been reviewed on several occasions²⁻⁵ and, therefore, I will only attempt to present here some of the general features that have emerged thus far, and discuss some of the important open questions.

The discussion will be restricted to SD nuclei in the $A=150$ and $A=190$ regions, i.e. to the nuclei with the largest quadrupole deformations ($\beta_2 \sim 0.6$ and 0.5 , respectively) and will address four main issues. First, the evidence for the stiffness of the SD minimum will be reviewed. This section will be followed by discussions on the role of pairing and of specific quasiparticle configurations in the second well. Evidence for other effects at large deformation will be addressed in this section as well. The discussion will then address the issue of the so-called "identical bands" and will conclude with a brief presentation on the feeding and decay of SD nuclei.

STABILITY OF THE SUPERDEFORMED MINIMUM

Figures 1 and 2 present the dynamic moments of inertia $J^{(2)}$ of all SD bands observed so far in the $A=150$ and $A=190$ regions. SD bands have now been identified in all Gd isotopes with $A=146-150$,⁶⁻¹¹ in $^{150,151}\text{Tb}$ ^{9,10,12} as well as in $^{151-153}\text{Dy}$ ^{1,13,14}. Reports of similar band structures in ^{145}Gd and ^{142}Eu have also become available^{15,16}, but these are not shown in fig. 1. For the $A=190$ region, bands have been identified

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Fig. 1. Dynamic moments of inertia $J^{(2)}$ for all SD bands in the $A=150$ region.

Fig. 2. Dynamic moments of inertia $J^{(2)}$ as a function of rotational frequency for all SD bands in the $A=190$ region.

in all Hg isotopes with $A=189-194$ ¹⁷⁻²², in $193-195\text{Tl}$ ²³⁻²⁵ and in the even Pb isotopes with $A=192-198$ ²⁶⁻²⁸. Furthermore, in many nuclei several SD bands have been reported. Thus, in both regions it has been possible to perform detailed spectroscopy in the SD well.

From the two figures, it is apparent that the $J^{(2)}$ values exhibit variations with $\hbar\omega$. Mean-field calculations which attempt to reproduce variations in $J^{(2)}$ have suggested that such variations may be attributed to three major factors which could contribute separately or cooperatively:

(i) shape changes as a function of $\hbar\omega$ (e.g. centrifugal stretching), (ii) changes in pairing at large deformations²⁹, and (iii) occupation of specific high-N orbitals^{29,30} (i.e. high-N orbitals from two major shells higher which plunge down as a function of deformation and come towards the Fermi surface at very large deformations, in this case $i_{13/2}$ protons and $j_{15/2}$ neutrons). The first of these possibilities, i.e. the changes in deformation, can be ruled out on the basis of measurements of transition quadrupole moments. As an example for the A=150 region, the case of the lowest SD band in ^{150}Gd is discussed here: in this nucleus $J^{(2)}$ is not only seen to decrease with $\hbar\omega$, but also exhibits a dramatic fall off at the lowest frequencies (fig. 1). This rapid change is also accompanied by an almost instantaneous decay out of the band. The DSAM lifetime measurements of ref. 10 have shown convincingly that there is no evidence for a change in the inband transition strengths for all transitions down to the lowest data point: a constant transition quadrupole moment $Q_t = 17 \pm 3$ eb fits the data extremely well and a sudden change in the nuclear shape can be ruled out. As an example for the A=190 region, the SD band in ^{192}Hg can be considered. In this case, as in most SD bands of this region (fig. 2), a smooth rise in $J^{(2)}$ of about 40% over the frequency range is observed. In contrast with measurements for SD states near A=150, where only fractional Doppler shifts $F(\tau)$ have been measured so far, one has been able to analyze detailed lineshapes for individual transitions between SD states in this case³¹. Such an analysis allows one to determine the variation of Q_t as a function of $\hbar\omega$, as opposed to previous studies where Q_t was assumed to be constant for all states in the band. The measured Q_t -values are displayed as a function of $\hbar\omega$ in fig. 3b. As can be seen, the quadrupole moment Q_t , and hence the deformation, remain essentially constant ($Q_t \sim 20 \pm 2$ eb) over the entire frequency range. This result rules out centrifugal stretching as an explanation for the rise in $J^{(2)}$: this is illustrated by the dashed line in fig. 3b, where the values of Q_t have been derived assuming that the change in $J^{(2)}$ is entirely due to a gradual change in deformation.

It should be noted that the available mean-field calculations also find the SD minimum to be rather stiff, i.e. the Q_t values are calculated to be rather constant. This is illustrated by the solid line in fig. 3b as well as by the inset in this figure, where the calculated variations in the β_2 and β_4 deformation parameters as a function of frequency are shown to be very small. The calculations were performed within the framework of the cranked shell model, using the Woods-Saxon approach, and include effects due to static and dynamical pairing^{29,31}. As discussed in ref. 29,32, these calculations also predict very small deformation changes in the SD bands of the A=150 region, in agreement with the measurements.

HIGH-N INTRUDER ORBITALS AND PAIRING

Differences in the variations of $J^{(2)}$ with $\hbar\omega$ from nucleus to nucleus have been attributed to changes in the occupation of specific high-N intruder orbitals (i.e. possibility (iii) above). These changes can have dramatic effects: in the case of the Dy isotopes for example, $J^{(2)}$ is seen to rise smoothly over the entire frequency range in ^{151}Dy (fig. 1), while a smooth decrease is seen in ^{152}Dy and an essentially constant value of $J^{(2)}$ is observed for the yrast SD band in ^{153}Dy (it is assumed that the most intensely populated band is the "ground" band in the second well). For these isotopes, the proton contribution has been assigned as $\pi 6^4$ (the nomenclature of ref. 30 is adopted and refers to $i_{13/2}$ intruder orbitals) and the observed differences have been attributed to changes in the occupation of the $j_{15/2}$ neutron orbitals ($\nu 7^1$, $\nu 7^2$ and $\nu 7^3$ for 151 - ^{153}Dy , respectively), which result³⁰ in contributions of varying magnitude to $J^{(2)}$. While the calculations of ref. 30 were performed without pairing

Fig. 3. Figure 3(a): Comparison between the measured and calculated (solid line) moments of inertia $J^{(2)}$ as a function of rotational frequency $\hbar\omega$ in the SD band of ^{192}Hg . (b): Comparison between the measured and calculated transition quadrupole moments Q_t in the SD band of ^{192}Hg . The dashed line represents a calculation assuming that the rise in $J^{(2)}$ is due to a change in deformation only (see text); the solid line is the result of the cranked shell model calculation discussed in the text. The inset shows the calculated change in the deformation parameters β_2 and β_4 over the frequency range of interest. The arrows point towards increasing frequencies.

and at a fixed deformation, more recent Woods-Saxon cranked shell model calculations^{29,32} have taken into account small variations of the shape with spin as well as changes in deformation from one nucleus to another. These calculations also treat pairing correlations self-consistently. The best indication for the importance of the inclusion of pairing correlations and shape effects in this mass region comes from the data on the Gd isotopes. In the calculations, the SD band of ^{150}Gd is assigned a $\pi 6^2\nu 7^2$ configuration. This is in agreement with the assignment of ref. 30, but the alignment of a pair of $j_{15/2}$ neutrons at $\hbar\omega \sim 0.4$ MeV (i.e. a band crossing) must be invoked to account for the sharp drop in $J^{(2)}$ at low $\hbar\omega$. The observation that the deexcitation out of the SD band in ^{150}Gd is extremely abrupt, with essentially all the intensity being lost over a single transition, has been interpreted as additional evidence for this band crossing, which in turn requires the presence of the pairing correlations¹⁰. Marked irregularities in the behavior of $J^{(2)}$ can also be seen in the yrast SD bands of $^{146,147}\text{Gd}$ as well as in an excited band in ^{148}Gd (fig. 1). At present, there is some argument regarding the exact orbitals involved in these crossings as well as concerning the role of pairing and/or octupole correlations^{6,7,11,32}. The general conclusion, however, remains that in all yrast SD bands near $A=150$ the variations of $J^{(2)}$ with $\hbar\omega$ reflect the major role played by the few nucleons in high-N orbitals, and the adopted configurations are $\pi 6^2, 3, 4$ for Gd, Tb, and Dy

respectively; $\nu 7^0$ or $\nu 7^1$ for $N=82-85$; $\nu 7^2$ for $N=86$ and $\nu 7^3$ for $N=87$. The number of occupied intruder orbitals varies in some of the excited bands.

Effects due to pairing are, perhaps, even more important in the $A=190$ region where mean-field calculations without pairing^{33,34} give proton and neutron contributions to $J(2)$ which remain essentially constant with $\hbar\omega$. The need to examine the effects of pairing (possibility (ii) in the discussion above) was originally pointed out by Ye et al¹⁹. This is done in the framework of cranked deformed shell model calculations already discussed above^{22,29}. For ^{192}Hg , the relevant high- N intruder orbitals which are occupied in the SD configuration are four ($i_{13/2}$) protons and four ($j_{15/2}$) neutrons, i.e. the SD configuration in ^{192}Hg can be labelled ($\pi 6^4 \nu 7^4$). Figure 3a compares the calculated dynamic moment of inertia with the data. In the calculations, pairing correlations were treated self-consistently by means of the particle number projection procedure²⁹, but the neutron pairing interaction strength was reduced. The rise in the calculated $J(2)$ can be ascribed to the combined gradual alignment of a pair of $N=6$ ($i_{13/2}$) protons and of a pair of $N=7$ ($j_{15/2}$) neutrons within the frequency range under consideration. The data are reproduced rather well. The calculations with pairing have also been very successful in reproducing the other SD bands of this region (see ref. 20-23, for example).

It is worth pointing out that the calculations are able not only to propose configurations for the yrast and excited SD bands, but also to account for details such as signature splitting between bands or relative changes in $J(2)$: this is discussed in detail in refs. 5 and 35. As an illustration of the power of the calculations we discuss here a detailed comparison between the moments of inertia of ^{193}Tl and $^{191,192}\text{Hg}$ (see fig. 4). The occupation of the third $i_{13/2}$ orbital in ^{193}Tl ($\pi 6^3$) results in an increase in the value of $J(2)$ with respect to ^{192}Hg at the lowest frequencies. In both ^{191}Hg and ^{193}Tl , $J(2)$ is essentially constant at the lowest frequencies before exhibiting the characteristic rise described above. This feature is also present in the calculations and is proposed to be a signature for the occupation of these high- j intruder orbitals by a single nucleon²³. In the ^{191}Hg band, the alignment of the $j_{15/2}$ neutron is blocked and the rise in $J(2)$ is attributed to the alignment of the $i_{13/2}$ protons²⁰ while in ^{193}Tl the opposite situation occurs. The fact that the rise in $J(2)$ with $\hbar\omega$ is very similar in both cases implies that neutron and proton alignments have contributions of comparable magnitude. Furthermore, the rise of $J(2)$ in ^{193}Tl starts at lower frequency than that in ^{191}Hg . This suggests that the neutrons align at somewhat lower frequency than the protons, in agreement with the calculations.

Fig. 4. Comparison between the dynamic moments of inertia $J(2)$ measured in the SD of ^{193}Tl , ^{192}Hg and ^{191}Hg (yrast SD band).

From the discussion above, it can be concluded that a good description of the SD bands within the framework of cranked shell model calculations with pairing can be achieved. Three points need, however, to be emphasized. First, the transition energies in some of the SD bands in both the $A=150$ and $A=190$ regions are surprisingly close to those of bands in neighboring nuclei and several bands near $A=190$ can be related to $^{192}\text{Hg}^{36}$. This is discussed in section 4. Second, the inclusion of pairing is crucial for reproducing the data and, in particular, the smooth increase of $J^{(2)}$ with $\hbar\omega$ near $A=190$. In the proton system, pairing is reduced by the presence of the $Z=80$ shell closure. As was shown in refs. 22 and 31, the calculations require that the neutron pairing be reduced as well if one wants to reproduce the similarities in the behavior of $J^{(2)}$ with $\hbar\omega$ observed in all nuclei in this region. Reduced pairing is to be expected on the basis of general arguments. Pairing is sensitive to the overlap between orbitals of interest. At the very large deformations being considered here, states originating from different shells approach the Fermi level, and these states will only be very weakly coupled through the pairing interaction. Moreover, the coupling between the all important unique-parity levels (i.e. the various components of the high- N intruders) is also severely reduced because of their sizable energy splitting at large deformation. Third, it has been suggested that other effects may play an important role as well. Some pairs of orbitals such as the $i_{13/2}$ - $f_{7/2}$ and the $j_{15/2}$ - $g_{9/2}$ orbitals, which are responsible for strong octupole correlations in light actinide nuclei, also appear close to the Fermi level in SD configurations around ^{152}Dy and ^{192}Hg . Several recent calculations^{21,37-39} have indicated that for many SD nuclei the minima in the total energy surfaces exhibit considerable octupole softness which is expected to persist even at the highest spins. Octupole correlations are also expected to reduce single-particle alignments, increase band interactions, and modify the deexcitation pattern of the SD states because of enhanced $B(E1)$ rates. Most of the anticipated effects remain to be observed experimentally. However, first evidence for strong mixing of quasiparticle excitations with octupole vibrations may have been seen in $^{193}\text{Hg}^{21}$ where two of the four SD bands are characterized by $J^{(2)}$ moments of inertia strikingly different from those of all other SD bands in this region (see fig. 2). Furthermore, there is indirect experimental evidence for enhanced $E1$ transitions linking one of the irregular bands with the yrast SD. These observations, together with the reduced alignments observed and the strong interaction between the crossing bands, have been interpreted as evidence for strong octupole correlations²¹. In the mass $A=150$ region, one of the proposed explanations for the behavior of one of the SD bands in ^{147}Gd invokes collective octupole excitations⁷ as well, but other interpretations are also possible¹¹.

It has been suggested recently⁴⁰ that the residual n-p interaction may also play a role in SD nuclei. Such an interaction is expected to be strong in situations where protons and neutrons occupy rotationally aligned high- N intruder orbitals with large spatial overlap, such as the $\pi i_{13/2}$ and $\nu j_{15/2}$ orbitals involved in the SD bands of the $A=150$ and 190 regions. Such an interaction is expected⁴⁰ to lower the energy of SD bands based on these specific intruder configurations with respect to other excitations in the SD well. Firm experimental evidence for the importance of this interaction is currently lacking even though it has been invoked to explain the strong feeding of a SD band in $^{142}\text{Eu}^{16}$ (interaction between $N=6$ odd proton and odd neutron) and the smooth rise of $J^{(2)}$ with $\hbar\omega$ in the lighter Hg isotopes¹⁷ (interaction between 4 $N=6$ protons and 4 $N=7$ neutrons). The latter is illustrated in fig. 5 where the latest data on the ^{192}Hg SD band are presented. From an analysis of an enlarged set of coincidence data it has been possible to extend the SD band by 2, and possibly 3 transitions⁴¹. The $J^{(2)}$ values keep rising with $\hbar\omega$, in contrast with the expectations based on cranked shell model

Fig. 5. Same as figure 3(a), but with the new data points at $\hbar\omega$ added (*). The figure illustrates that while the calculations predict that $J(2)$ will decrease at the highest frequencies, the data keep rising.

calculations, and the agreement between experiment and theory is certainly not as satisfactory as one was led to believe from fig. 3a. The reason for the continued rise is not clear yet, but it is possible that some of the effects discussed above may account for this feature. Clearly, more work on the subject will be necessary.

"IDENTICAL" BANDS

The discovery of multiple SD bands within a single nucleus has made it possible to investigate the microscopic structure of both the ground and excited states in the second well. However, a greater impetus for studies of excited bands has been the discovery that several pairs of bands have almost identical transition energies. The first reported⁴² cases consisted of the pairs ($^{151}\text{Tb}^*$, ^{152}Dy) and ($^{150}\text{Gd}^*$, ^{151}Tb) - the * denotes an excited SD band. Later, another similar pair ($^{149}\text{Gd}^*$, ^{150}Tb) was found⁹ (the notation $^{149}\text{Gd}^{**}$ is used in ref. 9 as it is suggested that the second excited SD band in ^{149}Gd is involved). This is illustrated in fig. 6 where the difference between "identical" transitions energies ΔE_γ is plotted versus the transition energy. It can be seen that, on average, the deviation is less than 1 keV for the first pair and only slightly larger for the other two. This implies that transition energies are equal to better than 3 parts in 1000. This is a rather surprising equality: γ -ray energies should scale with the moment of inertia J , which is proportional to $A^{5/3}$ ($J \sim MR^2$), so that adjacent mass nuclei would have energies different by ~ 14 keV. Furthermore, the spins of corresponding transitions in each pair necessarily differ by $1/2\hbar$, leading to differences in E_γ of ~ 13 keV. For ($A-1^*$, A) pairs, with A even, these differences would reinforce each other. A word of caution is in order since it is assumed that each pair of transitions being compared has the appropriate spins ($I+1/2, I$), but the spins of the SD bands have not been measured. Since the spacing between consecutive transitions in each band is ~ 50 keV, the maximum difference in energy in a pair of bands is ~ 25 keV if no spin correlation is involved. However, with three cases and not just an isolated one, it is unlikely that these degeneracies are accidental. Furthermore, in all three cases the excited ($A-1$)^{*} SD band is proposed to be characterized by a hole in the same specific orbital (see below).

Fig. 6. Differences in the γ -ray energies ΔE_γ between the SD bands in (a) ($^{151}\text{Tb}^*$, ^{152}Dy), (b) ($^{150}\text{Gd}^*$, ^{151}Tb) and (c) ($^{149}\text{Gd}^*$, ^{150}Tb).

A related case of identical transition energies occurs in ^{153}Dy - the first case where excited SD bands were reported¹⁴. Here, two excited bands have been interpreted as signature partners and the averages of the transition energies in the partners reproduce the γ -ray energies in ^{152}Dy within 1-3 keV. Finally, the two SD bands of ^{147}Gd have been related to the yrast SD bands of ^{146}Gd and ^{148}Gd respectively, although the average ΔE_γ are somewhat larger in this case (~ 5 keV)⁷. In the case of ^{147}Gd , another relation applies as well: one of the bands has γ -ray energies following closely (1-4 keV) the average of two successive transition energies in ^{148}Gd , while the other band shows the same property when compared with the SD band of ^{146}Gd .

The current interpretation⁴³ of these observations is done within the framework of the strong coupling limit of the particle-rotor model in which one or more particles are coupled to a rotating deformed core and follow the rotation adiabatically. In the strong coupling limit, transition energies in an odd nucleus, relative to those in an even-even core obey simple relations (here the moments of inertia for all cases are assumed to be identical). When $K \neq 1/2$, the following relation applies:

$$1/2 [E_\gamma (R+1/2) + E_\gamma (R-1/2)]_{\text{odd}} = E_\gamma (R)_{\text{even}} \quad (1)$$

This strong coupling relation provides a straightforward explanation for the ($^{153}\text{Dy}^*$, ^{152}Dy) pair. The two excited bands in ^{153}Dy have been interpreted¹⁴ as a $^{152}\text{Dy} \nu [514] 9/2$ structure with no signature splitting for which $K \neq 1/2$ and the relation above applies. For a $K=1/2$ band, the transition energies in the odd-nucleus are affected by the decoupling parameter, a , and obey the relation:

$$E_{\gamma} = \frac{\hbar^2}{2J} [4I-2 + 2(-1)^{I+1/2} a \delta_{K,1/2}] \quad (2)$$

Transitions from both signatures form degenerate doublets, with the $a=1$ case giving energies identical to those of the core, while the $a=-1$ case has energies mid-way between those of adjacent transitions in the core. The three pairs $(A-1^*, A)$ where identical energies have been observed can be interpreted as a case where $a=1$. In each case, the $(A-1)^*$ configuration is $\Lambda \pi ([301]1/2)^{-1}$. If the decoupling parameter a is calculated from the Nilsson wave function of the $[301]1/2$ orbital, a value of 0.85 is obtained⁴³ very close to, but not exactly 1. On the other hand, for a $[\text{Nn}_3 \Lambda] \Omega$ orbital, the decoupling parameter can be calculated from the asymptotic quantum numbers, by $a = (-1)^{\tilde{N}} \delta_{\Lambda,0}$, which would result in $a=0$ for the $[301]1/2$ orbital. However, if one employed a different coupling scheme in terms of pseudo-spin, the appropriate quantum numbers are $[200]1/2$, and $a=1$ ⁴³, hereby providing a natural explanation for the identical energies of the three pairs. In the pseudo-spin scheme⁴⁴, the natural parity orbitals form a pseudo-oscillator spectrum, labelled by the pseudo-asymptotic quantum numbers $\tilde{N}=N-1$, $\tilde{n}_z=n_z$. The pseudo-orbital angular momentum of the valence particles is strongly coupled to the core forming the total pseudo-orbital angular momentum, and the pseudo-spins are then added to form the total angular momentum $I=R+\tilde{S}$. The pseudo-Coriolis interaction is then expected to align the pseudo-spin with the total angular momentum⁴⁴. In the pseudo-asymptotic limit, the decoupling parameter has the value $a = (-1)^{\tilde{N}} \delta_{\Lambda,0}$, and $a=1$ follows for the orbital under discussion here.

It must be stressed again that the explanation of identical energies presented here follows only if the moments of inertia for odd and even nuclei are identical. It still is a puzzle why the moments of inertia J for adjacent nuclei appear to be constant to within $\sim 0.2\%$. Since J depends on several factors (mass, deformation, polarization effects, alignment and pairing), the equality in J is very striking and leads one to wonder about the possibility of a fundamental explanation. The standard models are unable to reproduce transition energies with an accuracy of ~ 1 keV. We note that only a few identical bands are observed among the many SD bands in this region and that three of these pairs of bands involve a common orbital. This suggests that the phenomenon is associated with only a few specific orbitals. Ragnarsson⁴⁵ has used a simple harmonic oscillator model to show that for particles or holes in certain orbitals there can be cancellation among the different terms contributing to changes in J . He has been able to reproduce the "identical" energies observed in $(^{152}\text{Dy}, ^{153}\text{Dy}^*)$, where the orbital occupied in $^{153}\text{Dy}^*$ is either $\nu[402]5/2$ or $\nu[514]9/2$. These orbitals slope upward with increasing β_2 - so-called oblate orbitals - so that a particle here would tend to decrease the deformation of the $(A+1)$ nucleus, compensating the increase in J due to the larger mass. Agreement for other cases calculated by Ragnarsson, including that involving the $\pi[301]1/2$ hole (responsible for the three pairs of bands with identical energies) is not as satisfactory, suggesting that other effects, such as changes in pairing, should be included.

There are even more examples of identical SD bands in the $A=190$ region³⁶. However, two features distinguish the bands in this region from those near $A=150$: (a) many of the bands occur in pairs separated by two mass units, and (b) a large number of bands can be related to the SD band in ^{192}Hg , which appears to serve as a doubly-magic core. The proposed configurations for these SD bands are characterized by $K \neq 1/2$ ^{4,35}. Within the strong coupling limit, relation (1) should apply and can account for the observations³⁵. However, there is again the requirement of equal

moments of inertia in all nuclei. Another way of relating the energies of different bands to those of a reference, ^{192}Hg , has been proposed by Stephens³⁶, using the quantity $\Delta i = 2\Delta E_\gamma / \Delta E_\gamma^{\text{ref}}$, where $\Delta E_\gamma = E_\gamma - E_\gamma^{\text{ref}}$ is obtained by subtracting the transition energy E_γ in a band of interest from the closest transition energy in ^{192}Hg (E_γ^{ref}), and $\Delta E_\gamma^{\text{ref}}$ is calculated as the energy difference between the two closest transitions in the reference. Δi has been called incremental alignment³⁶, but is not necessarily related to any physical alignment. In the strong coupling limit, $\Delta i = \pm 1/2$ for an odd nucleus referred to an even core. For even nuclei, bands with the same or different signatures have $\Delta i = 0$ or 1, respectively. Plots of Δi are shown in fig. 7, which illustrates that the SD bands of the A=190 region can be classified in two families. When additional particles (holes) with respect to ^{192}Hg occupy lower K members of the high-N intruder orbitals, values of Δi scatter significantly (fig. 7a). This is not surprising since particles in these intruder orbitals tend to both increase deformation and align with rotation, thus making the strong coupling scheme inappropriate. In contrast, when the orbitals involved do not show much variation with $\hbar\omega$, i.e. when there is little alignment, Δi values fall close to the limits of 0, $\pm 1/2$, ± 1 , which are expected in the strong coupling limit (fig. 7b).

Stephens et al.^{36,46} suggested that many of the cases which exhibit $\Delta i = 0$, $\pm 1/2$, or ± 1 also have integer alignment differences with respect to the core, which they refer to as quantized alignment. While the strong coupling limit corresponds to a zero alignment difference, they suggest alignments (with respect to ^{192}Hg) of 1h in the excited SD bands of ^{194}Hg , for example, which are then attributed to pseudo-spin alignment.

Fig. 7. Incremental alignment Δi as a function of rotational frequency for SD bands in $^{189-194}\text{Hg}$ and $^{194,196}\text{Pb}$ with ^{192}Hg as a reference. As discussed in the text, the data are grouped [(a) and (b)] in order to illustrate the existence of two families; in (b) Δi clusters around integer and half-integer values. The data on SD bands in the Tl isotopes have been omitted for clarity; these are discussed in ref. 24.

An alignment of $1\hbar$ in ^{194}Hg is not easy to understand. However, a word of caution is in order. Whereas extraction of Δi does not require knowledge of spin, determination of alignment does. So far the spins of SD band members have not been assigned using the conventional, tested techniques of γ -ray spectroscopy. Methods to infer the spin have been suggested^{47,48}. At present, it is not established whether these methods give the exact spin or have uncertainties of at least $1\hbar$ ⁴⁹. Thus, until spins can be assigned firmly, one cannot be certain whether the alignments have the putative value of $1\hbar$ ³⁶. It is quite possible that the strong coupling limit of the particle rotor model applies in the $A=190$ region as well as in the $A=150$ region. The caveat then remains that in this region the moments of inertia of neighboring nuclei have to be identical as well, a feature that present mean-field calculations cannot reproduce.

FEEDING AND DECAY OF SUPERDEFORMED STATES

Within the limited space available here, it would be impossible to review these subjects in their entirety. However, some very recent results should be discussed because they shed some new light on matters which have proven to be among the more difficult ones to study experimentally. Figure 8 presents very recent data⁵⁰ on the intensity with which the SD band in ^{152}Dy is populated in ^{32}S -, ^{48}Ca - and ^{82}Se -induced reactions. The SD intensity is given as a percentage of the total ^{152}Dy production and is plotted as a function of excitation energy in the compound nucleus. These data point towards the presence of a rather pronounced entrance-channel effect, i.e. the population of the SD band is enhanced by $\sim 30\%$ in the more symmetric fusion reaction. Similar results have also been obtained for the ^{149}Gd SD nucleus⁵⁰. It was proposed several years ago^{51,52} that entrance-channel effects might favor the SD shapes since projectiles and targets of essentially identical masses have a shape with an axis ratio close to 2:1 at the point of contact. This idea was originally proposed in attempts to account for the inhibition of neutron emission with respect to statistical model predictions observed in certain (H.I., xn) reactions. The result of fig. 8 may well represent one of the more intriguing examples of the interplay between nuclear structure and reaction dynamics.

Fig. 8. Relative intensity for the feeding of the SD band in ^{152}Dy . The data are from the Liverpool-Strasbourg collaboration⁵⁰.

There is also new information regarding the feeding of the SD states. Important elements affecting the feeding are the level densities of both normal and SD states, the mixing between the two classes of states at moderate excitation energy, the electromagnetic decay rates in the normal and SD minima, as well as the barrier separating the two minima. Schiffer and Herskind⁵³ have performed an extensive series of calculations, which successfully described many of the observed feeding features in ^{152}Dy and which have provided insight into the population mechanism. In particular, it was found to be important that, as the excitation energy increases, the level density for the SD states increases less rapidly than for the normal states. This results in a limited region in excitation energy where the density of SD states is larger than that of normal states. This region corresponds to the highest partial waves and is located beyond the point where the SD band crosses the normal states and becomes yrast. Schiffer and Herskind suggest⁵³ that the entry states for the SD bands originate from this region and that this feature accounts for the "colder" feeding of these bands. From measurements of the fold and sum-energy distributions in coincidence with transitions in the SD band and in the yrast cascade of ^{192}Hg , there is now experimental evidence⁵⁴ for the decay picture outlined above. Figure 9 compares the entry distributions for the feeding of the SD and the yrast states in ^{192}Hg , and it is clear that the SD band is fed from the higher partial waves, in a rather limited region in excitation energy and spin. It should be pointed out that it is important that the entire distribution has been measured rather than the average quantities which only give entry points.

Fig. 9. Population of entry states in ^{192}Hg measured in coincidence with the yrast transitions (a) and with the SD transitions (b). The two lines in the figure represent the "normal" and the SD yrast lines. The excitation of the latter at spin 0 was assumed to be 4.8 MeV.

While most of the SD bands have been found to be in coincidence with transitions between low-spin yrast states in the same nucleus, none of the transitions linking the SD bands with the yrast and near-yrast states have been identified. It is likely that many decay paths share the intensity and that the decay-out process is statistical in nature. Transitions between coexisting low-spin states of moderate prolate and oblate deformations in $A \sim 190$ Pt and Hg nuclei have been found⁵⁵ to exhibit unusually strong E0 admixtures. Since the known SD bands of Hg nuclei in this region extend to rather low spin ($I \sim 10\hbar$), it has been suggested recently⁵⁵ that E0 transitions could play an important role in the decay out of the SD states. If this were so, γ -ray techniques alone might be inadequate for studying the decay out of the SD bands, and electron measurements would also be needed. A limit on any E0 decay out of a SD band has been obtained recently⁵⁶ from a measurement of X-ray yields which relies on the fact that the presence of strong E0 decay is accompanied by intense K-shell ionization. Thus, by looking at the K X-ray yield in coincidence with SD transitions, one can probe for the presence of highly converted transitions. The K X-ray yields associated with the SD band in ^{192}Hg have been measured⁵⁶. The measured value was compared with that expected from the K-conversion of known discrete lines in the band and of transitions following the deexcitation into the yrast states. The possibility of strong E0 decay out of the SD band can now be ruled out: an upper limit of 10% was found. The strength of the E0 decay between states of different shapes is governed both by the change in deformation and the mixing between initial and final states. Although there is a very large shape change in the present case, these results indicate that there is very little mixing between the SD and yrast states. Thus, the situation appears to be very similar to that found in the actinide nuclei where E0 decay between the 0^+ state in the second minimum and the 0^+ ground state was found to occur with low probability⁵⁷.

CONCLUSIONS

Here, I have attempted to review some of the many facets of SD nuclei. In the $A=150$ and 190 regions, it has been possible to perform spectroscopic studies in the SD secondary well of surprising detail and both "ground" and excited bands have been observed. The most unexpected discovery so far is that a number of the excited bands have energies identical to those of the lowest SD bands in adjacent nuclei. The degeneracies of better than one part in 500 require that the moments of inertia be identical and also that the strong coupling limit applies, both to a remarkable degree. It is not clear whether this is a result of an accident or is a consequence of a symmetry which has yet to be identified. Although there has been much progress in this area of research, many questions remain and, indeed, have actually been raised by the new discoveries. Certainly, a major challenge is to determine the excitation energies and spins of SD levels since there is not a single SD band in the $A=150$ and 190 regions for which these properties are known. The limits of the regions of superdeformation in the periodic table need to be established. The known excited SD bands are believed to correspond to particle or quasiparticle excitations, but the collective modes associated with states of large deformation, e.g. the beta, gamma or octupole vibrations have yet to be found. If the deformation is stiff with respect to quadrupole distortion, the beta vibrations may lie at high excitation energies, but soft octupole modes may exist at lower energies, possibly giving rise to exotic bending modes. Further studies are also necessary to shed more light on the cause of identical bands. At present experiments are limited by the detection capabilities of current γ -ray detectors. The next generation detector arrays currently under construction (EUROGAM in Europe and GAMMASPHERE in the USA) will improve

the detection sensitivity by about two orders of magnitude and provide answers to the questions raised above. Many fascinating discoveries about superdeformation--and about nuclear structure in general--lie ahead.

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