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SPIN ALIGNMENT IN SUPERDEFORMED ROTATIONAL BANDS*

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Many superdeformed bands in different nuclei are found to have virtually identical moments of inertia and alignments that differ from each other by quantized amounts -- multiples of 1/2ħ. Psuedo spins represent the only source of quantized alignment that has been thought of to date. Additional puzzles in these bands are the absence of other larger effects on the moments of inertia, and a surprising number of alignments of 1ħ.

1. INTRODUCTION

It is now clear that there are striking regularities in the rotational bands observed in superdeformed nuclei in both the mass-150 and mass-190 regions. Evidence for this first appeared last fall[1-4] at the Copenhagen Workshop on the Nucleus at High Spin and has accumulated steadily since then, as has been apparent in the talks today. The surprising feature is that rotational bands, or regions of bands, in different superdeformed nuclei have been found to have identical (or equivalent -- i.e., identical averages of) transition energies within one or two keV -- much more similar than expected. In this talk I would first like to convince you that this behavior can be characterized as an alignment effect where the unexpected aspect of the behavior is that the alignment is quantized in units of 1/2 or 1ħ. In the second section, the data supporting this characterization will be examined, and in the third section some possible reasons why nuclei might behave in this way will be explored.

The argument that this is an alignment effect is illustrated in Fig. 1. This is a plot of spin *versus* gamma-ray energy (or rotational frequency, which is $E_\gamma/2$). The five possible spin values from I to I+2 are indicated on the ordinate, and by the light horizontal lines in the figure. The solid sloping line represents a (dynamic) moment of inertia, through which the five spins define five possible gamma-ray energies on the abscissa. The separation between the successive gamma-ray energies in the even-even system (I and I+2) is taken to be 40 keV, as is typical for superdeformed bands in nuclei of the mass-190 region, and it is apparent that the intermediate gamma-ray energies are equally spaced subdivisions of this interval. If this moment of inertia were the only one possible, then these five gamma-ray energies would be the only possible ones in this energy region. It would also follow in that case that all gamma-rays of the same energy would connect levels of the same spins.

This last conclusion is not consistent with the data because, for example, the superdeformed bands in ^{152}Dy and ^{151}Tb* have transitions with very nearly the same energies, but these transitions

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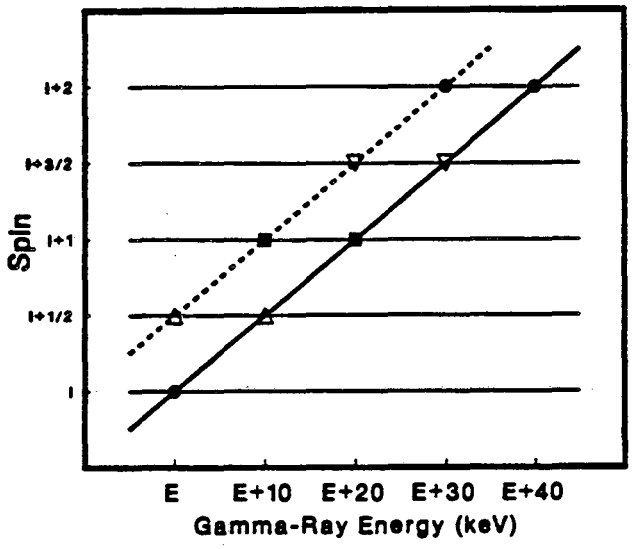

Fig. 1 The relationship between spin and gamma-ray energy for two different alignments.

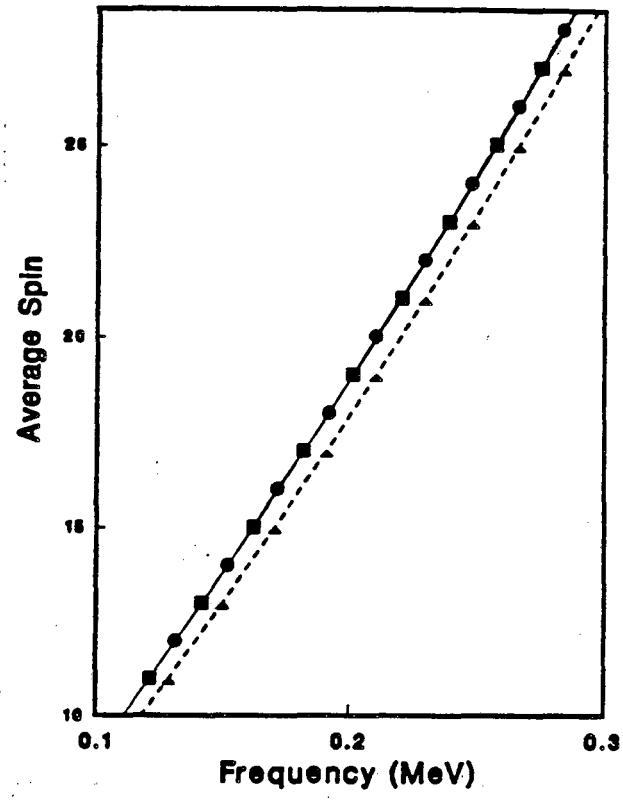

Fig. 2 Spin *vs.* frequency for the two excited bands in ^{194}Hg and the yrast band in ^{192}Hg.

cannot possibly connect levels of the same spin since one nucleus has even mass and the other odd. The dashed line in Fig. 1 represents a second moment of inertia line that provides a solution to this problem; the odd-mass nucleus with spin I+1/2 emits a transition of exactly the same energy as the even-even nucleus with spin I. Since the dashed line is parallel to the solid one, it has the same dynamic moment of inertia and thus the same separation between gamma-ray energies. This kind of situation is familiar from studies of normally deformed nuclei where we would say that the dashed line represents a band with the same moment of inertia but with an alignment of 1/2ħ. Similarily if the dashed line were shifted an equal distance further to the left, we would find that a band with odd spins (I+1) would have transition energies equal to those of the even spin (I) reference band and the alignment would be 1ħ. An excited band in ^{194}Hg compared with the yrast band in ^{192}Hg seems to be just such a case. Such very similar bands can be characterized as having the same moment of inertia but different alignments. In the examples we have discussed the alignments differed by exactly 1/2ħ and 1ħ, i.e. they were "quantized". The rotational bands in many superdeformed nuclei behave in this manner.

Figure 2 shows the data for two excited bands (signature partners) in ^{194}Hg and for the yrast band in ^{192}Hg on a plot like Fig. 1 (except that the abcissa scale is frequency instead of gamma-ray energy). In the higher frequency region the lines for the two nuclei are rather precisely parallel and differ by just 1ħ, as mentioned above. This implies that transitions from the odd spin states in ^{194}Hg (circles) have energies almost identical to those from even spin states in ^{192}Hg. It is also worth

noting that the curve through the data points is quite linear, suggesting a linear interpolation method to find alignments.

The method used to determine alignments[5] is illustrated in Fig. 3. We consider a "new" band in an odd-mass nucleus, one transition from which is indicated by a triangle on Fig. 3, and want its alignment relative to a band in a reference even-even nucleus, indicated by the circles and solid line. The alignment can be obtained by comparing the transition in the new band with the transition in the reference nucleus that is closest in energy. The alignment is labeled i in Fig. 3, and can be seen to be composed of two parts, the real difference in spin between the two emitting states ΔI and the interpolated "incremental alignment" Δi that represents the spin difference associated with the difference in gamma-ray energy, ΔE_γ, between the transition in the new band and that in the reference band. Using the difference in gamma-ray energy between the closest two transitions in the reference nucleus, ΔE_γ^0, which is associated with a spin change of $2\hbar$, the incremental alignment becomes: $\Delta i = 2\Delta E_\gamma/\Delta E_\gamma^0$. This incremental alignment does not require any knowledge of the spins, and can already indicate whether the alignment is quantized or not, and if so whether it is integer or half integer.

2. DATA

We will concentrate mainly on the data for superdeformed bands of the mass-190 region, though the methods apply equally well to the mass-150 region, and some data from that region will be considered. First the three bands shown in Fig. 2 will be examined in more detail. The similarity of the transition energies in the upper part of the ^{194}Hg bands to those in ^{192}Hg is illustrated in Fig. 4, where the circles are the differences between the transition energies from the odd-spin band members and those from the ^{192}Hg reference band and the squares are the differences between the transition energies from the even-spin band members in ^{194}Hg and the

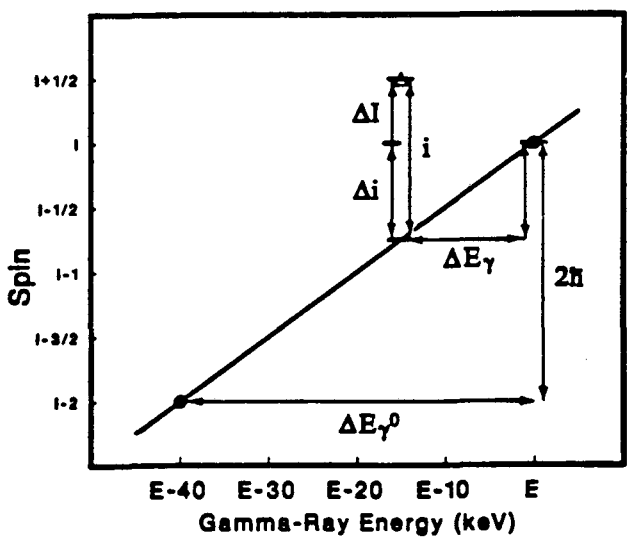

Fig. 3 Diagram to illustrate the alignment, i and the incremental alignment, Δi.

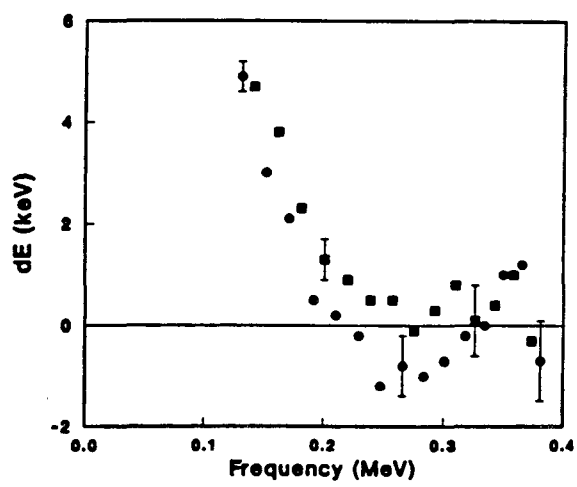

Fig. 4 Differences in transition energies between states in ^{194}Hg and those in ^{192}Hg.

average (midpoint) values of adjacent transition energies from ^{192}Hg. The average agreement of the last 10 transitions in both bands with those of ^{192}Hg is about 0.5 keV, which is within the experimental uncertainty. This region of close similarity occurs after relatively large differences in the lower-frequency region of the bands.

The incremental alignments derived from these data are shown in Fig. 5. The near-zero incremental alignment for the odd-spin sequence in ^{194}Hg reflects the fact that the transition energies are very nearly equal to those of the reference; whereas, 1ħ for the even-spin sequence indicates that these transitions are half-way between the ^{192}Hg transitions (the full separation in ^{192}Hg corresponds to 2ħ). Note that +1 and -1 are identical, and just reflect a different choice of reference transition and the lines at ±0.5 correspond to the other possible quantized alignments. Since real spins are quantized and thus their differences must be, it follows that whenever the alignment is quantized the incremental alignment must also be. Plots like Fig. 5 provide a simple means to examine data for these quantized alignment effects. We will return to the increasing alignments seen at the lower frequencies in Fig. 5.

Another important property of these bands is their spin. In previous[6-8] publications we have developed a method to determine the spins in these Hg superdeformed bands based on the relative energy spacings. In this method the $J^{(2)}$ moment of inertia ($J^{(2)} \equiv dI/d\omega \approx 4/\Delta E_\gamma$) is fit by a power series expansion in ω^2, which is then integrated to give the spin. Without any fit to, or requirement on, the spin values of the ^{194}Hg bands discussed above, the rms deviation of the calculated initial spins from integer values is 0.05ħ. Since the spins in even-mass nuclei must be integers, this provides rather convincing evidence that they are correctly determined -- any missing alignment would (accidentally) have to be an integer to this accuracy.

In Fig. 6 these spins are added to the incremental alignments to generate the (total) alignments of the bands in ^{194}Hg relative to the one in ^{192}Hg. It is apparent that the two bands in ^{194}Hg form

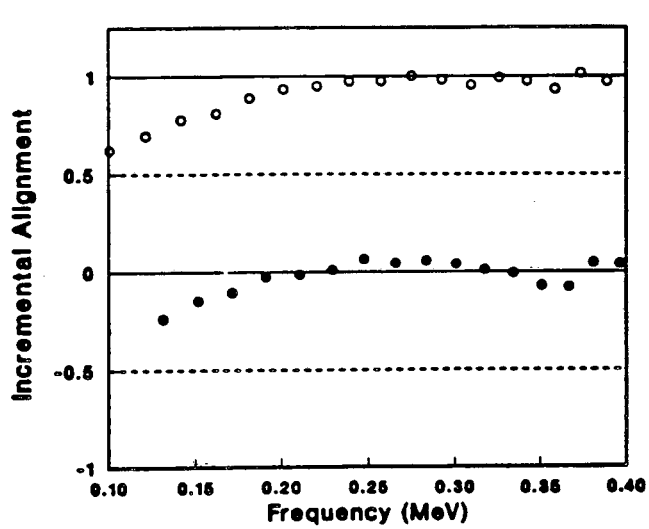

Fig. 5 Incremental alignment for the two excited ^{194}Hg bands relative to ^{192}Hg.

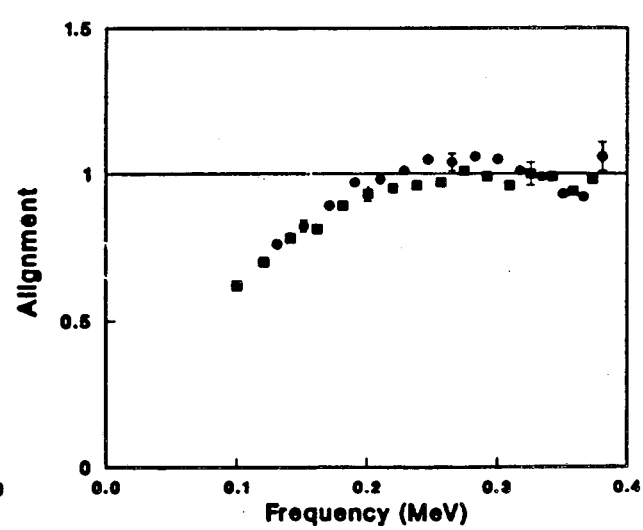

Fig. 6 Total alignment for the two bands in Fig. 5 relative to the yrast band of ^{192}Hg.

a common sequence whose aligned angular momentum, relative to ^{192}Hg, starts out as about 0.6ħ, but becomes (1.00 ± 0.04)ħ for frequencies above 0.2 MeV. Before discussing this behavior we will look at the data from other nuclei in this region.

A large number of new superdeformed bands have recently been found in the mass-190 region (^{189}Hg[9], ^{190}Hg[10], ^{191}Hg[11,12], ^{192}Hg[6,13], ^{193}Hg[14,15], ^{194}Hg[16,17], ^{193}Tl[9], ^{194}Tl[18], ^{194}Pb[19, 20], and ^{196}Pb[19]. Many of these bands are related to the band in ^{192}Hg as were the bands in ^{194}Hg discussed above. It is not surprising that some bands in this region are not members of the ^{192}Hg "family". A number of different orbitals will be available to the nucleons and certainly some of these will not have the special properties required to produce the very similar transition energies. Indeed, it is surprising that out of the eighteen known bands in this region (including excited bands and counting each signature as a separate band), nine do belong to the ^{192}Hg family. This is a much larger family than any found so far in the mass-150 region.

The superdeformed band in ^{192}Hg seems to be central to these nine bands, and we will use it as the reference band. This nucleus may represent a double-closed shell for superdeformed shapes, or its central position may be only apparent. While the zero-alignment position does depend on which of these bands is taken as reference, the main conclusions do not. The incremental alignments of these eight bands are plotted in Fig. 7, where we have also included the excited (*) superdeformed bands, ^{153}Dy*[21] and ^{151}Tb*[1], referred to the band in ^{152}Dy[22]. It is apparent that the data cluster around the lines drawn at ± 1, ± 0.5, and 0, although almost all the values for bands in the mass-190 region decrease below frequencies of about 0.2 MeV, and the values for one ^{191}Hg* band decrease at the highest frequencies. Since aligned angular momentum is not expected to be quantized, this is a very puzzling result.

One can draw some interesting conclusions from these incremental alignments without any additional knowledge about the angular momentum. All the odd-mass nuclei in Fig. 7 lie on dashed lines (corresponding to integer alignments) except for ^{151}Tb*, and all the even-mass nuclei

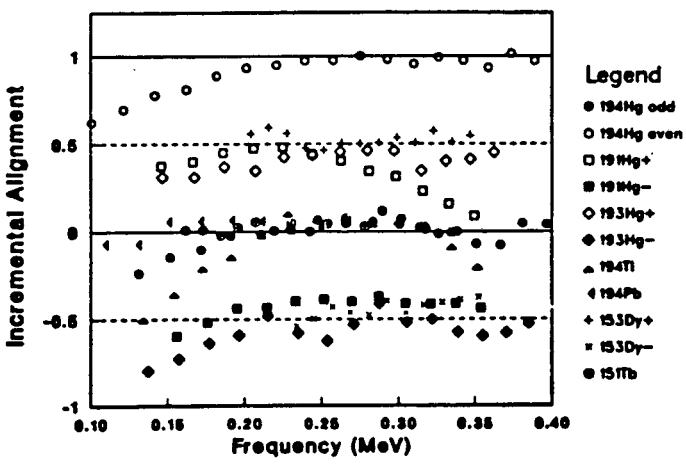

Fig. 7 Incremental alignments for the bands related to ^{192}Hg and ^{152}Dy.

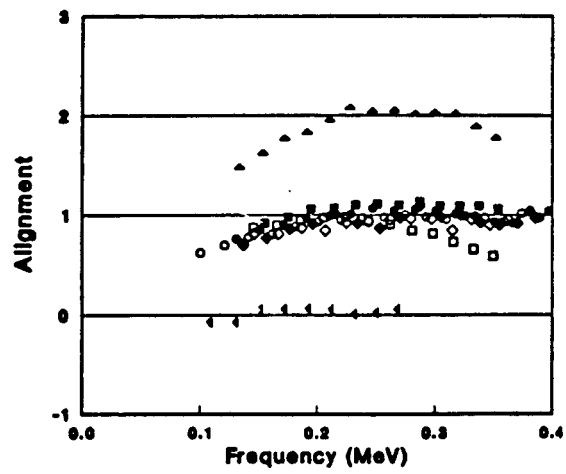

Fig. 8 Total alignments for the bands related to ^{192}Hg.

lie on solid lines (also corresponding to integer alignments), so that all the alignments, except that for that of $^{151}Tb^*$, must be very close to integers. This result is completely independent of any spin determinations, but can be extended in the mass-190 region where the spins can be rather reliably determined.

We can use the spins, together with the incremental alignments, to get (total) alignments relative to ^{192}Hg. The results are shown in Fig. 8. It is impressive that after a common initial rise the alignments do, indeed, all reach integer values. The initial rise represents the onset of the alignment with rotational frequency and is correspondingly larger for the ^{194}Tl case where the alignment is twice as large and absent for the ^{194}Pb case where the alignment is zero. These differences in the rise are not due to the spin assignments, as they are already clearly visible in Fig. 7. This region of increasing alignment must be due to the increasing Coriolis effects, and represents the generation of the quantized alignment as a function of frequency. Thus the integer alignments are established only above frequencies of about 0.2 MeV. At higher frequencies, the decrease in alignment for the +1/2 signature band of ^{191}Hg is the only obvious deviation from integer alignments in these bands, and it has been associated[12] with the [642]3/2 orbital, which is a member of a pseudo-spin doublet but also has some signature splitting.

The incremental alignments of the other nine bands in the Hg region are shown in Fig. 9. The four downsloping bands (losing alignment relative to ^{192}Hg) are $^{189,190,191}Hg$ and ^{196}Pb, all of which can be qualitatively understood on the basis of the orbitals likely to be involved, though we will not discuss those assignments here. The ^{194}Hg(yrast) band is close to zero alignment at the lower frequencies, but is the only band with increasing alignment at the highest frequencies. One of the ^{193}Tl bands has an alignment that approaches 3/2, and should probably be included with the "regular" bands in Fig. 8. Its signature partner has a decreasing alignment at the higher frequencies, similar to $^{191}Hg^*$. The band, $^{194}Tl(2)$ is very similar in alignment to one of the bands in ^{193}Tl; whereas, the other ^{194}Tl band is regular (Fig. 8). Finally there is the upbending band in ^{193}Hg. This is probably a band that has also been observed by the Liverpool group, who will

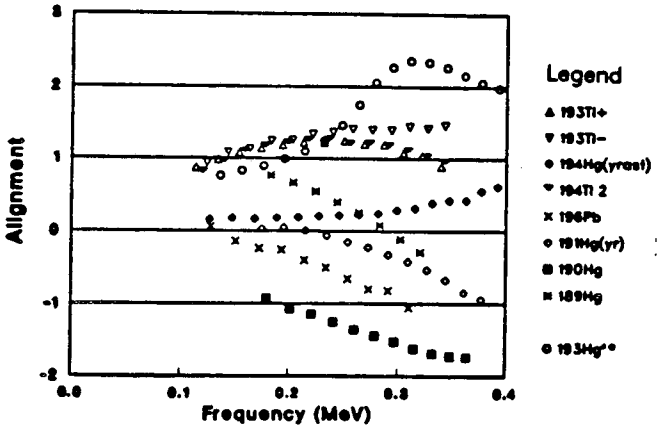

Fig. 9 Total alignments for the other bands in the mass-190 region relative to ^{192}Hg.

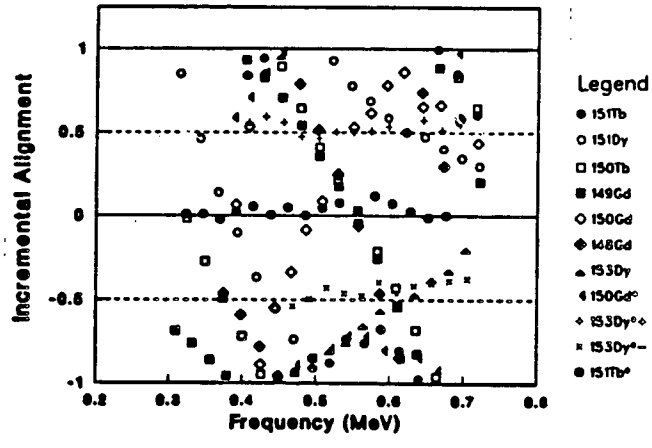

Fig. 10 Incremental alignments for all the bands in the mass-150 region relative to ^{152}Dy.

discuss it later today. We will not say more about it here.

For comparison, the incremental alignments of all the known bands in the mass-150 region relative to the band in ^{152}Dy are shown in Fig. 10 (references for these data are not included here). Except for the three bands previously shown in Fig. 7, these bands show no particular regularity relative to ^{152}Dy. It should be emphasized that this is a sensitive way of looking at these bands and this kind of irregularity is what should be expected, both in this region and the mass-190 region. It is the very regular bands, like ^{151}Tb* and ^{153}Dy* in Fig. 10 that require a special explanation. One difference between the two superdeformed regions is the presence of a large number (8) of bands all related to ^{192}Hg in the mass-190 region, but several smaller groups of related bands in the mass-150 region. This suggests that there may be only one (or very few) orbital with these special properties in the mass-150 region but several such orbitals in the mass-190 region. It should be pointed out that in both regions the "regular" bands sometimes do not fall on the quantized lines within the experimental uncertainty, and furthermore some of the "irregular" bands in Fig. 9 are not far from these lines. There is probably a continuous range of "similarity", though with a rather strong peak at "identical" (within present experimental uncertainty).

There are at least three puzzling properties observed in these superdeformed bands of both mass regions. First, the alignments seem to be quantized. Whereas alignments should be able to have any value, Figs. 7-10 show that almost always when the bands are parallel (the alignments constant) the alignments take on integer or half-interger values. It seems quite unlikely that this is accidental. Second, these alignments are not obscured by other effects on the moments of inertia of these superdeformed nuclei. This is quite a different puzzle from that mentioned first. <u>After</u> these alignments are generated, we have to understand why they are not obscured by much larger effects on the moments of inertia caused by changes in pairing, deformation, orbital alignments, mass, etc. We expect each of these other effects to produce changes in the moment of inertia that are considerably larger than the alignment effects considered. Finally, we need to understand why so many alignments in the mass-190 region have the value $1\hbar$. As we shall see, it would be much easier to understand a predominance of alignments of $1/2\hbar$.

3. INTERPRETATION

We will consider first the various symmetries that are used in discussing these superdeformed bands, and define the terminology used here. Figure 11 shows an isolated N = 5 shell using the standard parameters in the modified-harmonic-oscillator model. In a "pure" harmonic-oscillator these levels would all be degenerate at zero deformation and would be an exact representation of the SU(3) symmetry group. However, the energy splittings caused by the spin-orbit ($\boldsymbol{\ell}\cdot\mathbf{s}$) and anharmonicity ($\boldsymbol{\ell}^2$) terms are large -- about 8 MeV, and the SU(3) model has only been useful for very light nuclei, where N (and $\boldsymbol{\ell}$) is small. A better approximation for heavier nuclei is to exclude the intruder ($h_{11/2}$ in this example) and consider the remainder of the shell as a pseudo N = 4 shell, where a "pseudo SU(3) symmetry" would apply if the levels were isolated and degenerate at zero deformation. However, even this pseudo-SU(3) symmetry is split by about 4 MeV due to the $\boldsymbol{\ell}\cdot\mathbf{s}$ and $\boldsymbol{\ell}^2$ (or equivalent) terms. Nevertheless, most of the splitting in this case comes from the $\boldsymbol{\ell}^2$

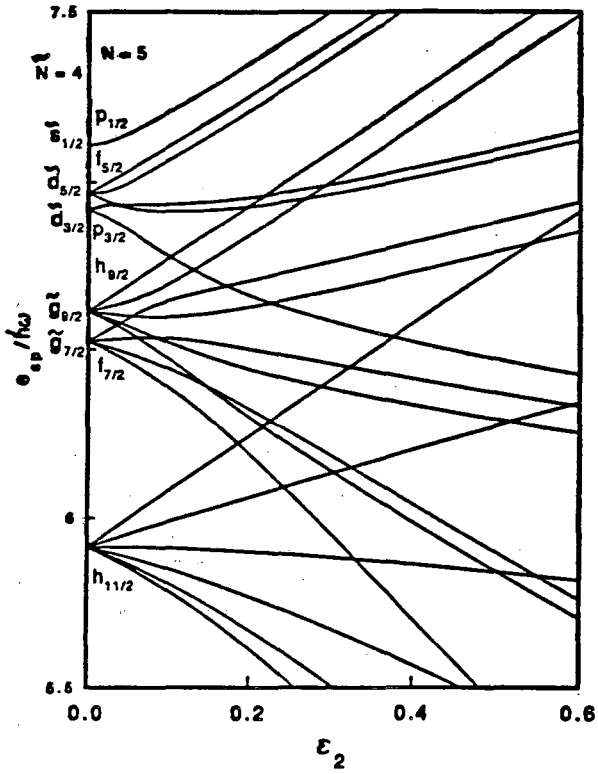

Fig. 11 Levels of the N = 5 shell calculated using the standard Nilsson parameters. Labeling for the pseudo N = 4 shell is also indicated.

term, which does not mix the levels and thus does not destroy the symmetry completely. For example, "pseudo-spin symmetry" would remain if the pseudo spin-orbit interaction really vanished. This would give rise to a two-fold degeneracy of the states, corresponding to the two possible orientations of the pseudo spin. In fact, these are not completely degenerate, but one can see these pseudo-spin doublets in Fig. 11, where the splitting is around 0.5 MeV -- comparable to the rotational frequencies we are considering. Thus, we might expect effects due to this symmetry to show up in these superdeformed nuclei. Of course, there might be other aspects of these symmetries that are important for superdeformed bands, but no others are apparent in Fig. 11.

3.1 Pseudo-spin alignment

The reason for an interest in pseudo-spin symmetry is that it can lead to quantized alignments. The arguments involve Coriolis matrix elements, whose interesting parts for the present purposes are the matrix elements of j_x. For asymptotic wave functions, $Nn_z\Lambda,\Sigma$, the diagonal matrix elements of j_x will be: $\langle Nn_z\text{-}\Lambda,\text{-}1/2 \mid j_x \mid Nn_z\Lambda,1/2\rangle = \delta_{\Lambda,0}$. This is part of the well known asymptotic limit for the decoupling parameter of $\Omega = 1/2$ bands. The value of 1 corresponds to aligning the intrinsic spin with the rotation axis, and gives a quantized alignment -- $1/2\hbar$. This has been used[2] in the mass-150 region for an $\Omega = 1/2$ orbital to account for the quantized alignments. For spin-orbit partners, the essential matrix element reads: $\langle Nn_z\Lambda,\text{-}1/2 \mid j_x \mid Nn_z\Lambda,1/2\rangle = 1$, which again produces alignment of the intrinsic spins when the rotational frequency is comparable with the spin-orbit splitting. For normal spin-orbit partners, this never happens because the spin-orbit splitting is several MeV. However, the same expression holds for pseudo quantum numbers, and in this case the pseudo spin-orbit splitting is only a few hundred keV. Thus for rotational frequencies of this size the pseudo-spins will align, just as they do in the $\Omega = 1/2$ bands. A difference is that there will be an increasing alignment at lower frequencies where the alignment is

as yet incomplete -- much as is observed in Fig. 6 and Fig. 8. Thus all the natural parity orbitals can generate quantized alignments, and so far this is the only way anyone has thought of to produce such alignments.

3.2. Absence of other effects on the moment of inertia

There are at least four effects on the moment of inertia (transition energies) that should be larger than the alignment effects discussed above, and thus should obscure the regularities observed. These are changes in pairing, deformation, orbital alignment, and mass. Each of these will be considered briefly. In some respects pairing is the most puzzling of these. The moments of inertia increase by nearly 50% over the range of observed states, suggesting substantial pairing. Yet from nucleus to nucleus the moment of inertia changes can be only a few parts per thousand. The effect of blocking (or anything else due to adding a nucleon) on the pairing seems to be extremely small, at least insofar as the pairing affects the moment of inertia. This behavior suggests weak pairing, probably only pairing vibrations. For pairing vibrations one supposes the blocking, and perhaps other effects, will be much reduced, but to our knowledge the effects of such pairing on the quasiparticle properties and on the moments of inertia have not been studied.

We have suggested[4] that the effects of deformation and orbital alignment systematically compensate each other in these superdeformed nuclei. This suggestion originates in the very regular behavior of the moment of inertia in pure harmonic-oscillator models (where the assumptions are made that the deformation of the density distribution is the same as that of the potential and that the system is at its equilibrium shape). In such a case the mass dependence of the moment of inertia is very smooth: for an isolated pure harmonic-oscillator shell, one finds the rigid sphere moment of inertia; and for the full pure harmonic-oscillator, the rigid body moment of inertia. In neither case is there any dependence on particular orbitals. Similarly, for the spin dependence of the moment of inertia in the pure harmonic-oscillator limit, one finds the rigid-body value at zero spin (as above) and it does not change as the spin increases, even though the deformation goes eventually to zero and the band terminates. This behavior, despite large changes in deformation, implies strong correlations between the deformation and the orbital alignments that generate the moment of inertia.

It is not difficult to understand the basis for this correlation. Particles in orbits that favor larger deformation also make positive contributions to the moment of inertia. However, the increased equilibrium deformation induced by the occupation of such an orbit causes a counter effect -- increased energy denominators in the (Inglis type) calculation of the moment of inertia, resulting in a negative contribution to the moments of inertia that cancels the positive contribution from the orbit. This cancellation works also for orbits favoring smaller deformations. For pure harmonic oscillator situations these positive and negative contributions to the moment of inertia can *exactly* compensate each other, and while this will not happen in general, the tendency seems likely to remain. This seems to offer a way for the combined effects of deformation changes and orbital alignments to be considerably reduced over *a priori* estimates of their separate contributions.

There is ample evidence in the spectra of normally deformed nuclei for these cancellation effects. For example, Fig. 12 shows the moments of inertia of a number of bands in the rare-earth

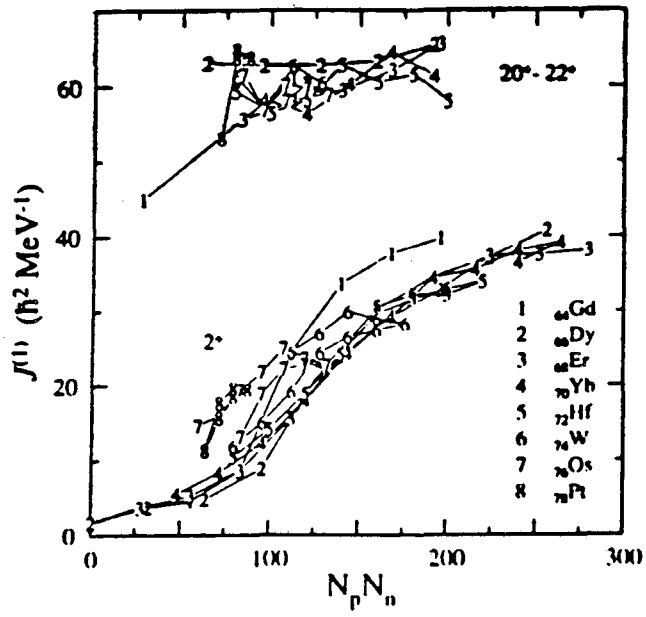

Fig. 12 Moments of inertia for bands in normally deformed rare-earth nuclei. Values are given for spins of two and for spins of 22.

region as a function of the product of the numbers of protons and neutrons in the nucleus[23]. At spins of 20, the variation is very small -- an overall rms deviation of about 5%. Not only are there no very large variations for particular particle numbers, this range of variation is even less than expected for a rigid-body moment of inertia (pure oscillator), which should have an $A^{5/3}$ mass dependence; i.e. about 40% for the range of masses in Fig. 12. This same kind of reduction in the mass dependence is also necessary for the superdeformed bands, since they have variations an order of magnititude smaller than the $A^{5/3}$ values. It is interesting that the anharmonicities in realistic nuclear potentials may systematically cause this reduction of the $A^{5/3}$ mass dependence in the mid-shell region. Both the $\ell \cdot s$ and the ℓ^2 terms lower in energy the high-ℓ orbits that contribute most to the moment of inertia. Thus extra moment of inertia will be generated at the beginning of the shells and insufficient moment of inertia near the end of the shells -- a systematic tendency of the right type to reduce (or even locally reverse) the $A^{5/3}$ mass dependence in both normal and superdeformed nuclei.

There is also evidence in normally deformed nuclei for the harmonic-oscillator behavior of the moment of inertia with spin. Figs. 13 and 14 show the behavior of the moment of inertia in two normally deformed rotational bands as the spin increases. In ^{166}Yb the deformation, as indicated by the B(E2) value, drops nearly a factor of two as the spin increases; whereas, the moment of inertia is quite smooth and nearly constant[24]. Even more dramatic is the ^{158}Er case, where the deformation drops to nearly zero at spin 38 and the band becomes non-collective, during which the moment of inertia is quite smooth and not far from constant[25]. These two cases demonstrate dramatically a remarkable correlation of deformation and orbital alignment effects in generating moments of inertia in normally deformed nuclei.

We have made plausibility arguments that: pairing vibrations might reduce considerably the effects of pairing on the moment of inertia; deformation and orbital alignment effects may tend systematically to compensate each other; and over some mass region the anharmonicities in the nuclear potential may reduce (or even reverse) the rigid-body $A^{5/3}$ mass dependence of the moment

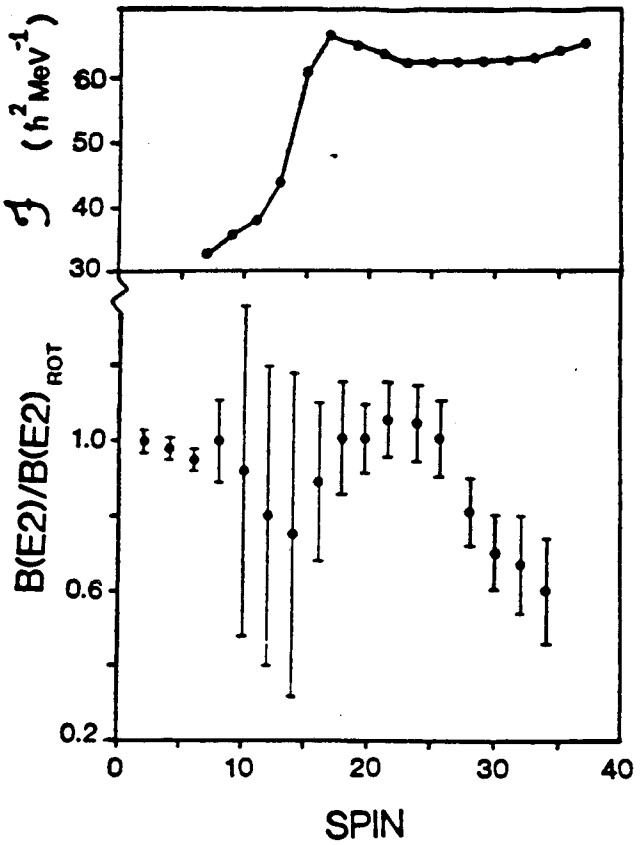

Fig. 13 The moment of inertia and the ratio of B(E2) values *vs.* spin for the band in ^{166}Yb.

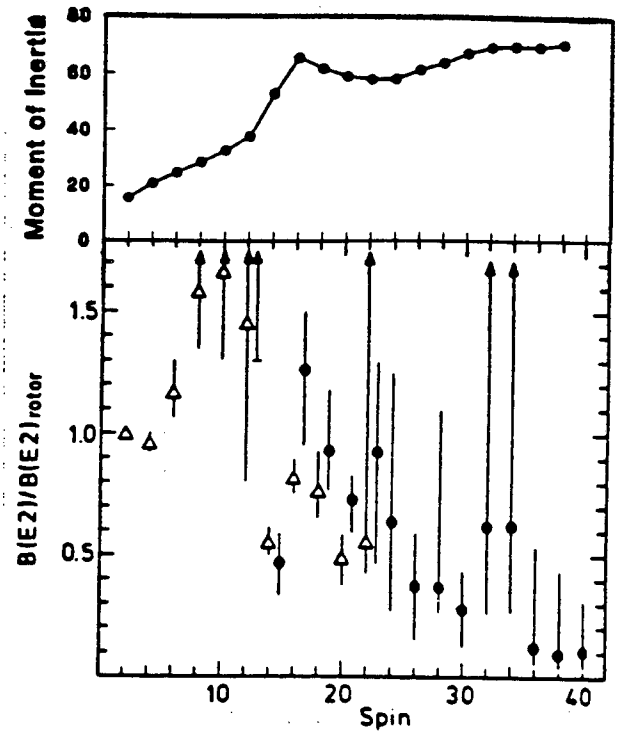

Fig. 14 The moment of inertia and ratio of B(E2) values *vs.* spin for the band in 158Er.

of inertia. These may be some of the reasons the rather small alignment effects that we have noted in the data (Section 2) are not obscured.

3.3 Alignments of 1ħ

The last puzzle has to do with why alignments of 1ħ are so common in the mass-190 region. The natural unit in pseudo-spin schemes is 1/2ħ, and cases like the bands in ^{193}Hg, which have one neutron beyond the reference nucleus, would really be expected to have an alignment of 1/2ħ if the neutron is in a pseudo-spin orbit or no alignment, if not. But it is observed to be 1ħ. The 1ħ value suggests a pair of pseudo-spin aligned particles, and that raises an interesting possibility. At these high angular momenta the pairing is strongly reduced due to the Coriolis force, which lifts the degeneracy of the time reversed nucleon orbits. In a psuedo-spin system, the time reversed states will be separated by an energy of order $\hbar\omega_{rot}$; whereas, the degenerate states will be those with the orbital motion time reversed, but both pseudo spins aligned with the rotation (identical rather than time reversed). The question arises as to whether these aligned pairs could scatter into other aligned orbits and thus generate some triplet pairing (spins aligned to 1ħ), competeing with the normal (singlet) pairing. This is only a speculation, and we do not see clearly how it would explain all the data in a simple way. However, calculations are necessary to evaluate whether this kind of pairing can exist in nuclei, and what its effects would be. It seems to offer the interesting possibility of a new type of collective motion in nuclei.

4. CONCLUSIONS

Superdeformed rotational bands are are turning out to be quite fascinating. They have similarities that are astounding and not easy to understand and the initial attempts at explanations for these properties lead to new and interesting ideas about nuclear structure. Some of the properties and ideas discussed in this talk are summarized below.

- In both the mass-150 and the mass-190 regions there are bands in different nuclei with very similar rotational energies . This is quite unexpected and not well understood.
- The similar bands can be characterized as having the same moments of inertia, but different alignments. Many of these alignments are found to be quantized (multiples of $1/2\hbar$).
- Pseudo-spin alignment represents the only source of quantized alignment anyone has so far thought of.
- The absence of other large effects on the moments of inertia is not understood, but there are ideas that might explain sizeable reductions in most of the these effects.
- The large number of alignments of $1\hbar$ might have to do with triplet pairing.

While it is clear we have much work to do in understanding these bands, it is also clear that the production of new experimental information and new theoretical ideas is very high. It would seem that the answers cannot escape us for long!

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