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Integer alignment and strong coupling limit in superdeformed nuclei

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Superdeformed bands in neighboring nuclei exhibit striking and unexpected similarities which previously have been interpreted in terms of pseudo-SU(3) symmetry and quantized angular momentum alignment. The spin and alignment of superdeformed bands near ^{192}Hg are investigated by their difference in static and dynamical moments of inertia. Special attention is drawn to the strong coupling limit and the possibility of quantized alignment in nuclei around ^{192}Hg.

During the last year, many superdeformed (SD) bands with almost identical moments of inertia have been observed, the first being reported in mass $A=150$ region [1]. The identical SD bands of ^{152}Dy (yrast) and of ^{151}Tb (excited) have been interpreted in terms of the complete decoupling of the odd particle occupying the $[301]\frac{1}{2}$ Nilsson orbital, or alternatively as a pseudospin alignment related to the pseudo-SU(3) symmetry [2]. It has been known for a long time that certain orbitals easily decouple from the rotational motion. This is well realized especially for unique parity orbitals such as $\pi h_{11/2}$ in the La isotopes [3]. The complete decoupling of the $[301]\frac{1}{2}$ orbital raises the question of whether the pseudo-SU(3) symmetry is particularly appropriate at SD shapes [2]. This observation has been followed by suggestions that SD bands have quantized integer alignments [4]. These suggestions are based on γ-ray energies differences between SD bands with similar moments of inertia. In the following it is shown how the strong coupling scheme can account for the difference in γ-ray energy in a simple and natural way without invoking the concept of integer angular momentum alignment. We then examine the measured SD moments of inertia. In order to extract alignments one needs to know the actual spin individual levels. Unfortunately, these are unknown for SD bands. We will discuss the fitting procedure used in previous works and show that spin uncertainties of at least $1\hbar$ are present. It has been shown in Ref. [5] that the existence of the pseudospin alignment crucially depends on the exact spin values and that a change in the assignments by only one unit can alter all conclusions. Also in our analysis, we cannot find any convincing reason for the presence of integer alignment. The SD bands in ^{191,193,194}Hg are also investigated. It is demonstrated that they can be understood reasonably in terms of strongly coupled bands built on orbitals resulting from cranked Woods-Saxon calculations. The need to invoke pseudo-SU(3) symmetry has not been demonstrated on the basis of the calculations nor from experimental facts and does not help in understanding the specific features of this mass region.

For the very elongated shapes considered here, most orbitals remain strongly coupled to the core. The Coriolis interaction matrix elements are small compared to the level splitting in the single-particle potential (see also Ref. [2] and the more extensive discussion in Ref. [6]). Therefore, the strong coupling limit is expected in general to be valid for superdeformed states. A decoupling parameter close to zero and a vanishing signature splitting is what one expects for most orbitals (the $\Omega=\frac{1}{2}$ and intruder orbitals excluded). The nuclei with axial symmetry, the γ-ray energy, E_γ, of a stretched $E2$ transition in a rotational band at spin I, can be obtained from the energies of the strongly coupled particle-rotor Hamiltonian [7],

$$E_\gamma=\frac{\hbar^2}{2\mathcal{J}}(4I-2)\,, \tag{1}$$

where we have assumed the decoupling parameter to be zero. We have also assumed that the resulting angular momentum of one or two particles ($\bar{j}$) is coupled to a core with angular momentum $\bar{R}$. The total angular momentum $\bar{I}$ is then obtained as $\bar{I}=\bar{R}+\bar{j}$.

For many SD nuclei in the Hg region, the moments of inertia $\mathcal{J}$ are similar to that of ^{192}Hg [4,8]. One can take the transition energies E_γ^0 of ^{192}Hg as a reference when comparing with the nearest transition energies E_γ' of a neighboring nucleus [4,8]. It follows from (1) that for bands with the same moment of inertia

$$E_\gamma^0-E_\gamma'=\Delta E_\gamma=2\frac{\hbar^2}{\mathcal{J}}\Delta I\,, \tag{2}$$

where ΔI is the difference in angular momentum between the two nuclei.

The same expression can also be obtained from the definition of the rotational frequency, $\hbar\omega=dE/dI=(\hbar^2/\mathcal{J})I$. Taking the difference between the nearest frequencies of two SD bands with the same moments of inertia, one obtains

$$\hbar\omega_0-\hbar\omega_1=\Delta\hbar\omega=\frac{\hbar^2 I_0}{\mathcal{J}_0}-\frac{\hbar^2(I_1-i_1)}{\mathcal{J}_1}=\frac{\hbar^2}{\mathcal{J}}(\Delta I+i_1)\,, \tag{3}$$

where $\mathcal{J}_0=\mathcal{J}_1=\mathcal{J}$ and i_1 is an initial alignment in the nucleus being compared. The initial alignment is defined as the decoupled angular momentum carried by the valence quasiparticles. The quantity $\Delta\hbar\omega/(\hbar^2/\mathcal{J})$ or $\Delta E_\gamma/(2\hbar^2/\mathcal{J})$ can be regarded as a normalized energy difference and has been defined previously as the incremental alignment Δi [4]. Let us mention that for strongly coupled bands the initial alignment vanishes, $i_1=0$, thus $\Delta I=\Delta i$ (actually $\Delta I=\Delta i\pm 2n$, where $n=0,1,2,3,\ldots$, depending on which γ-ray energy E_γ is taken for comparison).

When comparing transition energies of an even-even nucleus with a strongly coupled two-quasiparticle band of a neighboring even-even nucleus, one finds that the incremental alignment Δi approaches unity or zero for the odd-I and even-I sequence, respectively. Similarly, $\Delta i=\pm\frac{1}{2}$ for sequences of an odd-A nucleus. (One should note that the sign of Δi is opposite to that given in Ref. [4], where the alignment i has been defined as $i=\Delta i+\Delta I$. This definition always leads to an integer alignment i in strongly coupled bands with the same moments of inertia because both Δi and ΔI are half integer.)

The excited SD bands of ^{153}Dy, which have moments of inertia identical to those in ^{152}Dy (Ref. [2]), are striking examples of strongly coupled sequences. In ^{152}Dy, $4\hbar^2/\mathcal{J}$ has a value of 47 keV for almost the whole band, and ΔE_γ is ≈ 11 keV, resulting in an incremental alignment of $\pm\frac{1}{2}$. The band in ^{153}Dy has been discussed as being strongly coupled with a decoupling parameter of zero [2]. The incremental alignment of $\pm\frac{1}{2}$ shows the difference in transition energies due to the odd particle and reflects the fact that the strong coupling limit is valid up to very high frequencies. This is a "natural" interpretation since strongly coupled orbitals do not have any initial angular momentum alignment $[i_0(\omega=0)=0]$. Consequently, a half integer value of Δ_i does not imply integer alignment.

Many SD nuclei in the $A=190$ region (with nearly identical moments of inertia) have incremental alignments which cluster around values of 0, $\frac{1}{2}$, and 1. Suggestions have been made that the values of the incremental alignment reflects the alignment i of a nucleus versus a chosen reference, e.g., ^{192}Hg, and that i preferably takes the integer value of one [4]. The alignment i is a quantity which in principle can take any value and the presence of a quantized alignment, i.e., $i=0,1,2,\ldots$, would raise profound questions for nuclear structure theory. However, the above discussion shows that within the strong coupling limit, the observed incremental alignments do not necessarily imply integer alignments. To extract precise total alignment values i, a knowledge of the level spin is required. This point is discussed in the following.

In all superdeformed nuclei found so far, spins have not been measured although suggestions for spin assignments have been made for most of the bands. The presence of any alignment process will lead to additional uncertainties in the suggested spin assignments. Therefore, we are interested in a formalism, which focuses on relative changes in angular momentum caused by the alignment of quasiparticles (qp), rather than on a systematic analysis based on definite spin assignments.

Introducing the spin projection onto the rotational axis, $I_x=[(I+1/2)^2-K^2]^{1/2}$, one defines a "kinematical" moment of inertia, $\mathfrak{I}^{(1)}=I_x/\hbar\omega$ and a "dynamical" moment of inertia $\mathfrak{I}^{(2)}=dI_x/\hbar d\omega$. (For a perfect rigid rotor, $\mathfrak{I}^{(1)}=\mathfrak{I}^{(2)}$.) The dynamical moments of inertia $\mathfrak{I}^{(2)}$ are independent of the spin assignments, in contrast to $\mathfrak{I}^{(1)}$. The $\mathfrak{I}^{(2)}$ moments can also be expressed as ($\hbar=1$)

$$\mathfrak{I}^{(2)}=\frac{dI_x}{d\omega}=\mathfrak{I}^{(1)}+\omega\frac{d\mathfrak{I}^{(1)}}{d\omega}\,. \tag{4}$$

As a consequence, $\mathfrak{I}^{(2)}$ is very sensitive to changes caused by level crossings (resulting in alignment) and also to collective changes due to a decrease in pairing or a shift in deformation.

The quantity $\mathfrak{I}^{(2)}-\mathfrak{I}^{(1)}$ is independent of the chosen reference. By taking the difference of $\mathfrak{I}^{(2)}$ and $\mathfrak{I}^{(1)}$, the collective part of the moment of inertia is canceled (see also the more extensive discussion in Ref. [9]). If we define the alignment in a broader sense and associate all changes of the nuclear structure caused by rotation with an apparent alignment i_a (including changes due to pairing or deformation), then

$$\mathfrak{I}^{(2)}-\mathfrak{I}^{(1)}=\frac{di_a}{d\omega}-\frac{i_a}{\omega}\,. \tag{5}$$

This simple picture shows that an increase in $\mathfrak{I}^{(2)}-\mathfrak{I}^{(1)}$ is connected with an alignment and that $\mathfrak{I}^{(2)}-\mathfrak{I}^{(1)}$ becomes negative as soon as $di_a/d\omega<i_a/\omega$. If $\mathfrak{I}^{(2)}$ is constant and no alignment process is taking place, then $(\mathfrak{I}^{(2)}-\mathfrak{I}^{(1)})\omega=-i_a$ is constant (assuming i_a is preserved). For $\omega\rightarrow 0$, $(\mathfrak{I}^{(2)}-\mathfrak{I}^{(1)})\omega$ will also approach zero, unless we deal with decoupled, rotationally aligned orbitals where it approaches the value of the aligned angular momentum $-i$ of that orbital.

The absolute value of $(\mathfrak{I}^{(2)}-\mathfrak{I}^{(1)})\omega$ depends on the spin assignments; however, the slope indicating an alignment process does not depend sensitively on the actual value of the spins and is used in the following to investigate possible alignment processes.

When examining $\mathfrak{I}^{(2)}-\mathfrak{I}^{(1)}$ for SD nuclei in the Hg region (Fig. 1), one immediately notices a strong rise for all the bands. Lifetime measurements indicate that the deformation of ^{192}Hg is remarkably constant in the observed range [10], in accordance with mean-field calculations [10,11]. As shown by Eq. (5), the rise in $(\mathfrak{I}^{(2)}-\mathfrak{I}^{(1)})\omega$ implies that $di_a/d\omega$ is increasing more rapidly than i_a/ω. Because deformation changes are small, the increase in $\mathfrak{I}^{(2)}-\mathfrak{I}^{(1)}$ comes, most likely, from the alignment of quasiparticles and/or a decrease in pairing.

The SD bands in Hg nuclei are observed down to relatively low frequencies, typically 0.10–0.15 MeV. It has been suggested that the bands can be extrapolated to zero frequency by means of the Harris expansion in order to extract the spin values [12]. Because of the extremely smooth alignment process (see Fig. 1), a reasonable fit (see below) can be achieved for most nuclei in this mass region. In particular, the fit of yrast SD bands in even-even nuclei, which are expected to have even spins, always result in values very close to even spins. If, for example, we force the spins of the SD levels in ^{192}Hg to change by two units, the rms of the fit increases by more than 2 orders of magnitude. The rms values are defined as $\text{rms}=100[\sum(|x^i_{\text{exp}}=x^i_{\text{fit}}|^2)]^{1/2}$, where x^i represents the experimental and calculated I_x values used in the fit.

In order to demonstrate uncertainties connected with the fitting procedure, we show possible spin values for the

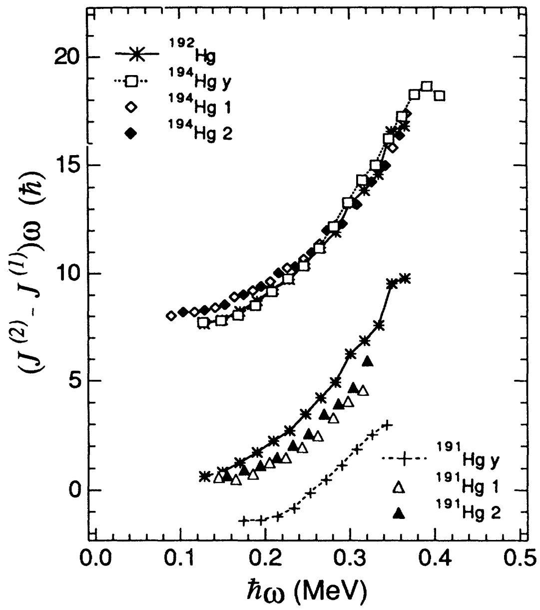

FIG. 1. Values of $(\Im^{(2)}-\Im^{(1)})\omega$ for the SD band in ^{192}Hg, compared with the three SD bands in ^{191}Hg. The spins are taken from Refs. [12] and [19]. A value of 7 is added to the $(\Im^{(2)}-\Im^{(1)})$ values of ^{192}Hg for comparison with the three SD bands in ^{194}Hg (Ref. [18]). The exit spins for the excited bands are 9 for band 1 and 10 for band 2. The spins of the ^{194}Hg yrast band are taken from Ref. [18].

two excited bands in ^{194}Hg in Table I. The unknown spins were obtained by a least-squares fit to the I_x values by means of the Harris expansion:

$$I_x=[(I+1/2)^2-K^2]^{1/2}=i_0+J_0\omega+J_1\omega^3 . \qquad (6)$$

The value of the spin I has to be an integer for even-even nuclei and half integer for odd-even ones. The alignment i_0 is unknown and has to be treated as a free parameter. If this value becomes larger than one, an equally good fit is obtained by changing the spins I by one unit.

Previously reported fits are based on the assumptions that the alignment gain i_0 below the known transitions is $0\hbar$ [12]. There has been no attempt to justify this kind of fitting procedure in the presence of an alignment process. Another basic assumption is that the nucleus continues to behave smoothly below the known states, excluding the possibility of low-frequency distortions. Figure 1 shows that an alignment process is present and that the total gain in alignment below $\hbar\omega\approx 0.15$ MeV is unknown. The onset of alignment leads to changes in slope and curvature in the I vs $\hbar\omega$ curve and consequently in all $\Im^{(1)}$ and $\Im^{(2)}$ curves. Since we do not know when or to what extent the alignment sets in, we can conclude that the spin assignments suggested in Refs. [8] and [12] are uncertain. For excited bands in odd-A nuclei, the presence of ongoing alignment processes results in uncertainties greater than for yrast SD bands in even-even nuclei.

From Table I, one can see that by changing the assignment for the excited bands in ^{194}Hg from odd to even spins the rms values are rather weakly affected. This fact suggests that at low frequencies, the actual spin values are expected to deviate from the simple Harris expansion. This is reflected by the rapid variations of J_1 when fitting the expansion to fewer points (Table I). Strong statements based solely on spin assignments should be avoided. It should be noted that a careful investigation of spin assignments carried out in Ref. [13] also suggests large uncertainties in this fitting procedure.

It is instructive to use the Harris expansion on bands of known angular momenta. In ^{177}Pt (Ref. [14]) for example, a four-point fit to the first transitions of the ground-state band built on the $[512]\frac{5}{2}$ level fails to reproduce the bandhead angular momentum by $\approx 1\hbar$. A similar fit to the ground-state band of ^{232}Th (Ref. [15]) results in a value close to the assigned spins. However, if the four lowest transitions are excluded from the fit, by taking only levels above the 8^+ state, the difference between the fitted and assigned spin is $1.6\hbar$. The presence of octupole degrees of freedom in superdeformed nuclei has also been

TABLE I. Values of i_0, J_0, and J_1 obtained from a fit to I_x assuming given exit spins I_{ex} and K values ($I_x=i_0+J_0\omega+J_1\omega^3$). The differences between the fit to four and nine data points are also presented.

Band	I_{ex}	K	i_0	J_0 4-point fit	J_1	rms	i_0	J_0 9-point fit	J_1	rms
^{192}Hg	10	0	0.06	86.8	130.2	0.03	−0.14	88.6	109.2	0.68
^{194}Hg 1	9	2	−1.13	95.3	52.6	0.23	−0.92	93.0	88.3	0.98
	9	7	−0.23	88.7	131.0	0.15	−0.39	90.4	105.7	1.56
	10	2	−0.21	95.8	46.8	0.09	0.03	93.3	86.8	0.98
	10	7	0.03	94.1	69.5	0.12	0.09	93.3	88.9	0.92
	11	2	0.76	96.1	45.4	0.26	0.98	93.6	85.2	0.99
	11	7	0.50	97.9	29.8	0.66	0.72	95.3	78.1	0.98
^{194}Hg 2	10	2	−1.05	94.8	65.6	0.57	−0.88	93.0	89.7	1.32
	10	7	−0.35	90.2	112.1	0.11	−0.45	91.1	101.4	1.42
	11	2	−0.12	95.3	61.2	0.58	0.08	93.3	88.6	1.33
	11	7	−0.003	94.8	67.0	0.48	0.11	93.5	89.3	1.24
	12	2	0.98	94.2	76.2	0.69	1.06	93.3	88.4	1.33
	12	7	0.58	97.4	46.1	0.57	0.78	95.1	81.2	1.31

discussed [16]. We can investigate a case from the normally deformed ^{225}Th (Ref. [17]) where such an interaction is observed. A fit to the four lowest transitions reproduces the assigned spins. However, the Harris expansion deviates as much as $2.3\hbar$ for a four-transition fit starting from the fifth transitions and above. Note that for all cases the data exhibit a very smooth and monotonic increase in $\Im^{(2)}$.

Another justification of the fitting procedure is that when the lowest transitions are removed, the assigned spin values should not change. However, if a pseudospin alignment is taking place at low frequency, the aligned pseudospin i_0 has to be taken into account in the fit [Eq. (6)]. The possible presence of pseudospin alignment at low frequency leads to an inconsistency, because the pseudospin alignment is the unknown quantity which is supposed to be determined by the fit.

By comparing the yrast bands of ^{192}Hg and ^{194}Hg, we note that they have almost the same $\Im^{(2)}$ moments of inertia, the transition energies of ^{194}Hg being exactly 4 keV less. This is valid for the 11 lowest transitions, above which the difference increases to ≈ 8 keV. If this is converted to incremental alignment, we have $\Delta i \approx 0.1\hbar$ at the bottom of the band increasing to almost $0.5\hbar$ for the highest frequencies (the alignment gain is also seen in Fig. 1).

Two excited SD bands have been observed in ^{194}Hg and are assigned as built on a two-quasiparticle state involving the [624] $\frac{9}{2}$ and the [512] $\frac{5}{2}$ neutron orbitals (see Fig. 2), resulting in either $K=2$ or 7 [18]. The excited two-qp band structure can couple strongly to the ^{192}Hg SD core, and will have even and odd spins, with a difference of $1\hbar$ in incremental alignment. The even spin sequence is thus

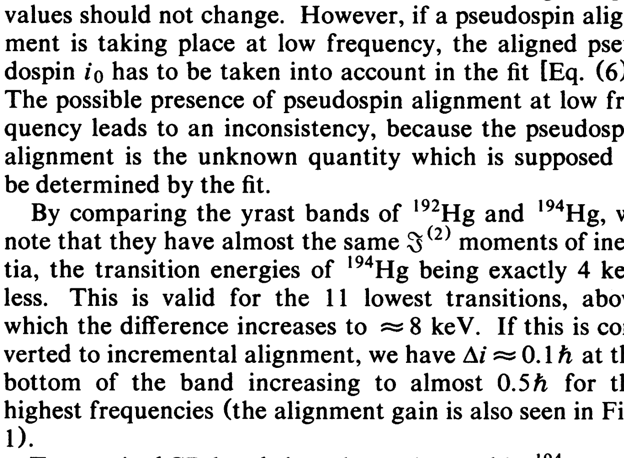

FIG. 2. Single-particle Woods-Saxon Routhians for neutrons for ^{192}Hg at the calculated equilibrium deformation. The normal-parity Nilsson orbitals ae labeled by means of the asymptotic quantum numbers $(Nn_z\Lambda)\Omega$, whereas the intruder orbitals are labeled using the principal oscillator number N. The parity π and signature α of individual levels are indicated in the following way: $\pi=+,\alpha=+\frac{1}{2}$ (solid line); $\pi=+,\alpha=-\frac{1}{2}$ (dotted line); $\pi=-,\alpha=+\frac{1}{2}$ (dash-dotted line); and $\pi=-,\alpha=-\frac{1}{2}$ (dashed line). Note that the $N=112$ gap is larger than the one shown in Ref. [18] because of slightly different deformation parameters.

expected to have the same transition energies as the even-even core. The data may be interpreted in this manner since the transition energies of band 2 of ^{194}Hg and of ^{192}Hg become equal within 1.5 keV. (Other configurations are also possible, but do not affect the conclusions drawn about the incremental alignment.)

The spins of ^{194}Hg band 2, which has an incremental alignment of zero (i.e., identical γ-ray energies as in ^{192}Hg), have been suggested to take odd values [8]. This is only possible if an alignment i of one unit is present in band 2 [see Eq. (3)]. In a fit of Eq. (6) to the spins of the lowest members of the band, both the odd and even spin assignments yield equally good results, the only difference being the initial alignment i_0 (see Table I). (Negative values of i_0, although unphysical, are reasonable since they simply mean that the fit does not properly take into account the changing slope at low frequencies.) The spin assignment for this particular case is thus connected with uncertainties of at least $1\hbar$. One cannot conclude from the fit which band has odd or which has even spins, nor can one determine the K value. The fit of band 2 to an even spin sequence is reasonable and accounts for the zero incremental alignment in a natural manner. Therefore, it is suggested that the difference in incremental alignment only reflects the difference in spin and that no integer alignment is present. The validity of the strong coupling scheme also suggests that there is no need to involve the alignment of pseudospin.

In ^{193}Hg, four SD bands have been observed, two of which interact strongly revealing a highly irregular pattern [16]. Two bands can be viewed as states built on the ^{192}Hg$\otimes$[624] $\frac{9}{2}$ or ^{192}Hg$\otimes$[512] $\frac{5}{2}$ configurations [16], the same as discussed above for ^{194}Hg (see Fig. 2). Both alternatives involve high-K orbitals, strongly coupled to the core, and have an incremental alignment of $\pm 1/2\hbar$. The incremental alignment for the two excited bands remains constant over the whole frequency range considered; this is related to the high-Ω orbitals being unsplit up to the highest frequencies (Fig. 2). Figure 2 clearly shows that the calculated initial alignment i_0 (defined as $i_0=-de^{\omega}/d\omega$) of the [624] $\frac{9}{2}$ and [532] $\frac{5}{2}$ orbital is zero. By analogy to ^{153}Dy and ^{152}Dy, one cannot conclude from the incremental alignment itself that an alignment of one unit should be present.

In ^{191}Hg, three different SD bands have been observed [19]. The band with the largest intensity (labeled y in Fig. 1) is suggested to be built on the lowest $j_{15/2}$ neutron configuration, thus blocking the first neutron alignment. This is correlated with the $(\Im^{(2)}-\Im^{(1)})\omega$ plot, showing smaller increase at the lowest frequencies. Figure 1 also shows the onset of an alignment in the yrast band of ^{191}Hg at $\hbar\omega \approx 0.12$ MeV. On the other hand, the two excited bands are expected to occupy the same intruder orbitals as ^{192}Hg. The signature splitting between the two excited bands is zero at the beginning of the band and does not increase to more than 50 keV. The two bands can be regarded as strongly coupled hole states with respect to the ^{192}Hg core [19]. One thus expects these orbitals to exhibit an incremental alignment of $\pm\frac{1}{2}$, and this is indeed observed over part of the frequency range.

The two excited bands in ^{191}Hg have been assigned to the [624]$\frac{3}{2}$ orbital (see Fig. 2). The favored signature (band 2, Fig. 1) has a constant incremental alignment of $-\frac{1}{2}$ relative to the ^{192}Hg core. This band is expected to start with $I=\frac{3}{2}$ which translates into an incremental alignment of $+\frac{1}{2}$ [Eq. (3)], in disagreement with the experimental value of $-\frac{1}{2}$. A possible alignment of one unit would shift the incremental alignment by the same amount and would account for this discrepancy. The difference between the assigned spins and the ^{192}Hg core can be seen in Fig. 1, where the two excited bands are displayed one unit lower than ^{192}Hg. However, if the spins are lowered by one unit, the discrepancy between the incremental alignment and the assigned spins would disappear and the values of $\Im^{(2)}-\Im^{(1)}$ would lie on the ^{192}Hg curve. In that case the signatures would be inverted, in disagreement with calculations. However, this discrepancy is not serious, since very small differences in deformation between the two configurations can lead to a signature inversion. (A difference in γ deformation of 1° combined with a reduced β_4 of 0.01 for the unfavored band is predicted in this case to lead to a signature inversion.) Since the bandhead level and the spins of the strongly coupled structure are not known, one has to wait for more experimental results in order to firmly establish theoretical band assignments.

For bands with similar moments of inertia, the incremental alignment is a very convenient method of relating the angular momentum of one band to another. The incremental alignment Δi can be obtained without knowledge of the spins. It has been suggested in Ref. [4] that the observed values of Δi (integer for even-even and half integer for odd-A nuclei) imply integer alignments, independently of spins. In our opinion, such a statement is incorrect, since it simply follows from the strong coupling limit. The values of Δi indicate that for SD shapes many orbitals remain strongly coupled to rather high frequencies.

To extract alignments, it is necessary to know the spin for all states. The varying moment of inertia and the unknown behavior at low spin makes any attempt to fit the spin values uncertain. We showed that an uncertainty of the order of $1\hbar$ is more realistic. Consequently, a change in the spin assignment of one unit drastically alters the conclusions given in Ref. [4]. Instead of a relative alignment of one unit, the total alignment becomes zero. Since the spins are unknown and the strong coupling limit can account for most of the observed features, we find no evidence of quantized integer alignment.

The similarity between SD bands in the Hg region is shown to depend strongly on an apparent similar alignment process. The strong coupling scheme does not explain why the moments of inertia are almost the same, neither does the pseudospin picture. The nearly identical moments of inertia, as well as the extremely smooth alignment processes are the crucial questions that need further investigations.

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