Spin Alignment in Superdeformed Hg Nuclei

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One of the superdeformed rotational bands in ^{194}Hg has transition energies (rotational frequencies) that are equal within about 0.1% to those of the (only known) band in ^{192}Hg. This excited (two-quasiparticle) band in ^{194}Hg has an aligned spin of $(1.00 \pm 0.04)\hbar$ relative to the very similar band in ^{192}Hg, suggesting an interpretation in terms of aligned pseudo (intrinsic) spin. The implied pseudospin symmetry may be a clue as to why the rotational frequencies are so similar.

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One of the most remarkable properties so far discovered of rotational bands in superdeformed nuclei is the extremely close coincidence in the energies of the deexciting γ-ray transitions (or rotational frequencies) between certain pairs of bands in different nuclei.[1,2] In the example reported here, the transitions of an excited band in ^{194}Hg are within about 1 keV of those of the yrast band of ^{192}Hg over a spin range of $20\hbar$. (The term "band" in this Letter should be understood to mean "superdeformed band.") This is an equivalence of the frequencies to within about 0.1%, which is much smaller than the kind of similarities we could expect, or hope to calculate, using present models of rotating nuclei. This seems so unlikely that, as an isolated case, one might think it is accidental, but the two cases very recently reported in the mass-150 superdeformed region[1] suggest this may be a relatively common feature of superdeformed nuclei. These near degeneracies in the frequencies of different bands suggest that there may be some underlying symmetry, which is not well understood. The present Letter will describe these unusual properties and examine some possible implications.

The Hg data having these striking properties are shown in Fig. 1, with transition energies listed in Table I. The first of the three spectra shown is for ^{192}Hg, and represents the strongest (presumably yrast) band in that nucleus.[3,4] The lower two bands (called "band 2" and "band 3") are weakly populated bands in ^{194}Hg and presumably correspond to excited two-quasiparticle bands, since there is a (3 times) more strongly populated band in ^{194}Hg (not shown here) that is the likely yrast band.[5,6] These energy regularities are already apparent in Fig. 1. First, and most remarkable, the transition energies in the upper part of band 2 are virtually identical to those in the ^{192}Hg band. It is also apparent, on closer inspection, that the energies of band 3 fall very close to the midpoint energies of adjacent transitions in band 2, strongly suggesting that these two bands are signature partners, and thus comprise a single "strongly coupled" band. This, of course, implies that the band-3 energies also fall very close to the midpoint energies of the ^{192}Hg yrast band.

The similarity of the transition energies in the upper

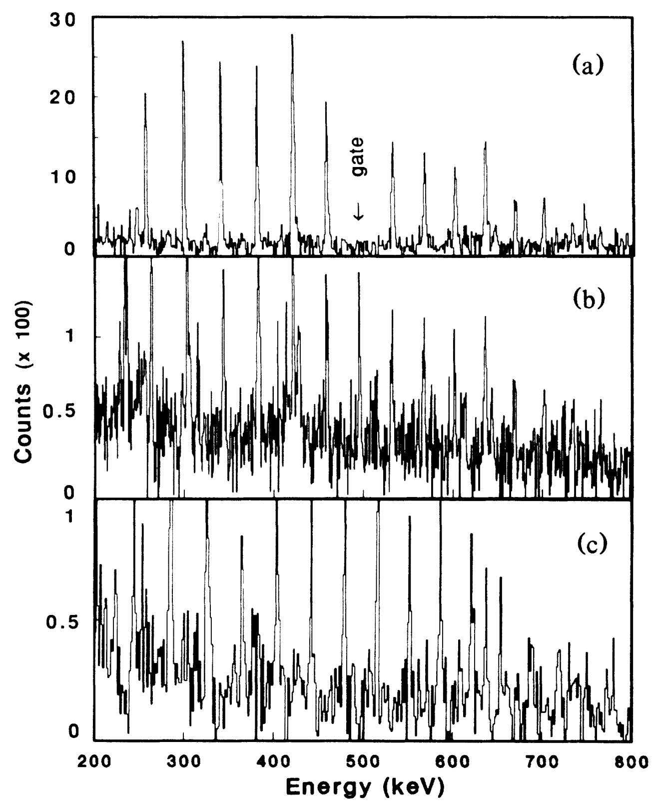

FIG. 1. Rotational spectra of (a) ^{192}Hg; (b) ^{194}Hg, "band 2"; and (c) ^{194}Hg, "band 3." The spectra are all double-gated (triple coincidences): (a) required the indicated gate plus any other in the band; (b) and (c) required any two of the transitions indicated by g in Table I.

TABLE I. Rotational transition energies. g denotes gate transitions for the spectra in Fig. 1.

^{192}Hg		Band 2		Band 3	
I_i	E_γ	I_i	E_γ	I_i	E_γ
10	214.6			10	201.2
12	257.7	13	262.7	12g	242.7
14	299.9	15	302.9	14	283.5
16	341.1	17g	343.2	16g	324.4
18	381.6	19	382.1	18g	363.6
20	420.8	21g	421.1	20g	402.5
22	459.1	23g	458.9	22g	440.9
24	496.3	25g	495.1	24	478.2
26	532.4	27g	531.6	26	514.8
28	567.9	29	566.9	28	550.1
30	602.3	31	601.6	30	585.4
32	635.8	33	635.6	32	619.8
34	668.6	35	668.7	34	652.3
36	700.6	37	701.7	36	685.0
38	732.1	39	733.3	38	717.4
40	762.8	41	762.1	40	747.2
42	793.4	43	(792.8)		

part of band 2 to those in ^{192}Hg is illustrated in Fig. 2, where the difference in transition energy between these two bands is plotted against frequency ($\frac{1}{2}$ the transition energy). In addition, we have plotted the difference in transition energy between band 3 and the average (midpoint) of the transition energies in ^{192}Hg. The average agreement of the last ten transitions in both bands 2 and 3 with those of ^{192}Hg is less than 0.5 keV—incredibly small. This region of close similarity occurs after relatively large differences in the lower-frequency region of the bands.

Another very important property of these bands is their spin. In previous[3,5] 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 fitted 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, the rms deviation of the calculated initial spins from the integers given in Table I is $0.05\hbar$. 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. It is surprising that it is the *odd-spin* sequence (band 2) that has transition energies nearly identical to those (of the even-spin sequence) in ^{192}Hg. This behavior, together with the lower-frequency rise in Fig. 2, can be explained as a spin-alignment effect.

In Fig. 3 the angular momentum alignment of bands 2 and 3 in ^{194}Hg relative to the ^{192}Hg band is plotted against the rotational frequency. This alignment is determined by subtracting from the (initial) spin of a transition in band 2 or 3, the (initial) spin of a ^{192}Hg transition of the same frequency (obtained using an interpolation procedure). It is again apparent that bands 2 and 3 form a common sequence whose aligned angular momentum, relative to ^{192}Hg, starts out as about $0.6\hbar$, but becomes $(1.00 \pm 0.04)\hbar$ over the last half of the observed band (frequencies above 0.2 MeV). This is *a priori* a totally unexpected result, since *aligned* angular

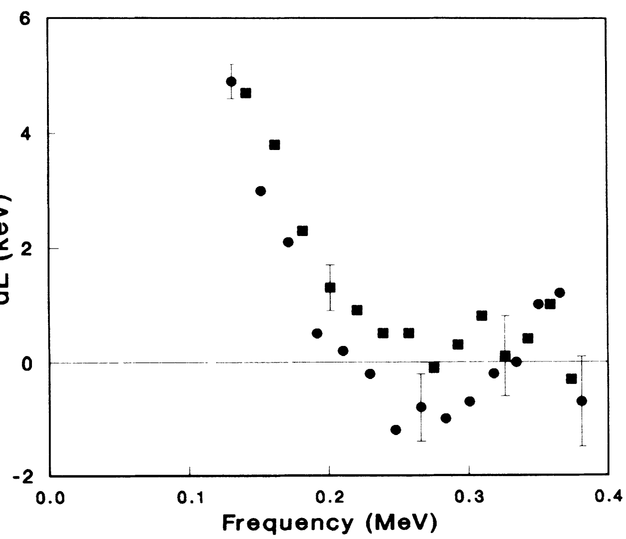

FIG. 2. The difference in the energy of the transitions in bands 2 in ^{194}Hg (circles) from those of the band in ^{192}Hg is plotted against the rotational frequency. The squares are the differences of the band-3 energies from the midpoints of the ^{192}Hg energies. The error bars indicate experimental uncertainties.

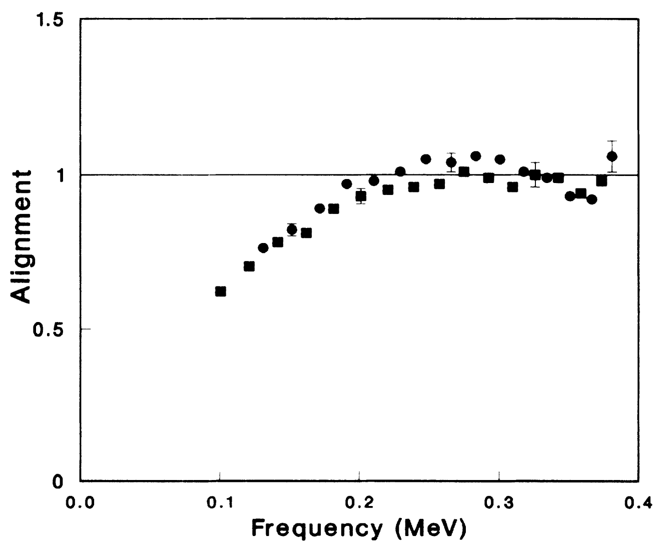

FIG. 3. The alignments (see text) of band 2 (circles) and band 3 (squares) in ^{194}Hg relative to the band in ^{192}Hg are plotted against the rotational frequency.

momenta need not be integers; however, a near-integer value is implied by the very similar transition energies and the integer angular momentum values in even-mass nuclei.

The only plausible explanation we have thought of for such a behavior is that the intrinsic spins ($\frac{1}{2}\hbar$ each) of the two extra neutrons have aligned with the rotation axis, while the orbital angular momentum remains strongly coupled to the nuclear symmetry axis. Although such behavior seems quite astounding, it was predicted in surprising detail by Bohr, Hamamoto, and Mottelson[7] seven years ago and is related to the concept of pseudospin.[8,9] The large spin-orbit force in nuclei causes a high-j orbital from each harmonic-oscillator shell to drop down into the next lower shell, and a corresponding orbital from the next higher shell to come into the energy range considered. For example, in the $N=5$ shell, the $h_{11/2}$ orbital drops down into the $N=4$ shell and the $i_{13/2}$ orbital from the $N=6$ shell comes into the energy range of the $N=5$ shell. The different parity of the $i_{13/2}$ orbital isolates it from the remaining $N=5$ orbitals, leaving a rather closely spaced group of odd-parity orbitals that can be reclassified as a complete "pseudo" $N=4$ shell. Thus, for example, $f_{7/2}$ and $h_{9/2}$ subshells can be reclassified as a pseudo $g_{7/2,9/2}$ pair. This concept is useful for deformed nuclei because the deformation preserves the approximate degeneracy of the pseudospin partners.

The important result for the present case is that the pseudo spin-orbit coupling is very small. This occurs because the mixture of parallel and antiparallel couplings of the intrinsic spin to the orbital angular momentum (e.g., $f_{7/2}$ and $h_{9/2}$) leaves very little residual (pseudo) spin-orbit coupling. Thus, in this scheme it should be easy to align the pseudo (intrinsic) spin, leaving the pseudo orbital angular momentum (l) strongly coupled to the symmetry axis. Nazarewicz[10] has used pseudospin to explain the properties of a $K=\frac{1}{2}$ band that might be involved in the superdeformed mass-150 region, but the spins are not known in that case. In the present example an alignment of rather precisely $+1\hbar$ seems clear, providing some reasonably direct evidence that pseudospin may be involved in these very similar bands. However, while pseudospin can provide a natural explanation for this "quantized" spin alignment, it cannot explain the absence of expected changes in the moment of inertia due to other effects.

Although such pseudospin alignment was predicted in Ref. 7, there are some problems in the details of the present case. First, although a single particle (or hole) in a pseudospin-partner system (two doubly degenerate orbitals) can result in aligned ($+\frac{1}{2}\hbar$) bands having both signatures, two particles in such a system will produce only one aligned ($+1\hbar$) band and it has signature zero (even spins). Since our experimental situation has *two* quasiparticles and bands of *both* signatures, there must be two pseudospin-partner systems involved. This is not a serious problem since virtually all the normal-parity orbitals belong to such pairs, and moving a particle from one of the top (antialigned) levels of a filled pair to one of the bottom (aligned) levels of an empty pair will produce (two) bands with alignment $+1\hbar$ and both signatures.

A second problem is that the alignment is not quantitatively borne out by recent cranked-shell-model calculations (e.g., Ref. 11). The levels of interest are probably the two pairs of levels: $[512]\frac{5}{2}$, $[514]\frac{7}{2}$ (empty) and $[642]\frac{3}{2}$, $[640]\frac{1}{2}$ (full). In the pseudospin notation, these become $[413]\frac{5}{2},\frac{7}{2}$ and $[541]\frac{3}{2},\frac{1}{2}$, respectively. To conform with the alignment of the pseudospins *only*, the pseudospin partners would need to be very close together, with an average (pseudo-l) alignment of zero, and individual alignments initially zero but developing into $\pm\frac{1}{2}\hbar$ as ω increases. The qualitative behavior[11] of these orbitals is much like that required above, but the $\pm\frac{1}{2}\hbar$ individual alignments do not develop for either pair in the required frequency range ($0<\omega<0.2$ MeV) and the pseudo-l alignment is significant for both pairs. The lack of the pseudospin alignment in the calculation comes about because the pseudo spin-orbit splitting is quite appreciable—about 0.5 MeV for both of the above pairs, whereas the experimentally observed alignment curve (Fig. 3) would require it to be around 0.1 MeV. It seems that rather minor changes might be able to solve that aspect of the problem since the pseudo spin-orbit coupling is the small difference of rather large quantities. However, the orbital alignment at $\omega=0.4$ in the calculation[11] is about $-0.2\hbar$ for the [413] pair and about $+0.35\hbar$ for the [541] pair, and why a net (and changing) l alignment does not show up in the experimental data is less easy to understand. There are, of course, other changes—in size (mass), deformation, and pairing—which we also would expect to affect the observed moments of inertia but do not appear to do so.

If we try to estimate the changes in the moment of inertia (i.e., in the frequencies or transition energies at a particular spin) caused by addition of a particle in a normal-parity orbital, it turns out to be of order 1%. The overall fluctuation in the moment of inertia for different configurations is of order 10%, but most of that comes from states having different configurations for the intruder orbits. Since most of the superdeformed bands known in the mass-150 region are believed to differ in the configuration of the intruder orbitals, we are able to understand the different frequency behavior (i.e., the absence of very similar bands) previously observed there. In the Hg region, ^{191}Hg has a frequency behavior[12] rather different from the heavier Hg isotopes, and is also believed to have a different intruder orbital configuration. A particle in a normal-parity orbital would be expected to produce an effect on the frequency that is nearly an order of magnitude smaller than that of the intruder orbitals, i.e., of order 1%, whereas, the observed cases (three out of perhaps twice that number known) are 10 times smaller than that. It is the absence of effects in the 1% range (for example, the expected $A^{5/3}$ mass dependence of the moment of inertia) that is so puzzling in these cases, and about which we will speculate briefly.

The fact that we can see these extremely similar bands must imply very weak pairing, particularly for the neutrons. The addition of two neutrons to ^{192}Hg appears to produce a low-lying two-quasiparticle band in which the moment of inertia is not at all affected (except by the alignment of exactly one unit of angular momentum). These neutrons must block levels near the Fermi surface in ^{194}Hg, and the lack of any effect on the moment of inertia seems to indicate very weak or absent pairing. This is not so surprising in superdeformed nuclei, particularly for spins above about $20\hbar$. It seems very likely that unusually weak pairing is one of the reasons this new type of behavior can be observed (i.e., is not obscured).

An additional clue about the physics producing these nearly identical frequencies in bands of different nuclei comes from the spin-alignment effects, which suggest that pseudospin [and perhaps pseudo SU(3)] is a more exactly realized symmetry in these Hg nuclei than our present calculations would indicate. This is intriguing because such symmetries imply correlations between Coriolis (alignment) and deformation effects which *do* tend to keep the moment of inertia constant. For example, 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 countereffect—increased energy denominators in the (Inglis-type) calculation of the moment of inertia, resulting in a negative contribution to the moments of inertia. This cancellation works also for orbits favoring smaller deformations. For certain harmonic-oscillator situations[13] [having SU(3) symmetry] these positive and negative contributions to the moment of inertia *exactly* compensate each other, and while this will not happen in general, the tendency will be there. Such a systematic compensation of deformation and Coriolis effects would help to reduce the frequency variations between superdeformed bands—for example, the effects of the above orbital alignments on the moment of inertia would be partially (or largely) compensated by slight deformation changes. How well this might work in realistic situations is not known at present, but it illustrates a way that the realization of pseudospin, and perhaps pseudo SU(3), symmetry could result in unusually similar moments of inertia.

Much more work is needed to understand these very similar bands. Additional experimental information on bands in this region is needed; first to determine how general these regularities are, then to establish whether this is really a pseudospin effect, and finally to define unambiguously the configurations involved. Even then a full explanation will require some new insights into the way angular momentum is generated in nuclei. Nevertheless, it is clear we have some very tantalizing clues into the nature of an extraordinary nuclear-structure effect.

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