Spins, Parity, Excitation Energies, and Octupole Structure of an Excited Superdeformed Band in ^{194}Hg and Implications for Identical Bands

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An excited superdeformed band in ^{194}Hg, observed to decay directly to both normal-deformed and superdeformed yrast states, is proposed to be a $K^{\pi} = 2^{-}$ octupole vibrational band, based on its excitation energies, spins, and likely parity. The transition energies are identical to those of the yrast superdeformed band in ^{192}Hg, but originate from levels with different spins and parities. The evolution of transition energies with spin suggests that cancellations between pairing and particle alignment are partly responsible for the identical transition energies. [S0031-9007(97)04582-1]

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The potential energy surface in a number of nuclei has an excited minimum (false vacuum) at large deformation. The lowest states in the superdeformed (SD) minimum lie among hot normal-deformed (ND) states several MeV above the ND yrast line at low spin, but are isolated by a barrier. As a consequence, they are cold ordered states, characterized by good quantum numbers such as K and signature, in addition to spin and parity. A major theme of nuclear structure studies is to understand the microscopic structure of cold SD bands. However, it has not been possible to perform standard spectroscopic tests of theory, i.e., to confront theory with experimental energies and interband transition rates of states *with specific spins and parities*. This is because energies and spin/parity quantum numbers have been determined for just two SD bands (in ^{194}Hg [1] and ^{194}Pb [2]), although $\sim$175 SD bands have been found in the $A = 150$ and 190 regions. These fundamental properties are necessary for a rigorous test of theory, e.g., of predictions of octupole susceptibility (reviewed in Ref. [3]) and of low-lying octupole vibrations [4,5] in SD nuclei.

There are many pairs of SD bands, in nuclei with different mass numbers, which have many transitions with equal energy (within 1 keV) or which have identical dynamic moments of inertia, $\mathcal{J}^{(2)}$ (e.g., see Refs. [6,7]). ($\mathcal{J}^{(2)} = 4/\Delta E_{\gamma}$, where ΔE_{γ} is the spacing between consecutive SD-band transitions.) This unexpected phenomenon has stimulated many explanations [7], but it is still not understood. The degeneracy may be due to a symmetry (which has yet to be identified) or to accidental cancellations of several effects [8]. An understanding of this phenomenon requires knowledge of the spins, parities, quadrupole moments, and microscopic structures of the identical bands, besides just transition energies. In this Letter, we report on the spins, parity, and excitation energies of an excited SD band in ^{194}Hg, labeled band 3 by Ref. [9]. (A preliminary report has been given [10].) We suggest that the band is built on an octupole vibration. Its transition energies are equal to those in the yrast SD band in ^{192}Hg, but the emitting states have opposite parity and spins differing by $1\hbar$.

Two experiments were performed at Gammasphere [11] with the ^{150}Nd(^{48}Ca,4n)^{194}Hg reaction, using 202 MeV beams provided by the Lawrence Berkeley National Laboratory 88" Cyclotron. The targets consisted of $\sim$1 mg/cm^2 of isotopically enriched Nd evaporated on $\sim$13 mg/cm^2 Au foils. In the two experiments, Gammasphere comprised 85 and 92 Compton-suppressed Ge detectors. In the second experiment, improved ("electronic honeycomb") Compton suppression yielded a $\sim$40% improvement in sensitivity in fourfold coincidences. A total of 5.1×10^9 events were available for analysis after selection of prompt, high-multiplicity events. The data were sorted by setting coincidence gates on either two or three transitions in the known SD bands in ^{194}Hg as described in Ref. [12]. Figures 1(a) and 1(b) show the γ rays coincident with triplets and pairs of transitions from SD band 3, respectively, clearly revealing two high-energy gamma rays at 4978 and 5030 keV in Fig. 1(b). The total coincidence data and the energy difference of the high-energy transitions show that the two high-energy lines directly connect the 11^{-} SD level to the 10^{+} and 12^{+} ND yrast states, as shown in the level scheme (Fig. 2). Coincidences with the 262-keV intraband transition show that the $\sim$5 MeV lines decay out of the same level as the bulk of the decay, which consists of unresolved quasicontinuum γ

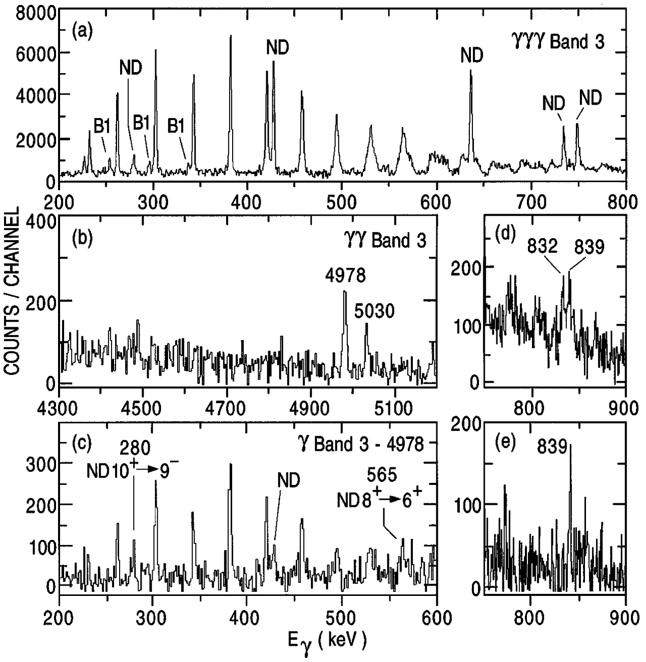

FIG. 1. (a) Low- and (b) high-energy portions of the spectra coincident with, respectively, triplets or pairs of transitions from band 3. Note the presence of band 1 lines ($B1$) in (a). (c) Pairwise coincidence spectrum obtained with one gate on the 4978-keV line and another on band-3 transitions, showing transitions from the 10^+ and 8^+ ND levels [13]. (d),(e) Portions of triple-coincidence spectra, showing the 832 and 839-keV interband lines; (d) from a gate on the 343-keV band-3 line and double gates on higher-lying band-3 transitions and (e) from a gate on the 296-keV band-1 line and double gates on band-3 transitions.

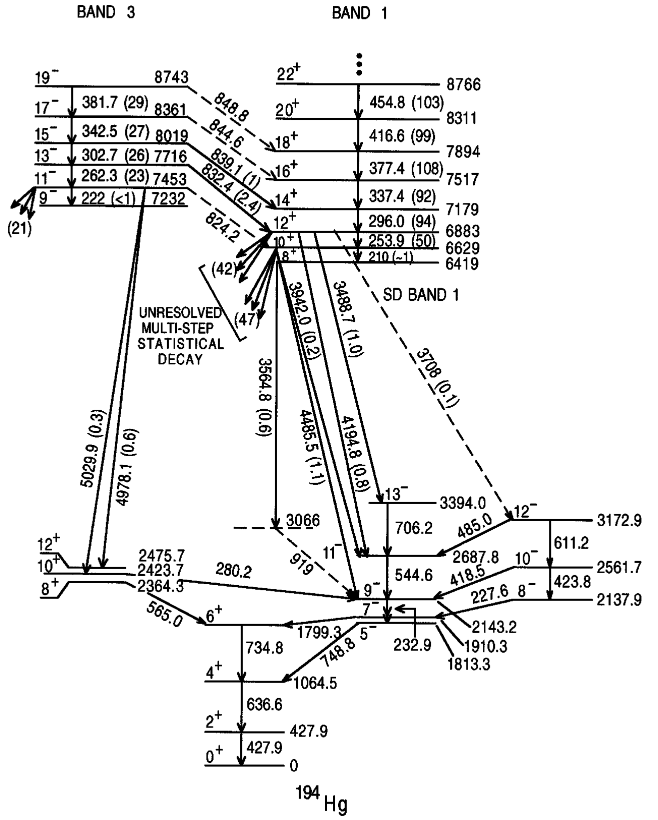

FIG. 2. Partial level schemes for the decay of SD bands 1 and 3 in ^{194}Hg. Dashed lines indicate tentative assignments. The transition intensities (in brackets) are normalized to 100 and 30 for the full-strength transitions in bands 1 and 3, respectively.

rays [14]. There is also evidence for direct decay branches from band 3 to band 1, e.g., the 832- and 839-keV lines in Figs. 1(d) and 1(e).

For the 4978-keV transition, the angular distribution coefficient was measured to be $A_2 = -0.38(25)$, which is consistent with an anti-stretched dipole assignment and rules out a stretched $E2$ or $\Delta I = 0$ dipole character ($A_2 \sim +0.35$). Decay out of SD states [14] is a statistical process analogous to [1] γ decay following neutron capture, where the observed [15] ratio of $E1$ to $M1$ rates is $\sim$5 for the primary γ rays, which are related to our 1-step decay lines. Hence, the $\sim$5 MeV transitions most likely have $E1$ multipolarity, leading to negative parity for band 3. For an excited SD band, this is the first time (a) that the excitation energies, spins, and likely parity have been determined and (b) that decay branches to both yrast SD and ND states have been established.

The enhanced statistics from this work confirms the level scheme for SD band 1 first proposed in Ref. [1], shows additional decay branches and provides better A_2 values [10]. The observed 1-step decays from bands 1 and 3 go to ND states of opposite parity, consolidating the assignments of opposite parity to those bands. No 1-step transitions from another excited band, labeled band 2 [9], have been identified, but its intraband transition energies [16] (midway between those of band 3), equal population intensity, and probable even spins (see below) suggest that it is the signature partner of band 3.

At the lowest observed frequencies, the excitation energy of band 3 above that of the vacuum band 1 is only 0.7 MeV (see Fig. 2) and it is extrapolated to be $\sim$0.8 MeV at zero frequency. In BCS theory, the lowest 2-quasiparticle (qp) excitation energy should be twice the pairing gap Δ, or $\sim$1.6 MeV for typical values [17] of Δ used in calculations which provide good reproductions of the $J^{(2)}$ values of SD bands in the $A \sim 190$ region. Since the experimental energies are significantly lower than those expected for 2-qp states, we suggest that band 3 is not a 2-qp neutron configuration [9], but is instead a collective vibrational band. Indeed, Refs. [4,5,18] have proposed that the lowest excited states in the SD minimum are octupole vibrations in $^{190-194}$Hg (and also in $^{192-198}$Pb. Our data support this interpretation: the experimental Routhian (orbital energies in the intrinsic frame) is close to the calculated one for the lowest octupole band in ^{194}Hg, with $K^\pi = 2^-$ (see Fig. 3), and the parity of the band is assigned as negative. A low-lying excited SD band in ^{190}Hg has also been proposed [4,19] to be an octupole vibrational band.

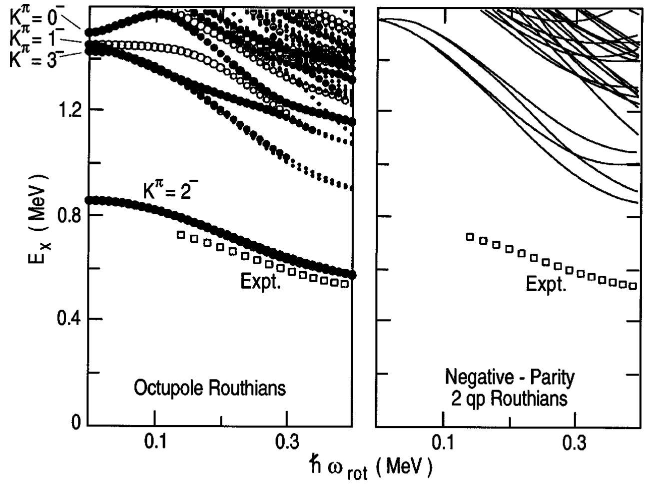

FIG. 3. Routhians for theoretical octupole vibrations (open and filled circles for signature 1 and 0) and negative parity 2-qp states (lines) compared with experimental data (open squares) for band 3. The calculation was performed with an octupole coupling constant 1.05 times the harmonic oscillator value, which also gives good agreement for $\mathcal{J}^{(2)}$—see Fig. 1 in Ref. [4].

The transitions connecting bands 3 and 1 must have *stretched* $E1$ character because of the spins and (likely) parities of the initial and final states. The measured $B(E1)$ values are $\sim 10^{-5}$ Weiskopf units (W.u.), which are significantly stronger than those ($\sim 10^{-7}$ W.u.) for the 1-step transitions to the ND yrast states. The $B(E1)$ values support the octupole-vibration assignment. Coriolis coupling with the lower-K octupole components provides a natural explanation for the observed $E1$ transitions, which would otherwise be K forbidden between states with $K^\pi = 2^-$ and 0^+. They can proceed through admixtures of $K^\pi = 1^-$ and, particularly, $K^\pi = 0^-$, which has the dominant $E1$ strength [4,20]. The octupole band in ^{190}Hg is predicted [4] to have a larger $K^\pi = 0^-$ admixture, which explains its higher $E1$ strength ($\sim 10^{-3}$ W.u.) [21]. The emerging systematics of low-lying excited bands and $E1$ rates in ^{194}Hg, ^{190}Hg [19,21], and ^{196}Pb [22] lend credence to the predictions [4,5] that octupole vibrations constitute the lowest excited states in the SD minimum of even-even mass-190 nuclei.

Since the spins for bands 1 and 3 are now known, both the dynamical and kinematic moments of inertia, $\mathcal{J}^{(2)}$ and $\mathcal{J}^{(1)}$, can be determined as a function of rotational frequency ($\hbar\omega = E_\gamma/2$)—see Fig. 4(a). Extrapolations of $\mathcal{J}^{(1)}$ and $\mathcal{J}^{(2)}$ to zero frequency show a significant convergence for each of the bands. This can be understood from familiar expressions based on the Harris expansion,

$$\mathcal{J}^{(2)} = \mathcal{J}_0 + 3\mathcal{J}_1\omega^2, \qquad (1)$$

$$I_x = \mathcal{J}_0\omega + \mathcal{J}_1\omega^3 + i\,, \qquad (2)$$

$$\mathcal{J}^{(1)} = I_x/\omega = \mathcal{J}_0 + \mathcal{J}_1\omega^2 + i/\omega\,. \qquad (3)$$

Since $\mathcal{J}^{(2)} = dI_x/d\omega$, integration of Eq. (1) gives Eq. (2), where i is a constant of integration. By comparing Eqs. (2) or (3) to the data, we obtain $i = 0$. Hence, at $\omega = 0$, both $\mathcal{J}^{(1)}$ and $\mathcal{J}^{(2)}$ have the same value, namely $\mathcal{J}_0$ [see Eqs. (1) and (3)], explaining the convergence seen in Fig. 4(a).

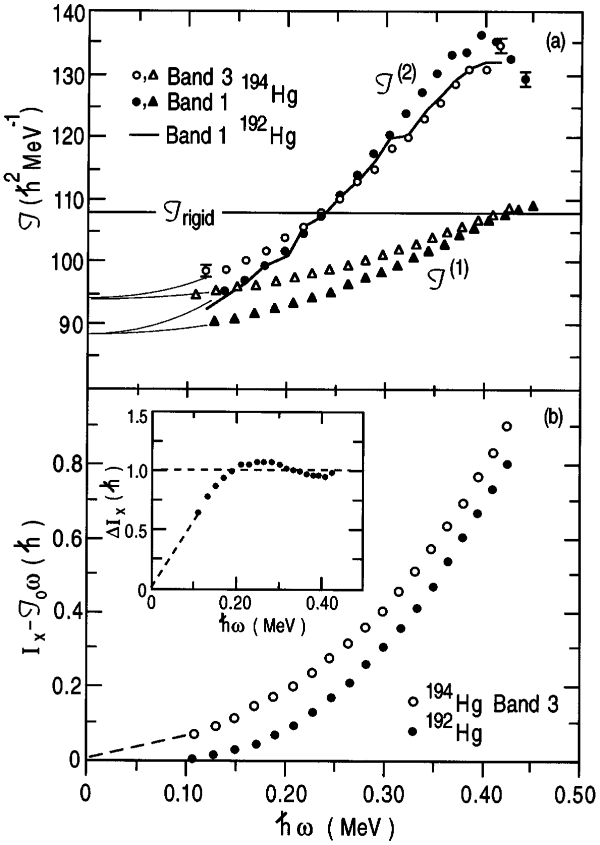

FIG. 4. (a) $\mathcal{J}^{(2)}$ (circles) and $\mathcal{J}^{(1)}$ (triangles) for bands 1 (filled symbols) and 3 (open symbols) in ^{194}Hg. The extrapolations to $\omega = 0$ (thin lines) are from fits with Eqs. (1) and (3). The solid line shows $\mathcal{J}^{(2)}$ for the vacuum SD band in ^{192}Hg. (b) $I_x - \mathcal{J}_0\omega$ for ^{194}Hg band 3 and ^{192}Hg vacuum band. $I_x = [I(I+1) - K^2]^{1/2}$, where $K^\pi = 2$ and 0, respectively. The term $\mathcal{J}_0\omega$ has been subtracted to amplify the ordinate scale, using the $\mathcal{J}_0$ value of ^{192}Hg. Inset: the spin difference ΔI_x for the two bands. The dashed line is an extrapolation using Eq. (2).

In Ref. [23] a procedure was proposed to deduce the spins of SD bands from Eqs. (1) and (2). However, it was necessary to make an assumption that $i = 0$ and there was criticism [24] about its validity. Bands with known spins (^{194}Hg bands 1 and 3 and ^{194}Pb band 1 [2]) indeed have $i = 0$. This occurs because Routhians generally have zero slope, i.e., no alignment, at $\omega = 0$. Common exceptions are high-N configurations which can exhibit alignment even at zero frequency, so that $i \neq 0$. We suggest an empirical guideline that it is safe to assume $i = 0$ when a band has $\mathcal{J}_0$, $\mathcal{J}_1$ values nearly equal to those of a band known to have $i = 0$. With this guideline, Eq. (2) yields even spins for ^{194}Hg band 2 and the ^{192}Hg vacuum band.

Finally, we discuss the implications of our results on the origin of identical bands. Band 3 of ^{194}Hg has transition energies which are identical to those of the vacuum band of

^{192}Hg for a large range of E_γ (382–854 keV). The present results, together with the observation of equal quadrupole moments [25], provide the most comprehensive collection of information about the properties of identical bands. This allows a critical question to be addressed: do states emitting equal-energy transitions have the same spin (in even nuclei), parity, and quadrupole moments?

The spins and parity of the vacuum SD band of ^{192}Hg have not been determined from experiment. However, Eq. (2) gives even spin values, as discussed above. Furthermore, a "ground" band with pair correlations in the SD false vacuum should have even spins and positive parity—as observed for the vacuum bands of ^{194}Hg (see Fig. 2 and Ref. [1]) and ^{194}Pb (Ref. [2]). On the other hand, the levels of band 3 have odd spin and negative parity. Hence, there is reasonable confidence that, *for this particular pair of identical bands, transitions of equal energy originate from states with different spin and parity.*

At low ω, the transition energies of the identical bands diverge and $\mathcal{J}^{(2)}$ for band 3 is larger than for the vacuum bands of ^{192,194}Hg (see Fig. 4). Reference [26] has shown that the larger $\mathcal{J}^{(2)}$ for the excited SD band can be explained by a reduction of pairing from blocking. The extrapolated value of $\mathcal{J}^{(2)}$ at $\omega = 0$ supports this interpretation. Here, I_x (defined in the Fig. 4 caption) and i are zero, i.e., there is no single-particle contribution to the spin. Hence, as the quadrupole moments for both bands are the same [25], a significant part of the $\sim$7% excess of $\mathcal{J}^{(2)}$ for band 3 must be due to a reduction of pairing.

Since $dI_x/d\omega = \mathcal{J}^{(2)}$, band 3 has a larger I_x at low ω. This is illustrated in Fig. 4(b), where $I_x - \mathcal{J}_0\omega$ is plotted for both bands, with $\mathcal{J}_0$ taken as the Harris parameter for ^{192}Hg. The difference in spin ΔI_x increases from zero; but the growth then slows for $\hbar\omega > 0.15$ MeV (see inset), as $dI_x/d\omega$ for ^{192}Hg increases due to alignment of high-N orbitals [9,27]. In other words, the unit spin difference and identical transition energies result from a complicated mechanism involving both pairing and particle alignment, i.e., from *accidental cancellations,* in agreement with the suggestions of Refs. [17,26]. However, an explanation based on a symmetry cannot be ruled out since that could still be the root cause of these cancellations.

The above interpretation shows that ΔI_x cannot be attributed solely to particle alignment (a few-particle effect) in band 3. Reduced pairing (a collective effect) plays an important role and there is, in fact, smaller particle alignment in band 3 at low ω. This interpretation contradicts the proposal by Ref. [28], which attributes the additional spin of band 3 to pseudospin alignment. It is also hard to envisage pseudospin alignment in an octupole vibrational band, which is a complicated (but coherent) superposition of 2-qp states. In any event, pseudospin alignment arising from two particles in a pseudospin doublet [28] would give the wrong (positive) parity for band 3.

In summary, we have determined the spins, likely parity, excitation energies, and some $B(E1)$ values of members of band 3 in ^{194}Hg. These properties indicate that this excited SD band is a $K^\pi = 2^-$ octupole vibrational band. Its transition energies are equal to those of the vacuum band in ^{192}Hg. However, it has opposite parity and a spin difference $\Delta I_x(\omega)$ which grows from 0 (at $\omega = 0$) and saturates at $1\hbar$. The evolution of $\Delta I_x(\omega)$ and $\mathcal{J}_2(\omega)$ shows that the integer spin difference and identical transition energies result in part from accidental cancellations between the effects of pairing and particle alignment.

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