Identification of the unfavored $N = 7$ superdeformed band in ^{191}Hg

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(Received 4 January 1995)

A new superdeformed band has been identified in ^{191}Hg bringing the total number of bands observed in this nucleus to four. The new band has properties similar to those of a superdeformed band reported recently in ^{193}Hg. Both bands are believed to be built on the unfavored signature of the $j_{15/2}$ intruder configuration. Comparisons between the data and cranked Woods-Saxon calculations highlight the strengths and weaknesses of theory in describing high-N orbitals at large deformation.

PACS number(s): 27.80.+w, 23.20.Lv, 21.10.Re

From the large number of superdeformed (SD) bands observed in the $A \sim 150$ and $A \sim 190$ regions, it has become apparent that the filling of the $\nu j_{15/2}$ and $\pi i_{13/2}$ subshells plays a major role in determining the evolution of the dynamic moment of inertia $\mathcal{J}^{(2)}$ as a function of the rotational frequency $\hbar\omega$. One of the early theoretical successes in understanding the single-particle structure of SD bands was the realization that isotonic and isotopic variations of $\mathcal{J}^{(2)}$ in the $A \sim 150$ region could be quantitatively reproduced by the occupation of specific numbers of these high-N proton and neutron orbitals [1,2]. It was not immediately clear whether such effects could also be observed for SD bands in the $A \sim 190$ region since the $\mathcal{J}^{(2)}$ moments of inertia of nearly all these bands exhibit the same smooth rise with increasing $\hbar\omega$ [2]. This rise has been attributed [3,4] to the alignment of both $\nu j_{15/2}$ and $\pi i_{13/2}$ quasiparticle pairs under the stress of rotation, in the presence of pairing. However, it has proven difficult to reproduce these moments of inertia to a high degree of accuracy in standard mean-field calculations with monopole pairing. Part of the discrepancy between theory and experiment resulted from the fact that $j_{15/2}$ quasineutrons were calculated (i) to align too quickly as a function of $\hbar\omega$ and (ii) to carry more aligned angular momentum than suggested by the data. Recently, new cranked Hartree-Fock-Bogoliubov (HFB) calculations using the SkM* parametrization of the Skyrme two-body interaction [5] and cranked Woods-Saxon calculations with both monopole and quadrupole pairing terms [6] have described more satisfactorily the evolution of $\mathcal{J}^{(2)}$ in a series of even-even Hg and Pb isotopes. The latter calculation concludes that higher-order terms in the pairing interaction are critical in describing properly the evolution of the moment of inertia with rotational frequency. Nevertheless, discrepancies still remain for both models and have been attributed to the description of the aligning intruder orbitals.

Additional information on the properties of these intruder orbitals can be derived from studies of excitations built on these configurations in odd-A SD nuclei around N=112, the neutron number for which the shell gap occurs at very large deformation [2]. In ^{193}Hg, the set of low-lying quasineutron orbitals, calculated in cranked mean field calculations to lie nearest to the Fermi surface at N=113, has recently been identified by Joyce *et al.* [7], and a new SD band which is believed to be associated with the unfavored $j_{15/2}$ orbital has been discovered. It was shown that the properties of the two signature partner bands based on the $j_{15/2}$ orbital agreed well with the calculations. The present paper reports on the observation of a similar excitation based on the unfavored $j_{15/2}$ orbital in ^{191}Hg (N=111). As a result, the behavior of the $j_{15/2}$ neutron signature partner bands near N=112 can now be compared in detail with the available calculations.

The nucleus ^{191}Hg was the first in the $A \sim 190$ region in which a SD band was identified (band 1) [8], and subsequently, two other SD bands were observed in this nucleus (bands 2 and 3) [9]. It was shown that the properties of all three bands were consistent with predictions from cranked Woods-Saxon calculations with pairing [9] where bands 2 and 3 were interpreted as signature partners built on the [642]3/2 orbital, and band 1 was associated with a favored ($\alpha = -1/2$) $\nu j_{15/2}$ intruder configuration calculated to be yrast at high spins.

A new study of SD structures in ^{191}Hg has been carried out with the early implementation phase of the GAMMASPHERE spectrometer [10] which consisted, at that time, of 36 Compton-suppressed Ge detectors. The

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^{160}Gd(^{36}S,5n) and ^{174}Yb(^{22}Ne,5n) reactions at 172 and 120 MeV, respectively, were utilized with beams provided by the 88-in. Cyclotron at the Lawrence Berkeley Laboratory. In both cases, stacks of two thin, 500 μg/cm^2 self-supporting targets of isotopically enriched materials were used. A total of 500 $\times 10^6$ triple and higher order coincidence events were recorded, and the data were subsequently analyzed by sorting all events into a three-dimensional histogram. Approximately 25% of the histogrammed data was from the ^{36}S induced reaction. The remaining 75% came from the Ne + Yb data set. A separate analysis of the two data sets did indicate a small increase in the intensity with which the higher SD band members were populated in the ^{36}S data, but the overall spectral quality was found to be similar for both reactions. From the three-dimensional histogram, double-gated one-dimensional spectra were created using full background subtraction and proper propagation of errors [11]. Furthermore, fourfold coincidence events were analyzed in order to confirm the observations deduced from the double-gated spectra in instances where the latter spectra were ambiguous due to contributions from unresolved doublets or other contaminating lines.

The three previously identified SD bands [8,9] have been extended, and their feeding into the yrast states has now been determined. Furthermore, a new SD band with interesting characteristics has also been identified. The energies of the transitions in each of the four SD bands are given in Table I. Representative spectra and relative intensity patterns are presented in Fig. 1 for bands 1 and 4. Previous work [8,9] with a Au backed target where all recoils are stopped in the target, placed the intensity of band 1, with respect to the total strength in the ^{191}Hg channel, at 2% and the intensities of bands 2 and 3 at 1%. The relative intensities between these bands are confirmed in the present experiment. The newly observed band (band 4) is populated with considerably less intensity, approximately 10% relative to band 1.

The dynamical moments of inertia $\mathcal{J}^{(2)}$ for all four SD bands are plotted as a function of $\hbar\omega$ in Fig. 2. From the figure, it is clear that the values of $\mathcal{J}^{(2)}$ in band 4 are on average 10% lower than those in bands 1–3 at the lowest

TABLE I. Measured energies and associated uncertainties (in keV) for the transitions in the four SD bands of ^{191}Hg.

Band 1	Band 2	Band 3	Band 4
	252.4 (0.7)	272.0 (1.0)	
310.9 (0.7)	292.7 (0.1)	313.1 (0.2)	280.9 (0.6)
351.5 (0.1)	333.1 (0.1)	352.5 (0.1)	323.6 (0.2)
391.6 (0.4)	372.7 (0.1)	391.5 (0.4)	367.1 (0.2)
431.3 (0.1)	411.8 (0.2)	429.7 (0.1)	410.3 (0.4)
470.1 (0.1)	450.3 (0.1)	467.1 (0.2)	452.6 (0.3)
508.4 (0.1)	488.1 (0.2)	503.9 (0.1)	494.1 (0.2)
545.9 (0.2)	525.2 (0.2)	539.7 (0.3)	535.4 (0.3)
582.4 (0.1)	561.6 (0.3)	575.0 (0.1)	575.0 (0.4)
618.5 (0.2)	597.2 (0.2)	609.5 (0.1)	614.3 (0.5)
653.7 (0.2)	632.1 (0.2)	642.7 (0.2)	650.8 (0.6)
688.3 (0.2)	666.2 (0.2)	676.1 (0.3)	687.6 (0.7)
722.2 (0.3)	699.9 (0.2)	708.5 (0.3)	723.2 (0.8)
755.6 (0.3)	732.7 (0.4)	740.0 (0.3)	756.0 (1.2)
788.8 (0.6)	765.2 (0.4)	771.3 (0.3)	789.0 (1.3)
	796.5 (0.6)	(800.5) (1.0)	

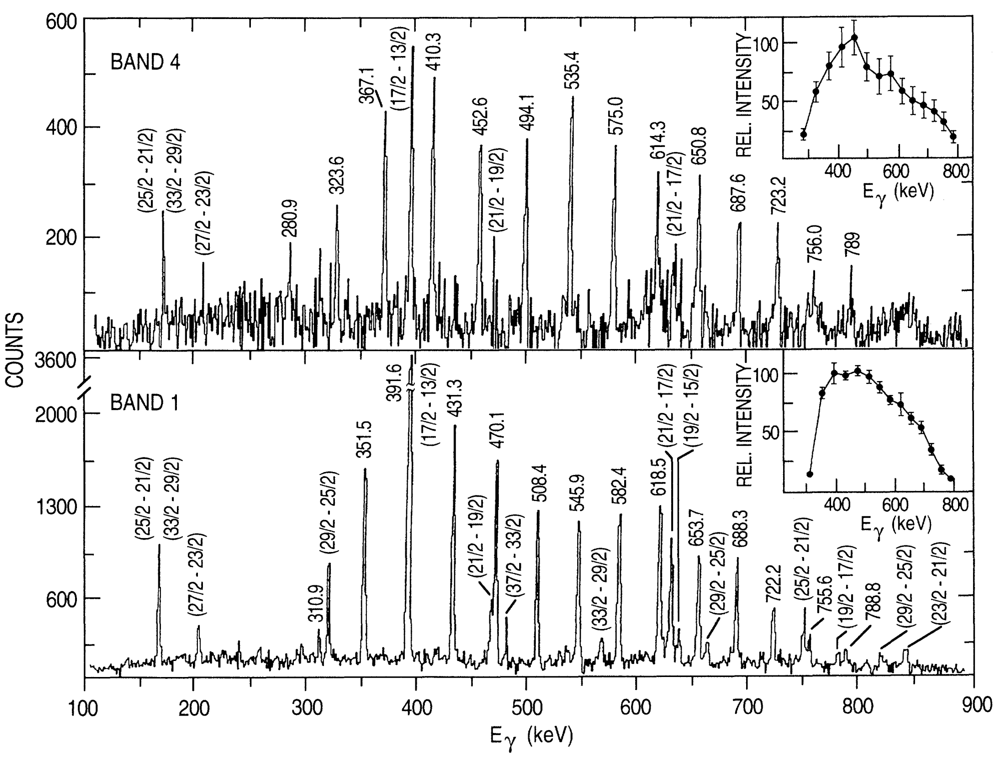

FIG. 1. Double gated spectrum for bands 1 and 4. Each member of the superdeformed band is labeled by its energy. Other transitions identified in ^{191}Hg are labeled by the spins of the initial and final levels. In the inset for each spectrum is the relative intensity profile for each band.

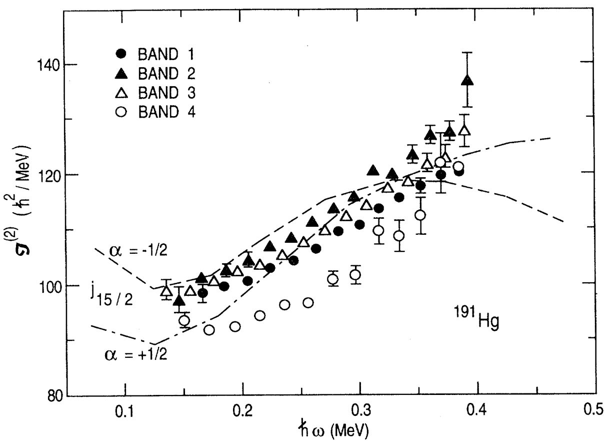

FIG. 2. Dynamical moment of inertia $\mathcal{J}^{(2)}$ $(\Delta E_\gamma/2)$ for the four SD bands observed in ^{191}Hg. Results from cranked Woods-Saxon calculations with self-consistent pairing (see text for details) are also included for the lowest-lying favored and unfavored $j_{15/2}$ intruder orbitals as dashed ($\alpha = 1/2$) and dot-dashed ($\alpha = -1/2$) curves.

frequencies. This observation is similar to that reported for band 5 in ^{193}Hg [7]. Interestingly, both new SD bands (in ^{191}Hg and ^{193}Hg) have nearly identical transition energies at the lowest and highest frequencies, but differences of as much as 8 keV occur near the middle of the bands ($0.2 \leq \hbar\omega \leq 0.35$ MeV). It has been suggested [7] that band 5 in ^{193}Hg is built on the unfavored signature of the N=7, $j_{15/2}$ neutron orbital, and that the behavior of $\mathcal{J}^{(2)}$ for the two signatures of the intruder orbital are influenced by (i) the blocking of the $j_{15/2}$ quasiparticle alignment, and (ii) the energy splitting of the two signatures which is determined by the amount of $\Omega = 1/2$ component mixed into the wave function of the two orbitals.

To investigate the impact of similar effects at N=111, the cranked shell model (CSM) calculations presented for bands 1–3 in Ref. [9] have been extended to the unfavored signature of the $j_{15/2}$ orbital. In these calculations, a Woods-Saxon potential [12] with the universal parameters of Ref. [13] was used and effects of static and dynamical pairing were calculated self-consistently by projecting good particle number at each rotational frequency. The deformation parameters ($\beta_2 = 0.475$, $\beta_4 = 0.065$, and $\gamma = 0°$) were kept fixed at each frequency. In contrast to the initial calculations of Ref. [9], where renormalizations of the pairing constants G of 60% and 120% for neutrons and protons were chosen in order to reproduce the moments of inertia of the SD bands in ^{194}Hg [4], we have used the more standard values of 90% of G for both protons and neutrons. These values have been shown to be more appropriate for SD bands in this mass region in Ref. [14]. The resulting calculated $\mathcal{J}^{(2)}$ values are given in Fig. 2, and it can be seen that the favored ($\alpha = -1/2$, dashed line) and unfavored ($\alpha = +1/2$, dot-dashed line) configurations show differences in $\mathcal{J}^{(2)}$ consistent with the data, i.e., at the lowest frequencies the unfavored signature lies lowest, but eventually crosses the favored signature at $\hbar\omega > 0.32$ MeV. Based on the analogy with the data for ^{193}Hg and on the comparison with the CSM calculations, band 4 is assigned to the unfavored signature of the $j_{15/2}$ configuration lying closest to the Fermi surface at N=111, i.e., [761]3/2. Thus, band 4 is proposed to be the signature partner of band 1.

For rotational bands in nuclei at normal deformation, it is often useful to transform the data into the rotating reference frame in order to facilitate comparisons with calculated quasiparticle routhians [16]. Such transformations cannot be carried out rigorously in the case of SD bands as they require the knowledge of spins and excitation energies, quantities which have not been firmly established in SD nuclei. Nevertheless, as was shown in Ref. [9], experimental routhians derived under reasonable assumptions facilitate the interpretation of the data. This was done recently in the case of ^{193}Hg [7]. Figure 3(a) presents experimental routhians for the four bands of ^{191}Hg. In all cases, the phenomenological representation of the rotating nuclear core was derived from a Harris fit [16] to the yrast SD band in ^{192}Hg [15].

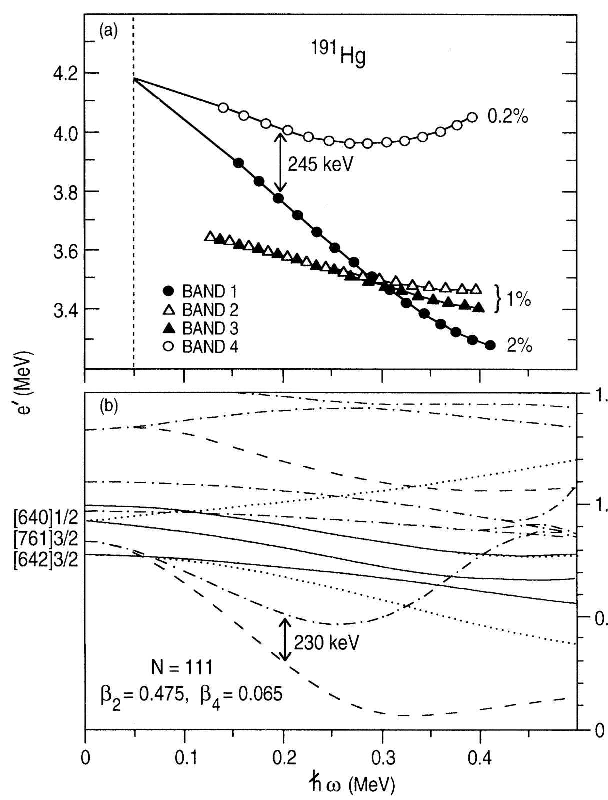

FIG. 3. (a) Experimental routhians for the four SD bands in ^{191}Hg obtained under the assumptions described in the text. For all cases the Harris parametrization [16] was taken as $E'_g(\omega) = -(\omega^2/2)\mathcal{J}_0 - (\omega^4/4)\mathcal{J}_1 + \hbar^2/(8\mathcal{J}_0)$ where $\mathcal{J}_0 = 88\hbar^2$ MeV^{-1} and $\mathcal{J}_1 = 113\hbar^4$ MeV^{-3}. The population intensities for the bands are given as a percentage relative to the total population of ^{191}Hg. (b) Results from cranked shell model calculations using a Woods-Saxon potential at N=111 with deformation parameters $\beta_2 = 0.475$, $\beta_4 = 0.065$, and $\gamma = 0°$.

For bands 2 and 3, spins were assigned using the fitting procedure outlined in Ref. [17], leading to spins for the lowest identified level in each band of 21/2 and 23/2 $\hbar$, respectively. These spin assignments are consistent with the measured average entry spins into the yrast states which have been found to be 11.4(1.4) and 12.5(1.4)$\hbar$ for bands 2 and 3. We note in addition that the signature quantum numbers which follow from the assigned spins are in agreement with the proposed quasiparticle configuration. The fitting procedure applied to bands 2 and 3 is suspect for band 1, as it does not yield half-integer spins for the levels. This is not surprising as band 1 is proposed to be based on an intruder configuration which carries alignment. Based on the fact that the measured entry spin into the yrast states for band 1 is 15.6(1.6)$\hbar$ and that the signature quantum number of the proposed configuration ($\alpha = -1/2$) further limits the spins of the band, we have assigned a spin of 31/2 $\hbar$ to the lowest level in the band. The resulting spins give an alignment relative to ^{192}Hg which is similar to that obtained for the assigned $j_{15/2}$ ($\alpha = -1/2$) band in ^{193}Hg where the spins of the corresponding levels have been determined in an independent manner [7]. Due to its weak population, an average entry spin into the yrast states could not be determined for band 4. The resulting spin assignments were made under the assumption that this band is the signature partner to band 1 as discussed above. This places the spin of the lowest level in band 4 at 25/2 $\hbar$.

The relative excitation energies of bands 2 and 3 were determined by requiring that the extrapolated energies at $\hbar\omega = 0.0$ are the same. For bands 1 and 4, the relative excitation energies were chosen such that the extrapolated energies become degenerate at $\hbar\omega = 0.05$ MeV. This requirement is motivated by the theoretical quasiparticle routhians calculated for the [761]3/2 orbital [see Fig. 3(b) and discussion below] which show that the two signatures of this orbital do not attain their maximum alignment until $\hbar\omega = 0.05$ MeV where they differ in energy by < 10 keV. (Note that similar extrapolations were proposed in Ref. [7] for ^{193}Hg.) The absolute excitation energy difference between the proposed signature pairs is of course arbitrary and is made qualitatively consistent with the measured relative population of the bands.

Figure 3(b) presents the neutron quasiparticle routhians for ^{191}Hg. These diagrams were calculated with the same Woods-Saxon potential and the same deformation parameters ($\beta_2 = 0.475$, $\beta_4 = 0.065$) used in the calculation of $\mathcal{J}^{(2)}$ presented in Fig. 2. However, no particle number projection was performed, and thus, the pair gap used at each rotational frequency ($\Delta_n = 0.66$ MeV) was the BCS value calculated at $\hbar\omega = 0$ MeV. As can be seen from Fig. 3(a), bands 1 and 4 have a signature splitting of $\Delta e' \sim$245 keV at $\hbar\omega = 0.20$ MeV, which agrees nicely with the result of the CSM calculations of $\Delta e' \sim 230$ keV at the same frequency. It should be noted that if bands 1 and 4 had been constructed in such a way that they would be degenerate at $\hbar\omega = 0.0$ MeV, the energy splitting would increase to 325 keV. In general, the trend of large signature splittings which increase with frequency is reproduced in the calculations. This gives confidence to the proposed quasiparticle assignments. A similar agreement between theory and experiment has been reported for the $j_{15/2}$ intruder pair in ^{193}Hg [7].

Even more revealing is a comparison between the experimental alignments for each band taken relative to the ^{192}Hg core and the calculated alignments for the proposed quasiparticle configurations. This comparison is summarized in Table II for each of the SD bands in ^{191}Hg along with alignments extracted for the ^{193}Hg $j_{15/2}$ intruder pair reported in Ref. [7]. The quoted alignments are average values determined from the slope of the routhian in the 0.1 to 0.3 MeV frequency range. The referencing of the experimental data to an even-even core allows for a direct comparison between experimental and theoretical single-particle alignments. The experimental alignments for the intruder orbitals in both ^{191}Hg and ^{193}Hg are reduced relative to the theoretical values which is not surprising, since the CSM calculations presented are performed at constant pairing and deformation. What is encouraging is the fact that the trends in alignment track for both experiment and theory, i.e., the favored signature at N=111 has larger alignment than it does at N=113 while the reverse is true for the unfavored signature.

Since the amount of signature splitting and alignment is dependent on the amount of $\Omega = 1/2$ component mixed into the intrinsic wave function, the fact that a consistent picture exists for the $j_{15/2}$ intruder pairs at N=111 and N=113 is noteworthy and indicates that the relative excitation energies of the $\Omega = 1/2$, 3/2, and 5/2 orbitals in the $j_{15/2}$ subshell is probably correct for the Woods-Saxon potential at large deformation. In addition, recent cranking calculations using a similar Woods-Saxon potential have shown that the use of the Lipkin-Nogami

TABLE II. Experimental and theoretical alignments for the SD bands in ^{191}Hg and for the two intruder bands of ^{193}Hg. The experimental alignments were deduced from single-particle routhians calculated using the same phenomenological core [see Fig. 3(a)], and the theoretical alignments were extracted from CSM calculations for N=111 and N=113 using the deformation parameters $\beta_2 = 0.475$, $\beta_4 = 0.065$, and $\gamma = 0°$ [see Fig. 3(b)]. All values are given in units of $\hbar$.

	^{191}Hg				^{193}Hg	
	Band 1 ($-$, $-1/2$)	Band 4 ($-$, $+1/2$)	Band 3 ($+$, $-1/2$)	Band 2 ($+$, $+1/2$)	Band 1 ($-$, $-1/2$)	Band 5 ($-$, $+1/2$)
Expt.	2.75	1.10	0.92	0.83	2.2	1.2
CSM	3.25	1.75	0.80	0.36	2.9	2.1

prescription for projecting good particle number and the inclusion of quadrupole pairing fields reduce the alignment of the $j_{15/2}$ quasiparticles [6] which is indicated by the comparison discussed above.

Bands 2 and 3 exhibit a signature splitting of 65 keV at $\hbar\omega = 0.4$ MeV which can be compared with the splitting of 210 keV derived from the theoretical routhians. This discrepancy between experiment and theory is large, but it should be noted that there are no other orbitals calculated near the Fermi surface which have similar signature splitting. Indeed, in the case of the [624]9/2 orbital $\Delta e' = 0$, while $\Delta e' > 400$ keV in the case of the [640]1/2 orbital, and the interpretation in terms of the [642]3/2 state remains the most plausible. Nevertheless, the noted discrepancy between calculated and measured splitting is sufficient to warrant more detailed comparisons between calculations and data for each band. Relative to ^{192}Hg, band 3 exhibits an alignment of nearly $1\hbar$. Furthermore, none of the transition energies in this band deviate by more than 3 keV from those of band 3 in ^{193}Hg, i.e., the two bands are "identical" and a similar alignment relative to ^{192}Hg applies to both bands. (This fact was noted in Ref. [18] and interpreted in terms of pseudospin alignment.) In the CSM calculations, the favored signature ($\alpha = -1/2$) of the [642]3/2 configuration has nearly the same average alignment as band 3 ($0.8\hbar$). Furthermore, the slope of the routhian is nearly constant with $\hbar\omega$, i.e., the orbital is calculated to contribute little to the dynamical moment of inertia of the core. Thus, the values of $\mathcal{J}^{(2)}$ for band 3 are expected to track those of ^{192}Hg closely, and these considerations reinforce the assignment of band 3 to the favored signature of the [642]3/2 configuration.

In contrast to band 3, the situation is less clear for band 2. Indeed, as can be seen in Table II, the discrepancy between the measured alignments and those calculated for the unfavored signature ($\alpha = +1/2$) of the [642]3/2 orbital is rather large. This fact coupled with the discrepancy in signature splitting makes the assignment of band 2 less straightforward. In this context, the situation is different from that seen in ^{193}Hg, where bands could be firmly assigned as signature partners because $M1$ transitions linking the proposed signature partners were seen [19,20]. For bands built on the [642]3/2 orbital, the $B(M1)$ rates are calculated to be small [21], and similar linking transitions are not expected to compete with the $E2$ in-band γ rays. This situation then leads us to consider another possible interpretation of band 2. In the quasiparticle diagram of Fig. 3(b), the [642]3/2 orbital is crossed at high frequency ($\hbar\omega \sim 0.35$ MeV) by the favored ($\alpha = +1/2$) signature of the [640]1/2 orbital. The latter orbital is characterized by an average alignment of $0.7\hbar$. Because of the similarity in calculated alignments and the near constant slopes in Fig. 3(b) of the routhians associated with the favored signatures of the [642]3/2 and [640]1/2 orbitals, the γ-ray energies of SD bands corresponding to these configurations will be such that the bands may appear to behave as signature partners at low frequencies, while in fact they are not. Coupling these observations with the fact that identical SD bands built on different configurations have been observed in ^{193}Hg [20], an interpretation where band 2 is associated with the favored [640]1/2 orbital cannot be ruled out. If this scenario is correct, the unfavored signature partners to the [642]3/2 and [640]1/2 orbitals remain to be observed.

In summary, a new superdeformed band has been observed in ^{191}Hg with properties suggesting that it is associated with the unfavored $j_{15/2}$ intruder orbital. A similar band has recently been reported in ^{193}Hg and was given the same assignment. The extracted signature splitting between the favored and unfavored $N = 7$ orbitals is consistent with CSM calculations using a Woods-Saxon potential. The splitting is also larger than that observed in ^{193}Hg, an observation which is consistent with theoretical predictions. The experimental alignments of the intruder orbitals are reduced relative to the calculated values, and this has been related to known inadequacies of the model. While the previous assertion [9] that bands 2 and 3 are signature partners built on the [642]3/2 quasiparticle configuration is still the most likely explanation of the data, an alternative interpretation which associates band 2 with the favored signature of the [640]1/2 orbital can at present not be ruled out. From the present study and the one on ^{193}Hg of Ref. [7], it can be seen that the calculated quasineutron spectrum for the Hg isotopes in the vicinity of the $N = 112$ gap provides a fair description of the SD bands. However, discrepancies still remain which point to the necessity of using a more sophisticated approach to the pair correlations.

This work was supported by the DOE under Contracts Nos. W-31-109-ENG-38, DE-AC03-76F00098, W-7405-ENG-48, DE-FG05-88ER40441, and the NSF.

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