Collective and quasiparticle excitations in superdeformed ^{190}Hg

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Superdeformed (SD) states of ^{190}Hg have been studied with the Eurogam Phase 2 γ-ray spectrometer using the ^{160}Gd(^{34}S,4n) reaction. Two new excited SD bands have been found and identified as belonging to this nucleus, bringing the total number of SD bands in ^{190}Hg to 4. One of the new bands has a dynamic moment of inertia that is very similar to that of the yrast SD band of ^{190}Hg and most other SD bands in the $A\sim 190$ region. In contrast, the other band has a dynamic moment of inertia which is mainly constant as a function of rotational frequency and exhibits a dramatic increase at the lowest frequencies. The observed dynamic moments of inertia are compared with the results of random phase approximation calculations based on the cranked shell model. Finally, the known excited SD band has been extended towards lower frequencies and new transitions have been found linking this band to the yrast SD band. The extracted $B(E1)$ values of the new linking transitions give further support for the possible octupole vibrational character of this band. [S0556-2813(96)00908-9]

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I. INTRODUCTION

It is well known that excited bands of deformed nuclei can be built on collective vibrational states as well as on single-particle or quasiparticle excitations. Since the first observation of discrete superdeformed (SD) bands [1,2], about 70 excited SD bands have been found in nuclei in various regions of the nuclear chart. However, only in two cases has it been suggested that an excited SD band is built on a collective vibrational state. One of these is the first excited SD band in ^{190}Hg [3,4], while the other is an excited SD band in ^{152}Dy [5,6]; both cases are thought to correspond to octupole vibrational bands. It is the direct decay of these SD bands to the yrast SD bands which distinguishes them from other excited SD bands. The transitions linking the bands have only been identified in ^{190}Hg [4] and therefore this is the only case in which the evidence for this collective behavior is direct.

The presence of octupole correlations within the superdeformed well has been predicted by various theoretical calculations [7]. In fact, it has been suggested that for nuclei in the $A\sim 150$ and $A\sim 190$ regions octupole vibrational modes will play a more important role in the second minimum than in the first. Random phase approximation (RPA) calculations by Nakatsukasa *et al.* [4,8] suggest that the lowest excited states in ^{190}Hg will be based upon octupole vibrational modes. These states are expected to be at excitation energies such as are now becoming accessible experimentally, due to the advent of the new generation of large γ-ray detector arrays with much improved detection efficiency such as Eurogam Phase 2 and Gammasphere [9]. One of the experimental signatures predicted for such modes is the existence of strong electric dipole transitions connecting the excited octupole vibrational states to yrast SD states [6].

An excited superdeformed band was found in ^{190}Hg in an experiment performed at the Lawrence Berkeley National Laboratory with the early implementation phase of the Gammasphere array [3]. In this experiment, this excited SD band in ^{190}Hg was observed to decay into the yrast SD band, although the transitions linking the bands were not identified. A subsequent experiment with the Eurogam Phase 2 array resulted in the direct observation [4] of a series of three to four dipole transitions connecting this excited band to the

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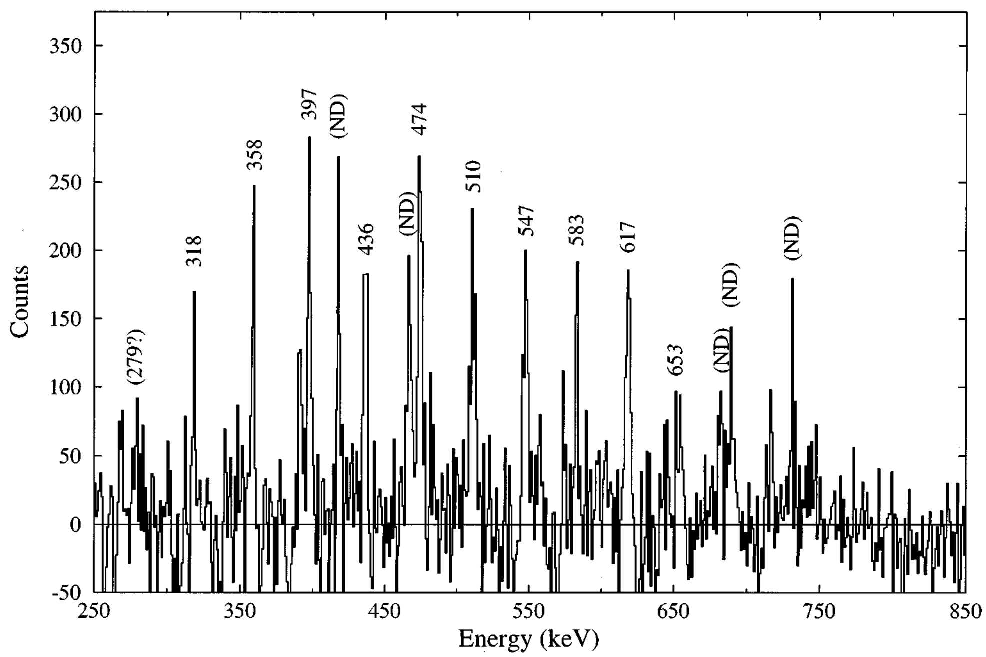

FIG. 1. Spectrum obtained by triple gating on band 3. Band members are labeled with their energies while known transitions from the normal-deformation decay scheme are labeled ND.

yrast band. The observed dynamic moment of inertia and Routhian of this band are in good agreement with RPA calculations for the lowest octupole vibrational mode. In this paper, we report on the observation of two new excited bands in ^{190}Hg, which provide a further test of the role of collective vibrations in the excited SD states in this nucleus. We also report on the extension of the previously known [3] excited SD band to lower frequencies and the identification of two new candidate transitions linking this band to the yrast SD band.

II. EXPERIMENTAL PROCEDURE

High angular momentum states in ^{190}Hg were populated via the ^{160}Gd(^{34}S,4n) reaction at a beam energy of $\approx$155 MeV. Gamma rays were detected with the Eurogam Phase 2 spectrometer [9]. This spectrometer consisted of an array of 54 escape-suppressed germanium detectors, 30 of which were large volume coaxial detectors [10] positioned at forward and backward angles with respect to the beam. The remaining 24 detectors, arranged in two rings close to 90° to the beam direction, were four-element clover detectors [11]. The ^{34}S beam, provided by the Vivitron accelerator (CRN Strasbourg), was incident upon two stacked, self-supporting targets of isotopically enriched ^{160}Gd, each of a thickness of $\sim$ 0.5 mg/cm^2. Events were written to tape when more than three escape-suppressed detectors in the array detected γ rays within the coincidence time window. (For this condition, the clover detectors were treated as a single detector.) Approximately 5×10^8 such events were recorded, of which about 80% were from the 4n reaction channel. When two elements in a single clover detector registered γ rays in the same (escape-suppressed) event, the energies recorded by each element were added in the off-line analysis to obtain a single γ-ray energy.

III. DATA ANALYSIS AND EXPERIMENTAL RESULTS

A. Two new excited bands

The events were sorted into an ungated three-dimensional array (a ''cube'') containing $\sim2.5\times10^9$ triple γ-ray coincidence events. SD structures were searched for using an automated band-searching program capable of searching for bands with varying dynamic moments of inertia. Two new excited SD bands (labeled bands 3 and 4 hereafter) have been found, both of which are weaker than the previously known [3,4] excited SD band (band 2). These bands have almost identical transition energies above $\sim$540 keV. Double and triple γ-gated coincidence matrices were then sorted, with gates corresponding to the energies of the new bands, using the method prescribed by Beausang *et al.* [12]. Spectra of the two new bands obtained from these matrices are shown in Figs. 1 and 2. Both bands can be definitely assigned to ^{190}Hg on the basis of transitions established in the normal decay scheme [13] which are seen in coincidence with them.

It can be seen from Fig. 1 and Table I that the energy spacings between successive transitions in band 3 vary smoothly just as in most SD bands in the $A\sim190$ region. In contrast, strong variations are present in the lowest part of the sequence in band 4: The spacing varies from 20 to 30 keV within the 446-467-487-515 keV part of the sequence before becoming constant higher in the band with $\Delta E_\gamma\approx35$ keV. It should be noted that the 467 keV and 487 keV lines are both contaminated by transitions placed in the yrast and the near-yrast decay scheme. The information reported in Table I was carefully checked under different gating conditions. Because of the low intensity of the two new bands (and the contamination of some of the band members by transitions associated with the normal decay of the nucleus), it has not been possible to establish the multipole character of the transitions experimentally. However, the two bands have the general characteristics common to many SD bands

TABLE I. Energies and relative intensities of the four superdeformed bands.

Band 1		Band 2		Band 3		Band 4	
E_γ (keV)	I_γ	E_γ (keV)	I_γ	E_γ (keV)	I_γ	E_γ (keV)	I_γ
316.9 (4)	5.9 (1.1)	481.1 (6)	3.1 (1.0)	(279)	(≤1)	446.3 (4)	9 (2)
360 (1)	64 (3)	511.4 (4)	8 (2)	318.0 (3)	2.2 (1.2)	466.5 (4)	14 (4)
402.34 (4)	100 (17)	543.2 (3)	17 (3)	358.3 (4)	3.0 (1.3)	486.7 (4)	14 (4)
442.98 (6)	100 (8)	575.6 (2)	20 (4)	397.4 (4)	3.9 (1.0)	515.0 (4)	14 (3)
482.71 (6)	100 (9)	608.1 (3)	22 (4)	435.9 (4)	4.1 (1.0)	547.7 (4)	14 (3)
521.30 (6)	100 (9)	641.6 (3)	19 (4)	474.0 (5)	4.1 (1.1)	582.7 (4)	14 (4)
558.6 (1)	81 (8)	674.5 (5)	10 (3)	510.6 (4)	4.0 (1.0)	617.7 (4)	14 (4)
594.9 (1)	70 (12)	707.1 (6)	4 (1)	547.7 (8)	3.2 (1.1)	653.6 (4)	11 (3)
630.1 (1)	50 (14)			582.9 (7)	2.1 (1.2)	689.6 (6)	6 (2)
664.1 (1)	40 (5)			617.9 (7)	1.1 (0.9)	723.3 (6)	3.9 (1.2)
696.9 (1)	25 (4)			651.5 (7)	≤0.5	760.4 (6)	1.1 (1.0)
728.5 (4)	14 (4)					(791)	(≤1)
757.4 (4)	6 (2)						
783.5 (6)	2.1 (1.2)						
(801.8 (8))	(≤1)						

in this mass region (e.g., γ-ray spacing, frequency range in which they are observed) and in fact have transition energies nearly identical to those of other SD bands, most notably SD band 1 in ^{191}Hg. On the basis of these similarities the two new structures observed here are assumed to be SD bands composed of stretched $E2$ transitions.

No connecting transitions from either of the two new bands to other SD bands or to the normally deformed states have been found, although there are some indications that band 4 may have a weak decay branch to band 1. The peaks suggesting this feature are marked in Fig. 2 with solid triangles. An analysis comparing these peaks to the background fluctuations in this region of the spectrum is inconclusive: They are on the margin of statistical significance. Therefore

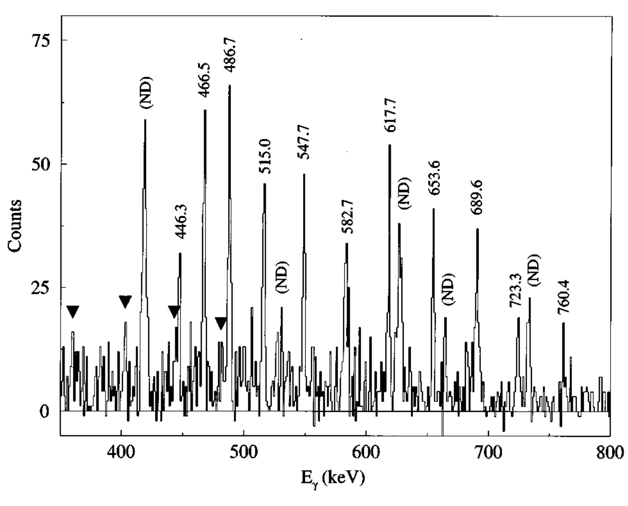

FIG. 2. Spectrum obtained by quadruple gating on band 4. Band members are labeled with their energies, transitions established in the normal decay are labeled ND, and transitions thought to arise from coincidence with band 1 are labeled with solid triangles. As indicated in the text, the presence of the latter transitions is considered to be only a possibility in view of the available statistics.

it must be stressed that the evidence for this decay path remains only tentative.

To estimate spins for the levels in the new bands by looking at the spins of the levels in the normal deformed region into which they appear to decay is difficult because of the contaminating (467, 487, 616, and 692 keV) transitions from the normally deformed states. However, the existence of a relatively highly populated, 12^+, yrast state in the normally deformed portion of the decay scheme gives some guidance as to the difference in spins between bands 1 and 4: The presence of at least three peaks (at 420, 664, and 789 keV) corresponding to transitions known to be above this isomer in the spectra gated on band 4 suggests that the average spin at which this band decays to the normal deformed states is at least $4\hbar$ higher than for band 1. Using the spin-fitting procedure prescribed by Becker *et al.* [14] one obtains a spin of 14 $\hbar$ for the lowest level in band 3 and, for a given rotational frequency, band 3 appears to have a spin higher than band 1 by $2\hbar$. It is not possible to use this fitting procedure to estimate the spins of band 4 as the moment of inertia is not a smooth function of rotational frequency in this case.

B. New transitions linking band 2 to band 1

The data were also sorted into a second cube suitable for analysis using the RADWARE code [15]. This analysis package was used to extract the relative intensities of the four SD bands and of the transitions linking the first excited band SD (band 2) to the yrast SD band (band 1). The relative intensities of the four bands are listed in Table I along with the measured transition energies. The intensities of the linking transitions are listed in Table II (normalized to the total intensity of band 1). A close inspection of this cube also suggested the presence of an additional transition in band 2 as well as new linking transitions between bands 2 and 1. Figure 3 gives the relevant portion of the level scheme for bands 1 and 2. Transitions marked with dotted lines are of intensities which put them at the limits of the sensitivity of the array, but for which all possible consistency checks from the

TABLE II. Energies, intensities, and $E1$ strengths of the linking transitions.

E_γ (keV)	I_γ	$B(E1)$ (mW.u.)
702 (1)	3 (2)	1.5 (10)
757 (1)	6 (2)	1.9 (7)
812 (1)	7 (2)	1.5 (6)
864 (1)	8 (2)	2.3 (7)
910.9 (3)	6 (2)	2.9 (13)
950.8 (3)	3 (1)	$\geqslant$0.9

coincidence spectra suggest that the proposed placement is correct. Figure 4 shows the existence of a 951 keV line which is in coincidence with band 1 transitions up to and including the 483 keV transition and also with the lowest band 2 transitions. Figure 4 shows sections of double-gated spectra where the energies have been detected in coincidence with at least one member of band 2 and at least one member of band 1. The coincidence gates required for each spectrum are listed in the form (list1)vs(list2), where the energies in list1 are the gates set using band 1 transitions and the energies in list2 are the gates set using band 2 transitions. The dotted lines superimposed on the data represent the expected spectra as calculated from the proposed SD level scheme with the RADWARE code. It can be seen that the agreement between the calculated spectra and the observed spectra is satisfactory. In these spectra, no attempt has been made to model the depopulation of the SD bands to the normal deformed states, and thus there is no fit for the normal deformed peak occurring at 840 keV, which appears in all the spectra in the inset. The presence of a weak 481 keV transition in band 2 (below the 511 keV transition) was also inferred from the data. Although it has not been possible to resolve the 481 keV and 483 keV transitions in the spectra, a shift in the centroid of the peak by approximately 0.5 keV has been observed in the appropriate gates, corresponding to a contribution to the spectrum from a lower energy transition. The peak areas calculated from the proposed level scheme agree well with the measured intensities.

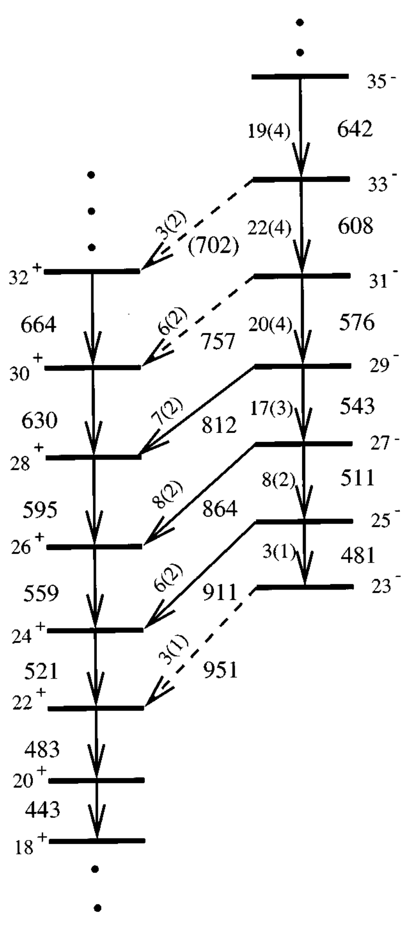

FIG. 3. Proposed level scheme for SD bands 1 and 2 in ^{190}Hg. The absolute spins for these bands have not been firmly established, but the difference of $1\hbar$ between states in bands one and 2 is quite firm.

Similarly, the observed coincidence relations confirm the existence of the 757 keV $(31^-)\rightarrow(30^+)$ transition proposed in [4] and suggest an additional transition of energy 702 keV linking the (33^-) level of band 2 to the (32^+) level of band 1. The existence of this last transition could not be definitely established from the data, as it lies at the limits of the sensitivity of the array; however, the calculated spectrum as a whole fits the observed spectrum better if this weak branch is allowed.

IV. DISCUSSION

A. Cranked shell model calculations

Although the possibility of octupole correlations in the superdeformed well has been the subject of many theoretical investigations [7], the experimental evidence for the occurrence of this phenomenon has until recently been indirect. Calculations based on the random phase approximation (RPA) [4,8] have suggested that of the mercury isotopes, superdeformed ^{190}Hg should display the characteristics of octupole collectivity at the lowest excitation energy. The eigenvalues of the total Routhians for seven of the lowest negative parity states predicted by these calculations are shown as functions of rotational frequency in Fig. 5. These calculations use the cranked Nilsson potential and include both quasiparticle excitations and octupole collectivity. The pairing gaps were assumed to be constants and were taken as $\Delta_n=0.8$ MeV and $\Delta_p=0.6$ MeV at $\hbar\omega=0$, and the deformation parameter ϵ was set to be 0.44. This deformation was chosen to reproduce the frequency of the experimentally observed crossing of the $j_{15/2}$ neutrons, which is partially responsible for the rise in the dynamic moment of inertia seen throughout the $A\sim190$ region [16]. The degree of collectivity for each state is indicated in Fig. 5 by the size of the symbol, so that those states calculated to have a large $E3$ transition amplitude (greater than 200 e fm^3) are represented by the smallest symbols, those with an intermediate $E3$ transition amplitude (i.e., between 100 e fm ^{3} and 200 e fm ^{3}) have intermediate-sized symbols, and the noncollective states (with $E3$ amplitudes of less than 100 e fm^3) are indicated by the largest symbols.

At rotational frequency $\hbar\omega=0$, the first excited states are predicted by these calculations to be purely vibrational in

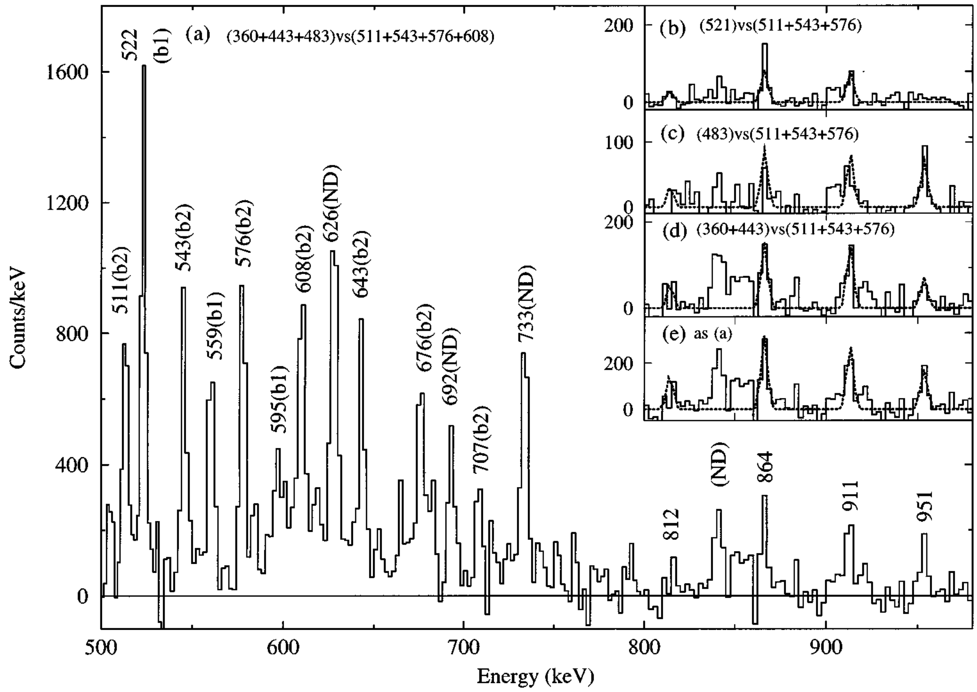

FIG. 4. Spectra identifying the higher energy linking transitions. The main figure is obtained by setting gates on members of band 1 and band 2. The gates are given in the form (list 1)vs(list 2), indicating that the γ rays in the spectra have come in coincidence with at least one member of list 1 and at least one member of list 2. The inset shows a series of similar spectra with slightly varied gating conditions, with the gates given in the same format so that, for example, the list (521)vs(511+543+576) indicates that all γ rays indicated in the spectrum are in coincidence with the 521 keV transition and at least one of the 511, 543, or 576 keV transitions. The solid lines represent observed intensities, the dotted lines those calculated from the proposed SD level scheme. The decay of the SD bands into the normal states of the nucleus has not been taken into account in the fit and thus the peak corresponding to the 840 keV transition in the normal decay is not fitted in any spectrum.

character. As the frequency increases, the various octupole states will be mixed by the increasing effect of the Coriolis force. Furthermore, the quasiparticle excitations which are at first located at higher excitation will be brought lower in excitation energy until eventually they become favored. As the SD bands in this mass region extend to relatively low rotational frequencies, octupole correlations should be expected to have a strong influence on the behavior of any excited SD band observed in this nucleus. It can be clearly seen from Fig. 5 that there is an $\alpha=0$ (α is the signature quantum number) noncollective band (indicated by large black triangles) which becomes rapidly favored as the rotational frequency increases, crossing several of the collective bands. The presence of this ''intruding'' noncollective band among the initially lower collective states should have a marked effect on the properties of bands which it crosses and should give an added indication of how important octupole correlations are in the behavior of superdeformed ^{190}Hg.

Calculations which do not include a contribution from collective modes predict that the first excited state in SD ^{190}Hg will be built upon the positive-parity two-quasiparticle configuration involving the two $N=7$ neutron levels close to the Fermi surface. The structure of the two-quasiparticle states produced by these calculations is very different from that shown in Fig. 5. Perhaps the most important difference between the two descriptions lies in the fact that when no vibrational states are considered, there are no level crossings at low excitation energies or rotational frequencies. The aligned two-quasiparticle band described above has the same parity as the vibrational states which it is brought down among; therefore as this state comes down in energy, it interacts with all states of the same signature. For pure quasiparticle calculations, similar behavior is not seen. Thus one would expect to be able to tell whether octupole vibrations play a part in defining the band structure of SD ^{190}Hg from the behavior of the low-lying excited states.

B. Evidence for the octupole vibrational nature of band 2

The initial results of the present experiment [4] established the existence of links between the first excited SD band (band 2) and the yrast SD band in ^{190}Hg. These links established the relative excitation of band 2 with respect to band 1 to be close to 1 MeV. An analysis of the angular correlations suggested that the linking transitions were of dipole character and therefore established the difference in spin between states in the two bands as, most likely, $1\hbar$. The results reported here show the possible existence of new linking transitions at both lower and higher spins. On the assumption that the assignment of the multipolarity of the original linking transitions is correct, $B(E1)$ values for all the γ rays can be derived from the following expressions:

$$\frac{B(E1)}{B(E2)}=\frac{1}{1.3\times10^{6}}\frac{E_{\gamma}^{5}(E2)}{E_{\gamma}^{3}(E1)}\frac{I_{\gamma}(E1)}{I_{\gamma}(E2)}\quad(\mathrm{fm}^{-2}) \qquad (1)$$

and

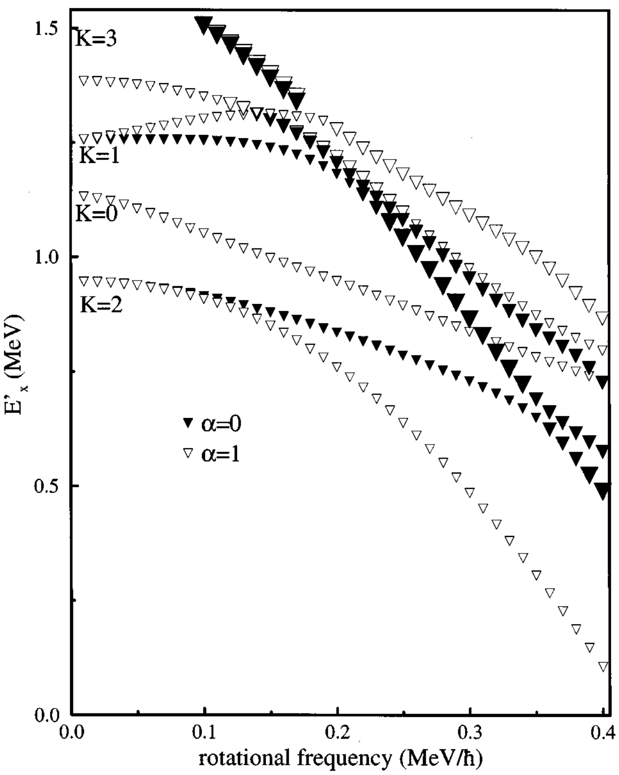

FIG. 5. Eigenvalues of the RPA calculations for the lowest seven excited states in ^{190}Hg, calculated relative to the yrast SD band. The solid triangles indicate states with $\alpha=0$; the open triangles indicate states with $\alpha=1$. The size of the symbols is intended to give an approximate guide to the collectivity of particular states: Small triangles represent states which are strongly collective (i.e., with an $E3$ transition amplitude greater than 200 $e\,\mathrm{fm}^3$), medium-sized triangles represent weakly collective states (i.e., with an $E3$ amplitude between 100 $e\,\mathrm{fm}^3$ and 200 $e\,\mathrm{fm}^3$), and large triangles noncollective states (i.e., those with an $E3$ amplitude less than 100 $e\,\mathrm{fm}^3$). Pairing gaps are fixed at $\Delta_n=0.8$ MeV and $\Delta_p=0.6$ MeV).

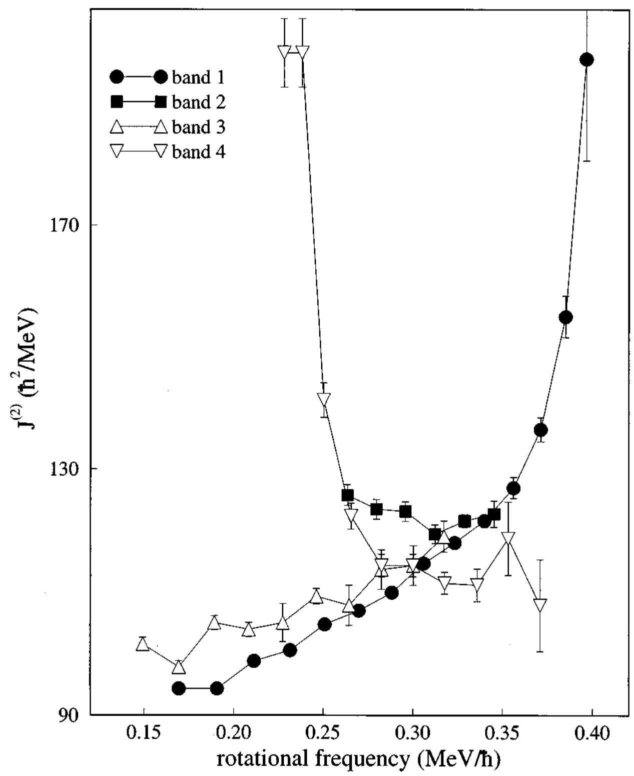

FIG. 6. Experimental dynamic moments of inertia ($\mathfrak{J}^{(2)}$) as a function of rotational frequency for the four SD bands in ^{190}Hg.

$$B(E2)=\frac{5}{16\pi}Q_0^2|\langle IK20|(I-2)K\rangle|^2, \qquad (2)$$

using the measured [17] quadrupole moment for band 1 [$Q_0=18(3)$ e b] and assuming that band 2 has the same quadrupole moment.

The $E1$ strengths obtained in this way are given in Table II along with the intensities of the linking transitions. Raising or lowering the spin assignments for the levels by a few units does not significantly affect the $B(E1)$ values within the experimental errors. The strengths of the known linking transitions obtained here are consistent with those obtained in the previous analysis [4]. $E1$ transitions can only favorably compete with very strong in-band $E2$ transitions if the nucleus has a transition dipole moment arising from octupole vibrations.

If the linking transitions are assumed to be magnetic dipole transitions, then $M1$ strengths can be extracted in a similar manner. Whereas the strengths calculated for electric dipole transitions are of the order of 1×10^{-3} Weisskopf units (W.u.), $M1$ transitions of the same energies and intensities would have to be of the order of 0.1 W.u. $M1$ transitions of such strength (and indeed stronger) are observed in SD nuclei between strongly coupled signature-partner bands [18]; however, this is not the situation in ^{190}Hg. In this nucleus, the yrast band is presumably a paired, positive-parity band built on the vacuum state, in which case any excited bands (unless they are built on collective vibrations) will involve a different quasiparticle configuration. $M1$ transitions of this strength are extremely unlikely to be configuration-changing transitions. Thus it seems most probable, given the consistency of the extracted $E1$ strengths, that these transitions are indeed of electric dipole character. This lends additional support to the argument [4] that band 2 is best explained in terms of the lowest octupole vibrational mode, which can be identified as the ($K=2$, $\alpha=1$) mode at low frequencies.

C. Dynamic moments of inertia

A feature of band 2 that initially suggested that this band might have some unusual properties is the behavior of its dynamic moment of inertia ($\mathfrak{J}^{(2)}$) [3]. Figure 6 shows the $\mathfrak{J}^{(2)}$ values associated with each of the four SD bands in ^{190}Hg as a function of rotational frequency. Band 1 has a $\mathfrak{J}^{(2)}$ moment which is typical of SD bands in even-even nuclei in the $A\sim190$ region [16]. It displays a smooth increase with rotational frequency, which is understood to be due to the combination of three effects [17]: the gradual alignment of a pair of $j_{15/2}$ neutrons, the alignment of a pair of $i_{13/2}$ protons at a somewhat higher frequency, and decreasing pairing correlations with increasing rotational frequency. As

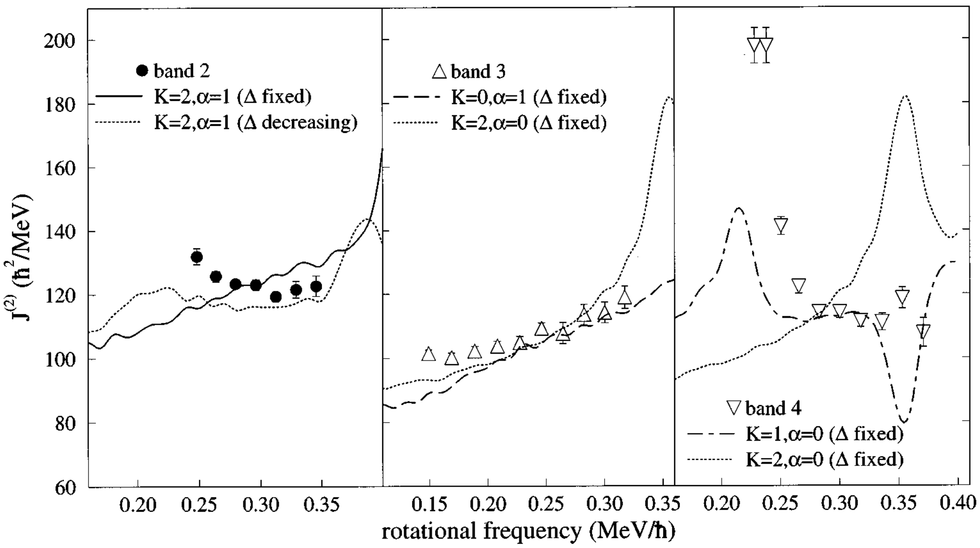

FIG. 7. Comparison between some of the predicted dynamic moments of inertia and the experimental data for (a) band 2, (b) band 3, and (c) band 4.

was mentioned earlier, cranked shell model (CSM) calculations without an octupole vibrational component suggest that the first quasiparticle excitation available in ^{190}Hg would involve the occupation of both the $N=7$ orbitals which lie close to the Fermi surface. This would result in a SD band with a $\mathfrak{J}^{(2)}$ moment of intertia with a reduced slope compared with that of band 1 and a slightly higher overall magnitude at lower frequencies. Clearly the $\mathfrak{J}^{(2)}$ moment of band 2 is completely different: Its average value is large, and instead of rising with frequency, it displays a gradual, small reduction. Figure 7(a) presents a comparison between the theoretical $\mathfrak{J}^{(2)}$ values for the lowest octupole vibrational mode obtained in the RPA calculations (see Fig. 5) and the measured values for this band. Although the detailed behavior of the band is not accurately reproduced by the calculations performed with fixed pair gaps, the overall magnitude is. If pairing is allowed to reduce dynamically with increasing frequency, the agreement between calculation and data is much improved.

The behavior of the $\mathfrak{J}^{(2)}$ moment of band 3 is very similar to that of band 1; however, there are some minor differences. At low frequency its magnitude is slightly larger and the increase with $\hbar\omega$ is a little less pronounced. When comparing this behavior to the results of the RPA calculations with fixed pair gaps, one can see from Fig. 7(b) that there is reasonable agreement with the second excited octupole state ($K=2$, $\alpha=0$, i.e., the signature partner of band 2) over most of the frequency range in which band 3 is observed. (Although the K values are only strictly appropriate as $\hbar\omega\to 0$, they will be used as labels for the states which can be identified with them at $\hbar\omega=0$ throughout this discussion.) However, there is no sign of the calculated sharp rise above $\hbar\omega=0.3$ MeV. Also, the $K=2$, $\alpha=0$ state is predicted to be the next available excitation above the $K=2$, $\alpha=1$ state (see Fig. 5): Thus one would expect that if band 3 was based upon this state, it would be more strongly populated than is experimentally the case (although there is signature splitting between the two $K=2$ modes, it is not sufficient to explain the large difference in the intensities of the two bands). Similarly, one would not expect to observe any other excited bands with intensities in between those of band 2 and band 3. This is not the case here, as the intensity of band 4 is closer to that of band 2 than the intensity of band 3. Thus it is mainly on the grounds of these intensity considerations that one is not inclined to assign the $K=2$, $\alpha=0$ configuration to band 3. The $\mathfrak{J}^{(2)}$ behavior is also fairly well reproduced by the calculations for the $K=0$, $\alpha=1$ mode. However, this mode is predicted to have a strong decay branch to the yrast band. There is no evidence for such a decay path in the data. This might imply that band 3 is built on a two-quasiparticle excitation and does not involve octupole correlations at all. It must not be forgotten that the energy levels shown in Fig. 5 are only for the negative-parity states (there will be no positive-parity one-phonon octupole vibrational states). It is possible that the lowest positive-parity two-quasiparticle excitations are populated at lower excitation energies than the higher vibrational states. Presumably the first positive-parity two-quasiparticle state will involve the occupation of both signatures of the $7_{3/2}$ neutron orbitals. The $\mathfrak{J}^{(2)}$ moment of such a band would be expected to display behavior similar to that of band 3; however, this band is not observed to high frequencies and therefore it has not been possible to observe whether the crossing of the $N=7$ orbitals, responsible for the rapid rise in the $\mathfrak{J}^{(2)}$ moment of band 1 towards higher frequencies, also occurs for this band. Clearly, in view of this situation, no definite configuration assignment for band 3 can be made.

Band 4, like band 2, has a dynamic moment of inertia that bears little resemblance to those typical of this mass region. It is approximately constant in the $\hbar\omega=0.25$–0.40 MeV frequency range (in this respect it is similar to band 2), with an average value of $\sim 113\hbar^2$/MeV. At the lowest frequencies, below $\hbar\omega=0.23$ MeV, it shows a dramatic increase in $\mathfrak{J}^{(2)}$ reaching values of almost $200\hbar^2$/MeV. This rise in the $\mathfrak{J}^{(2)}$ moment suggests a sudden change in alignment due to a band crossing.

The RPA calculations predict that crossings will occur at frequencies around $\hbar\omega=0.23$ MeV between the band based on the $\alpha=0$ signature of the $K=1$ mode and a two quasiparticle band involving the occupation of the favored $N=7$ and the unfavored $N=6$ neutron orbitals. The crossing frequency is very much dependent on the pairing forces included in the calculations. Above the crossing, the two-quasiparticle excitation is favored. For such a configuration, in which only one of the pair of $N=7$ orbitals is occupied, the alignment of these orbitals is blocked [16] and thus one would expect the associated $\Im^{(2)}$ moment to be relatively constant as a function of frequency. This is in good agreement with the observed behavior of band 4. Figure 7(c) shows a comparison between the $\Im^{(2)}$ moments calculated for the vibrational state which can be identified with the $\alpha=0$ signature of the $K=1$ mode at $\hbar\omega=0$ and that of band 4. It can be seen that the predicted interaction between the $K=1$ state and the two-quasiparticle state is slightly stronger than that observed here.

Although the agreement between the calculated behavior of this configuration and the experimentally observed characteristics of band 4 is fairly good, there is another possibility which must be considered. The calculations have been performed with fixed pairing gaps ($\Delta_n=0.8$ MeV, $\Delta_p=0.6$ MeV); if these gaps are allowed to reduce dynamically with increasing rotational frequency, all the band crossings are lowered and the crossing between the two-quasiparticle state and the $K=2$, $\alpha=0$ mode is brought down to approximately $\hbar\omega=0.28$ MeV. This interaction is weaker than that involving the $K=1$ state and thus the rise in the calculated $\Im^{(2)}$ moment will be sharper. Therefore it is possible that band 4 may be the signature partner of band 2.

If band 4 is based on a vibrational state at low frequencies, one might expect to observe some decay (over a smaller frequency range than band 2) into band 1. The experimental evidence for such a branch is very weak; however, the calculations for the $K=2$, $\alpha=0$ state suggest that in this case the decay to the yrast SD band should be much weaker than that which is seen to occur for band 2. Taken with the unusual behavior of the $\Im^{(2)}$ moment, it seems that the properties of band 4 are consistent with it being built upon either the $K=1$, $\alpha=0$ mode or the $K=2$, $\alpha=0$ mode at low frequencies. At higher frequencies, band 4 is built upon a two-quasiparticle excitation involving the occupation of the unfavored (positive) signature of the $N=6$ neutron orbital and the negative signature of the $N=7$ neutron orbital.

V. CONCLUSIONS

Two new excited SD bands (bands 3 and 4) have been observed in ^{190}Hg, bringing the total number of SD bands observed in this nucleus to 4. One of these bands, band 3, is probably the weakest SD band yet observed in the $A\sim190$ region, with an intensity comprising about 0.04% of the total intensity of the reaction channel. This band displays the general properties associated with the majority of SD bands in the mercury isotopes. The other new band, band 4, exhibits a crossing at low frequency ($\sim$0.23 MeV) and has a fairly constant dynamic moment of inertia at higher rotational frequencies.

Two of the excited SD bands in this nucleus (bands 2 and 4) display unusual properties which cannot be explained considering only quasiparticle excitations. The decay of band 2 to the yrast band (and its large value of $\Im^{(2)}$) indicated the possible presence of octupole vibrational modes [4]. All three excited SD bands have been discussed here, and it has been shown that it is possible to account for their behavior consistently within the framework of RPA calculations including an octupole vibrational component. Band 2 has been associated with the lowest octupole vibrational mode (with $K=2$ and $\alpha=1$ at zero rotational frequency). Band 3 is thought to be a positive-parity two-quasiparticle excitation, most likely involving the occupation of the two signatures of the $N=7$ neutron orbital. The band crossing which perturbs band 4 at lower frequencies is interpreted as a crossing between an octupole vibrational mode and a two-quasineutron excitation involving the occupation of the unfavored $N=6$ orbital and the favored $N=7$ intruder orbital.

From all the available evidence ^{190}Hg can be regarded as the superdeformed nucleus which exhibits most clearly the properties associated with collective excitations. It will be interesting to see if similar excitations can also be found, not only in other nuclei of the $A\sim190$ region of superdeformation, but also in nuclei of the $A\sim80$, 130, and 150 mass regions.

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