Microscopic Structure of High-Spin Vibrational States in Superdeformed $A=190$ Nuclei

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Microscopic RPA calculations based on the cranked shell model are performed to investigate the quadrupole and octupole correlations for excited superdeformed (SD) bands in even-even $A=190$ nuclei. The $K=2$ octupole vibrations are predicted to be the lowest excitation modes at zero rotational frequency. The Coriolis coupling at finite frequency produces different effects depending on the neutron and proton number of nucleus. The calculations also indicate that some collective excitations may produce $J^{(2)}$ moments of inertia almost identical to those of the yrast SD band. An interpretation of the observed excited bands invoking the octupole vibrations is proposed, which suggests those octupole vibrations may be prevalent in even-even SD $A=190$ nuclei.

I. INTRODUCTION

Superdeformed (SD) rotational bands provide us with an opportunity of studying a finite quantum many-body system at the limits of a strong Coriolis field and large deformation. As an example of elementary excitations in rapidly rotating nuclei, low-frequency vibrational motion at high spin is of great interest. Since the large deformation and the rapid rotation of SD bands may produce a novel shell structure, we expect features of surface vibrational motions quite different from those of spherical and normal-deformed (ND) nuclei. In this paper quadrupole and octupole vibrations built on the SD yrast band are discussed in terms of a microscopic model based on the cranked mean field extended by the random-phase approximation (RPA).

In a recent paper [1] (to which we refer hereafter as NMMS), we have discussed the quadrupole and octupole correlations in excited SD bands in $^{190,192,194}$Hg. We have found that the $K=2$ octupole vibrations are the lowest excitation modes in these SD nuclei and the interplay between rotation and vibrations produces different effects depending on neutron number. From a comparison with the experimental $J^{(2)}$ moments of inertia, we have proposed a new interpretation that most of the observed excited bands are the $(K=2)$ octupole vibrations. In this paper, we extend this work to all even-even SD nuclei observed in $A=190$ region and compare our theoretical results with new experimental data. Assuming that the observed excited SD bands correspond to the lowest octupole vibrations, the observed properties (Routhians, $J^{(2)}$ moments of inertia, and linking transitions into the yrast SD bands) will be consistently explained for all even-even $A=190$ nuclei.

II. COLLECTIVE EXCITATIONS IN RAPIDLY ROTATING SUPERDEFORMED NUCLEI

Before discussing explicit examples of excited SD bands, let us discuss the characteristics of elementary excitation modes in high-spin SD and ND states in even-even nuclei.

ND nuclei belong to a family of nuclei with “open-shell” configurations. At low spin, since the pairing correlations produce an energy gap $\Delta$ (typically 1 MeV), the excitation energies of the lowest two-quasiparticle ($2qp$) states are at least $2\Delta \approx 2$ MeV and the collective (isoscalar) excitations become the lowest excitation modes which have been universally observed in experiments. However, this situation is changed at high spin by many rotationally aligned $2qp$ states coming down rapidly with frequency. These aligned $2qp$ bands erase the energy gap and become the dominant modes of low-energy excitation. Thus, at present, very few experimental data are available for the collective modes of excitation at high spin.

On the other hand, SD nuclei are characterized as “closed-shell” nuclei with a large shell gap near the Fermi surface. In addition, the large deformation tends to reduce the aligned angular momenta of high-$j$ orbitals. These properties of the SD shape keep an energy gap in the quasiparticle spectra even in the high-spin region. (see quasiparticle Routhians in NMMS and compare them with those of ND nuclei, e.g., in Ref. [1]). As a result, the collective states may be still the lowest modes
even at high spin. In this sense, the SD nuclei could provide an observatory of the collective excitations in rapidly rotating systems.

In the A=150 region, the behavior of excited SD bands have been well accounted for as single-particle excitations except for a few cases in $^{152}$Dy, $^{148}$Gd, and $^{150}$Gd. This may be because the pairing correlations are extremely suppressed in the A=150 region. Since the pairing correlations may increase the quadrupole and octupole collectivity, we expect the different feature of near-yраст excitation spectra in the A=190 region.

In even-even SD $A=190$ nuclei, most of excited bands have $J^{(2)}$ moments of inertia very similar to those of the yrast SD bands, which show a gradual increase with frequency. On the other hand, atypical $J^{(2)}$ moments almost constant with frequency have been observed universally in odd-A SD nuclei and have been explained by invoking occupation of a quasiparticle state associated with neutron $N=7$ $(j_{15/2})$ orbitals. These experiments provide important information on the quasiparticle spectra around the $N=112$ SD shell gap, which tells us the $N=7$ orbitals is the lowest at high frequency and the blocking of the $N=7$ orbitals leads to the lack of alignment producing a constant $J^{(2)}$. If we try to interpret the excited bands in even-even nuclei as the simple 2qp states, it is a puzzle why the similar atypical $J^{(2)}$ have not been observed in the even-even cases. We will show in the next section that the collective excitations can provide a possible answer to this mystery.

### III. MICROSCOPIC STRUCTURE OF COLLECTIVE EXCITATIONS

In this section, we give a brief review of our theoretical model and discuss the $J^{(2)}$ moments of inertia for the excited bands. See NMMS for a complete description of the model and details of numerical calculations.

In the cranked shell model extended by the RPA theory, vibrational excitations built on the rotating vacuum are microscopically described by superpositions of a large number of 2qp states. The RPA also allows us to describe non-collective 2qp excitations and weakly collective states which are difficult to discuss by means of macroscopic models. Effects of the Coriolis force on these various modes of excitation are automatically taken into account in RPA solutions since the mean field is affected by the cranking term $-\omega_{rot} J_z$.

The model Hamiltonian is assumed to be of the form:

$$H' = h'_{s.p.} + H_{\text{int}},$$

where $h'_{s.p.}$ is a cranked single-particle Nilsson Hamiltonian including the pairing field. The quadrupole deformation and pairing gaps are determined by the standard Strutinsky procedure at $\omega_{rot} = 0$. We have adopted the phenomenological prescription given in Ref. [1] for the pairing gaps at finite frequency (which is characterized by a “critical” frequency $\omega_c$). The residual interactions are separable multipole interactions,

$$H_{\text{int}} = H_{\text{pair}} - \frac{1}{2} \sum_{\lambda K} \chi_{\lambda K} Q^{(1)}_{\lambda K} Q^{(1)}_{\lambda K},$$

where $H_{\text{pair}}$ is a residual pairing interaction consistent with the mean field and $Q_{\lambda K}$ are multipole operators defined in doubly-stretched coordinates $r_i$ ($i = x, y, z$) [2]. The coupling strengths of the interactions $\chi_{\lambda K}$ are determined in the same way as in NMMS. However, since we do not know exactly the self-consistent interactions in a realistic Nilsson potential, we have done the calculations with two different values of the octupole coupling strengths; the “harmonic-oscillator” value ($f_3 = 1$) [2] and the one increased by 5% ($f_3 = 1.05$). We use this symbol $f_3$ as a scaling factor of the coupling strengths. See eq.(3.13) in NMMS.

After diagonalizing the Hamiltonian [3] with the RPA theory, it is written as

$$H' = \text{const.} + \sum_{\alpha,n} \hbar \Omega_{\alpha n} X_{\alpha n}^\dagger X_{\alpha n}^\sigma, \quad (3.3)$$

for even-even nuclei at finite rotational frequency. Here $\alpha$ (=0,1) indicates the signature quantum number. $X_{\alpha n}^\dagger$ and $\hbar \Omega_{\alpha n}$ are the n-th RPA-normal-mode creation operator and its excitation energy, respectively. Since we take the yrast SD band as the RPA vacuum, $\hbar \Omega_{\alpha n}$ gives the Routhian (excitation energy in the rotating frame) relative to the yrast SD band.

From the RPA eigenenergies, we calculate the $J^{(2)}$ moments of inertia for excited SD bands as follows (see NMMS for details): The relative difference between the excited and yrast bands is given by $J^{(2)} = -d^2\hbar \Omega_{\alpha n}/d\omega_{rot}^2$, and added to the experimental $J^{(2)}_0$ of the yrast band, $J^{(2)}_0 + j^{(2)}$. This procedure allows us to take into account the complex correlations which are implicitly included in $J^{(2)}_0$; e.g., the pairing fluctuation, the higher-order pairing.

In the RPA theory, excited states $|n\rangle$ ($n \neq 0$) are described by superposition of 2qp excitations,

$$|n\rangle = \sum_{\mu \nu} \{\psi_n(\mu \nu)a_{\mu}^\dagger a_{\nu}^\dagger + \varphi_n(\mu \nu)a_{\mu}a_{\nu}\} |0\rangle, \quad (3.4)$$

where $|0\rangle$ is the RPA vacuum and $\psi_n(\mu \nu)$ ($\varphi_n(\mu \nu)$) are the RPA forward (backward) amplitudes. The backward amplitudes are generally smaller than the forward amplitudes if the mean field is stable enough. A non-collective state has a single dominant 2qp component, namely $|\psi_n(\sigma \rho)|^2 \approx 1$ and $|\varphi_n(\mu \nu)|^2 \approx 0$ for $(\mu \nu) \neq (\sigma \rho)$. On the other hand, a collective state may be characterized by the coherent contributions from many different 2qp components and substantial contributions from backward amplitudes.

As is discussed in sec. [1] the lowest $N = 7$ neutron quasiparticles change $J^{(2)}$ moments of inertia most significantly. Therefore, the observed excited bands in even-even nuclei, which show the $J^{(2)}$ identical to those of the
yrast $J^{(2)}$, cannot be the lowest 2QP states associated with these orbitals. A possible explanation for this similarity of $J^{(2)}$ is interpreting them as 2QP excitations involving high-$K$ orbitals. For instance, bands 2 and 3 in $^{194}$Hg have been originally assigned as two-quasineutron excitations $[624 9/2] \otimes [512 5/2]$ [13]. However, this does not explain why we have not observed 2QP excitations associated with the neutron $N = 7$ orbitals which should be lower in energy at high frequency (see discussion in sec. III).

Instead, we presume those excited bands could be the collective states. First of all, the excitation energies of collective states may be lower than any 2QP state. In addition, some collective bands may produce the RPA amplitudes over many 2QP’s. In a highly collective state, the amplitude $|\psi_n(\mu \nu)|$ of each 2QP component is small and the peculiar effect of the neutron $N = 7$ orbitals can be smeared by the other components. This “smearing” has been actually demonstrated for $^{194}$Hg in NMMS, and will be also done for Pb isotopes in sec. IV.

IV. COLLECTIVE EXCITATIONS IN Hg NUCLEI

In this section, results of the RPA calculations are presented for the excited states in SD Hg nuclei. Since we have already published this result in NMMS, here we briefly review the main results of NMMS and discuss new experimental data on $^{194}$Hg. The main conclusions of NMMS are summarized as follows.

1. The $K = 2$ octupole vibrations are the lowest excitation modes ($E_x \approx 1$ MeV, $B(E2; 0^+ \rightarrow 2^+)$ $\approx 10$ s.p.u.) in these Hg isotopes at $\omega_{rot} = 0$.

2. The $\gamma$ vibrations are higher in energy and less collective ($E_x \geq 1.4$ MeV, $B(E2; 0^+ \rightarrow 2^+)$ $< 2 \sim 3$ s.p.u.) than the lowest octupole vibrations at $\omega_{rot} = 0$.

3. In $^{190}$Hg, two observed excited SD bands, bands 2 and 4, are assigned to the lowest octupole bands with signature $\alpha = 1$ and 0, respectively. The $\alpha = 1$ octupole vibration is rotationally aligned, while the $\alpha = 0$ is crossed by a two-quasineutron band at high frequency.

4. In $^{192}$Hg, bands 2 and 3 are assigned to the lowest ($K = 2$) octupole bands with signature $\alpha = 1$ and 0, respectively. Both bands are crossed by a two-quasineutron band at high frequency.

5. In $^{194}$Hg, bands 2 and 3 are assigned to the lowest ($K = 2$) octupole bands with signature $\alpha = 0$ and 1, respectively.

6. The strongest mixture of low-$K$ components ($K = 0$ and 1) at finite frequency is predicted for band 2 of $^{190}$Hg, which explains why strong dipole decay into the yrast SD band has been observed only for this band.

For $^{194}$Hg, recent GAMMASPHERE experiments have revealed the excitation energies and spins of the yrast [14] and excited (band 3) SD bands [15]. The experimental Routhians of band 3 relative to the yrast SD band have been extracted from these experimental data [15]. The experiments indicate that band 3 is very low-lying, $E_x \approx 0.8$ MeV at $\omega_{rot} = 0$, which seems to support our interpretation of collective vibrations because the lowest 2QP states have been predicted to be at $E_x \approx 1.5$ MeV in NMMS.

In Fig. 1 we compare the experimental Routhians with the theoretical results presented in NMMS and Ref. [16] (indicated by (1) and (2), respectively) and with Routhians calculated with slightly different parameters (indicated by (3)). The parameter sets used for the calculations are; (1) the same parameters as in NMMS (dynamically reduced pairing and $f_3 = 1$), (2) the same as in Ref. [16] (constant pairing gaps and $f_3 = 1.05$), and (3) the same as (1) except $f_3 = 1.057$ and $h\omega_c = 0.5$ MeV for protons (see eq. (3.4) in NMMS). It turns out that the previous calculation (2) had predicted the experimental Routhians very nicely, while the calculation (1) had overestimated the excitation energy by about 200 $\sim$ 300 keV. The parameters (3) are chosen to reproduce the experiments: it seems to suggest that the reduction of proton pairing is smaller than expected in NMMS and the optimal octupole coupling strengths are slightly larger than the harmonic-oscillator values. This is consistent with the discussion in NMMS in which we have shown the slightly larger coupling strengths ($f_3 = 1.05$) reproduce the experimental $J^{(2)}$ even better.

Experimental information has also been obtained on the signature splitting of bands 2 and 3 (assuming they are signature partners). This is discussed in a paper by F. Stephens in this proceedings [17]. Again, the agreement becomes better for the result with the slower pairing reduction and the larger octupole coupling.
RPA eigenenergies of negative-parity states for $^{192,194,196,198}$Pb calculated with $f_3 = 1.05$. Open (solid) circles indicate states with $\alpha = 0$ (1). Large, medium, and small circles indicate RPA solutions with $E3$ transition amplitudes larger than 200 efm$^3$, larger than 100 efm$^3$, and less than 100 efm$^3$, respectively. If we take $f_3 = 1$, the excitation energy of the lowest octupole states will be around 1.2 MeV at $\omega_{\text{rot}} = 0$.

V. COLLECTIVE EXCITATIONS IN Pb NUCLEI

In this section, the results are presented for excited states in SD even-even Pb nuclei. In $^{192,194,196,198}$Pb, the predicted properties of $\gamma$ vibrations are similar to those in Hg nuclei (see the previous section and NMMS); the excitation energy ($E_x \approx 1.5 \sim 1.6$ MeV) is higher than the lowest octupole state and their weak collectivity will be dissipated at high spin. Therefore, the observation of the $\gamma$ vibration is expected to be more difficult than the octupole vibrations. Hereafter, let us focus our discussion on the collective octupole excitations.

Figure 2 shows the calculated Routhians with negative parity relative to the yrast SD bands for even-even Pb nuclei. The quadrupole deformation $\epsilon = 0.44$, the pairing parameters $\Delta(0) = 0.8$ (0.7) MeV with $\hbar\omega_c = 0.5$ (0.5) MeV for neutrons (protons), and $f_3 = 1.05$ are used throughout (cf. sec.III-A in NMMS). The lowest states are again the $K = 2$ octupole vibrations for all nuclei.

A. $^{194}$Pb and $^{196}$Pb

The excited SD bands in even-even Pb nuclei have been observed in $^{194}$Pb (bands 2 and 3) [18] and $^{196}$Pb (bands 2, 3, and 4) [19]. We assume the lowest octupole bands ($\alpha = 0$ and 1) correspond to the observed excited bands (bands 2 and 3) in $^{194}$Pb and $^{196}$Pb. Unfortunately we could not give unique assignment to band 4 in $^{196}$Pb (see below).

The calculated $J^{(2)}$ moments of inertia are shown in Fig. 3(a) together with the experimental data. The signature of excited bands is determined by following the experimental suggestions [18][19]. As is discussed in sec.III, the $J^{(2)}$ identical to those of the yrast SD band are reproduced by means of the "smearing" effect. The results calculated with $f_3 = 1.05$ agree with the experiments especially well. There is an experimental suggestion that

FIG. 2. RPA eigenenergies of negative-parity states for $^{192,194,196,198}$Pb calculated with $f_3 = 1.05$. Open (solid) circles indicate states with $\alpha = 0$ (1). Large, medium, and small circles indicate RPA solutions with $E3$ transition amplitudes larger than 200 efm$^3$, larger than 100 efm$^3$, and less than 100 efm$^3$, respectively. If we take $f_3 = 1$, the excitation energy of the lowest octupole states will be around 1.2 MeV at $\omega_{\text{rot}} = 0$.

FIG. 3. (a) Calculated (solid lines) and experimental (symbols) $J^{(2)}$ moments of inertia for excited SD bands in $^{194}$Pb (upper) and $^{196}$Pb (lower). Thin solid lines are the results with $f_3 = 1$ while the thick lines indicate the results with $f_3 = 1.05$. Dotted lines indicate the yrast $J^{(2)}$. Experimental data are taken from Ref. [18][19].

(b) $E3$ transition amplitudes of the corresponding octupole states calculated with $f_3 = 1.05$. 

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the band-head energy of bands 2 and 3 in $^{196}\text{Pb}$ is around 870 keV [19], which again indicates better agreement with the results with $f_3 = 1.05$ (Fig. 3).

In order to clarify how the “smearing” works, we show examples of RPA amplitudes calculated with $f_3 = 1.05$ for the lowest $\alpha = 1$ octupole state in $^{196}\text{Pb}$: At $\omega_{\text{rot}} = 0$, the largest component is a two-quasineutron $\nu(56)$ (occupying $N = 5$ and $N = 6$ orbitals) with $|\psi|^2 = 0.14$, while it will be a two-quasiproton $\pi(56)$ with $|\psi|^2 = 0.12$ at $h\omega_{\text{rot}} = 0.3$ MeV. As you can see, even the largest component occupies less than 10% of the total sum of forward amplitudes $\sum_{\mu\nu} |\psi(\mu\nu)|^2 \approx 1.48$. As is discussed before, the neutron $N = 7$ orbitals give the most significant effect on $J^{(2)}$ moments of inertia. The largest component associated with neutron $N = 7$ is $|\psi|^2 = 0.04$ (0.02) at $h\omega_{\text{rot}} = 0$ (0.3) MeV. Therefore, the blocking of $N = 7$ orbitals turns out to be extremely weak in this collective excitation, which results in the $J^{(2)}$ almost identical to those of the yrast band.

The experiment [19] has also observed decay transitions from excited SD bands (bands 2, 3, and 4) into the yrast SD band in $^{196}\text{Pb}$ (the dipole character of decays from band 3 was confirmed). Assuming the $E1$ transitions, the experimental $B(E1)$ values have been extracted from the branching ratio; $B(E1)_{\text{exp}} \approx 10^{-6}$, $10^{-5}$, and $10^{-4}$ W.u. for bands 2, 3, and 4, respectively. Using the $E1$ recoil charge ($-Ze/A$ for neutrons and $Ne/A$ for protons), the calculations with $f_3 = 1.05$ at $h\omega_{\text{rot}} = 0.3$ MeV have suggested $B(E1)_{\text{cal}} \approx 10^{-7}$, $10^{-6}$ W.u. for bands 2 and 3, respectively. If we assume band 4 is an either $K = 0$ or 1 octupole band, the $B(E1)_{\text{cal}}$ would be about $10^{-5}$ W.u. Although the calculation underestimates the absolute magnitude by a factor of 10, the relative difference among bands 2, 3, and 4 is well reproduced. However, the band-head energies of $K = 0$ and 1 octupole states are predicted to be around 1.5 MeV which is much higher than the experimental suggestion ($\approx 1$ MeV); this weakens our interpretation of band 4 as an octupole state. Note that, since we could not make the reliable prediction about $\beta$ vibrations, we cannot deny a possibility that band 4 is a $\beta$ vibration. Besides, if the transitions from band 4 are $M1$, it could be a 2qp band, because the $J^{(2)}$ moments of this band show the atypical behavior which might suggest effects of the neutron $N = 7$ orbitals.

Figure 3(b) shows the $E3$ amplitudes ($K = 0$, 1, 2, and 3) of the lowest octupole states as functions of frequency. The $K$-mixing turns out to be weak for both bands 2 and 3 in $^{196}\text{Pb}$. Since the $E1$ strength is supposed to be carried by the low-$K$ component ($K = 0$ and 1), it provides the small $B(E1)$ for bands 2 and 3 ($10^{-7} \sim 10^{-6}$ W.u.).

The calculation suggests the relatively strong Coriolis mixing for $(K, \alpha) = (2, 1)$ octupole band in $^{194}\text{Pb}$. This leads to $B(E1)_{\text{cal}} \approx 10^{-6} \sim 10^{-5}$ W.u. which is the largest among the octupole states shown in Fig. 3. Further experimental investigation about the linking transitions between excited and yrast SD bands in $^{194}\text{Pb}$ may clarify the octupole collectivity of this band.

B. $^{192}\text{Pb}$ and $^{198}\text{Pb}$

Although the excited SD bands in even-even $\text{A}=190$ nuclei have been observed so far only in $^{190,192,194}\text{Hg}$ and $^{194,196}\text{Pb}$, we expect this will be significantly extended in near future by means of the new generation $\gamma$-ray detectors. Among those candidates, $^{192}\text{Pb}$ and $^{198}\text{Pb}$ may be relatively easy to access because the yrast SD bands have been already observed. In this section, we make a prediction on the properties of octupole bands in these nuclei.

The octupole states in $^{192}\text{Pb}$ are similar to those (bands 2 and 4) in $^{190}\text{Hg}$: the lowest octupole phonon with signature $\alpha = 1$ is rotationally aligned, and the second lowest with $\alpha = 0$ is crossed by a 2qp band (Fig. 3). In Fig. 3 we show the calculated $J^{(2)}$ moments of inertia for the lowest octupole bands in each signature sector. The $\alpha = 1$ band shows the large and almost constant $J^{(2)}$, while the $\alpha = 0$ shows a bump at frequency $h\omega_{\text{rot}} \approx 0.3$ MeV (if we take $f_3 = 1$, the position of this bump will be shifted to $h\omega_{\text{rot}} \approx 0.23$ MeV). Since the aligned octupole phonon is a result of strong Coriolis mixing, the $\alpha = 1$ band has substantial amounts of $K = 0$ and 1 components at finite frequency, which will lead to the relatively strong $E1$ decays into the yrast SD band ($B(E1)_{\text{cal}} \approx 10^{-6} \sim 10^{-4}$ W.u.).

In $^{198}\text{Pb}$, the lowest $K = 2$ octupole states ($\alpha = 0$ and 1) are predicted to have no signature splitting. Their $J^{(2)}$ moments of inertia are identical to each other and similar to those of the yrast SD band (Fig. 3). In this case, since the Coriolis mixing is very weak, the $E1$ strengths are predicted to be small ($B(E1)_{\text{cal}} \approx 10^{-7} \sim 10^{-6}$ W.u.).

![FIG. 4. Calculated $J^{(2)}$ moments of inertia for the lowest octupole bands with $\alpha = 0$ (lower) and $\alpha = 1$ (upper) in $^{192}\text{Pb}$ (left) and $^{198}\text{Pb}$ (right). $f_3 = 1.05$ is used in the calculations. Dotted lines indicate the yrast $J^{(2)}$. Experimental data are taken from Ref. [21].](image-url)
VI. CONCLUSIONS: “OCTUPOLE PARADISE”

The microscopic structure of the γ and the octupole vibrations built on the SD yrast bands in $^{190,192,194}$Hg and $^{192,194,196,198}$Pb were investigated by means of the RPA based on the cranked shell model. For all these even-even nuclei, the $K = 2$ octupole vibrations are predicted to be the lowest.

New experimental data on SD $^{194}$Hg seem to support our interpretation in NMMS that bands 2 and 3 may be $K = 2$ octupole vibrational states. The results in Ref. \[10\] calculated with slightly different parameters agreed better with the experimental Routhians for band 3, which may suggest the pairing reduction at finite frequency should be smaller and the optimal octupole coupling strengths be larger than the ones used in NMMS.

For the observed excited bands in SD Pb isotopes, the following configurations have been assigned:

$^{194}$Pb Band 2 : the $(K,\alpha) = (2, 1)$ octupole vibration.
Band 3 : the $(K,\alpha) = (2, 0)$ octupole vibration.

$^{196}$Pb Band 2 : the $(K,\alpha) = (2, 0)$ octupole vibration.
Band 3 : the $(K,\alpha) = (2, 1)$ octupole vibration.
Band 4 : indefinite.

With these assignments, our calculation accounted for the $J^{(2)}$ moments of inertia and the observed decays of excited bands into the yrast SD band ($^{196}$Pb). It is also suggested that the relatively strong Coriolis mixing in the $(K,\alpha) = (2, 1)$ octupole vibration in $^{194}$Pb may lead to the strong E1 decay into the yrast SD band. It would be interesting for the experiment to search for these decay transitions in this nucleus.

We have also done the calculations on excited SD bands in $^{192}$Pb and $^{198}$Pb. The following octupole bands are predicted (possible experimental signatures are indicated in italics):

$^{192}$Pb (i) the $\alpha = 1$ aligned octupole vibration [large $J^{(2)}$ and E1 linking transitions].
(ii) the $(K,\alpha) = (2, 0)$ octupole vibration crossed by a 2QP band [a bump of $J^{(2)}$ at $h\omega_{\text{rot}} = 0.2 \sim 0.3$ MeV].

$^{198}$Pb the signature-paired $K = 2$ octupole vibrations [$J^{(2)}$ similar to those of the yrast].

As mentioned above, the $K = 2$ octupole vibrations are predicted to be the lowest in the region where the SD bands have been observed so far ($79 \leq Z \leq 83$, $109 \leq N \leq 116$). Since the E1 strength only come from the Coriolis mixing of the $K = 0$ and 1 components, the most direct evidence of octupole correlations, namely the strong decays into the yrast SD band, have been observed in limited cases (band 2 in $^{190}$Hg and band 4 in $^{198}$Pb). However, if future experiments extend this region into $N < 108$ or $N > 116$, the $K = 1$ octupole vibrations are predicted to become the lowest (or close to the lowest). Then, strong E1 decay should be observed, and would be good experimental evidence for octupole collectivity.

From these calculations and from a comparison with available experiments, we would like to conclude that the octupole vibrations are prevalently observed in even-even SD A=190 nuclei (“Octupole Paradise”). The observation of the high-spin collective excitations is very difficult in ND nuclei, because the energy gaps at the Fermi surface quickly disappear due to many aligned 2QP states, so that non-collective modes of excitation become dominant at high spin. The large deformation and large shell gap in SD nuclei may overcome this situation and provide us with a valuable opportunity to observe a variety of collective excitations in rapidly rotating quantum systems.

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