γ-vibrational states in superheavy nuclei

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Recent experimental advances have made it possible to study excited structure in superheavy nuclei. The observed states have often been interpreted as quasi-particle excitations. We show that in superheavy nuclei collective vibrations systematically appear as low-energy excitation modes. By using the microscopic Triaxial Projected Shell Model, we make a detailed prediction on γ-vibrational states and their E2 transition probabilities to the ground state band in Fermium and Nobelium isotopes where active structure research is going on, and in 270Ds, the heaviest isotope where decay data have been obtained for the ground-state and for an isomeric state.

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One of the important predictions in nuclear physics is the emergence of a region of long-lived superheavy elements beyond the actinides, the so-called ‘island of stability’. The question concerns the precise location of the next closed neutron shells beyond $Z = 82$ and $N = 126$. To reach the island, much of the experimental effort has been focused on the direct creation of superheavy elements. In recent years, progress has also been made in structure studies for nuclei beyond Fermium, thanks to the development of detector systems for decay and in-beam studies using recoil separators and heavy ion fusion reactions \cite{1,2}. It has been suggested that by studying the transmutation nuclei, in particular their excited structure, one can gain useful information on relevant single-particle states \cite{3}, which is key to locating the island.

The nuclei of our interest, the Fm (Z = 100) and No (Z = 102) isotopes, belong to the heaviest mass region where structure can currently be studied experimentally. The yrast property of these nuclei shows that they are generally good rotors. Rotational behavior of some of these yrast bands has been successfully reproduced by several models (see, for example, Refs. \cite{4,5,6,7}). The discussion on excited configurations so far have been focused on quasi-particle excitations \cite{8,9,10,11}. On the other hand, a deformed rotor can, according to the collective model, undergo dynamical oscillations around the equilibrium shape, resulting in various low-lying collective vibrational states. Ellipsoidal oscillation of the shape is well known as γ vibration \cite{12}. It is thus natural to consider γ vibrational states in superheavy nuclei, and in fact, this excitation mode has begun to draw one’s attention \cite{13,14}. Knowledge on vibrational states in superheavy nuclei is particularly useful for this less known mass region because of the interpretation of the observed low-lying spectroscopy.

Early calculation of γ-vibrational states in heavy nuclei was performed by Marshalek and Rasmussen \cite{15} using the quasi-boson approximation, and by Bès \textit{et al}. \cite{16} using the quadrupole-plus-pairing model based on deformed Nilsson states \cite{17}. Modern treatment of γ vibration includes

\begin{equation}
\hat{H}_0 - \frac{2}{3} \hbar \omega \left[ \varepsilon \hat{Q}_0 + \varepsilon ' \frac{\hat{Q}_{+2} + \hat{Q}_{-2}}{\sqrt{2}} \right],
\end{equation}

where $\hat{H}_0$ is the spherical single-particle Hamiltonian with inclusion of appropriate spin-orbit forces parameterized by Bengtsson and Ragnarsson \cite{28}. The axial and triaxial parts of the Nilsson potential in Eq. (1) contain the deformation parameters $\varepsilon$ and $\varepsilon '$ respectively, which are related to the conventional triaxiality parameter by $\gamma = \tan^{-1}(\varepsilon '/\varepsilon )$. Pairing correlation in the Nilsson states is taken into account by using a standard BCS calculation, within a model space of three major shells for each kind of nucleon ($N = 5, 6, 7$ for neutrons and $N = 4, 5, 6$ for protons).

The rotational invariant two-body Hamiltonian

\begin{equation}
\hat{H} = \hat{H}_0 - \frac{\chi}{2} \sum \mu \hat{\Omega}_\mu \hat{\Omega}_\mu - G_M \hat{P}^+ \hat{P} - G_Q \sum \mu \hat{P}_\mu \hat{P}_\mu \quad (2)
\end{equation}
is diagonalized in the three-dimensional angular-momentum-projected basis \( \{ \Phi_{MK}^I \}, 0 \leq K \leq I \} \), where \( \Phi_{MK}^I \) is the angular-momentum-projector \([19]\). The wave function thus takes the form

\[
|\Psi_{IM}^\sigma\rangle = \sum_{0 \leq K \leq I} f_{IM}^\sigma \Phi_{MK}^I \langle \Phi |,
\]

where \( \sigma \) specifies the states with the same angular momentum \( I \). The wave function \([3]\) is explicitly written as a superposition of projected \( K \) states. The two-body forces in Eq. \([2]\) are quadrupole-quadrupole (\(QQ\)), monopole-pairing, and quadrupole-pairing interaction, respectively. The strengths of the monopole and quadrupole pairing forces are given respectively by \( G_M \) and \( G_Q \) in Eq. \([2]\), where

\[
G_M = \frac{G_1 \pm G_2 N^{-Z/A}}{A},
\]

with “+” for protons and “−” for neutrons. We use \( G_1 = 21.24 \), \( G_2 = 13.86 \), and assume the quadrupole-pairing strength in Eq. \([2]\) to be \( G_Q = 0.13 G_M \), which are found to be appropriate for this mass region \([21, 29]\). The \(QQ\)-force strength \( \chi \) is determined such that it holds a self-consistent relation with the quadrupole deformation \( \epsilon' \) \([23]\).

The nucleus \(^{256}\)Fm is taken as our discussion example because it is perhaps the only nucleus in this mass region where some observed states were thought to be \( \gamma \) vibrational states \([13]\). Figure 1 shows the calculated energies as functions of triaxiality parameter \( \epsilon' \) for various angular momenta. Although this figure looks similar to the one shown in the seminal paper of Davydov and Filippov \([24]\), it is obtained from a fully microscopic theory. Unlike the asymmetric rotor model, our spectrum depends not only on the deformation parameters but also microscopically on the detailed shell filling. In Fig. 1, each curve is labeled by \( I_g \). It turns out (see later discussions) that for the nuclei studied in the present paper, \( K \) mixing is very small. Therefore, \( \epsilon' \approx K \), and we can practically use \( I_g \) to label the states. One sees that, for the \( g \) band \((K = 0)\) in \(^{256}\)Fm, the energies are nearly flat as \( \epsilon' \) varies, and the values remain very close to those at zero triaxiality. Thus, we can conclude that the triaxial basis has no significant effect on the \( g \) band in such a superheavy rotor, and one can practically describe \( g \) band using an axially deformed basis.

On the other hand, it has a large effect on excited bands with \( K \neq 0 \) (second and higher excited bands are not shown in this figure, but will be discussed in Fig. 3). Their excitation energies are indeed very high at \( \epsilon' \approx 0 \), but come down quickly as the triaxiality in the basis increases. At \( \epsilon' = 0.105 \), the first excited band \((K = 2)\) nicely reproduces the observed \( 2^+ \) band in \(^{256}\)Fm \([33]\). In our calculation, the triaxial parameter \( \epsilon' \) serves as a free parameter adjusted to reproduce the \( 2^+ \) bandhead. It should be noted that the excited bands studied in this paper are obtained by introducing triaxiality in the basis (quasiparticle vacuum). They are collective excitations, not quasi-particle excitations.

The above results can be further understood by studying the \( K \) mixing coefficients for each projected \( K \) state in the total wave function of Eq. \([3]\). It is found that for \(^{258}\)Fm (and for all nuclei studied in this paper), \( K \) mixing is negligibly small. States in the \( g \) band are essentially the projected \( K = 0 \) state for any \( \epsilon' \). The basis triaxiality does not influence the \( g \) band result, and the rotational behavior of the \( g \) band can be understood by using a simple axially-deformed rotor. The excited bands are also built by rather pure projected \( K \) states. For example, the first excited band with the bandhead spin \( I = 2 \) is mainly the projected \( K = 2 \) state (labeled as \( I_2 \)). The fact of very small \( K \) mixing in these nuclei sets up a favorable condition for the occurrence of \( K \) isomeric states \([8, 10, 34]\).

In Fig. 2, we present results for even-even Fm and No isotopes with neutron number from \( N = 150 \) to 156. This is the mass region where active structure study is currently going on. In Fig. 2, theoretical results for both \( g \) and \( \gamma \) bands are predicted up to \( I = 10 \). The axial and triaxial deformation parameters used in the present calculations are listed in Table I. We note that deformation in nuclei is a model-dependent concept. Our deformations are input parameters for the deformed basis, and in principle, it is not required that the numbers in Table I are exactly the same as nuclear deformations suggested by other models. Nevertheless, it turns out that our employed ax-

| \( \epsilon' \) | 0.240 | 0.255 | 0.250 | 0.230 | 0.240 | 0.260 | 0.250 | 0.230 |
|---|---|---|---|---|---|---|---|---|
| \( \epsilon'' \) | 0.100 | 0.100 | 0.103 | 0.105 | 0.100 | 0.100 | 0.100 | 0.100 |

**TABLE I:** Axial and triaxial deformation parameters used in the calculation.
In the present set of parameters, we find that the rotational behavior very similar to that of Fm and No isotopes and deformation parameters are very close to those calculated in Refs. [37, 38], and follow the same variation trend along an isotopic chain as predicted by other models (for example, the most deformed isotope has the neutron number 152 and a decreasing trend for heavier isotopes is expected). A strict test for using these parameters will be whether the calculation can describe all observables, the most relevant one being the B(E2) value (see discussions below). The triaxial parameter \( \epsilon' = 0.105 \) that gives the correct position of the experimentally observed excited band in \(^{256}\)Fm \([33]\) corresponds to \( \gamma = 25^\circ \) in terms of the usual gamma parameter, if one uses as a rough estimate \( \gamma = \tan^{-1}(\epsilon'/\epsilon) \). Note that there are no existing data that are firmly assigned to be \( \gamma \)-vibrational states. The excited band starting from \( I^\pi = 2^+ \) in \(^{256}\)Fm \([33]\) was assumed by Hall et al. to be \( \gamma \)-vibrational states. Now our results strongly support the interpretation of Hall’s \( 2^+ \) band as \( \gamma \)-vibrational band. For those nuclei that have no \( \gamma \) band data to compare with, we simply employ \( \epsilon' = 0.1 \) in the calculation. Overall, we predict \( \gamma \)-vibrational bands in these nuclei, with the rotational behavior very similar to that of \( g \) bands. With the present set of parameters, we find that the \( I_K = 2_2 \) bandhead energy lies low, generally at 0.6 – 0.8 MeV above the ground state.

The type of \( \alpha \)-decay experiment \([39]\) makes the identification of excited states in the heaviest nuclei possible. We take an example from the heaviest isotopes and perform calculations for \(^{270}\)Ds. With the same interaction strengths as used for the Fm and No isotopes and deformation parameters \( \epsilon = 0.225 \) and \( \epsilon' = 0.1 \), we obtain the sequence of ground state rotational band energy \( E(I_K = 2_0) = 0.048 \), \( E(4_0) = 0.159 \), \( E(6_0) = 0.332 \), \( E(8_0) = 0.568 \), and \( E(10_0) = 0.863 \) (all in MeV), in a good agreement with the experimental estimation \([39]\). Furthermore, we predict very low-lying collective \( \gamma \) vibrations, with the bandhead energy \( E(2_2) = 0.565 \) MeV. The results will be presented later in the discussion on \( \gamma \) phonon states. We note that at present, there is no better way to determine the triaxiality for \(^{270}\)Ds, and using \( \epsilon' = 0.1 \) for the whole mass region is a natural choice. What we want to emphasize is that with this assumption, there is a low-lying \( \gamma \) band in this truly superheavy nucleus.

Recently, a great deal of experimental effort has been made to understand low-lying excited structure in transfermium nuclei. The discussion so far has been focused on quasi-particle excitations only \([8, 10, 11]\). Our present results suggest that there must exist an important part of low-energy collective vibrations, in particular at the energy region below 1 MeV. It is easy to make the following estimation. The pairing energy gaps from our BCS calculation for \(^{256}\)Fm are \( \Delta \approx 0.5 \) MeV for neutrons and \( \Delta \approx 0.8 \) MeV for protons, which are needed amount to correctly reproduce the rotational behavior (e.g. moment of inertia). Thus, energy of a 2-quasiparticle state should be greater than \( 2\Delta \), i.e. 1 MeV. Therefore, we expect that a 2-quasiparticle excitation energy is generally higher, which lies at or above 1 MeV in this mass region. This is a useful criterion to identify a low-lying excited state as a collective state rather than a quasiparticle excitation. Of course, certain residual interactions may push the quasiparticle configurations down. Very recently, possible occurrence of low-lying alternative parity bands in superheavy nuclei due to octupole correlations has been suggested \([40]\).

A detailed prediction for \( \gamma \) band depends on pairing strengths which are parameters in the model. The parameters \( G_1 \) and \( G_2 \) in \([4]\) are adjusted in accordance with the size of single-particle space, and are chosen so that they can give correct rotational sequences for the superheavy mass region (as presented in Fig. 2). Figure 3 shows the deviation from the current prediction if the pairing strengths \( G_M \), and thus \( G_0 \) (since \( G_0 \) is proportional to \( G_M \)), are allowed to vary by \( \pm 10\% \). It is observed that the curvature of the curves, i.e. the rotational frequency \( \omega = \Delta E/\Delta I \), increases with increasing pairing strength. Pairing also shifts the \( \gamma \) bandhead; a stronger pairing leads to a higher bandhead. In Fig. 3, about 20% of
deviation is seen for the \( \gamma \) bandhead when pairing changes by 10%. However, even with this amount of uncertainty in pairing, the predicted \( \gamma \) bandhead energy is still within 1 MeV of excitation, and thus the conclusion for the occurrence of low-energy \( \gamma \) vibrations remains valid.

Multi-phonon \( \gamma \) bands are rotational bands built on top of \( \gamma \) vibration classified by phonons. In Fig. 4, we plot all the states for spins \( I \leq 10 \) obtained by diagonalization for \( ^{256}\text{Fm} \) and \( ^{270}\text{Ds} \). One sees that the excited states are clearly grouped according to \( K = 0, 2, 4, \ldots \). We identify the first excited band \( (K = 2) \) as the \( \gamma \) band, the second excited band \( (K = 4) \) as the \( 2\gamma \) phonon band, the third excited band \( (K = 6) \) as the \( 3\gamma \) phonon band, and so on, with presence of strong anharmonicity in vibration. We have calculated all eight nuclei discussed in Fig. 2, and obtained similar patterns as for \( ^{256}\text{Fm} \). In particular, we predict \( 2\gamma \) phonon bands for them with the bandhead energy at about 1.8 MeV. \( 2\gamma \) phonon states were observed in the rare earth nuclei \( ^{166}\text{Er} \) and \( ^{168}\text{Er} \). To compare with those \( 2\gamma \) phonon bandhead energies, 2.029 MeV in \( ^{166}\text{Er} \) and 2.056 MeV in \( ^{168}\text{Er} \), \( 2\gamma \) phonon states in superheavy nuclei lie lower. No \( 3\gamma \) phonon states have yet been seen experimentally in any known examples of nuclear spectroscopy. According to our calculations, they should appear at about 3 MeV in Fm and No isotopes. To compare with \( ^{256}\text{Fm} \), a more compressed multi-phonon \( \gamma \) vibrational spectrum is seen for \( ^{270}\text{Ds} \), again with strong anharmonicity.

The wave functions obtained after diagonalization of the Hamiltonian are used to calculate the electric quadrupole transition probabilities

\[
B(E2 : (I_i, K_i) \rightarrow (I_f, K_f)) = \frac{1}{2I_i + 1} \left| \langle \Psi_{I_f, K_f} | \hat{Q}_2 | \Psi_{I_i, K_i} \rangle \right|^2
\]

between an initial state \( (I_i, K_i) \) and a final states \( (I_f, K_f) \). The explicit expression for the reduced matrix element in the projected basis can be found in Ref. [25]. Note that we now use \( K \) instead of \( \sigma \) to specify states with the same angular momentum \( I \) to keep the familiar convention. In the calculation, we use the standard effective charges of 1.5\( e \) for protons and 0.5\( e \) for neutrons.

In Table II, we list calculated \( B(E2) \) values within the \( g \) bands, the inter-band linking transitions between \( \gamma \) bands and \( g \) bands, and between \( 2\gamma \) bands and \( \gamma \) bands. It is found that for each of the nuclei, the \( g \) band \( B(E2) \) values correspond to a rather constant transition quadrupole moment, reflecting the fact that these systems are good rotors. The inter-band transitions are on average by two to three orders of magnitude smaller than the in-band transitions within the \( g \) bands. These predicted \( B(E2) \) values may help in determining the structure of low-lying states.

To summarize, we have applied the Triaxial Projected Shell Model to Fm and No isotopes as well as \( ^{270}\text{Ds} \) to predict \( \gamma \) vibrational states in superheavy nuclei. Shell model diagonalization is carried out in an angular-momentum-projected triaxially-deformed basis. It is found that the calculation simultaneously leads to a consistent description of ground state band and multi-phonon \( \gamma \) bands in these nuclei. The physics of the bands is discussed in terms of \( K \) mixing, suggesting a microscopic connection between the excited vibrational states and the nuclear ground state properties in the heaviest nuclei where structure study can be performed experimentally. In- and inter-band \( B(E2) \) values are predicted. This work calls for attention on collective excitations in the low-energy region where active structure studies are currently carried out.

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TABLE II: Calculated in-band $B(E2, I_0 \rightarrow (I - 2)_0)$ values for $g$ bands, inter-band transitions from $\gamma$ bands to $g$ bands $B(E2, I_2 \rightarrow I'_0)$, and from $2\gamma$ bands to $\gamma$ bands $B(E2, I_2 \rightarrow I'_0)$. Numbers are given in W.u..

| $I_{K, J} \rightarrow I'_{K, J}$ | $^{250}\text{Fm}$ | $^{252}\text{Fm}$ | $^{254}\text{Fm}$ | $^{256}\text{Fm}$ | $^{258}\text{No}$ | $^{256}\text{No}$ | $^{258}\text{No}$ | $^{270}\text{Ds}$ |
|--------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| $2_0 \rightarrow 0_0$    | 314             | 341             | 333             | 297             | 316             | 351             | 334             | 301             |
| $4_0 \rightarrow 2_0$    | 449             | 488             | 476             | 425             | 452             | 501             | 478             | 431             |
| $6_0 \rightarrow 4_0$    | 496             | 539             | 526             | 470             | 500             | 554             | 528             | 476             |
| $8_0 \rightarrow 6_0$    | 522             | 567             | 554             | 496             | 526             | 582             | 555             | 502             |
| $2_2 \rightarrow 0_0$    | 3.45            | 3.61            | 3.72            | 3.97            | 3.68            | 3.60            | 3.57            | 3.64            |
| $2_2 \rightarrow 2_0$    | 5.18            | 5.47            | 5.63            | 5.83            | 5.51            | 5.45            | 5.30            | 5.27            |
| $2_2 \rightarrow 4_0$    | 0.29            | 0.31            | 0.32            | 0.31            | 0.30            | 0.31            | 0.29            | 0.27            |
| $3_2 \rightarrow 2_0$    | 6.16            | 6.45            | 6.64            | 7.09            | 6.57            | 6.43            | 6.37            | 6.49            |
| $3_2 \rightarrow 4_0$    | 2.75            | 2.95            | 3.02            | 3.02            | 2.92            | 2.93            | 2.79            | 2.68            |
| $2_2 \rightarrow 0_0$    | 1.89            | 1.96            | 2.02            | 2.23            | 2.03            | 1.96            | 1.98            | 2.08            |
| $2_2 \rightarrow 2_0$    | 6.35            | 6.72            | 6.91            | 7.17            | 6.76            | 6.69            | 6.51            | 6.48            |
| $5_2 \rightarrow 4_0$    | 0.64            | 0.71            | 0.73            | 0.70            | 0.68            | 0.71            | 0.65            | 0.60            |
| $5_2 \rightarrow 6_0$    | 5.27            | 5.48            | 5.66            | 6.14            | 5.63            | 5.48            | 5.48            | 5.67            |
| $5_2 \rightarrow 7_2$    | 3.59            | 3.91            | 3.99            | 3.94            | 3.82            | 3.87            | 3.86            | 4.03            |

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