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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 quasiparticle 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 ^{270}Ds, 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 nucleon 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 [1,2]. It has been suggested that by studying the transfermium nuclei, in particular their excited structure, one can gain useful information on relevant single-particle states [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. [4–7]). The discussion on excited configurations so far has been focused on quasiparticle excitations [8–11]. 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 [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 [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 [15] using the qasiboson approximation, and by Bès *et al.* [16] using the quadrupole-plus-pairing model based on deformed Nilsson states [17]. Modern treatment of γ vibration includes the Tamm-Dancoff method, the random phase approximation [18], and others [19,20]. In Ref. [21], a shell-model-type method for describing γ-vibrational states was introduced, which is based on the Triaxial Projected Shell Model [22], a generalized version of the original Projected Shell Model [23] by extending it to a triaxially deformed basis. It was shown [21] that by performing diagonalization in a basis constructed with exact three-dimensional angular-momentum-projection on triaxially deformed states, it is feasible to describe γ-vibrational states in a shell model framework. In this way, one can achieve a unified treatment of ground-state band (g band) and multiphonon γ-vibrational bands (γ band) in one calculation, and the results can be quantitatively compared with data. The underlying physical picture of generating γ-vibration in deformed nuclei is analogous to the classical picture of Davydov and Filippov [24]. Subsequent papers [25–27] studied electromagnetic transitions by using wave functions obtained from the shell model diagonalization.

The Projected Shell Model [23] is a shell model that uses deformed bases and the projection technique. In the present calculation, we use the triaxially-deformed Nilsson plus BCS basis $|\Phi\rangle$. The Nilsson potential is

$$\hat{H}_0 - \frac{2}{3}\hbar\omega\left[\varepsilon\hat{Q}_0 + \varepsilon'\frac{\hat{Q}_{+2} + \hat{Q}_{-2}}{\sqrt{2}}\right], \tag{1}$$

where $\hat{H}_0$ is the spherical single-particle Hamiltonian with inclusion of appropriate spin-orbit forces parametrized by Bengtsson and Ragnarsson [28]. The axial and triaxial parts of the Nilsson potential in Eq. (1) contain the deformation parameters ε and ε', respectively, which are related to the conventional triaxiality parameter by $\gamma = \tan^{-1}(\varepsilon'/\varepsilon)$. The pairing correlation in the Nilsson states is taken into account by 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

$$\hat{H} = \hat{H}_0 - \frac{\chi}{2}\sum_\mu \hat{Q}^+_\mu\hat{Q}_\mu - G_M\hat{P}^+\hat{P} - G_Q\sum_\mu \hat{P}^+_\mu\hat{P}_\mu \tag{2}$$

