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OBLATE COLLECTIVE ROTATIONAL MOTION IN ^{185}Hf

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Oblate collective rotational motion in ^{185}Hf

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Abstract

The configuration dependent total energy surface in the rotating frame for the neutron rich new nucleus ^{185}Hf, calculated with WoodsSaxon potential predicts a very stable oblate collective rotation, namely a γ deformation of about $-60°$, for the yrast high spin states. The stability of the oblate collective rotation is explained based on the strong negative γ deformation drive of the both valence quasiprotons and quasineutrons toward $\gamma \approx -60°$.

The collective rotational nuclei mostly have a prolate shape and some are found to be triaxially deformed, but the oblate collective rotation, namely the $\gamma = -60°$, is very rarely observed in the nuclear yrast spectroscopy. Therefore it is very interesting to search for this rotational mode which provides an important new phase to study the interplay between the collective rotation and the valence quasiparticle motion. A strong γ deformation drive of the lowest rotating quasiparticle orbital toward $\gamma = -60°$ may be generated when the Fermi level lies in the upper part of a high-j shell according to the general role for the shape of rotating quasiparticle orbital [1]. The rather clear evidence for the oblate collective rotation, was found in the aligned rotational bands based on the $\pi(h_{11/2})^1\nu(h_{11/2})^2$ configuration observed in ^{131}La [2]. The experimental results for ^{131}La show the alignment of a pair of $h_{11/2}$ neutrons is the origin of the oblate collective rotation since the Fermi level of neutrons leis in the upper part of the $h_{11/2}$ shell. The

new neutron rich nucleus ^{185}Hf, discovered recently in LanZhou Lab. [3], may be a best candidate for the oblate collective rotational nuclei since both proton and neutron Fermi levels are in the upper part of a high-j shell, $i_{13/2}$ and $h_{11/2}$ respectively. Indeed, the present calculation predicts a very stable oblate collective rotation for both the yrast band and the excited band states.

The total routhian surface (TRS) approach, for details see for an example ref.[4], based on the cranked Hartree- Fock- Bogolyubov equations (CHFB) and the Strutinsky method [5], has been very successful in interpreting and predicting low energy nuclear structure phenomena, and it is a microscopic theory with predictive power. Therefore it is natural to extend the TRS approach to studying the structure of nuclei far from the β stability line, such as ^{185}Hf. The hamiltonian describing a quasiparticle moving in a deformed potential rotating around the x- axis with a given frequency ω may be written as,

$$H^{\omega} = H_{sp} + H_{pair} - \omega J_x, \tag{1}$$

where the H_{sp} denotes the deformed single particle hamiltonian of which the mean field is parameterized by a deformed Woods-Saxon potential with so called universal parameter set [6]. The nuclear shapes are described with the quadrupole (β_2, γ) and hexadecapole (β_4) deformation parameters in the present calculation. The H_{pair} stands for the pairing interaction, approximated by a monopole pairing force with the strength computed at each deformation point using the average gap method [7]. At the rotational frequency $\omega = 0$ the pairing gap Δ_0 is determined selfconsistently by solving the BCS equations. At high spins, $\omega > 0$, the Coriolis force $-\omega J_x$ possesses the antipairing effect which may be approximated by a decreasing pairing gap with increasing ω,

$$\Delta(\omega) = \begin{cases} \Delta_0(1 - 0.5(\omega/\omega_c)^2), & \text{if } \omega < \omega_c; \\ 0.5\Delta_0(\omega_c/\omega)^{3/2}, & \text{if } \omega > \omega_c. \end{cases} \tag{2}$$

The pairing gap is reduced by about 50% at $\hbar\omega = \hbar\omega_c = 0.7$ Mev as a reasonable value for the mass region. The total routhian energy surface, namely the total energy in the rotating frame as a function of the deformation β_2 and γ, of nucleus (Z,N) for a given

quasiparticle configuration μ may be calculated by

$$E^{\mu}(Z,N,\beta_2,\gamma;\omega) = E_{ld}(Z,N,\beta_2,\gamma) + E_{corr}(Z,N,\beta_2,\gamma;\omega=0)$$
$$+[< \Psi^{\omega}_{\mu} \mid H^{\omega} \mid \Psi^{\omega}_{\mu} > - < \Psi^{\omega=0}_{\mu} \mid H^{\omega} \mid \Psi^{\omega=0}_{\mu} >]. \quad (3)$$

Where the E_{ld} is the liquid drop model energy [8], the E_{corr} is the quantal effect correction to the energy, which includes both the shell correction [5] and the pairing correction [9]. The term in the brackets describes the contribution to the energy due to rotation, which includes contributions from both the quasiparticle vacuum rotation and the rotating quasiparticles which belong to the configuration μ. The excitation of these rotating valence quasiparticles could has a strong driving effect on the nuclear shapes and thus play an important role in the shape transition. The hexadecapole deformation β_4 is fixed at a value corresponding to the minimum of the liquid drop energy at given (β_2,γ) in the present calculation. The total routhian is thus minimized with respect to the β_2 and γ deformations to obtain the equilibrium nuclear shape.

The total routhian surfaces calculated for the yrast states of ^{185}Hf are shown in Fig.1 (a), (b) and (c) for $\hbar\omega = 0.1$ MeV, 0.2 MeV and 0.4 MeV respectively. The well developed oblate shape minima in the TRS diagrams are found at around $\beta_2 = 0.2$ and $\gamma = -60°$ for the yrast states from low to very high rotational frequencies, i.e. from low to very high spins. These results indicate that the neutron rich new nucleus ^{185}Hf is first of all a deformed nucleus both at the ground band states and the aligned band states, and secondly is an oblate collective rotor, namely the $\gamma = -60°$, which is surprisingly well established. The calculated total angular momenta of the yrast states at $\hbar\omega$ =0.1 MeV, 0.2 MeV and 0.4 MeV are $7.5\hbar$, $13.5\hbar$ and $35.5\hbar$ respectively. The oblate shape minimum emerged at around $\beta_2 = 0.2$ and $\gamma = -60°$ persist up to a very high frequency $\hbar\omega \approx 0.6$ MeV, the corresponding spin I=52.5, until a strongly deformed but slightly triaxial shape with $\beta_2 = 0.4$ and $\gamma = 14°$ is established for the yrast state at $\hbar\omega = 0.7$ MeV, the corresponding spin I=78.5. We have never seen yet such a so stable oblate collective rotation in any one of observed nuclei. There are two factors which are important for understanding the formation of such a stable oblate collective rotation.

First of all, the calculated total energy surface for the ground state, $\omega = 0$, presents the softness of the γ deformation in the region of γ from 60° to −90° at $\beta_2 \approx 0.2$, this also can be seen by viewing the TRS diagram at a low frequency like Fig.1 (a). Secondly, the γ driving force of both lowest rotating quasiproton and quasineutron orbitals drives the nucleus toward $\gamma \simeq -60°$. This γ driving effect must be very strong because of a strong γ driving force acting on a γ-soft core. The γ deformation driving tendency of the odd neutron orbital in ^{185}Hf presents a strong negative γ drive toward −60° since the neutron Fermi level lies at the upper part of the $i_{13/2}$ high-j shell. Because of this negative γ drive of the $i_{13/2}$ neutron orbital the ground band states of ^{185}Hf have a equilibrium γ deformation around −60°, as shown in Fig.1 (a) and (b). Further more, the lowest two quasiproton orbitals also have a very strong negative γ driving force toward −60° for the same reason, namely the proton Fermi level in ^{185}Hf lies at the upper part of a high-j shell $h_{11/2}$. Therefore, the alignment of a pair of $h_{11/2}$ protons occurring at higher spins in ^{185}Hf leads to a γ drive to $\gamma = -60°$ and thus the equilibrium γ deformation of −60° could persist up to very high spins. In addition, the present calculation shows that this strong negative γ drive of the $h_{11/2}$ quasiprotons is the origin of the oblate collective rotation for the lowest negative parity band states in ^{185}Hf. In order to investigate the two dimensional driving force of rotating quasiparticle orbitals in the (β_2,γ) deformation plan, we introduce the quasiparticle routhian surface (QRS), defined as the quasiparticle energy in the rotating frame as a function of the β_2 and γ deformations. The calculated QRS of the three quasiparticles $\pi(h_{11/2})^2\nu(i_{13/2})^1$ which is the intrinsic configuration of the aligned yrast band states of ^{185}Hf is shown in Fig.1 (d). The deep minimum around $\beta_2 = 0.2$ and $\gamma = -60°$ in Fig.1 (d) demonstrates a very strong negative γ drive from $\gamma = 0$ (prolate) to $\gamma = -60°$ (oblate) in a β_2 deformation range of 0.1 to 0.4. This is the driving force that is essentially responsible for the deep minimum shown in Fig.1 (c) which indicates the stable oblate collective rotation persisting up to very high spins in ^{185}Hf. In fact, the general pattern, particularly the local pattern around the minimum in Fig.1 (c), could be understood simply by adding the pattern of Fig.1 (d) onto the pattern of Fig.1 (a) or (b).

In summary, a surprisingly stable oblate collective rotation, i.e. $\gamma = -60°$, in the neutron rich new nucleus ^{185}Hf is predicted by the present TRS calculation and interpreted from the viewpoint of the very strong negative γ drive toward $\gamma = -60°$, generated by both proton and neutron quasiparticle orbitals when the Fermi level lies at the upper part of a high-j shell, as demonstrated by the introduced QRS diagram. It is expected that there must be more nuclei far from the β stability line which could behave as the oblate collective rotors like ^{185}Hf according to the mechanism discussed above.

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Captions of Figures
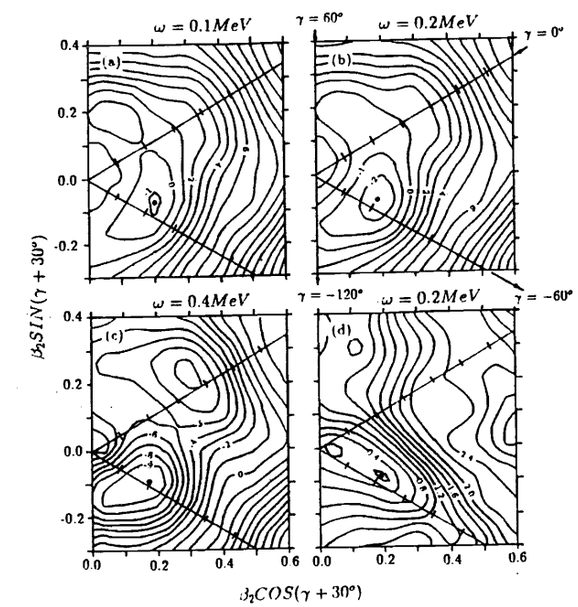
Fig.1 The contour plots of the total energy routhian surfaces for the yrast configuration of ^{185}Hf, shown in the panel (a), (b) and (c) for $\hbar\omega = 0.1$ MeV, 0.2 MeV and 0.4 MeV respectively, with the contour scale 1.0 MeV. The panel (d) is the contour plot of the quasiparticle energy routhian surface of the three quasiparticle configuration $\pi(h_{11/2})^2\nu(i_{13/2})^1$ in ^{185}Hf at $\hbar\omega = 0.2$ MeV, with the contour scale 200 keV.The coordinates are same for all four panels, the abscissa, ordinate and the axes of prolate (oblate) collective, $\gamma = 0°$ ($\gamma = -60°$) and non-collective $\gamma = -120°$ ($\gamma = 60°$) rotation are indicated. The minima are indicated by the heavy solid circles.