Systematic study on shape evolutions in superdeformed nuclei

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Introduction

Superdeformed (SD) nuclei at high spin states in several mass regions are investigated using statistical approach with cranked Nilsson Strutinsky formalism to explore the equilibrium deformations in the ground state and their evolution with spin. Shape transitions from normal deformed to superdeformed states with increasing spin is studied and a clear picture of shape coexistence is provided. Detailed information on spin, rotational energy and dynamical moment inertia is compared with available experimental data and the impact of temperature and pairing on superdeformed configuration are discussed.

Formalism

The grand canonical partition function for a hot rotating nucleus is given by [1]

$$Q(\alpha_Z,\alpha_N,\beta,\lambda)=\sum_i \exp(-\beta E_i+\alpha_Z Z_i+\alpha_N N_i+\lambda M_i) \quad (1)$$

with respect to the Lagrangian multipliers $\alpha_Z, \alpha_N, \beta, \lambda$ which conserve the proton number, neutron number, total energy for a given temperature T = 1/β and angular momentum M along the space fixed z axis and are fixed by the following equations given in terms of single particle energies [2]

$$<N>=\sum_i \left[1+\exp\left(-\alpha_N+\lambda m_i^N+\beta\varepsilon_i^N\right)\right]^{-1}, \quad (2)$$

$$<Z>=\sum_i \left[1+\exp\left(-\alpha_Z+\lambda m_i^Z+\beta\varepsilon_i^Z\right)\right]^{-1}, \quad (3)$$

$$<M>=\sum_i n_i^N m_i^N+\sum_i n_i^Z m_i^Z , \quad (4)$$

$$<E>=\sum_i n_i^N \varepsilon_i^N+\sum_i n_i^Z \varepsilon_i^Z . \quad (5)$$

The excitation energy E^* of the system is

$$E^* = E(M, T) - E_0. \quad (6)$$

The free energy of the system is given as

$$F = E - TS. \quad (7)$$

Calculations are carried out for all the parameters like total energy, excitation energy, specific heat as a function of angular momentum M from 0 ħ to 16 ħ, temperature T from 0 MeV to 5 MeV and deformation parameter ε from -0.6 to +0.6 (in steps of 0.1). The most probable values are obtained after minimizing the free energy.

Results and discussion

Every region of superdeformation possesses their own characteristics, so systematic investigations on similarities and differences among the SD bands in different mass regions are needed for a deeper understanding of SD structure. In this work, we made detailed investigation on rotational energies, spins, moment of inertia of the SD rotational bands taking into account of one critical nucleus in each region. The nuclei selected are ^{188}Pb (neutron deficient even-even), ^{147}Gd (neutron deficient even-odd), ^{136}Pm (neutron rich odd-odd), ^{112}Mo (neutron rich even-even), ^{78}Kr (proton rich N ≈ Z), ^{60}Zn (doubly magic N = Z), and ^{40}Ca (doubly magic N = Z) in the mass regions A ≈ 190, A ≈ 150, A ≈ 130, A ≈ 110, A ≈ 80, A ≈ 60, and A ≈ 40 respectively. For brevity, we present only the results of ^{40}Ca here.

SD band in A ≈ 40 region

After nearly 15 years of systematic search, new islands of superdeformation have been found in the nuclear chart around A ≈ 40 mass region (e.g., ^{36}Ar and ^{40}Ca). Nuclei in this region offer an opportunity to explore this coexistence of non-collective spherical and highly collective-highly deformed states. We have investigated the coexistence of spherical, deformed, and superdeformed states at low spin in ^{40}Ca and have found that the SD states of ^{40}Ca are nearly axially symmetric.

The dynamical moment of inertia $j^{(2)}$ behavior suggests that several among the SD bands around this region may exhibit the identical band phenomenon and backbending is seen around 30 ħ (Fig. 1(c)). In addition to the ground state of ^{40}Ca having a spherical shape, a SD state is also observed with respect to the spherical ground state. The first excited stated being a prolate one has been interpreted as 4p-4h excitation across the N, Z = 20 shell gap and the SD state as 8p-8h excitation.

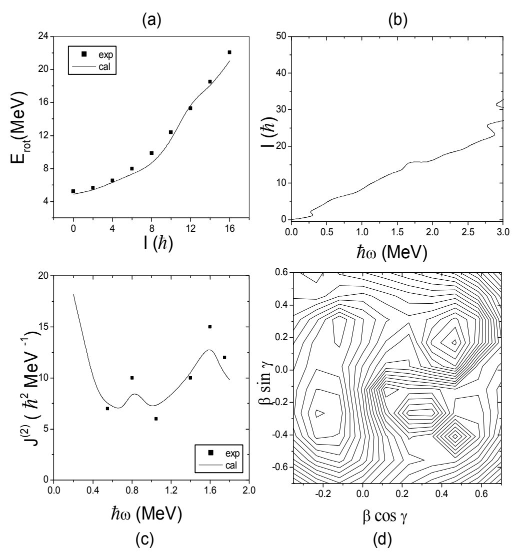

Fig. 1 (a) Rotational energy as a function of spin (b) Rotational frequency as a function of spin (c) $j^{(2)}$ as a function of rotational frequency (d) Contour plot of energy in the β, γ plane.

The main results are:

(i) The majority of the SD shapes are predominantly axially symmetric in nature. Evidences are also there for triaxial SD bands like ^{154}Er based on the development of single particle triaxial shell gaps in non-axially deformed nuclei, but in several cases triaxiality is found to be suppressed due to pairing correlations.

(ii) The structure of deformed nuclei is quite different from spherical nuclei. For example, while actinide nuclei undergo fission, deformed nuclei in 150<A<190 region do not. Likewise nuclei in 150<A<190 region have prolate ellipsoidal form, whereas nuclei in the 80<A<130 region have possibly oblate form.

(iii) $j^{(2)}$ in A ≈ 190 region shows a similar ħω dependence which is in contrary to A ≈ 150 region which shows a variety of behavior as a function of ħω such as a turnover of $j^{(2)}$. This result suggests that there may exist a competition between pairing and antipairing effects in the A ≈ 150 region.

(iv) Several features of SD bands in A ≈110 region are similar to those of smooth terminating bands in A ≈ 60 region such as the smooth drop of $j^{(2)}$ with increasing ħω to values much lower than $j^{(2)}$. Experimentally determined properties of SD states reasonably agree with our theoretical predictions.

(v) In the A ≈ 80 SD nuclei, the population of $h_{11/2}$ intruder orbitals is responsible for SD shapes where as $g_{9/2}$ intruder orbitals is responsible for A ≈ 60 region. The coexistence of prolate - oblate shape dominates the structure of low spin states in the A ≈ 80 region. The characteristic features of TES's are the γ softness for A ≈ 60 region (^{62}Zn) and oblate- prolate coexistence for A ≈ 80 region (^{72}Kr).

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References

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