Collective enhancement and nuclear shape transitions

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Introduction

The Nuclear Level Density (NLD), the number of energy levels per unit of excitation energy, is a crucial statistical property that exhibits a remarkable characteristic of rapidly increasing with higher excitation energy [1]. In deformed nuclei, collective enhancement in level density (CELD) arises from additional degrees of freedom associated with collective motions [2]. Since, rotational effects are generally more dominant than the vibrational effects, deformed nuclei generally exhibits a more noticeable enhancement. Hansen et al. introduced an enhancement factor, K_{rot}, to the intrinsic level density which is a deformation dependent factor [3]. This enhancement effect tends to diminish at higher excitation energies, a phenomenon known as fadeout. This study focuses on investigating CELD and its fadeout in ^{185}Re nuclei, utilizing Free Energy Surfaces (FES) as a tool to explore nuclear shape transitions and their connection to the CELD behavior at excited states.

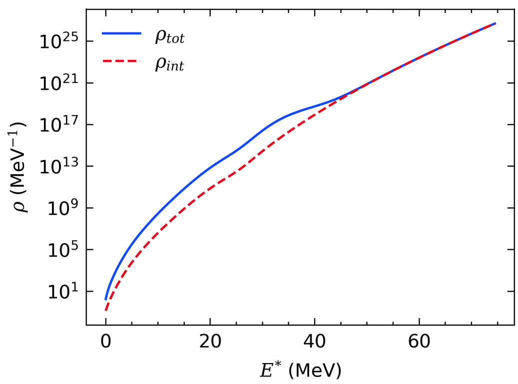

FIG. 1: Intrinsic and collective level densities plotted as a function of excitation energy.

Theoretical Framework

The total free energy at high spin and temperature using Nilsson-Strutinsky method is given by [4],

$$F_{TOT} = E_{RLDM} + \sum_{Z,N} \delta F$$

The shell corrections to free energy and spin are rewritten as

$$F_{TOT} = E_{LDM} + \sum_{Z,N} \delta F^{\omega} + \frac{1}{2}\omega \left(I_{TOT} + \sum_{Z,N} \delta I \right)$$

where $\delta F^{\omega} = F^{\omega} - \tilde{F}^{\omega}$ and $I_{TOT} = \xi_{rig}(\omega) + \delta I$.
The intrinsic level density equation is obtained as

$$\rho_{int} = \frac{\exp(S)}{(2\pi)^2\sqrt{D}}$$

where $S = \Omega + \beta E - \alpha N - \mu M$, is the entropy of the system and D is the determinent obtained by the second derivatives of grand potential Ω and $\alpha = \beta\lambda$ and $\mu = \beta\gamma$.
The total level density of a nucleus is given by [3],

$$\rho_{tot} = \rho_{int} * K_{coll}$$

where $K_{coll} = K_{rot} * K_{vib}$

$$K_{rot} = \begin{cases} (\sigma^2 - 1) f(E^*) & \text{if } \sigma^2 > 1 \\ 1 & \text{if } \sigma^2 \leq 1 \end{cases}$$

Here, $\sigma^2 = \frac{IT}{\hbar^2}$ and $I = \frac{2}{5} m_0 A R^2 (1 + \frac{\beta_2}{3})$. $f(E^*) = \left\{ 1 + \exp \frac{E^* - E_{cr}}{d_{cr}} \right\}^{-1}$ is the Fermi function which represents the fadeout of collective motions. $E_{cr} = 120\beta_2 A^{1/3}$ and $d_{cr} = 1400\beta_2^2/A^{2/3}$.

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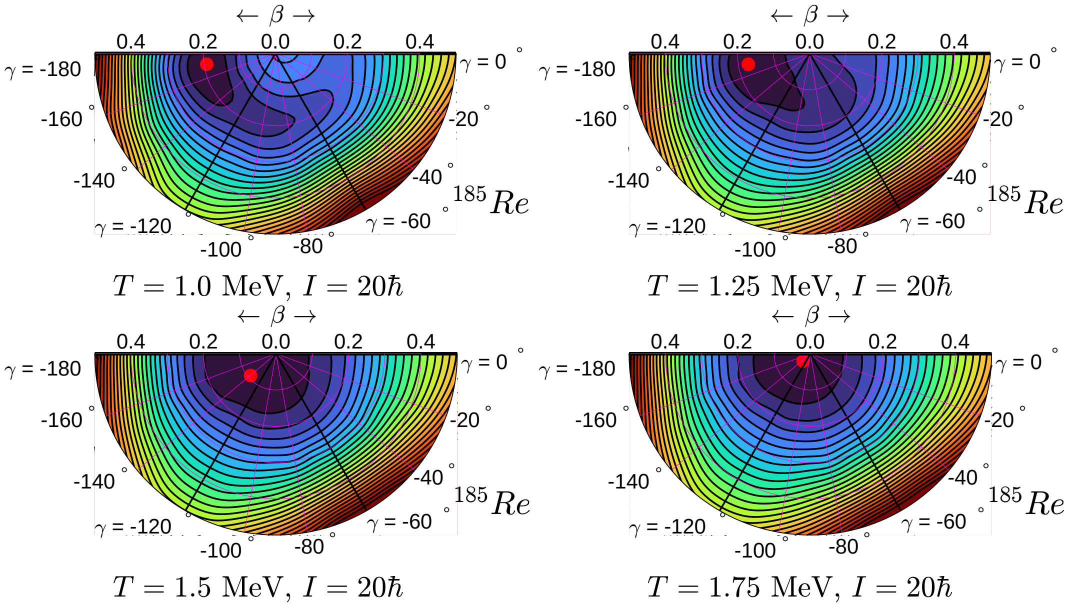

FIG. 2: The Free Energy Surfaces (FES) plotted as a function of β_2 and γ at different temperatures with $I = 20\hbar$.

Results and Discussion

In this study, we focus on the ^{185}Re nucleus to investigate the phenomenon of collective enhancement in level density. Experimentally, P. Roy *et. al.* observed a collective enhancement in the ^{185}Re compound nucleus, which was noticeable only at lower excitation energies [5]. Fig. 1 illustrates both the intrinsic and collective level densities as functions of excitation energy, revealing a clear enhancement in the NLD. However, this CELD fades out beyond an excitation energy of 40 MeV.

Fig. 2 shows the FES plotted against the quadrupole deformation (β_2) and the triaxiality (γ) parameter at various temperatures, with the angular momentum fixed at $20\hbar$. Initially, the nucleus exhibits a non-collective oblate shape with $\beta_2 = 0.2$. As the temperature increases, a distinct change in the most probable nuclear shape is observed. At $T = 1.5$ MeV, the nucleus exhibits a nearly spherical shape with it's most probable shape at $\beta_2 = 0.1$ and $\gamma = -140°$. At $T = 1.75$ MeV, the most probable shape of the nucleus is showing a spherical structure. The critical temperature for the fadeout of the collective enhancement was calculated as 1.62 MeV [5]. Therefore, at $T = 1.75$ MeV, the spherical shape of the nucleus likely accounts for the observed fadeout of the CELD.

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