Theoretical Studies of Giant Dipole Resonances for Sn Isotopes

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Introduction

Study of isovector giant dipole resonance (GDR) has drawn attention in the literature to understand the structural properties of an excited nucleus [1]. A number of experiments have been performed over the years to study how the GDR width changes with the nuclear excitation energy and angular momentum [2]. These experiments have invoked a series of theoretical investigations of GDR at finite excitation and angular momentum to clarify the role of spin, quantum and thermal fluctuations. As the collective dynamics associated with the GDR is strongly correlated to the individual nucleonic motion, complete understanding of this process has yet not been achieved. The GDR built on an excited state of a nucleus having finite angular momentum makes the scenario even more complicated.

In the time-independent framework, different variants of the random phase approximation (RPA) [3] and quasi-particle RPA(QRPA) have been employed to study the GDR responses. Apart from the time-independent or static frameworks, nuclear oscillations have been studied by employing time-dependent prescriptions e.g. time-dependent density functional theory (TDDFT). Although, GDRs built on excited states have been studied using finite-temperature QRPA (FT-QRPA), it fails to reproduce the experimental data for GDR widths satisfactorily as the prescription lacks the proper accounting of the collective excitation. Relativistic mean field theory at finite temperature is also proposed, but it suffers from the drawback of having sharper temperature dependence of GDR width compared to the experimental data. The temperature dependence of experimentally obtained GDR width can be reproduced almost accurately by implementing the phonon damping model (PDM) which is a microscopic prescription for GDR. In this model, strengths of coupling between the single-particle states and the phonon excitation are varied alongside the phonon energy to reproduce the ground-state GDR width. Then, the temperature dependence is obtained using the values of the parameters required to reproduce the ground-state GDR.

On the other hand, thermal shape fluctuation model (TSFM) has been used widely to calculate GDR widths. In TSFM, deformed configurations of nuclei become available at a finite temperature due to the thermal excitation, resulting in a broadening of the GDR width and it is assumed that, the collective vibration is adiabatic in nature, i.e., the timescale considered for the thermal fluctuation is much smaller than the time required for the damping of the GDR vibration. Being a statistical model, TSFM requires a Helmholtz's free energy surface (FES) associated with different deformations to be computed. In the existing studies in the literature, the FESs are constructed using macroscopic-microscopic prescription i.e. macroscopic description like liquid drop model is used to obtain the bulk part of the free energy and then, microscopic shell correction is added to it separately.

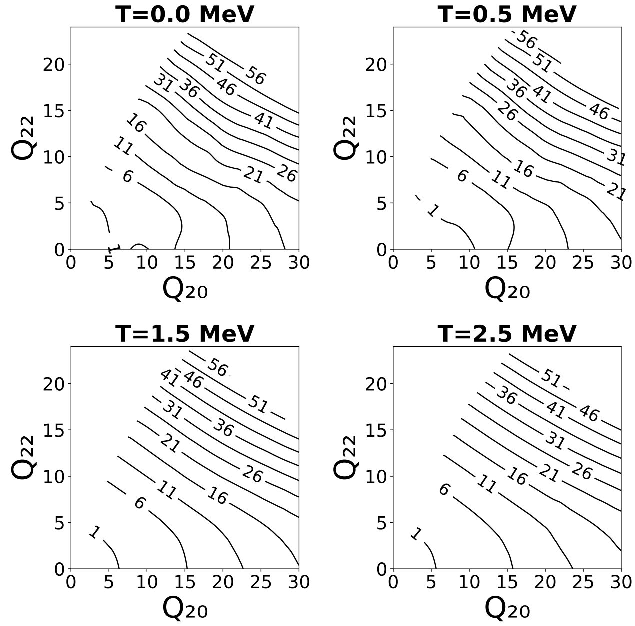

FIG. 1: Free energy surfaces using SkM* functional at different temperatures.

In the present work, we have calculated the FESs of ^{118}Sn microscopically at different temperatures by utilizing the finite-temperature density functional theory (FT-DFT) where pairing interactions are treated within the Hartree-Fock-Bogoliubov (HFB) formalism and angular momentum of the system is not considered. Therefore, our prescription is suitable for systems having very low angular momentum or no angular momentum at all. Constant Helmholtz free energy contours have been plotted against the deformation coordinates Q_{20}, Q_{22}, the quadrupole moments in units of 100 fm^2, at different temperatures and shown in Fig.-1. The constant free energy contours in Fig.-1 have been constructed using SkM* energy density functional and the free energy values

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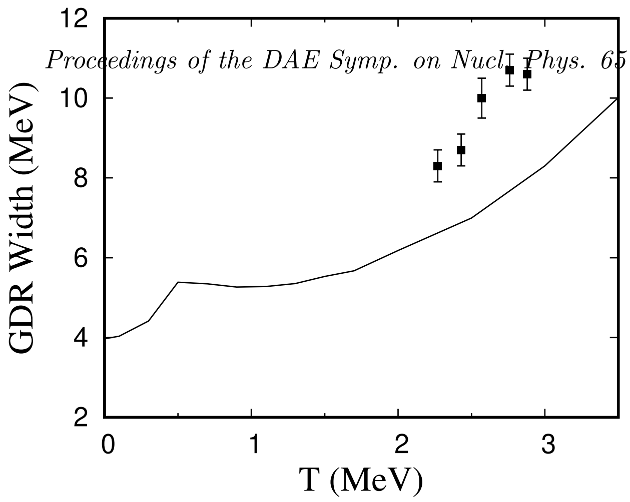

FIG. 2: Calculated GDR width for ^{118}Sn along with experimental data [4].

have been computed in the unit of MeV. The calculated FESs for ^{118}Sn have been implemented to calculate GDR widths at different temperatures in accordance with the assumptions of the TSFM. Finally the calculated GDR widths have been plotted against temperature and shown in Fig.-2 and compared with data for ^{118}Sn taken from ref.-[4].

Calculations and Results

We consider quadrupole moments Q_{20} and Q_{22} in units of 100 fm^2 as collective vibrational coordinates. The expectation value $<\mathcal{O}>$ of an observable $\mathcal{O}$ is then given by,

$$<\mathcal{O}>=\frac{\iint dQ_{20}dQ_{22}\ P\left(Q_{20},Q_{22}\right)\mathcal{O}}{\iint dQ_{20}dQ_{22}\ P\left(Q_{20},Q_{22}\right)} \quad (1)$$

where, $P\left(Q_{20},Q_{22}\right)$ is the relative probability that a particular shape (Q_{20}, Q_{22}) would appear with respect to the spherical configuration ($Q_{20}=0$, $Q_{22}=0$). An excited nucleus is supposed to be thermalized system with temperature being T and then the relative probability is given by,

$$P\left(Q_{20},Q_{22}\right)\propto\exp\left(-\frac{F\left(Q_{20},Q_{22}\right)-F_0}{T}\right) \quad (2)$$

where, $F\left(Q_{20},Q_{22}\right)$ represents the FES with F_0 being the value at the minimum which represents the spherical configuration. The isovector GDR strength function is given by the Breit-Wigner formula [1],

$$\mathcal{F}=\sum_{\{x_i\}}\mathcal{F}_{x_i}=C_n\frac{NZ}{A}\sum_{\{x_i\}}\frac{E^*\Gamma_{x_i}}{\left(E^{*2}-E_{x_i}^2\right)^2+\left(E^*\Gamma_{x_i}\right)^2} \quad (3)$$

where, N, Z and A represent the neutron number, atomic number, and mass number, respectively, of the nucleus and C_n is the normalization constant. GDR strength function $\mathcal{F}$ in eqn.-3, therefore, represents the $\mathcal{O}$ in eqn.-1 and the excitation energy E^* is equivalent to a finite temperature T and calculated from the difference between the energies of the ground-state (g.s.) deformations,

$$E^*=\left(E_{HFB}^{T}\right)_{g.s.}-\left(E_{HFB}^{T=0}\right)_{g.s.} \quad (4)$$

A deformed nucleus is supposed to be an ellipsoid and the sum in eqn.-3 is taken over the three axes of the ellipsoid. If the centroid energy and the FWHM of the resultant GDR response are represented by E_{x_i} and Γ_{x_i}, respectively, along the x_i axis, they are given by,

$$E_{x_i}=E_0\ \exp\left(\frac{R_{x_i}\left(Q_{20},Q_{22}\right)-R_0}{R_0}\right)$$

$$\text{and,}\quad \Gamma_{x_i}=0.05E_{x_i}^{1.6} \quad (5)$$

where, the empirical expression for E_0 is,

$$E_0=18.0A^{-1/3}+25.0A^{-1/6} \quad (6)$$

and R_{x_i} defines the length of the semi-major axes of the ellipsoid representing the deformed nucleus while R_0 represents the radius of the spherical nucleus. In the purpose of the present study, R_{x_i} is obtained by computing the geometric radius from the self-consistent density distributions. Apart from the thermal shape fluctuation, GDR width contains the contribution due to particle evaporation as well. We have calculated the neutron evaporation width following the statistical prescription of Weisskoff and incorporated it to obtain the final results presented in the Fig.-2.

In Fig.-2 our obtained results have been plotted against temperature and experimental data taken from [4] have also been shown for comparison. In our model of calculation, we have taken the GDR contribution from ^{118}Sn isotope only. Therefore, instead of the data presented in ref.-[5], we have taken the re-evaluated data from ref.-[4]. In Fig.-2 it can clearly be seen that, the calculated GDR widths underestimate the experimental data. In the present calculation we have considered Q_{20} and Q_{22} as the coordinates and the element of the space in eqn.-1 has been taken to be $dQ_{20}dQ_{22}$, which can easily be shown to be equivalent of taking β, γ, the Bohr's deformation parameters to be the coordinates and $\beta d\beta d\gamma$, the element of the space. The existing literature establishes the fact that, it is more suitable to take $\beta^4\sin\left(3\gamma\right)d\beta d\gamma$ to be the volume element at higher temperatures and this would effect in enhancing the width further. Theoretical investigations using these different volume elements in β, γ space is currently under progress.

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