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Electromagnetic dipole transitions in nuclei at finite temperature

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Abstract. Describing the properties of highly excited or hot nuclei remains as a major challenge both for nuclear theory and experiment. We developed self-consistent finite-temperature relativistic quasiparticle random phase approximation (FT-RQRPA) using the relativistic energy density functional with point-coupling interaction to study temperature effects on electromagnetic transitions. We investigate electric dipole (E1) and magnetic dipole (M1) transitions in calcium and tin nuclei at temperatures from $T = 0$ to 2 MeV. Our results show that both E1 and M1 responses change with temperature, with E1 strength undergoing slight modifications and new low-energy peaks emerging due to thermal blocking. The M1 strength shifts significantly to lower energies, and new M1 states emerge that are forbidden at zero temperature. These findings can be important for modeling gamma strength functions in astrophysical nuclear reactions.

1 Introduction

Understanding the response of nuclei to an external field, particularly electromagnetic dipole transitions, is not only crucial for nuclear physics but also essential for modelling astrophysical phenomena such as in the study of the radiative neutron capture cross section and rates and r-process nucleosynthesis within stellar environments [1]. Up to now, the electric dipole (E1) and magnetic dipole (M1) strength in nuclei have been studied extensively in various experiments [2–4] and theoretical studies [5–7]. It is known that both E1 and M1 transitions exhibit intriguing behavior in the low-energy region, such as the development of low-energy strength in E1 transitions, commonly referred to as the pygmy dipole resonance. Moreover, the behavior of the γ-ray strength function (γSF) shows a notable enhancement at lower transition energies, and the nature of this enhancement, whether it is E1 or M1, remains an open question [8, 9].

Studying the properties of highly excited or hot atomic nuclei is equally important for understanding their behavior under extreme conditions and gaining better insights into astrophysical phenomena occurring in stellar environments. Experiments on hot nuclei are primarily based on gamma decay measurements following fusion reactions induced by heavy-ion collisions, inelastic scattering of alpha particles and alpha-induced fusion reactions [10–12]. However, measuring E1 and M1 transitions in highly excited nuclei poses a significant challenge, necessitating highly efficient gamma detector arrays with high energy resolution. So far, experimental studies have mainly focused on the giant dipole resonance (GDR), particularly its centroid energy and width. However, there is no experimental data regarding the low-energy region of E1 transitions as well as M1 transitions at finite temperatures. On the theoretical side, although a considerable amount of work has been conducted to understand the behavior of E1 transitions at finite temperatures [13–15], further studies are needed to explore the temperature dependence of M1 transitions.

In this work, we performed calculations using the finite-temperature relativistic quasiparticle random phase approximation (FT-RQRPA) with the point-coupling interaction DD-PCX to study the effect of temperature on the E1 and M1 transitions.

2 Method

Recently we used the fully self-consistent FT-RQRPA based on a relativistic energy density functional (REDF) to study E1 and M1 transitions in selected calcium and tin nuclei. The nuclear properties are described within the finite-temperature Hartree-Bardeen-Cooper-Schrieffer (FT-HBCS) framework [16], assuming spherical symmetry. In both the FT-HBCS and FT-RQRPA, the REDF with point-coupling DD-PCX interaction [17] was implemented. The DD-PCX interaction was optimized using both the ground state and excitation properties of nuclei, hence making this interaction suitable for this study. The point-coupling REDF is determined from the Lagrangian density,

$$\mathcal{L} = \mathcal{L}_{\text{PC}} + \mathcal{L}_{\text{IV-PV}}, \tag{1}$$

where $\mathcal{L}_{\text{PC}}$ includes fermion contact interaction terms as isoscalar-scalar, isoscalar-vector and isovector-vector channels [See Refs. [17, 18] for the detailed information]. For the M1 excitations, the Lagrangian density also includes the relativistic isovector-pseudovector (IV-PV) contact interaction,

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$$\mathcal{L}_{\text{IV-PV}} = -\frac{1}{2}\alpha_{\text{IV-PV}}[\bar{\Psi}\gamma^5\gamma^\mu\vec{\tau}\Psi]\cdot[\bar{\Psi}\gamma^5\gamma_\mu\vec{\tau}\Psi]. \tag{2}$$

Here, $\alpha_{\text{IV-PV}}$ is a free parameter which needs to be adjusted. For the DD-PCX interaction, the coupling strength parameter $\alpha_{\text{IV-PV}} = 0.63$ MeVfm^3 is obtained by minimizing the relative error between experimentally determined M1 peak position and theoretically calculated centroid energies of ^{48}Ca and ^{208}Pb [7, 19].

The finite temperature RQRPA matrix is given by

$$\begin{pmatrix} \widetilde{C} & \widetilde{a} & \widetilde{b} & \widetilde{D} \\ \widetilde{a}^+ & \widetilde{A} & \widetilde{B} & \widetilde{b}^T \\ -\widetilde{b}^+ & -\widetilde{B}^* & -\widetilde{A}^* & -\widetilde{a}^T \\ -\widetilde{D}^* & -\widetilde{b}^* & -\widetilde{a}^* & -\widetilde{C}^* \end{pmatrix} \begin{pmatrix} \widetilde{P} \\ \widetilde{X} \\ \widetilde{Y} \\ \widetilde{Q} \end{pmatrix} = E_\nu \begin{pmatrix} \widetilde{P} \\ \widetilde{X} \\ \widetilde{Y} \\ \widetilde{Q} \end{pmatrix}, \tag{3}$$

where E_ν denotes the excitation energies while the eigenvectors are represented by $\widetilde{P}, \widetilde{X}, \widetilde{Y}, \widetilde{Q}$. The $\widetilde{A}$ and $\widetilde{B}$ matrix elements contribute at both zero and finite temperatures. The other elements of the FT-RQRPA matrix begin to play a role as the temperature rises, since they are affected by the varying occupation factors. For the explicit forms of the matrices, we refer the reader to Refs. [15, 20–22]

3 Results

In Figure 1, we display the isovector electric dipole (E1) strength distributions for ^{48,52,60}Ca and ^{100,124,132}Sn nuclei at temperatures $T = 0, 0.5, 1,$ and 2 MeV. At zero temperature, low-energy strength increases by increasing neutron number, as expected [5]. At low temperatures, the higher-energy region of the E1 strength, or giant dipole resonance region (GDR), remains largely unchanged. However, when the temperature is raised to 2 MeV, E1 strength slightly shifts toward lower energies due to the weakening of the repulsive residual interaction. Additionally, we observe the emergence of new low-energy peaks in all nuclei, with this effect being more pronounced in neutron-rich nuclei, such as ^{60}Ca. This phenomenon is linked to thermal unblocking effects at finite temperatures, which create new excitation channels, particularly in the low-energy region of the electric dipole response due to the transitions from thermally unblocked discrete states to continuum. Due to the scattering of particles around the Fermi levels and into high-energy states, the low-energy states are more significantly affected. Of course, the treatment of the continuum also plays an essential role in properly describing excited states, especially in the low-energy region of neutron-rich nuclei at high temperatures. For instance, increasing temperature to higher values and beyond $T > 2$ MeV, can lead to the formation of unphysical strength in the low-energy region. Therefore, one should be careful when performing calculations at high temperatures for nuclei far from the stability line.

In Figure 2, we also display the M1 transition strength distributions for the same nuclei with increasing temperature. At zero temperature, we do not observe any M1 strength in ^{40}Ca and ^{60}Ca, since there are no spin-orbit (SO) partners available for M1 transitions, and all the states are fully occupied for both protons and neutrons. For ^{52}Ca, a strong peak in M1 excitation is observed around 9 MeV due to the valence neutron transitions between $(1f_{7/2}, 1f_{5/2})$ states. Additionally, a low-energy M1 peak is also obtained around 3 MeV due to the neutron $(2p_{3/2}, 2p_{1/2})$ transition. For ^{100}Sn and ^{132}Sn, which are closed-shell nuclei, the pairing correlations do not contribute. At zero temperature, the M1 strength for ^{100}Sn is obtained as a single peak at 9.47 MeV, primarily arising from the proton and neutron $(1g_{9/2}, 1g_{7/2})$ transitions. For ^{132}Sn, the M1 response exhibits a single peak around 9.0 MeV, which is mainly formed with a neutron $(1h_{11/2}, 1h_{9/2})$ and proton $(1g_{9/2}, 1g_{7/2})$ transitions.

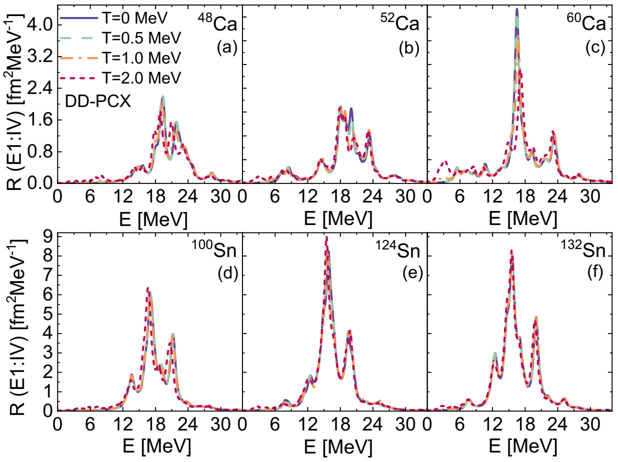

Figure 1. The isovector electric dipole (E1) strength distributions for ^{48,52,60}Ca (a)-(c) and ^{100,124,132}Sn (d)-(f) nuclei. The calculations are performed using the FT-RQRPA with DD-PCX interaction at temperatures T = 0, 0.5, 1, and 2 MeV [15, 22].

With increasing temperature, especially beyond $T = 1$ MeV, changes in the M1 strength of nuclei become more noticeable. The most striking effects are observed in ^{40}Ca and ^{60}Ca, where the development of M1 strength is evident. This occurs because particles are promoted to higher-energy levels at finite temperatures, leading to the thermal unblocking of forbidden M1 transitions. The new strength develops mainly due to transitions between proton and neutron $(1d_{5/2}, 1d_{3/2})$ and $(1f_{7/2}, 1f_{5/2})$ levels.

The M1 strength in Ca and Sn nuclei displays a behavior similar to that of the E1 strength with increasing temperature. Specifically, the excited states start to shift downward, and the formation of new excitations can be observed in the low-energy region. For instance, in ^{132}Sn at $T = 2$ MeV, new excited states appear at 2.14 MeV and 2.09 MeV, formed by proton $(1d_{5/2}, 1d_{3/2})$ and neutron $(2f_{7/2}, 2f_{5/2})$ transitions, respectively. Apart from the softening of the repulsive residual interaction with increasing temperature and the changes in the single (quasi) particle levels, the behavior of the M1 states is also sensitive to changes in spin-orbit (SO) splittings of the levels, as these excitations occur between SO partners. It has been observed that SO splittings are sensitive to temperature changes, decreasing as the temperature increases (see Ref. [22] for more information). It is also observed that the M1 strength is more sensitive to changes in temperature compared to the E1 strength. This can be related to the collectivity of the excitations: in the case of E1, many transitions contribute to the GDR region, whereas in the case of M1, it is mainly formed by a few transitions. Therefore, the M1 strength is more sensitive to temperature effects.

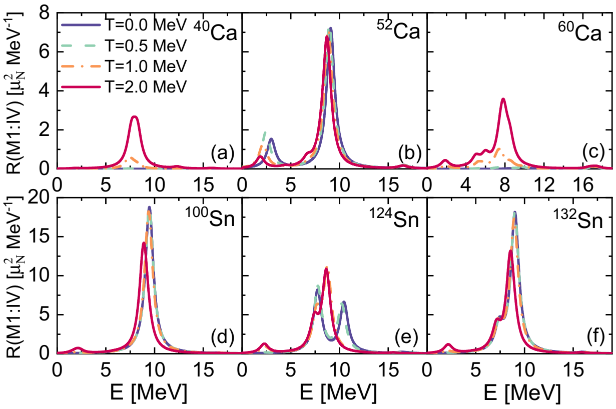

Figure 2. The isovector magnetic dipole (M1) strength distributions ^{40,52,60}Ca (a)-(c) and ^{100,124,132}Sn (d)-(f) [15, 22].

4 Conclusion

The self-consistent FT-RQRPA based on the relativistic energy density functional has been applied to study the temperature dependence of the E1 and M1 excitations. The impact of temperature on the E1 and M1 strength has been demonstrated. It has been shown that temperature leads to a shift of the E1 and M1 strength toward lower energies and to the formation of new excited states due to thermal unblocking. One of the most striking impacts of temperature is the formation of the M1 strength in ^{40}Ca and ^{60}Ca, which are forbidden at zero temperature since all the SO components are fully occupied. Such changes in the excitation spectrum of electromagnetic dipole transitions with temperature can impact astrophysical reaction rates and cross sections of photonuclear and radiative-capture reactions. Further studies on the possible contributions of electric and magnetic transitions at finite temperature in the γ-strength functions for (n,γ) reactions are in progress.

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