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Investigating finite-temperature dependence of electromagnetic dipole transitions in nuclei

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A self-consistent finite temperature relativistic quasiparticle random phase approximation (FT-RQRPA) based on relativistic energy density functional is developed to describe temperature effects in electromagnetic transitions. The isotopic chain of $^{100-140}$Sn nuclei is considered to study the evolution of electric dipole (E1) and magnetic dipole (M1) transitions at temperatures ranging from $T = 0$ to 2 MeV. The analysis reveals that E1 giant resonance is moderately modified with temperature increase, and new low-energy excitations appear at higher temperatures, making a pronounced impact, particularly in neutron-rich nuclei. This happens because of the unblocking of new transitions above the Fermi level due to thermal effects on single-particle states. However, the M1 strength peaks undergo a notable shift towards lower energies in Sn nuclei, primarily attributed to the decrease of spin-orbit splitting energies and the weakening of the residual interaction. This effect is particularly pronounced, especially above critical temperatures (T_c), where the pairing correlations vanish. In conclusion, the E1 and M1 responses demonstrate considerable dependence on temperature, and their effects could be important in modeling gamma strength functions and their applications in astrophysically relevant nuclear reaction studies.

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1. Introduction

Electromagnetic dipole transitions provide significant insights into the structural and dynamic properties of atomic nuclei due to their central role in various nuclear processes and reactions. The behavior of these transitions is highly dependent on temperature effects. As nuclear systems are exposed to higher temperatures, for instance in hot stellar environments, the increased thermal energy influences the collective motion of nucleons, thereby altering the distribution of states within the nucleus. The significance of finite temperature effects in electric dipole (E1) is evident across various applications in nuclear physics and astrophysics [1–3]. From an experimental perspective, measuring electric (E1) and magnetic dipole (M1) transitions in highly-excited nuclei is a significant challenge. For giant dipole resonance (GDR), which involves the collective oscillation of protons against neutrons, elevated temperatures can enhance the width and strength of the resonance [4]. The pygmy dipole resonance (PDR), characterized by the low-energy excitations of a more localized nature, also exhibits sensitivity to temperature changes, often resulting in modifications to its strength function [2, 5]. Numerous experimental and theoretical studies have uncovered fascinating patterns in gamma-ray strength functions (γSFs), with a significant increase in strength (an upbend structure) observed at lower transition energies [1]. Although the source of this upbend structure at low energies is not yet clear, temperature-induced changes could be a possible explanation. These temperature-induced changes in the E1 and M1 excitations can have significant implications for astrophysically relevant quantities such as neutron capture cross-section, nuclear reaction rates, and element abundances in stellar environments. Thus, it is essential to study the effects of temperature on electromagnetic transitions.

Various extensions of the random-phase approximation (RPA) based on relativistic and non-relativistic energy density functionals have been explored in previous research to study the impact of temperature on electric multipole excitations [2, 6]. All these studies have shown the appearance of new excited states, especially in the low-energy region, linked to the thermal unblocking impact of temperature on single-particle states close to the Fermi level. We developed a completely self-consistent finite temperature relativistic quasiparticle RPA (FT-RQRPA) in order to investigate both natural parity E1 and unnatural parity M1 transitions in closed- and open-shell nuclei at finite temperatures [7, 8]. In this work, the evolution of the E1 and M1 transitions from temperature T = 0 to 2 MeV is represented for $^{100-140}$Sn isotopic chain.

2. Theoretical framework

To analyze the temperature effects on E1 and M1 transitions, we established a self-consistent FT-RQRPA based on relativistic energy density functional (REDF) [7, 8]. The properties of closed- and open-shell even-even nuclei are described within the finite temperature Hartree-Bardeen–Cooper–Schrieffer (FT-HBCS) framework [9]. The REDF with point coupling DD-PCX interaction [10] and separable pairing interaction are implemented in both the FT-HBCS and FT-RQRPA. The point-coupling REDF determined from the Lagrangian density $\mathcal{L}_{PC}$ [10, 11], which includes fermion contact interaction terms as isoscalar-scalar, isoscalar-vector, isovector-vector channels. For the detailed description of the relativistic point coupling model see Refs. [10, 11]. For the case of M1 excitations, the Lagrangian density ($\mathcal{L}$) also includes the relativistic isovectorpseudovector (IV-PV) contact interaction, i.e., $\mathcal{L} = \mathcal{L}_{\text{PC}} + \mathcal{L}_{\text{IV-PV}}$, which is necessary for the FT-RQRPA residual interaction for the unnatural parity excitations of M1 type [12].

At finite temperature, the occupation probabilities of single particle states are given by $n_i = v_i^2(1-f_i)+u_i^2 f_i$, where u_i and v_i are the BCS amplitudes. The temperature dependent Fermi-Dirac distribution function is defined as $f_i = [1+exp(E_i/k_B T)]^{-1}$, where T and k_B are temperature and Boltzmann constant, respectively. E_i is the quasiparticle (q.p.) energy of a state and is calculated using $E_i = \sqrt{(\varepsilon_i - \lambda_q)^2 + \Delta_i^2}$ relation, where ε_i represents the single-particle energies and λ_q denotes chemical potentials for either proton or neutron states. Δ_i indicates the pairing gap of the given state. The finite temperature non-charge exchange RQRPA matrix is given by

$$\begin{pmatrix} \widetilde{C} & \widetilde{a} & \widetilde{b} & \widetilde{D} \\ \widetilde{a}^{+} & \widetilde{A} & \widetilde{B} & \widetilde{b}^{T} \\ -\widetilde{b}^{+} & -\widetilde{B}^{*} & -\widetilde{A}^{*} & -\widetilde{a}^{T} \\ -\widetilde{D}^{*} & -\widetilde{b}^{*} & -\widetilde{a}^{*} & -\widetilde{C}^{*} \end{pmatrix} \begin{pmatrix} \widetilde{P} \\ \widetilde{X} \\ \widetilde{Y} \\ \widetilde{Q} \end{pmatrix} = E_w \begin{pmatrix} \widetilde{P} \\ \widetilde{X} \\ \widetilde{Y} \\ \widetilde{Q} \end{pmatrix}, \tag{1}$$

where E_w denotes the excitation energies and $\widetilde{P}, \widetilde{X}, \widetilde{Y}, \widetilde{Q}$ are the eigenvectors, and T-dependent matrix elements on the left-hand side of the matrix in Eq. (1) are extensively discussed in Ref. [7]. Further, the reduced transition probability at finite temperature for E1 and M1 is calculated as described in Refs. [7, 8].

3. Results

First, the FT-RQRPA approach is employed to investigate the temperature and isospin dependence of the low- and high-energy E1 response. The isovector E1 strength distributions across the $^{100-140}$Sn isotopic chain at temperatures of $T = 0$, 0.5, 1, and 2 MeV, is shown in Fig. 1 [panels (a)-(f)] . At lower temperatures $T = 0$ and 0.5 MeV, the isotopic dependence of the low-energy modes for $E < 10$ MeV is clearly evident in the Sn isotopes. The low-energy strength, also known as the pygmy dipole strength, becomes more pronounced as the Sn isotopes shift from lighter to heavier mass numbers. Notably, in the ^{140}Sn nucleus, a substantial increase in low-energy E1 excitations is observed within the 4-9 MeV range, which can be attributed to the higher neutron content.

At finite temperatures, the highly collective GDR region undergoes only slight modifications in both strength and excitation energies. As the temperature increases to $T = 1$ and 2 MeV, newly emerging low-energy peaks appear below 5 MeV in the neutron-rich $^{124-140}$Sn isotopes as a result of thermal unblocking. This is illustrated separately on the right side in [panels (i)-(vi)] of Fig. 1. The effect of temperature is most significant in the low-energy region of the ^{140}Sn nucleus, attributed to its high neutron content, and mainly formed with the transition around the Fermi level. At finite temperatures, the promotion of nucleons to higher energy states leads to changes in occupation probabilities, with states above the Fermi level becoming more populated and those below less occupied, thereby broadening the Fermi surface. Consequently, thermal unblocking effects significantly contribute to the emergence of new excitation channels, especially in the low-energy region of the E1 response.

Next, the evolution of isovector M1 response as a function of temperature is analyzed for $^{100-140}$Sn isotopes as shown in Fig. 2. At $T = 0$ MeV, the M1 excitations are anticipated to arise

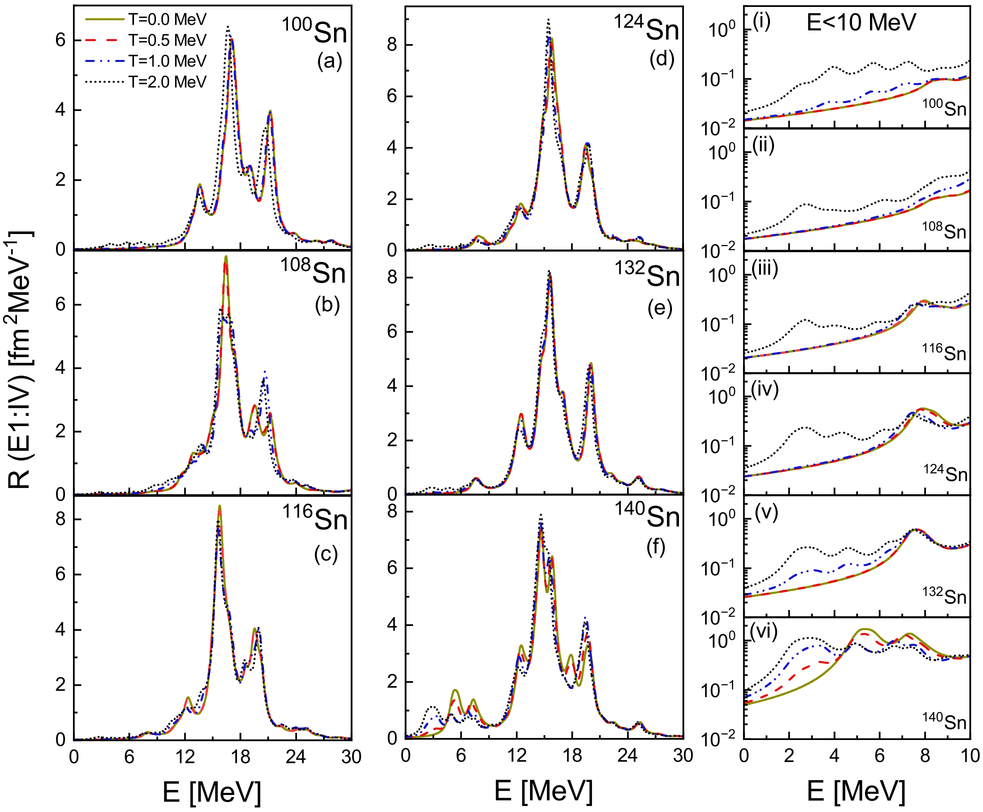

Figure 1: The isovector E1 strength distributions for $^{100-140}$Sn isotopes [Panels [(a)-(f)] at T = 0 to 2 MeV. Low-energy part of the E1 strength below 10 MeV is also shown in logarithmic scale in panels (i)-(vi). Reprinted (figure) with permission from [7]. Copyright (2024) by the American Physical Society.

from proton $\pi(1g_{9/2} \rightarrow 1g_{7/2})$ and the neutron $\nu(1g_{9/2} \rightarrow 1g_{7/2})$, $\nu(2d_{5/2} \rightarrow 2d_{3/2})$, and/or $\nu(1h_{11/2} \rightarrow 1h_{9/2})$ transitions until the higher state in the spin-orbit (SO) configuration becomes fully occupied to block the M1 transitions. In closed shell nuclei such as ^{100}Sn and ^{132}Sn, the pairing correlations do not contribute, therefore, the M1-excitation energy is primarily influenced by the SO splitting energy and residual interaction. At T = 0 MeV, the M1 strength is obtained as a single peak for ^{100}Sn, which is mainly formed with the proton and neutron ($1g_{9/2}$ and $1g_{7/2}$) transitions. The M1 response exhibits two peaks in the high-energy region as the number of neutrons increases along the Sn isotope chain. Proton transitions are mostly responsible for the first peak at lower energy, whereas neutron transitions dominate the second peak at higher energy. A detailed description at T = 0 MeV is given in Ref. [13]. As observed in Fig. 2, similar results are obtained for the T = 0.5 MeV case, where the M1 strength distribution slightly shifts to the lower energies.

In addition to the downward shift in the M1 strength at higher temperatures, we also observe a change in the ^{108,124,140}Sn nuclei from a two-peak to a single-peak structure of M1 strength. Due to the vanishing of pairing correlations at critical temperatures, the configuration energies between the proton and neutron components start to approach one another, which results in the merging of two peaks into a single peak at higher temperatures. For each considered Sn nucleus at T = 1 and 2 MeV, the structure of M1 strength distributions at finite temperatures is investigated by

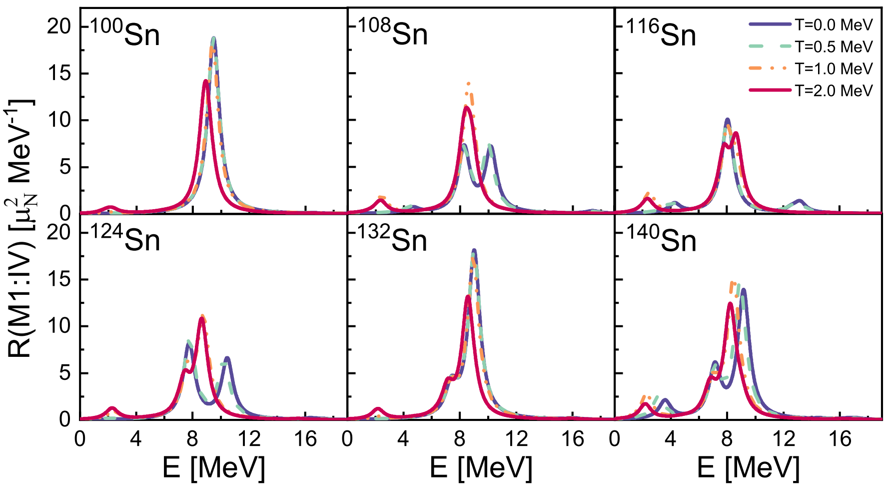

Figure 2: The isovector M1 transition strength distributions of $^{100-140}$Sn isotopes, calculated using the FT-RQRPA at temperatures $T = 0$, 0.5, 1, and 2 MeV. Reprinted (figure) with permission from [8]. Copyright (2024) by the American Physical Society.

analyzing all transitions that contribute to these states. In addition to the major $\nu, \pi(1g_{9/2} \rightarrow 1g_{7/2})$ transitions, this study has shown that $\nu, \pi(1h_{11/2}{\rightarrow}1h_{9/2})$ transitions also begin to contribute at higher temperatures in the high-energy region of $^{100-140}$Sn nuclei. Due to thermal unblocking, a finite contribution from $\nu(1i_{13/2}{\rightarrow}2i_{11/2})$ and $\nu(1h_{9/2}{\rightarrow}2h_{11/2})$ transitions is also obtained in the neutron-rich Sn isotopes. Moreover, all Sn isotopes at finite temperatures exhibit a new low-energy M1 peak below $E = 5$ MeV. In the lower-mass Sn isotopes, the $\nu(2d_{5/2}{\rightarrow}2d_{3/2})$ transition is the major contributor to the low-energy peak, and $\nu(2f_{7/2}{\rightarrow}2f_{5/2})$ transition also begins contributing in the neutron-rich nuclei.

4. Summary

Temperature evolution of isovector E1 and M1 transitions in $^{100-140}$Sn isotopes has been investigated within the self-consistent FT-RQRPA framework based on relativistic energy density functional. Both E1 and M1 strength distributions modify with increase in temperature, and shift left towards lower energies due to the thermal unblocking effects. Moreover, new low-energy excitations start to appear especially in neutron-rich Sn nuclei, and this effect is significant above the critical temperature T_c. It is also demonstrated that the M1 response is more sensitive to the temperature. The changes in the M1 response are influenced not only by the weakening and disappearance of the pairing correlations and the softening of the repulsive residual interaction but also by the decreasing of SO splitting energies. The investigation of gamma strength functions by implementing the FT-RQRPA is currently in progress.

5. Acknowledgements

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References

[1] S. Goriely, P. Dimitriou, M. Wiedeking, T. Belgya, R. Firestone, J. Kopecky et al., *Reference database for photon strength functions*, Eur. Phys. J. A **55** (2019) 172.

[2] E. Yüksel, G. Colò, E. Khan, Y. F. Niu and K. Bozkurt, *Multipole excitations in hot nuclei within the finite temperature quasiparticle random phase approximation framework*, Phys. Rev. C **96** (2017) 024303.

[3] H. Wibowo and E. Litvinova, *Nuclear shell structure in a finite-temperature relativistic framework*, Phys. Rev. C **106** (2022) 044304.

[4] O. Wieland, A. Bracco, F. Camera, G. Benzoni, N. Blasi, S. Brambilla et al., *Giant dipole resonance in the hot and thermalized* ^{132}Ce *nucleus: Damping of collective modes at finite temperature*, Phys. Rev. Lett. **97** (2006) 012501.

[5] O. Wieland, A. Bracco, F. Camera, S. Aogaki, D. Balabanski, E. Boicu et al., *Extra yield in hot ni isotopes below the giant dipole resonance*, in *Nuovo Cimento C-Colloquia and Communications in Physics*, no. 2, 2024.

[6] Y. Niu, N. Paar, D. Vretenar and J. Meng, *Low-energy monopole and dipole response in nuclei at finite temperature*, Physics Letters B **681** (2009) 315.

[7] A. Kaur, E. Yüksel and N. Paar, *Electric dipole transitions in the relativistic quasiparticle random-phase approximation at finite temperature*, Phys. Rev. C **109** (2024) 014314.

[8] A. Kaur, E. Yüksel and N. Paar, *Finite-temperature effects in magnetic dipole transitions*, Phys. Rev. C **109** (2024) 024305.

[9] A. L. Goodman, *Finite-temperature hfb theory*, Nuclear Physics A **352** (1981) 30.

[10] E. Yüksel, T. Marketin and N. Paar, *Optimizing the relativistic energy density functional with nuclear ground state and collective excitation properties*, Phys. Rev. C **99** (2019) 034318.

[11] T. Nikšić, N. Paar, D. Vretenar and P. Ring, *Dirhb—a relativistic self-consistent mean-field framework for atomic nuclei*, Computer Physics Communications **185** (2014) 1808.

[12] G. Kružić, T. Oishi, D. Vale and N. Paar, *Magnetic dipole excitations based on the relativistic nuclear energy density functional*, Phys. Rev. C **102** (2020) 044315.

[13] G. Kružić, T. Oishi and N. Paar, *Evolution of magnetic dipole strength in* $^{100-140}$Sn *isotope chain and the quenching of nucleon g factors*, Phys. Rev. C **103** (2021) 054306.