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Nuclear Reaction Rate Uncertainties in the r-Process: Insights from Self-Consistent FT-RQRPA Calculations of Dipole Transitions

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Abstract. Understanding nuclear astrophysical network calculations, particularly for processes like the rapid neutron capture process (r-process), requires precise knowledge of astrophysical reaction rates at finite temperatures in hot stellar environments. These rates depend on Maxwellian-averaged cross sections (MACS) for radiative neutron capture over a broad energy range. Within a statistical framework, their calculation relies on three key nuclear inputs: the Neutron-Nucleus Optical Model Potential (OMP), the γ-ray Strength Function (γSF), and the Nuclear Level Density (NLD). While OMP uncertainties are comparatively small, the γSF and NLD introduce significant variations in neutron-capture rate predictions. In this work, we employ a fully self-consistent finite-temperature relativistic quasiparticle random-phase approximation (FT-RQRPA) based on a relativistic energy density functional with point-coupling interactions to evaluate temperature-dependent modifications of dipole strengths. Using the benchmark case $^{61}\mathrm{Ni}(n,\gamma)^{62}\mathrm{Ni}$, we demonstrate that finite-temperature effects can enhance neutron-capture cross sections and astrophysical rates by up to $\sim$100% relative to the zero-temperature baseline. Such modifications are especially relevant under r-process conditions, where elevated temperatures prevail and even moderate changes in capture rates can significantly alter abundance predictions. These findings highlight the importance of incorporating microscopic finite-temperature effects in γSF when evaluating astrophysical reaction rates. Ongoing work extends this approach to entire isotopic chains and will assess the global impact on r-process nucleosynthesis through large-scale reaction network simulations.

1 Introduction

The astrophysical rapid neutron capture process (r-process) is responsible for producing roughly half of the heavy elements beyond iron in the universe [1]. Its predictive modeling requires accurate input for a variety of nuclear properties far from stability, including masses, β-decay rates, neutron capture cross sections, fission probabilities, photon emission and absorption rates. Uncertainties in these nuclear inputs propagate into the modeled isotopic abundance distributions, heating rates in kilonova ejecta, and cosmochronometry estimates. Among these properties, the neutron-capture and photodissociation reaction rates play a particularly critical role in shaping the r-process path, especially during freeze-out when equilibrium between (n, γ) and (γ, n) breaks. Previous studies have estimated that capture rate uncertainties, driven by choices in level densities, optical potentials, and γ-ray strength functions (γSF), can span orders of magnitude for neutron-rich nuclei near the r-process path [1–3].

Thus, reducing the uncertainties in γSF and dipole transition rates (E1, and M1) under astrophysical conditions is vital to improving the reliability of r-process simulations. In hot stellar environments (temperatures of order $\sim$0.1–1 MeV and above), nuclei exist at excitation, and thermal effects can modify the occupation of quasiparticle states, open new excitation channels (thermal unblocking) [4], and alter transition strengths. A framework that accounts for both finite temperature and pairing correlations self-consistently is therefore desirable for predicting γSF under astrophysical conditions. Recently, the finite-temperature relativistic quasiparticle random phase approximation (FT-RQRPA) has been developed to address this challenge. Kaur et al. [5–8] introduced a self-consistent FT-RQRPA based on a relativistic energy density functional with density-dependent point-coupling interaction and studied isovector electric dipole (E1) transitions in several nuclei over a temperature range of 0 to 2 MeV. These studies reveal that with increasing temperature, the giant dipole resonance (GDR) region is modestly modified, but importantly new low-energy E1 strength peaks emerge, especially in neutron-rich nuclei, due to thermal unblocking of states, which are forbidden at zero temperature. As a result, the corresponding electric dipole polarizability α_D systematically increases with temperature, with stronger sensitivity in neutron-rich nuclei. These developments suggest that finite-temperature effects can nontrivially influence the γ-strength in astrophysical conditions and thus r-process reaction rates.

Despite significant progress in modeling nuclear inputs for the r-process, a systematic study directly linking finite-temperature FT-RQRPA dipole strengths and their associated uncertainties to the r-process reaction-rate uncertainties has not yet been carried out. In this work, we address this gap by performing FT-RQRPA calculations of E1 transitions at finite temperatures for representative neutron-rich nuclei, using $^{61}\mathrm{Ni}(n, \gamma)^{62}\mathrm{Ni}$ as a benchmark case. The resulting dipole strengths are propagated into neutron-capture cross sections and astrophysical rates, allowing us to quantify the sensitivity of reaction rates to finite-temperature effects. This study demonstrates the influence of temperature-dependent dipole strengths on radiative neutron-capture rates. While the present work focuses on the benchmark case $^{61}\mathrm{Ni}(n, \gamma)^{62}\mathrm{Ni}$, the methodology can be systematically extended to entire isotopic chains of astrophysical interest. Future work will explore the consequences of these temperature-dependent rates in large-scale r-process network calculations, allowing for a more comprehensive assessment of nuclear structure uncertainties on predicted abundance patterns.

This paper is organized as follows. In Section 2 we present the theoretical framework and computational methodology, describing the FT-RQRPA implementation, the extraction of γ-strengths and reaction rates, and the uncertainty propagation strategy. Section 3 discusses the results, including the sensitivity of the rates to uncertainties in the dipole strength due to temperature effects. Finally, Section 4 gives conclusions and perspectives for further work.

2 Methodology

This section outlines the principal components of our methodology: (i) the finite-temperature relativistic quasiparticle random-phase approximation (FT-RQRPA) applied to dipole transitions, and (ii) its connection to radiative neutron-capture and photodissociation reaction rates.

2.1 FT-RQRPA for dipole transitions

We employed the finite-temperature HartreeBardeenCooperSchrieffer (FT-HBCS) framework to describe the properties of even-even spherical closed- and open-shell nuclei. The E1 strength at finite temperature is analyzed using the recently formulated finite-temperature relativistic quasiparticle random-phase approximation (FT-RQRPA) [5–8], built on top of the FT-HBCS approach. In the calculations, we have adopted the relativistic density-dependent point-coupling interaction DD-PCX [9], which is specifically optimized for modeling E1 transitions, as it incorporates constraints from experimental dipole polarizability data. In addition, a separable form of the pairing interaction is used consistently in both the frameworks. At finite-temperature, the occupation probabilities follow the Fermi-Dirac distribution

$$n_i = v_i^2(1 - f_i) + u_i^2 f_i, \tag{1}$$

where u_i and v_i are the BCS amplitudes. The T-dependent Fermi-Dirac distribution function is defined as $f_i = [1 + exp(E_i/k_{\mathrm{B}}T)]^{-1}$, where k_{B} is the Boltzmann constant, and E_i denotes the quasiparticle energy of state. The finite temperature non-charge exchange RQRPA matrix is given by

$$\begin{pmatrix} \widetilde{C} & \widetilde{a} & \widetilde{b} & \widetilde{D} \\ \widetilde{a}^{+} & \widetilde{A} & \widetilde{B} & \widetilde{b}^{T} \\ -\widetilde{b}^{+} & -\widetilde{B}^{*} & -\widetilde{A}^{*} & -\widetilde{a}^{T} \\ -\widetilde{D}^{*} & -\widetilde{b}^{*} & -\widetilde{a}^{*} & -\widetilde{C}^{*} \end{pmatrix} \begin{pmatrix} \widetilde{P} \\ \widetilde{X} \\ \widetilde{Y} \\ \widetilde{Q} \end{pmatrix} = E_w \begin{pmatrix} \widetilde{P} \\ \widetilde{X} \\ \widetilde{Y} \\ \widetilde{Q} \end{pmatrix}, \tag{2}$$

where E_w denotes the excitation energies, and $\widetilde{P}, \widetilde{X}, \widetilde{Y}, \widetilde{Q}$ are eigenvectors. The detailed expressions for the FT-RQRPA matrices can be found in Refs. [7, 8]. One key feature of FT-RQRPA is that as temperature increases, thermal unblocking allows transitions that were forbidden at zero temperature to contribute, thereby producing new low-energy strength in the dipole strength distribution. At finite temperature, the reduced transition probability is calculated as

$$B(EJ, \widetilde{0} \to w) = \left| \langle w || \hat{F}_J || \widetilde{0} \rangle \right|^2. \tag{3}$$

The detailed expression is given in Refs. [7,8]. $|w\rangle$ denotes the excited state and $|\widetilde{0}\rangle$ is the correlated FT-RQRPA vacuum state. $\hat{F}_J$ is the transition operator of the relevant excitation. Following microscopic study within SRPA theory including also $2p2h$ excitations [6], the spreading effects in E1 transition strength can be approximated by folding the FT-RQRPA strength distribution $R_{E1}(E) = \sum L(E,w)B(E1)$ with a Lorentzian function,

$$L(E,w) = \frac{1}{2\pi}\frac{\Gamma(E)}{(E-w-\Delta(E))^2+\Gamma(E)^2/4}, \tag{4}$$

where w is the excitation energy of the FT-RQRPA response, and $\Delta(E)$ and $\Gamma(E)$ are the real and complex part of the self-energy as $\Sigma(E) = \Delta(E) + i\Gamma(E)/2$. $\Gamma(E)$ denotes energy-dependent width, that can be obtained from measured decay width of particle γ_p and hole γ_h states, and is given by $\Gamma(E) = \frac{1}{E}\int_0^E d\epsilon[\gamma_p(\epsilon) + \gamma_h(\epsilon - E)](1 + C_G)$. Using the collective width $\Gamma(E)$, the energy shift $\Delta(E)$ of the self energy can be obtained using the dispersion relation as $\Delta(E) = \frac{1}{2\pi}\mathcal{P}\int_{-\infty}^{\infty} dE' \frac{\Gamma(E')}{E'-E}(1 + C_E)$, assuming different interference coefficients C_G and C_E in the real and complex parts of the self-energy. The interference coefficients C_G $(= -0.584)$ and C_E $(= -1.149)$ of the E1 strength are constrained by minimizing the χ^2 objective function to reproduce the experimental photoabsorption/photoneutron γSF [5–8]. Finally, the dipole γ-ray strength function $f_{E1}(E_\gamma, T)$ is extracted using the relation,

$$f_{E1}(E_\gamma, T) = \frac{1}{3\pi^2\hbar^2c^2}\frac{R(E1;E_\nu)}{E_\nu}. \tag{5}$$

2.2 Linking dipole strength to reaction rates

A central challenge in nuclear astrophysics is the determination of reliable reaction rates for processes such as the rapid neutron-capture process (r-process), where neutron-rich nuclei far from stability govern the path of nucleosynthesis. In statistical model calculations, radiative neutron-capture rates are obtained from Maxwellian-averaged cross sections (MACS), which depend on nuclear structure properties across a broad excitation-energy range. Three microscopic inputs are essential in this context: the neutron-nucleus optical model potential (OMP), the nuclear level density (NLD), and the γ-ray strength function (γSF). Among these, uncertainties in the γSF and NLD dominate the variations in predicted neutron-capture rates, while OMP uncertainties are typically less pronounced [2, 10].

The γ-ray strength function encodes the probability distribution of electromagnetic transitions and is particularly sensitive to collective dipole modes. At finite temperature, both the pygmy dipole strength at low energies and the appearance of thermally unblocked transitions can strongly influence the γSF, and hence the calculated capture rates. To address this temperature dependence, we employ the FT-RQRPA based on relativistic energy density functional with point coupling interaction. This framework enables microscopic calculations of both electric and magnetic dipole (E1 and M1) transitions, providing input directly connected to the γSF at astrophysical conditions.

2.2.1 Cross sections and MACS

Within statistical framework [2], the radiative neutron-capture cross section ($\sigma_{n,\gamma}(E)$) with some approximations, can be expressed in terms of the γ-strength function $f_{XL}(E_\gamma)$, where X denotes the multipolarity and L the transition type:

$$\sigma_{n,\gamma}(E) \propto \sum_{XL} \int_0^{E+S_n} W(E, E_\gamma)\, f_{XL}(E_\gamma)\, \rho(E + S_n - E_\gamma)\, dE_\gamma, \qquad (6)$$

where S_n is the neutron separation energy and $\rho(E)$ is the nuclear level density at excitation energy E. $W(E, E_\gamma)$ represents weighting factors that collect kinematic factors, average spinparity population, etc.

For astrophysical applications, the relevant observable is the Maxwellian-averaged cross section (MACS), defined at stellar temperature T as

$$\langle \sigma v \rangle_T = \left(\frac{8}{\pi m} \right)^{1/2} \frac{1}{(kT)^{3/2}} \int_0^\infty \sigma(E)\, E\, e^{-E/kT}\, dE, \qquad (7)$$

where m is the reduced mass and k the Boltzmann constant. The MACS serves as the input to r-process network calculations [11].

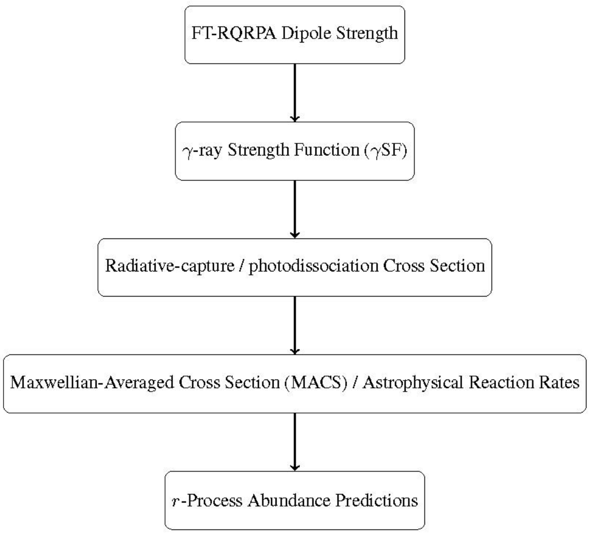

Figure 1. Schematic flowchart illustrating the link between microscopic dipole strength distributions, γ-SF, reaction cross sections, astrophysical reaction rates, and their ultimate impact on r-process abundance predictions.

2.2.2 Flow of nuclear input to astrophysical output

In this work, the FT-RQRPA dipole strength distributions are used to constrain the γ-strength function, which in turn directly affects the evaluation of MACS and the corresponding astrophysical reaction rates. These rates then feed into r-process network calculations to determine abundance patterns. Figure 1 schematically illustrates this chain of connections. By linking FT-RQRPA dipole strength distributions to statistical model calculations of MACS, we assess the impact of finite-temperature effects on neutron-capture reaction rates.

3 Results and Discussion

Using the finite-temperature FT-RQRPA dipole strengths (E1) in the 0–2 MeV region (as described in the methodology) as input, the ^{61}Ni$(n,\gamma)^{62}$Ni reaction cross sections and corresponding astrophysical reaction rates were calculated with the TALYS-2.0 code [12]. Except for the γSF, the nuclear input parameters required for cross-section calculations, such as nuclear masses, discrete excited levels, decay schemes, optical model potentials (OMP), and nuclear level densities (NLD), were taken from the default parameter sets implemented in TALYS. Figure 2 shows the relative change in the neutron-capture cross section for the reaction ^{61}Ni$(n,\gamma)^{62}$Ni as a function of incident neutron energy when finite-temperature effects are included in the γ-strength function (γSF). Com-

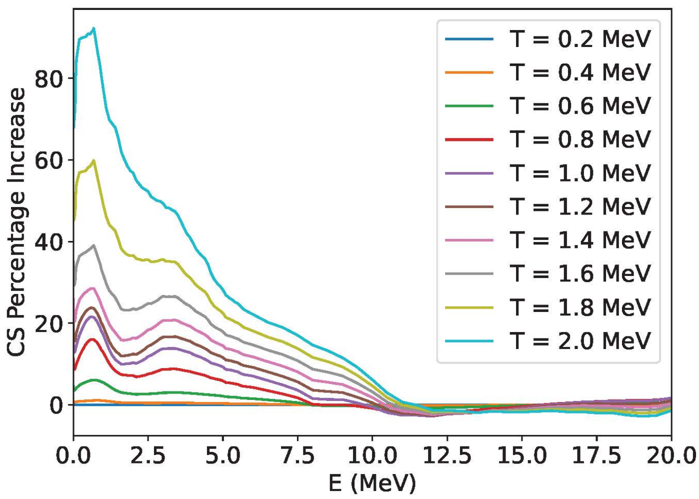

Figure 2. Percentage increase in the neutron-capture cross section (CS) for ^{61}Ni$(n,\gamma)^{62}$Ni as a function of incident neutron energy (E). The enhancement is defined relative to the zero-temperature baseline, i.e. $(\sigma_T - \sigma_0)/\sigma_0 \times 100$. The finite-temperature γSF leads to substantial modifications, reaching nearly 100% in some energy regions.

pared to the zero-temperature baseline, the cross section systematically increases with temperature, with the enhancement becoming particularly pronounced in the low- to intermediate-energy region. The largest relative increase observed is close to 100%, highlighting the significant impact of temperature-dependent dipole strength on reaction cross sections. This result emphasizes that neglecting finite-temperature modifications to the γSF can lead to substantial underestimation of reaction rates relevant for stellar nucleosynthesis.

The corresponding impact on astrophysical reaction rates is shown in Figure 3, where the percentage increase is plotted as a function of the stellar plasma temperature for reaction rate calculations. Each curve corresponds to a different FT-RQRPA γSF input (0.2–2.0 MeV) relative to the $T = 0$ baseline. The stellar plasma temperature spans typical r-process conditions (up to $\sim$10 GK). The reaction rate increases monotonically with temperature, following the trend expected from the underlying dipole strength redistribution at finite temperatures. At the highest studied temperature ($T = 2.0$ MeV), the rate enhancement reaches nearly 100%. This finding is particularly relevant for the r-process, where finite-temperature conditions prevail, and even moderate changes in neutron-capture rates can propagate into large variations in predicted abundance

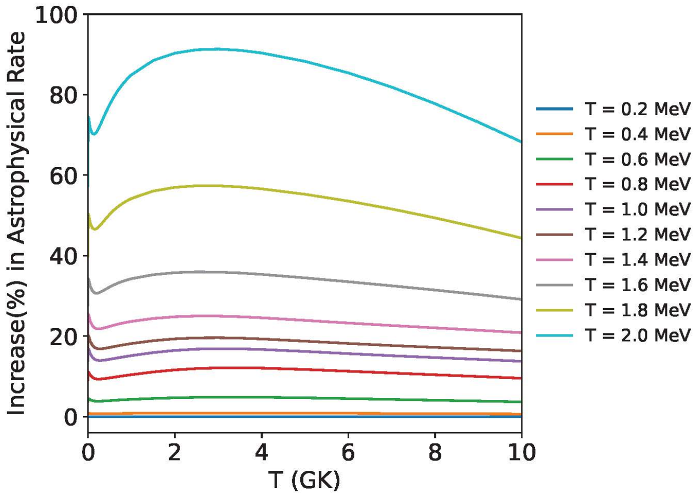

Figure 3. Temperature dependence of the percentage increase in the astrophysical reaction rate for ^{61}Ni$(n,\gamma)^{62}$Ni. The enhancement is obtained by comparing reaction rates calculated with FT-RQRPA γSF inputs to those with $T = 0$ γSF (baseline, same as in Figure 2). The temperature on the horizontal axis corresponds to the stellar plasma temperature at which the reaction rate is evaluated (see eqn. 7), corresponds to typical r-process conditions (up to $\sim$10 GK). A rise approaching 100% is observed at $T = 2.0$ MeV, underscoring the significant role of finite-temperature effects in the γSF under r-process conditions.

patterns. The results further confirm that among the key nuclear inputs: optical model potential, nuclear level density, and γ-strength function, the latter introduces one of the largest uncertainties in theoretical predictions of r-process rates, and needs to pursuit carefully.

The quantitative evidence presented here underscores the necessity of employing self-consistent finite-temperature models such as FT-RQRPA in the evaluation of nuclear dipole strength distributions. By explicitly incorporating the temperature dependence of the γSF, the present approach provides a physically motivated framework that includes finite temperature and nuclear pairing effects in a self-consistent EDF framework and in this way reduces systematic biases in astrophysical modeling.

4 Conclusions and Outlook

In this work we have analyzed the influence of temperature-dependent dipole strengths, calculated within the FT-RQRPA framework, on neutron-capture cross sections and astrophysical reaction rates for the benchmark case of $^{61}\mathrm{Ni}(n,\gamma)^{62}\mathrm{Ni}$. Our results demonstrate that finite-temperature effects can enhance the cross section and the corresponding astrophysical rate by up to $\sim 100\%$ relative to the zero-temperature baseline. Such large modifications are non-negligible for nucleosynthesis modeling, as they may directly affect r-process abundance predictions.

The present study focuses on a single isotope as a proof of principle. In ongoing and future work, we aim to extend this analysis systematically to entire isotopic chains, particularly in regions of astrophysical interest near closed neutron shells. Furthermore, the impact of these modified rates will be explored in large-scale r-process network calculations to assess their consequences for abundance distributions. By combining microscopic finite-temperature strength functions with reaction-network simulations, we will provide a more comprehensive assessment of nuclear-structure uncertainties in astrophysical environments.

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