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Threshold-aligned Pygmy Dipole Strength and Its Impact on Astrophysical (n, gamma) and (gamma, n) Rates

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Radiative neutron capture processes

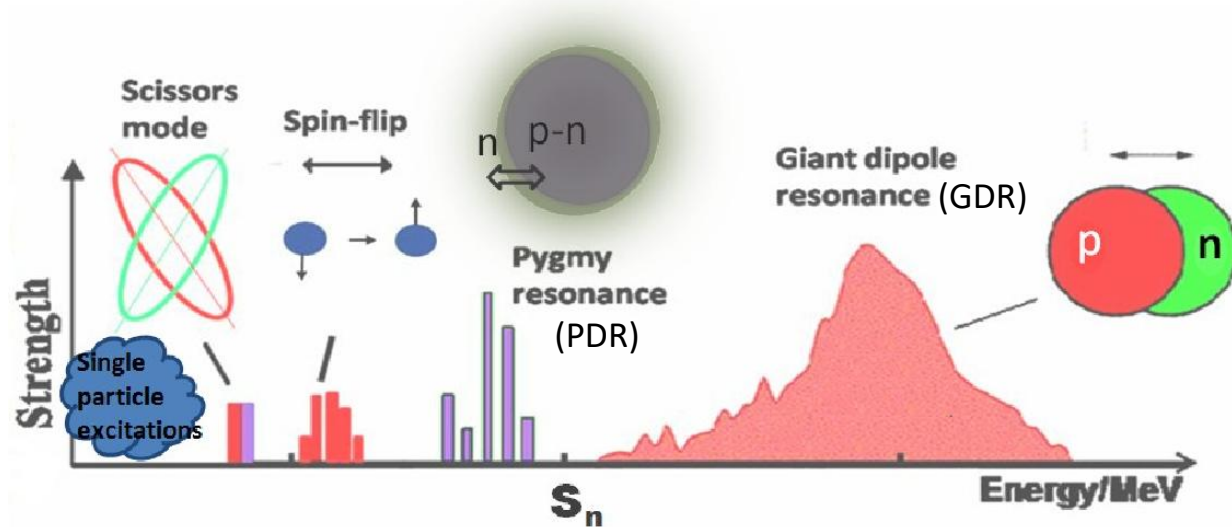
- Radiative neutron capture processes are crucial for complete understanding of nuclear astrophysical network calculations like, r-process, s-process.
- However, All such data are not accessible in the accelerator-based experiments, and one needs to rely on theoretical estimates.
- Within a statistical framework, the radiative neutron capture cross-sections and relevant reaction rates calculations require-

- (i) neutron-nucleus optical model potential (OMP),
- (ii) nuclear level density (NLD), and
- (iii) γ -ray strength function (γ SF),

- In our recent study, we have calculated temperature effects in electric and magnetic dipole (E1 and M1) transitions using a self-consistent finite-temperature relativistic quasiparticle random phase approximation (FT-RQRPA) based on a relativistic energy density functional with point-coupling interactions. Currently, we examine their impact on crucial astrophysical reaction rate calculations.

Electromagnetic dipole response of a nucleus

Dipole response of a nucleus involving electric (E1) and magnetic (M1) transitions



10.1103/PhysRevC.85.044302

- Dipole response give information on the fundamental properties of nuclei.
- Provide insight into the behaviour of nuclear matter under extreme conditions, and important for modelling astrophysics phenomena.

Astrophysical Interest

- Dipole strengths → Provides information about neutron skin and symmetry energy in EOS → Relevant for modelling of neutron stars.
- Electromagnetic transitions play a role to understand the nucleosynthesis process in stars and supernovae.
- Impact the radiative capture processes and reaction rates in the stellar environment.

Relativistic nuclear energy density functional (RNEDF)

The point-coupling RNEDF determined from the Lagrangian density

$$\begin{aligned}\mathcal{L}_{PC} = & \bar{\psi}(i\gamma \cdot \partial - m)\psi n \\ & - \frac{1}{2}\alpha_S(\rho)(\bar{\psi}\psi)(\bar{\psi}\psi) - \frac{1}{2}\alpha_V(\rho)(\bar{\psi}\gamma^\mu\psi)(\bar{\psi}\gamma_\mu\psi) \\ & - \frac{1}{2}\alpha_{TV}(\rho)(\bar{\psi}\vec{\tau}\gamma^\mu\psi)(\bar{\psi}\vec{\tau}\gamma_\mu\psi) \\ & - \frac{1}{2}\delta_S(\partial_\nu\bar{\psi}\psi)(\partial^\nu\bar{\psi}\psi) \\ & - e\bar{\psi}\gamma \cdot A\frac{1-\tau_3}{2}\psi\end{aligned}$$

- Free nucleon terms
- Isoscalar-scalar, isoscalar-vector, isovector-vector interaction terms
- Derivative term (effects of finite range interaction)
- Electromagnetic *interaction*

➤ By integrating the Hamiltonian density over the r-space we obtain the total energy:

$$E_{RMF} = \int d^3r \mathcal{H}(r)$$

[T. Nikšić et al., *Comput. Phys. Commun.* 185, 1808 (2014)]
[DD-PCX: E. Yüksel et al., *Phys. Rev. C* 99, 034318 (2019)]

➤ **Nuclear state properties** are described within finite temperature Hartree-Bardeen-Cooper-Schrieffer (FT-HBCS) framework supplemented with pairing correlations (Separable Pairing force).

[A. L. Goodman, *Nucl. Phys. A* 352, 30 (1981)]

➤ **Collective excitations in Nuclei:** Relativistic Quasiparticle Random Phase Approximation (RQRPA).

HBCS+RQRPA are prominent tools for calculations.

Finite temperature calculations needs extra work!

➤ At finite temperature (FT), the occupation probabilities of single particle states are given by

$$n_i = v_i^2(1 - f_i) + u_i^2 f_i$$

➤ The T-dependent Fermi-Dirac distribution function is obtained as

$$f_i = [1 + \exp(E_i/k_B T)]^{-1}$$

Finite temperature RQRPA

- The starting point in the Equation of Motion method is definition of a suitable Excitation operator

$$\Gamma_v^\dagger = \sum_{a \geq b} X_{ab}^v a_a^\dagger a_b^\dagger - Y_{ab}^v a_b a_a + \underbrace{P_{ab}^v a_a^\dagger a_b - Q_{ab}^v a_b^\dagger a_a}_{\text{Red terms contribute at } T > 0}$$

two-quasiparticle creation/destruction and one-quasiparticle creation/destruction operators.

- The FT-RQRPA equations can be combined into a single matrix

$$\begin{pmatrix} \tilde{C} & \tilde{a} & \tilde{b} & \tilde{D} \\ \tilde{a}^+ & \tilde{A} & \tilde{B} & \tilde{b}^T \\ -\tilde{b}^+ & -\tilde{B}^* & -\tilde{A}^* & -\tilde{a}^T \\ -\tilde{D}^* & -\tilde{b}^* & -\tilde{a}^* & -\tilde{C}^* \end{pmatrix} \begin{pmatrix} \tilde{P} \\ \tilde{X} \\ \tilde{Y} \\ \tilde{Q} \end{pmatrix} = \hbar\omega \begin{pmatrix} \tilde{P} \\ \tilde{X} \\ \tilde{Y} \\ \tilde{Q} \end{pmatrix}$$

In the limit $T \rightarrow 0$
FT-RQRPA \rightarrow RQRPA

- The reduced transition probability is

$$S(TJ) = |\langle \omega || \hat{F}_J || \tilde{0} \rangle|^2 = \left| \sum_{c \geq d} \left\{ \begin{aligned} &(\tilde{X}_{cd}^\omega + (-1)^{j_c - j_d + J} \tilde{Y}_{cd}^\omega)(u_c v_d + (-1)^J v_c u_d) \sqrt{1 - f_c - f_d} \\ &+ (\tilde{P}_{cd}^\omega + (-1)^{j_c - j_d + J} \tilde{Q}_{cd}^\omega)(u_c u_d - (-1)^J v_c v_d) \sqrt{f_d - f_c} \end{aligned} \right\} \langle c || \hat{F}_J || d \rangle \right|^2$$

- H. Sommermann, *Ann. of Phys.* 151, 163 (1983)
- E. Yüksel et al., *Phys. Rev. C* 96, 024303 (2017)
- A. Kaur, E. Yüksel, N. Paar, *Phys. Rev. C* 109, 014314 (2024)

Gamma Strength functions

$$S(E1; E) = \sum_{\nu} S(E1; 0 \rightarrow \nu) \delta(E - E_{\nu})$$

- The RQRPA discrete spectrum is averaged with a Lorentzian function

$$R(E1; E) = \sum_{\nu} \frac{1}{2\pi} \frac{\Gamma(E) S(E1; 0 \rightarrow \nu)}{(E - E_{\nu} - \Delta(E))^2 + \Gamma(E)^2/4}$$

$$f_{E1}(E) = \frac{16\pi e^2}{27 \hbar^3 c^3} R(E1; E)$$

Where, $\Gamma(E)$ is width at half maximum and $\Delta(E)$ is energy shift.

- The energy-dependent width $\Gamma(E)$ can be calculated from the measured decay width of particle and hole states:

$$\Gamma(E) = \frac{1}{E} \int_0^E d\epsilon [\gamma_p(\epsilon) + \gamma_h(\epsilon - E)] (1 + C_G)$$

S. Drozd et al., Phys. Rep. 197, 1 (1990).

- $\Delta(E)$ is energy shift can be obtained from $\Gamma(E)$ by a dispersion relation.

$$\Delta(E) = \frac{1}{2\pi} \mathcal{P} \int_{-\infty}^{\infty} dE' \frac{\Gamma(E')}{E' - E} (1 + C_E)$$

- C_E and C_G are used to fit the experimental data of E1 photoabsorption and photoneutron strength functions.

- This empirical way of determining $\Gamma(E)$, $\Delta(E)$ has the advantage of including, contributions from the excitation beyond 2p-2h.

Results

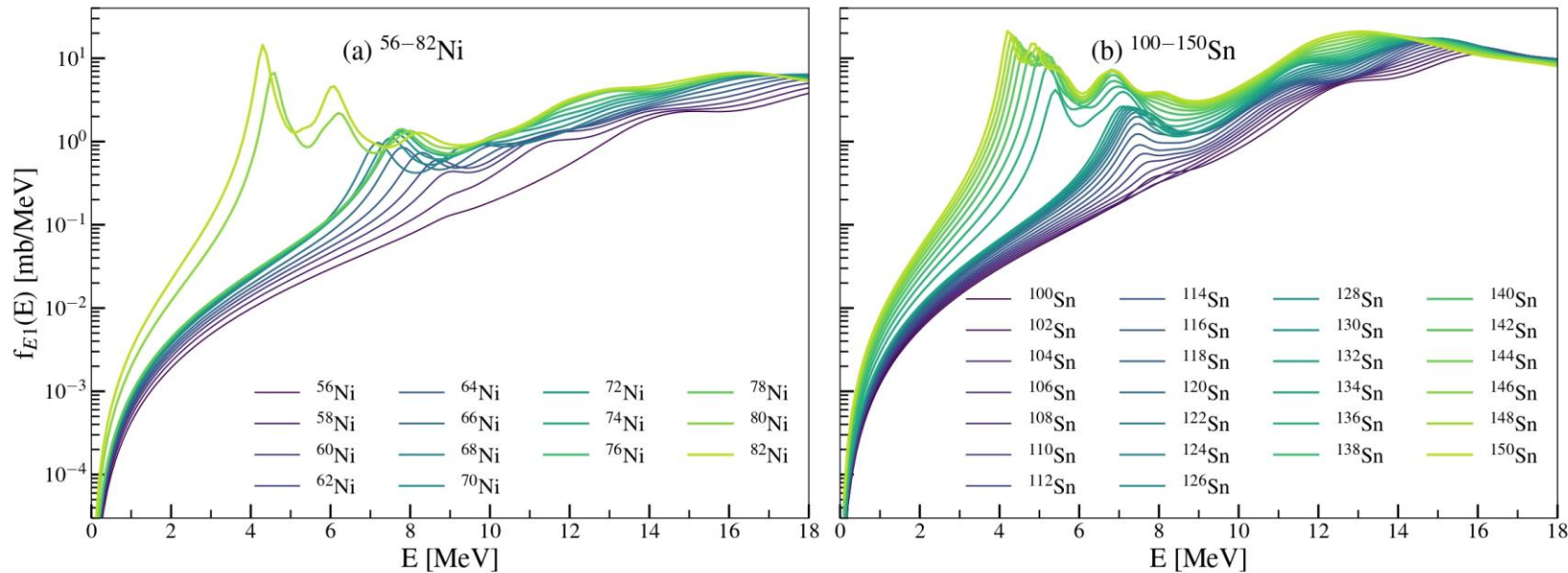
Calculations are performed using DD-PCX interaction

- At $T=0$ MeV, low-energy excited states begin to emerge, as neutron number of Sn isotopes increases.
- This enhancement is moderate in Ni isotopes but becomes more pronounced in neutron-rich Sn isotopes.

- At $T=0$ MeV, the role of the PDS both in (n,γ) and (γ,n) reactions is investigated for Ni, Sn isotopic chains.
- The aim is to investigate how the position of the PDS excitation energy with respect to the neutron threshold impacts reaction-rate calculations.

At finite temperature

- Giant dipole resonance (GDR) region exhibits only minor changes at higher temperatures.
- At $T=1$ and 2 MeV, new low-energy excited states start to emerge below $E < 5$ MeV for neutron-rich nuclei.
- These newly formed states at low energies are created through single quasiparticle transitions due to thermal unblocking effects.



[arXiv:2603.12928](https://arxiv.org/abs/2603.12928)

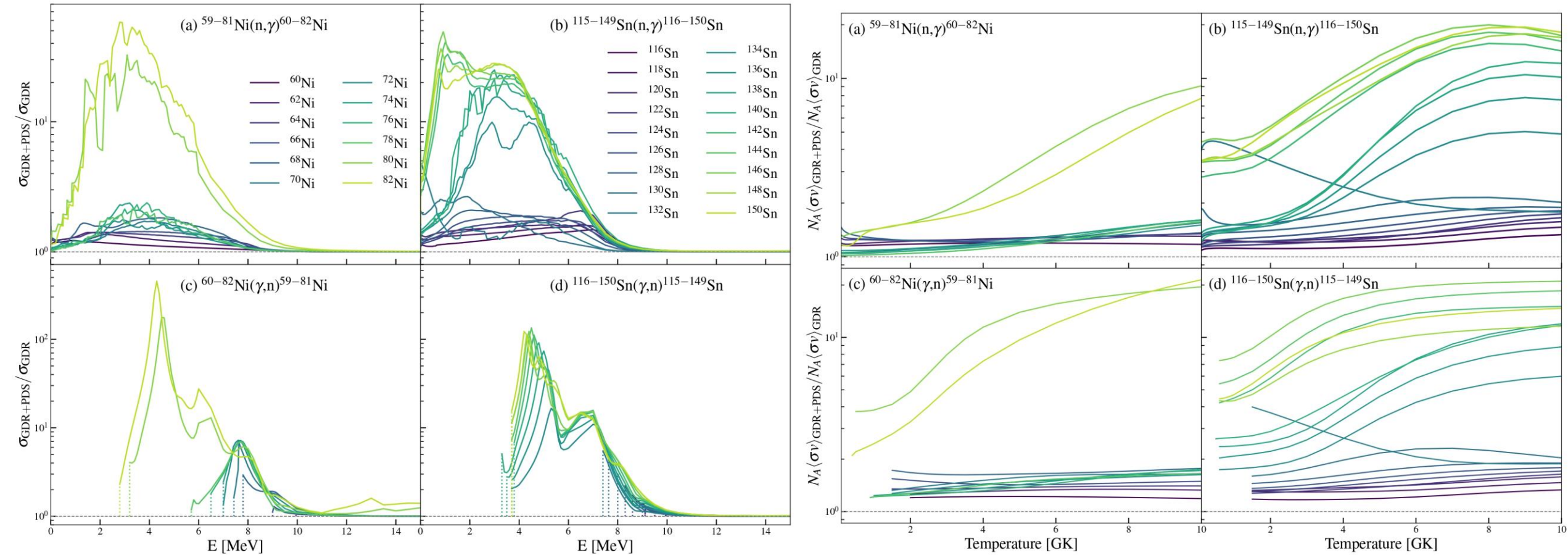
Phys. Rev. C **109**, 014314 (2024)

Phys. Rev. C **112**, 014307 (2025)

Results

- Left figure presents the energy-dependent ratios of neutron-capture (n, γ) and photoneutron (γ, n) reaction cross sections along the Ni and Sn isotopic chains, obtained using γ SFs including both GDR and PDS contributions with respect to those only with GDR. The inclusion of the PDS produces a systematic enhancement of the reaction cross section ratios over a finite low-energy interval.
- For ^{68}Ni and ^{132}Sn , both the reaction rate and the crosssection ratio start at comparatively higher values than those of their neighboring nuclei. similar behavior is observed for the astrophysical reaction rates shown in right Figure.

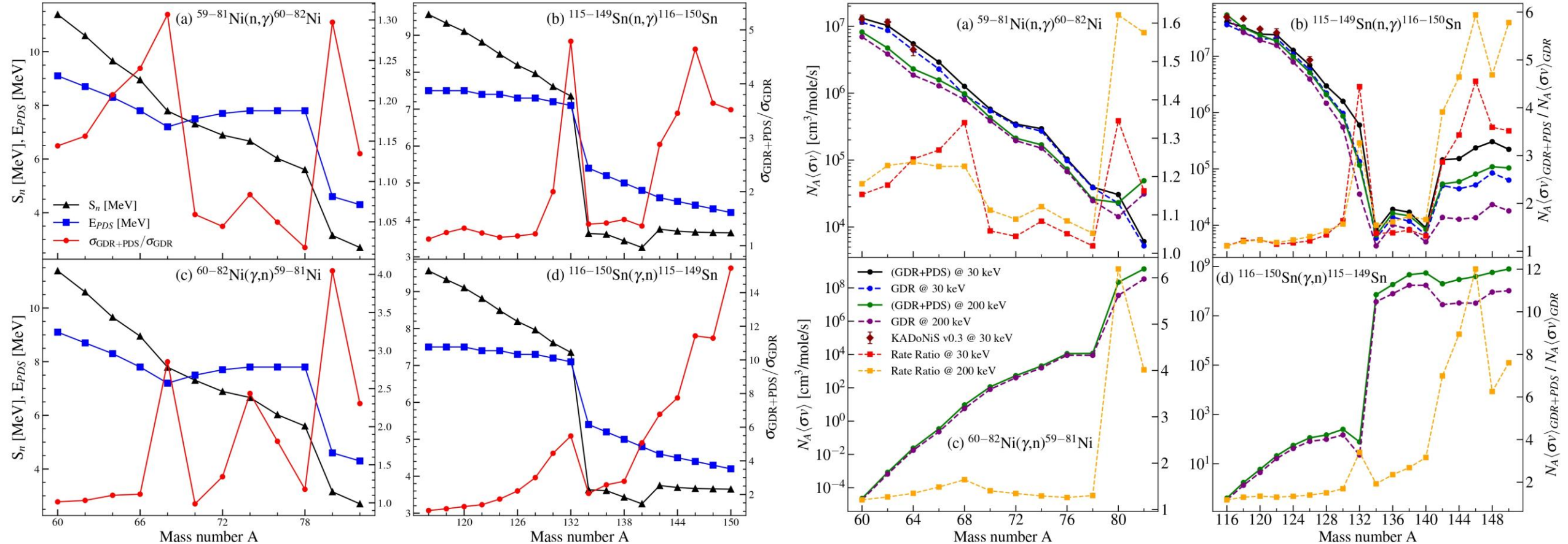
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Results

- Ratios of (n, γ) (a), (b) and (γ , n) (c), (d) cross sections calculated with and without pygmy contributions (right y-axis), evaluated at 30 keV and at Sn + 30 keV, respectively.
- Pronounced enhancements of the cross-section ratios are observed for 68Ni and 132Sn, reflecting an alignment between PDS peak energy and Sn.
- similar behavior is observed for the astrophysical reaction rates shown in right Figure.

arXiv:2603.12928



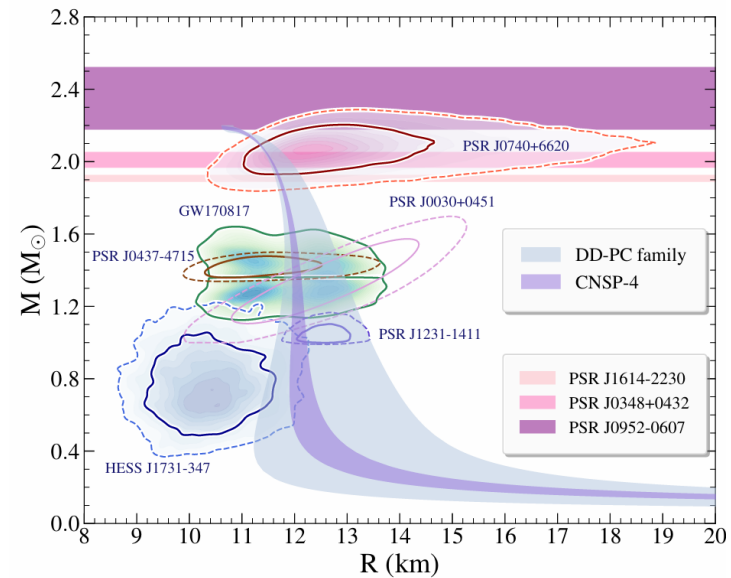
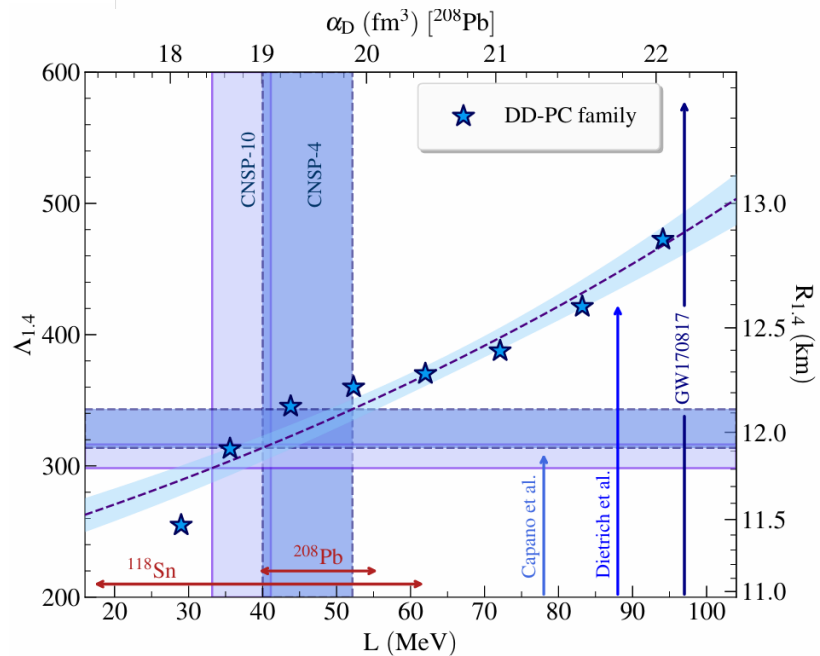
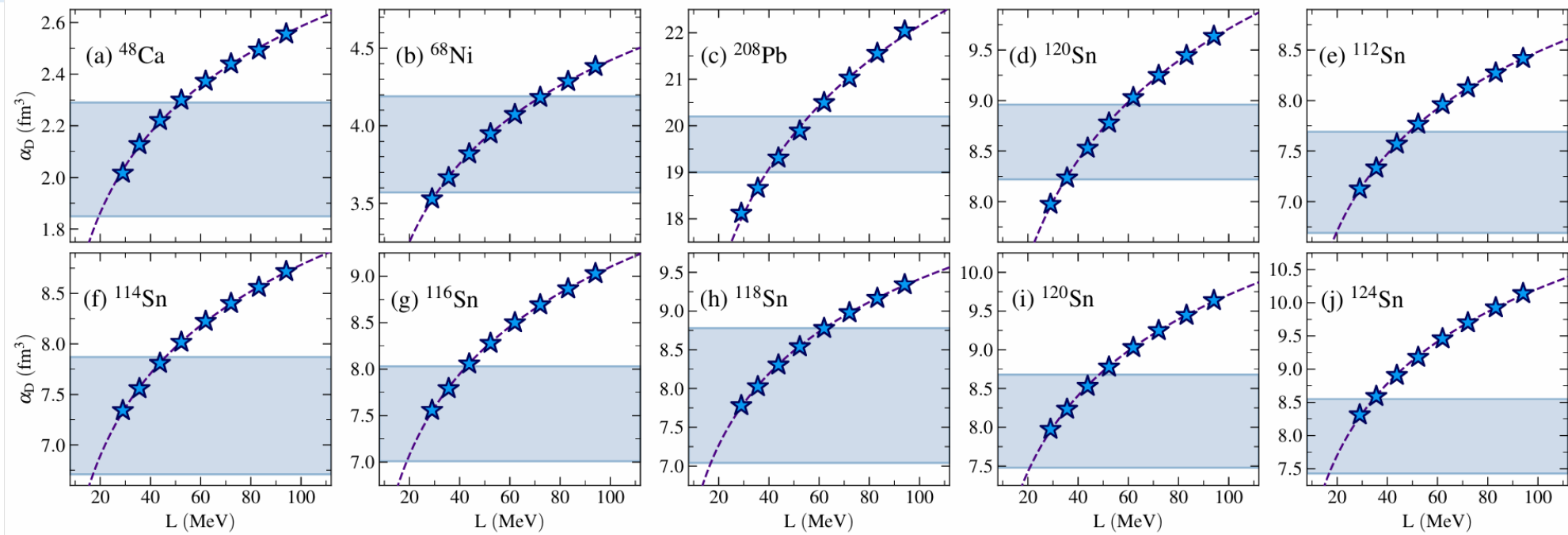
Summary

A self-consistent finite temperature RQRPA framework is developed to study the finite temperature effects on E1 and M1 transitions.

- Presented calculations, based on description of γ SFs in the relativistic EDF framework with density dependent point coupling interaction, show that the impact of PDS is not only governed by its total strength but also by its energy alignment with neutron separation energy
- The sensitivity patterns identified here underscore the need for further systematic microscopic studies based on advanced theoretical approaches including assessment of theoretical uncertainties in PDS, and novel experimental constraints targeting low-energy dipole strength in neutron-rich nuclei.

Further studies is going on to calculate the possible contributions of E1 and M1 transitions at zero and finite temperatures γ strength functions in crucial astrophysical reaction rate calculations.

Dipole polarizability of finite nuclei as a probe of neutron stars



$$\alpha_D = \frac{8\pi e^2}{9} \int_0^\infty E^{-1} S(E1; E) dE$$

$L = 46.08 \pm 6.06$ MeV (CNSP-4) and
 $L = 37.16 \pm 3.96$ MeV (CNSP-10)

CNSP-4: $\begin{cases} 313.80 \leq \Lambda_{1.4} \leq 343.18, \\ 11.92 \leq R_{1.4} \leq 12.12 \text{ km}, \end{cases}$

CNSP-10: $\begin{cases} 298.39 \leq \Lambda_{1.4} \leq 316.35, \\ 11.81 \leq R_{1.4} \leq 11.94 \text{ km}. \end{cases}$

Acknowledgments

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