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Threshold-Aligned Pygmy Dipole Strength Shapes r-Process Reaction Rates

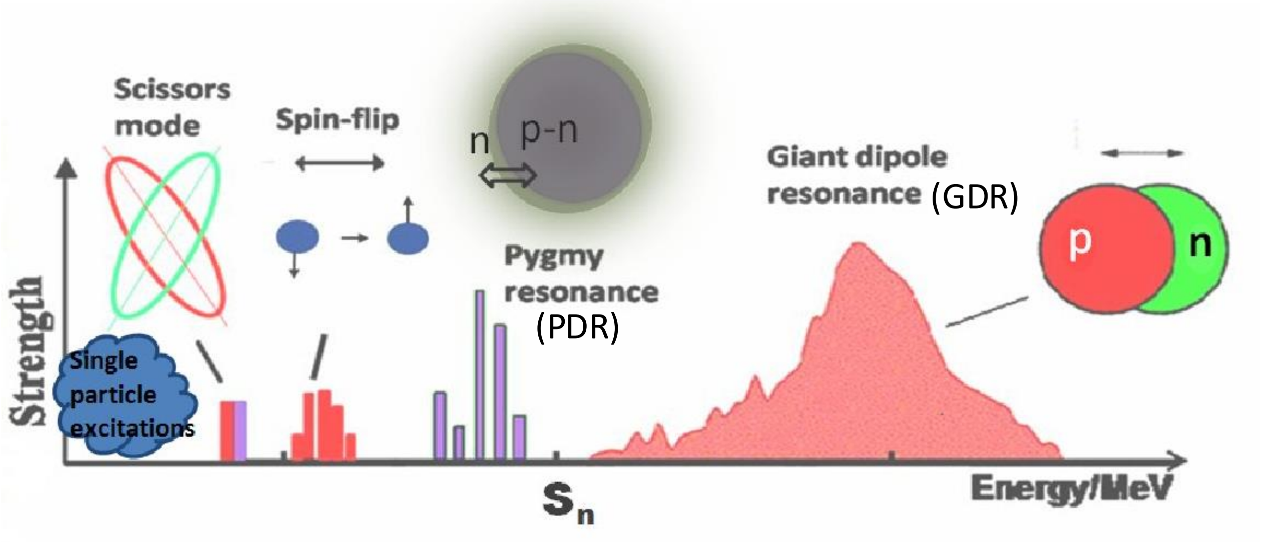
Dr. Tanmoy Ghosh

Collaborators: Prof. Nils Paar, Dr. Amandeep Kaur

Department of Physics,
University of Zagreb, Zagreb, Croatia
Email: tghosh@phy.hr

Electromagnetic dipole response of a nucleus

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



10.1103/PhysRevC.85.044302

- 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 (γSF),

- 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

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

- 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

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

Finite temperature RQRPA

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

$$\Gamma_\nu^\dagger = \sum_{a\geq b} X_{ab}^\nu a_a^\dagger a_b^\dagger - Y_{ab}^\nu a_b a_a + P_{ab}^\nu a_a^\dagger a_b - Q_{ab}^\nu a_b^\dagger a_a \Rightarrow$$

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

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

- *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, Γ(E) is width at half maximum and Δ(E) is energy shift.

- The energy-dependent width Γ(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. Drozdz et al., Phys. Rep.197, 1 (1990).

- Δ(E) is energy shift can be obtained from Γ(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 Γ(E), Δ(E) has the advantage of effectively accounts for spreading due to more complex configurations beyond the basic RQRPA space.

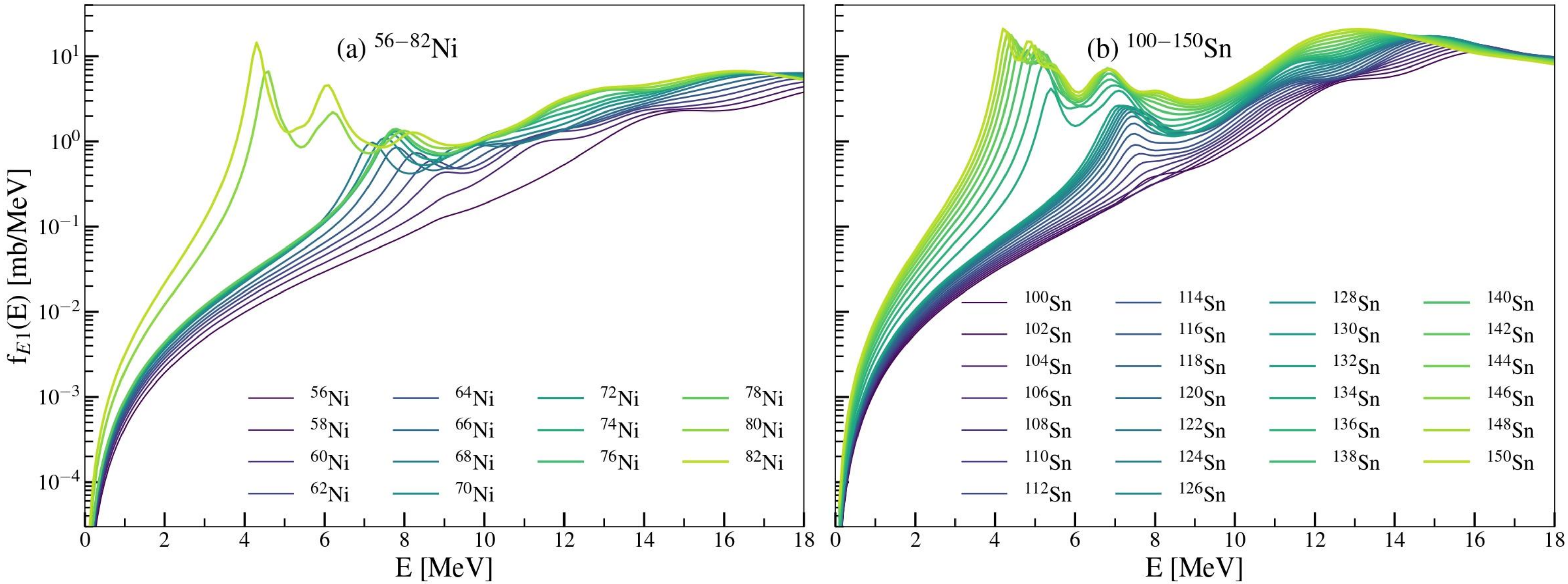
Low-energy strength grows toward neutron-rich nuclei

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.

arXiv:2603.12928



PDS selectively enhances reaction rates

- 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 γSFs 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 68Ni and 132Sn, 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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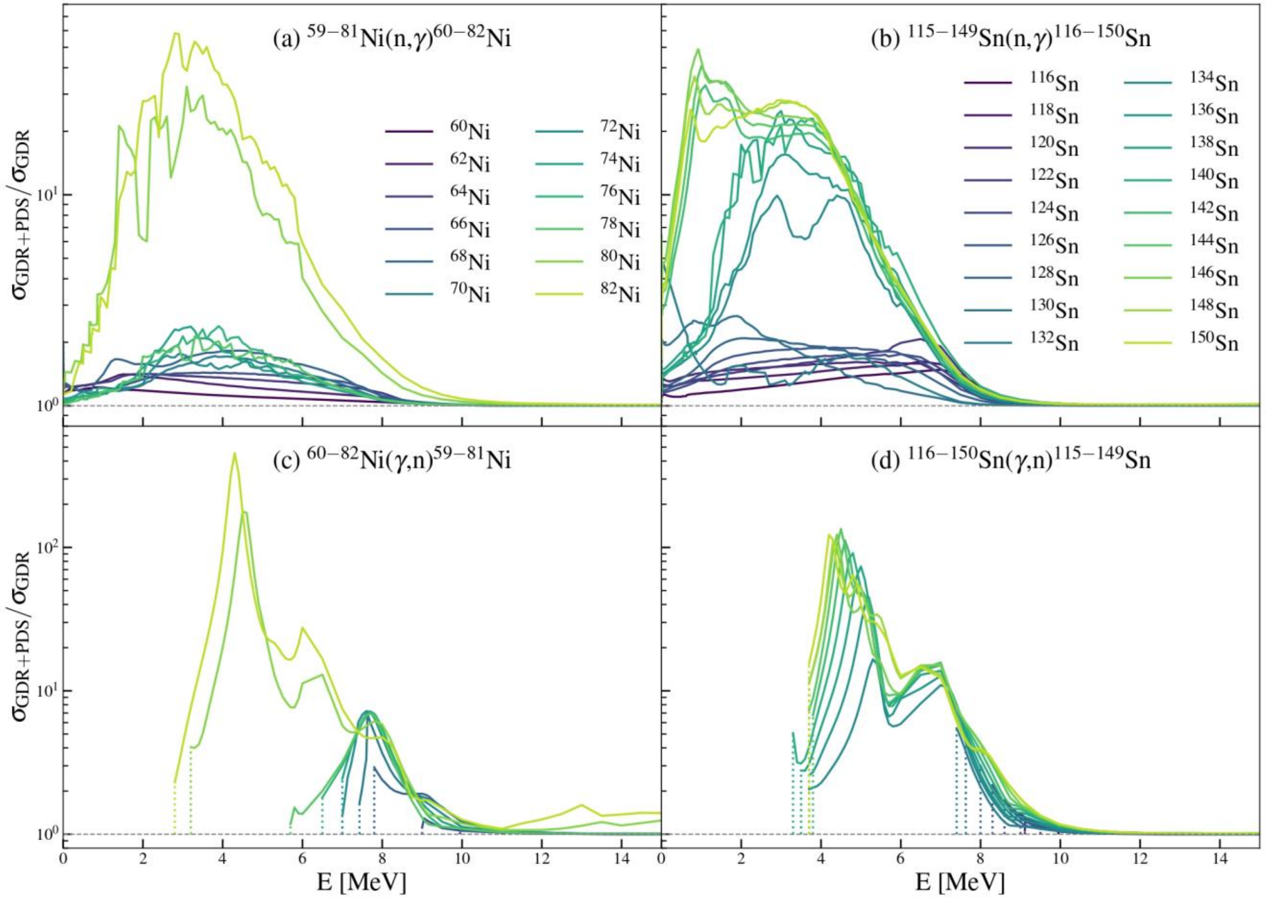

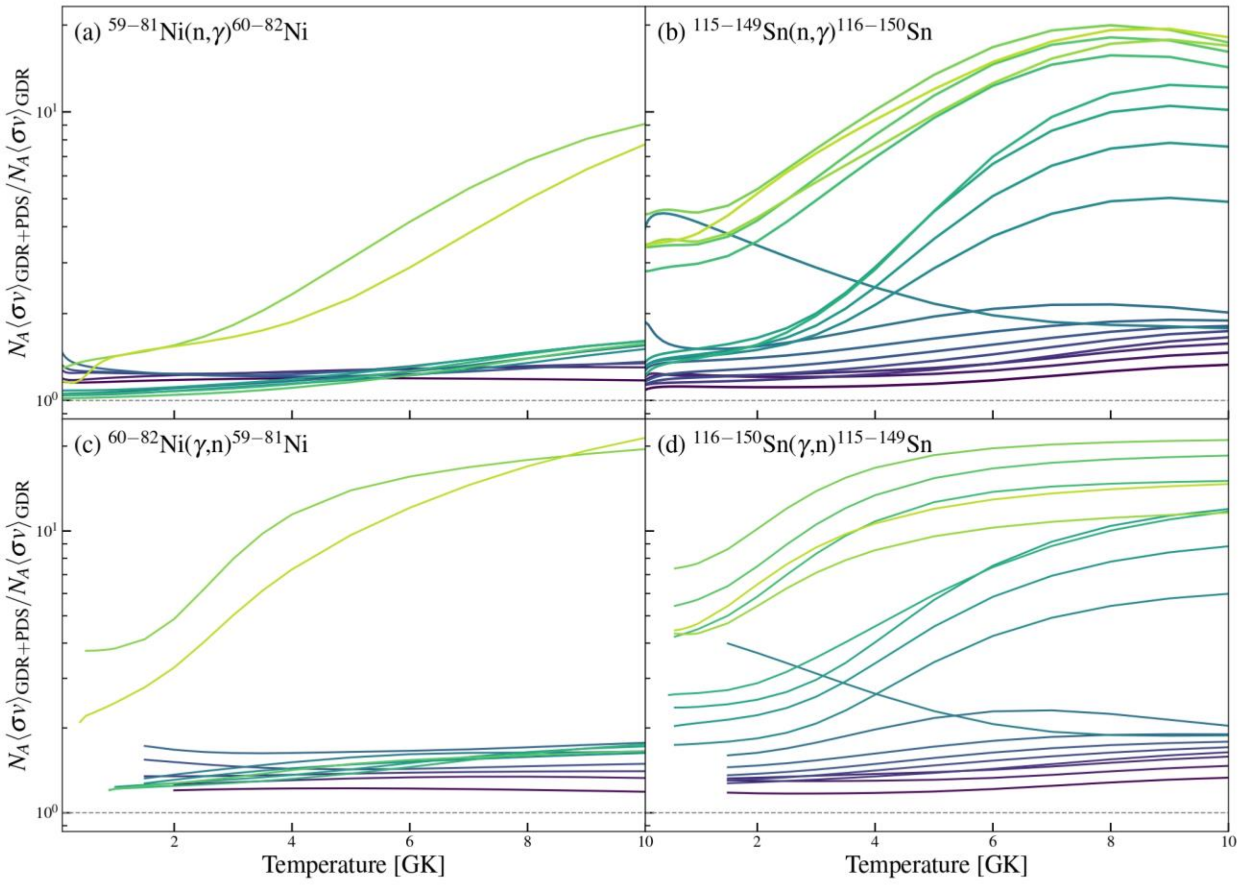

Threshold alignment controls the enhancement

- 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.

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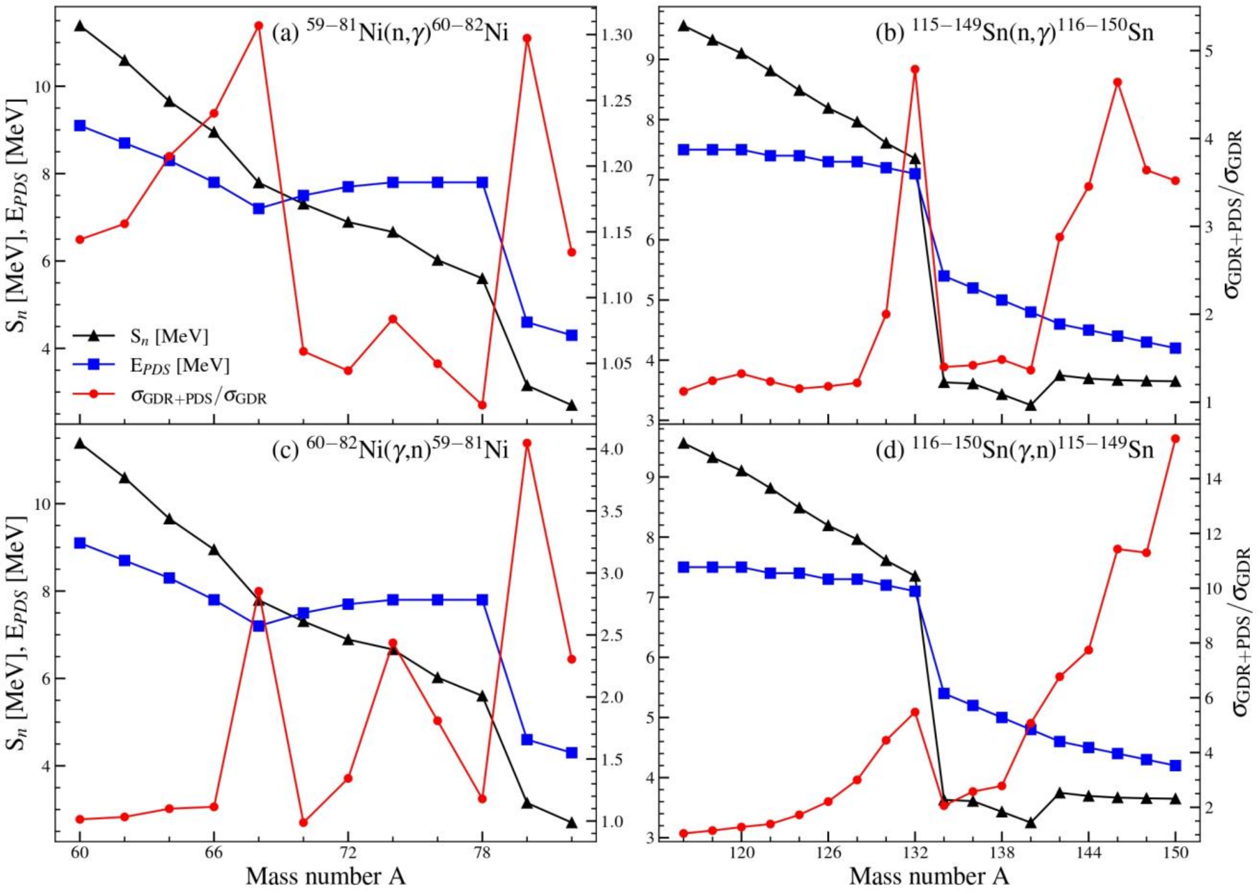
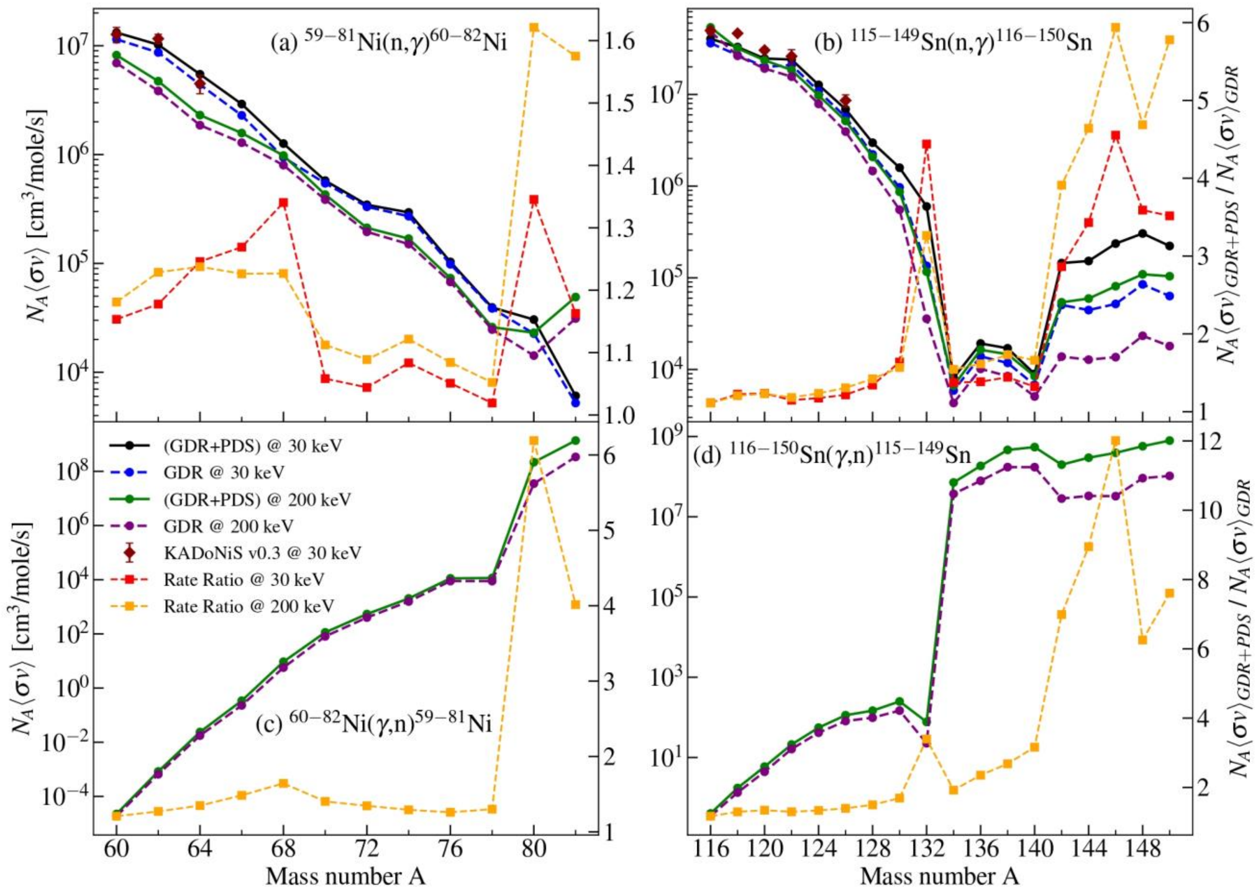




Summary

For astrophysical reaction rates, the amount of pygmy strength matters—but at low temperature, where that strength lies relative to the neutron threshold can matter even more.

- Presented calculations, based on description of γSFs 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 uncertaintes in PDS, and novel experimental constraints targeting low-energy dipole strength in neutron-rich nuclei.

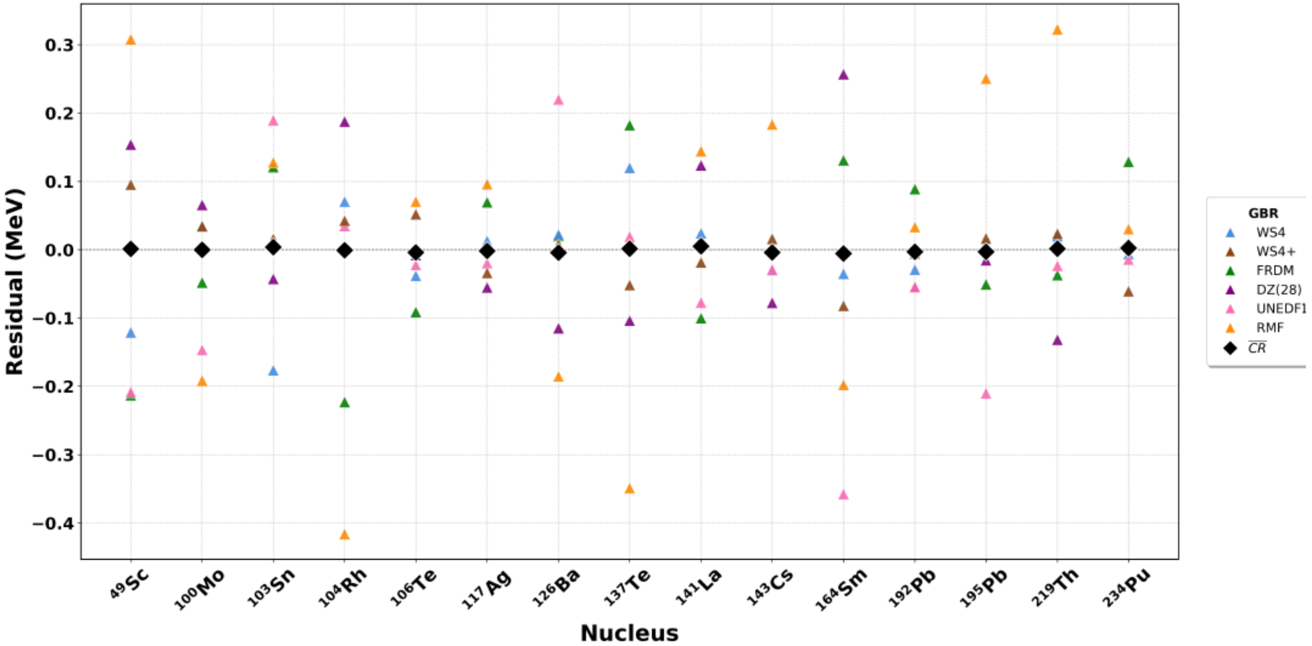
Further studies is going on to calculate the possible contributions of E1 and M1 transitions at zero and finite temperatures γ strength functions in crucial astrophysical reaction rate calculations.

Physics-guided ensemble learning of nuclear masses for astrophysical applications

Main message

ELMA combines Gradient Boosting Regressor (GBR) correction of raw residuals (RR) with weighted model averaging of the resulting corrected residuals (CR) across six global nuclear mass models.

- Models used: WS4, WS4+, FRDM, DZ(28), UNEDF1, and RMF.
- Workflow: $\mathrm{RR} \rightarrow$ GBR correction $\rightarrow \mathrm{CR} \rightarrow$ weighted average.
- Final full-dataset performance: $0.0616\,\mathrm{MeV} \approx 62\,\mathrm{keV}$.
- Validation: improved Q_α residuals and stable behaviour over repeated train/test partitions.
- Output product: mass excesses and binding energies for about 6300 nuclei, accessible via `ddnp.in`.



S. Agrawal et. al. APS Open Sci. 1, 000085 (2026)

Acknowledgments

Collaborators:

Nils Paar

University of Zagreb, Croatia

Amandeep Kaur

University of Zagreb, Croatia

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