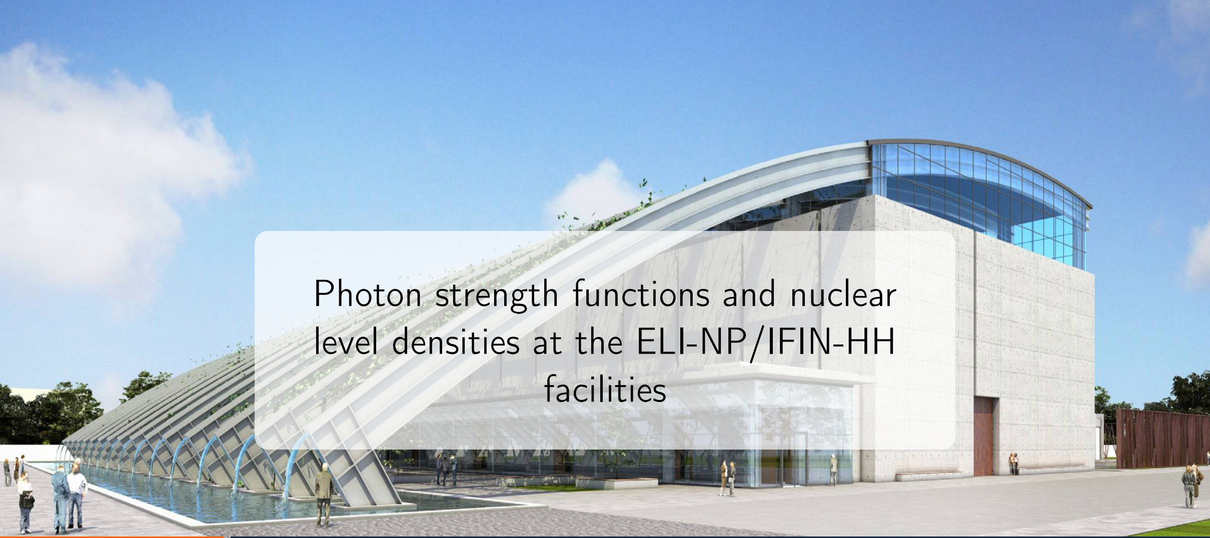

Photon strength functions and nuclear level densities at the ELI-NP/IFIN-HH facilities

Pär-Anders Söderström
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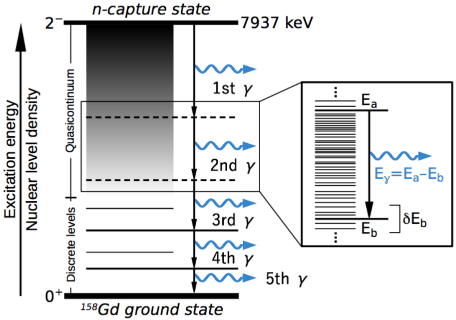
Fifth International Conference on Nuclear Photonics



K. Hagiwara, et al.: *Prog. Theo. Exp. Phys. 2019 (2019) 023D01*

Fermi's Golden Rule

$$\lambda_{i\to f} = \frac{2\pi}{\hbar}|\langle f|H'|i\rangle|^2\rho(E_f) \quad (1)$$

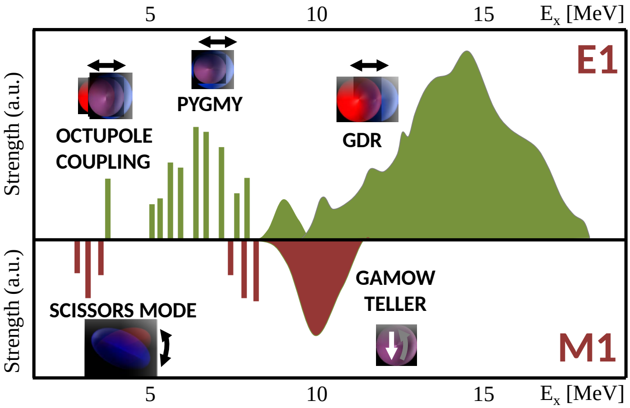
$$P(E_x, E_\gamma) \propto \mathcal{T}(E_\gamma)\rho(E_x - E_\gamma) \quad (2)$$

Hauser-Feshbach model

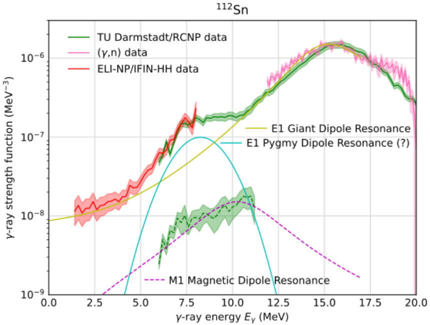
$$\sigma(\mathrm{n},\gamma) \propto \sum_{J^\pi, XL}\int \mathcal{T}_{XL}(E_\gamma)\rho(E_x, J, \pi)\mathrm{d}E_\gamma \quad (3)$$

- Decay probability proportional to transition strength times the density of final states
- Measure decay probabilities for γ rays of different energy as a function of excitation energy, $P(E_x, E_\gamma)$
- Cross sections proportional to transition strength times the density of final states

Photon strength functions



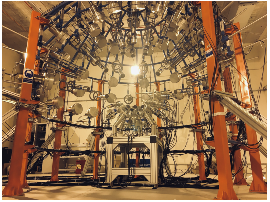
A. Zilges, et al.: J. Phys. Conf. Ser. 580 (2015) 012052



$$f_{XL}(E_\gamma) = \frac{\mathcal{T}(E_\gamma)}{2\pi E_\gamma^{2L+1}}, \qquad (4)$$

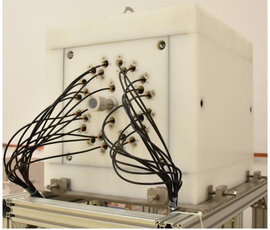
`https://www.eli-np.ro/thematics/pnp.php`

ELIGANT - ELI Gamma Above Neutron Threshold



- An array of CeBr and LaBr for γ-rays, liquid scintillators and Li-glass detectors for neutrons
- Tested in-beam (2022-2025 campaigns at ROSPHERE, IFIN 9MV)

P.-A. Söderström, et al.: Nucl. Instrum. Methods Phys. Res. A 1027 (2022) 166171



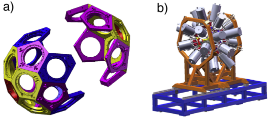
- ^{3}He tube array contained in a paraffin moderator for neutron counting
- Detector is operational
- Tested in-beam

C. Clisu, et al.: EPJ Web Conf. 284 (2023) 01015

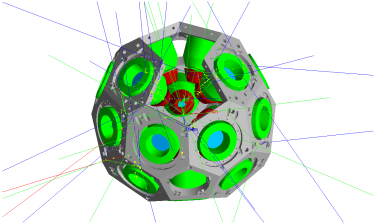
P.-A. Söderström, et al.: Submitted, arXiv:2510.00042 [physics.ins-det]

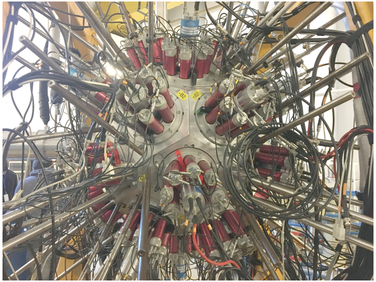
ELI-NP, IFIN-HH, and Tandem $\rightarrow$ ELIFANT

- Combining the large volume γ-ray detectors with the ROSPHERE anti-Compton shields
- In-beam experiments using the 9MV Tandem at IFIN-HH
- Collaboration between ELI-NP and Department of Nuclear Physics
- Clean measurements of high-energy γ-rays

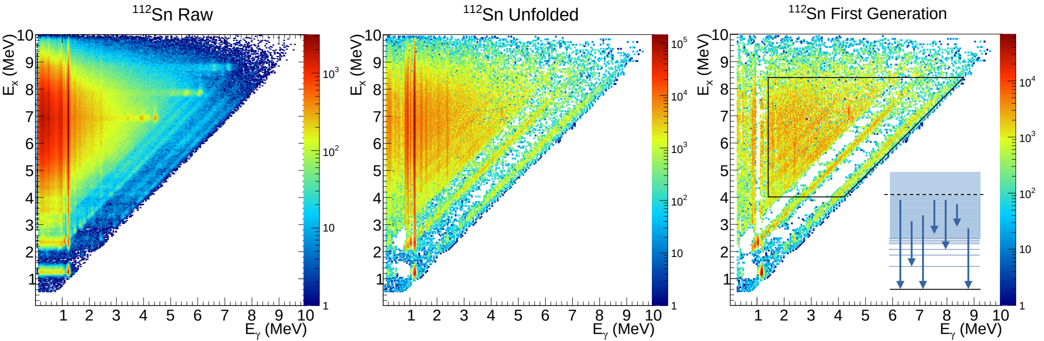


S. Aogaki, et al.: Nucl. Instrum. Methods Phys. Res. A 1056 (2023) 168628



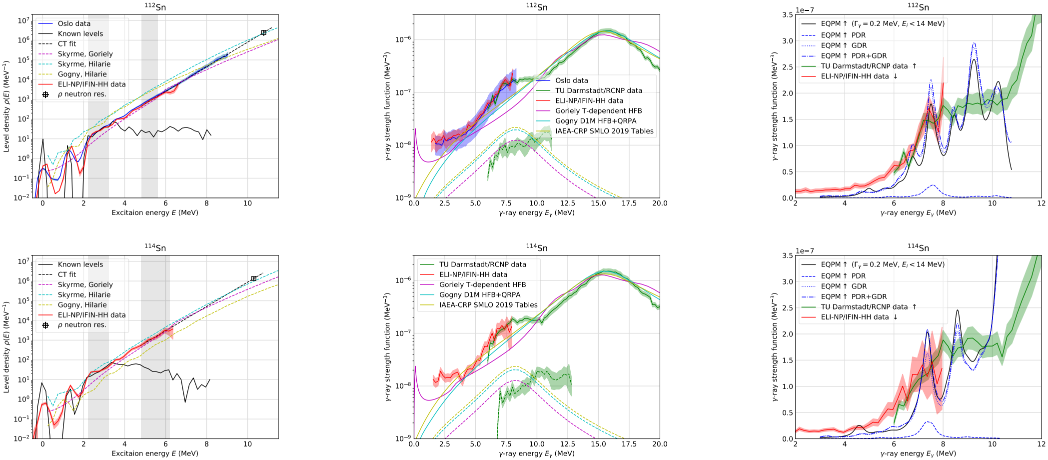


Gamma strength with ion beams



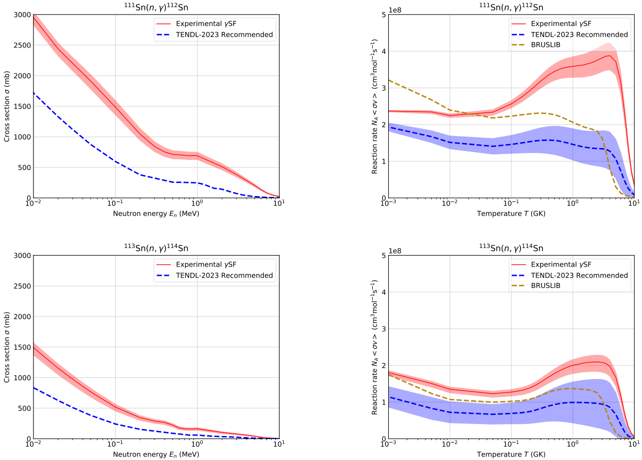
- Oslo method can measure γ-ray strength functions and level densities simultaneously
- Introduces some model dependence in the results
- Currently only done in the Oslo Cyclotron Laboratory (in the traditional approach)
- First experiment at IFIN-HH facilities in March 2023 (P.-A. Söderström (ELI-NP), M. Markova (U. Oslo))

First experiment: results from the Sn nuclei



P.-A. Söderström, et al.: Phys. Rev. C 112 (2025) 024327, Calculations: N. Tsoneva

Astrophysics from the Sn nuclei

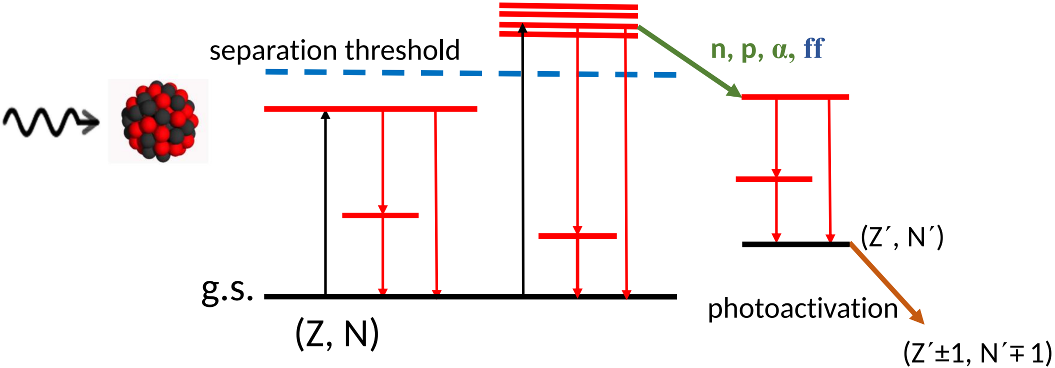


Including the newly measured results in the cross-section calculations

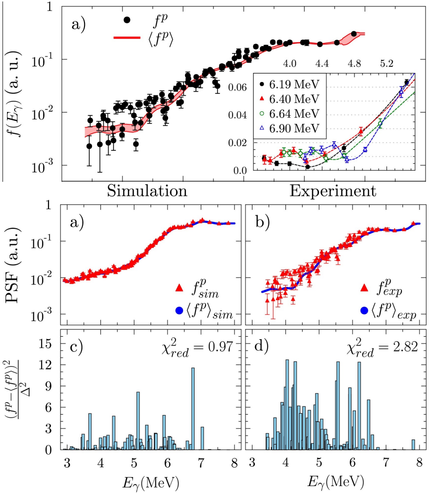
$$\sigma(\mathrm{n},\gamma) \propto \sum_{J^\pi, XL} \int \mathcal{T}_{XL}(E_\gamma)\rho(E_x, J, \pi)\mathrm{d}E_\gamma \tag{5}$$

yield a significantly increased neutron-capture cross-section compared to TENDL, and a significantly higher neutron-capture reaction rate for $^{111}\mathrm{Sn}(\mathrm{n},\gamma)^{112}\mathrm{Sn}$ at temperature $T \approx 4$ GK.

P.-A. Söderström, et al.: Phys. Rev. C 112 (2025) 024327, Calculations: Y. Xu



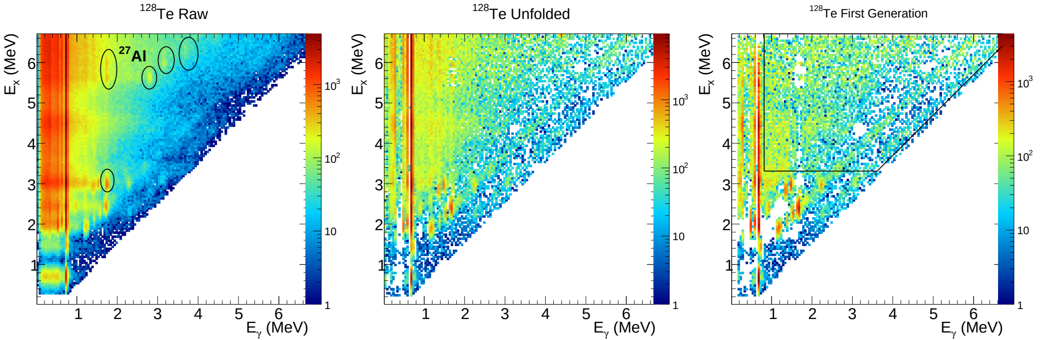
- Incoming γ ray can select individual states to excite
- Above particle separation threshold, particle decay to neighbouring nucleus, fission, etc.
- ... or γ-decay. This type of branching probabilities will be one key topic for measurements



- Is there a unique gamma strength function in ^{128}Te?
- Experimental spread significantly higher than `DICEBOX` simulations
- Deviations cannot be explained by the statistical uncertainties and the expected PT fluctuations alone
- Does the decay widths not follow a PT distribution?
- Is the BA hypothesis not fulfilled in this nucleus?
- Will the observed fluctuations remain in non-trivial ($J^\pi = 1^-$) spin distribution?

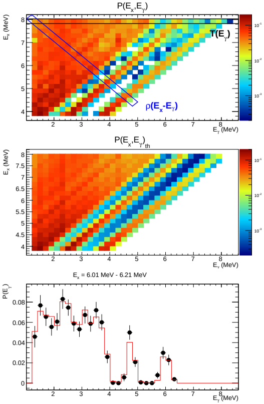
J. Isaak, et al.: Phys. Lett. B 788, 225 (2019)

^{128}Te experiment at IFIN-HH



- Experiment performed with ^{128}Te target at IFIN-HH in 2024
- Carbon backing, huge carbon background at $E_x > 7$ MeV
- Limited excitation energy range

P.-A. Söderström, et al.: Phys. Scr. 100, 075301 (2025)



- If we know the level densities, $\rho(E_x)$, and the transition probabilities, $\mathcal{T}(E_\gamma)$, the decay probability matrix can be calculated from

$$P(E_x, E_\gamma)_{\text{th}} = \frac{\rho(E_x - E_\gamma)\mathcal{T}(E_\gamma)}{\sum_{E_\gamma} \rho(E_x - E_\gamma)\mathcal{T}(E_\gamma)}, \quad (6)$$

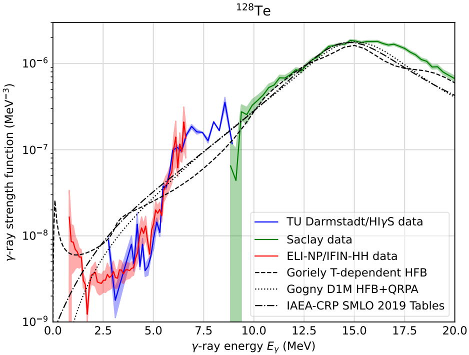
- Use χ^2 fit to find any $\rho(E_x)$ and $\mathcal{T}(E_\gamma)$ that reproduce the data
- Infinite number of solutions, but related via differential equations
- Only depend on three parameters as

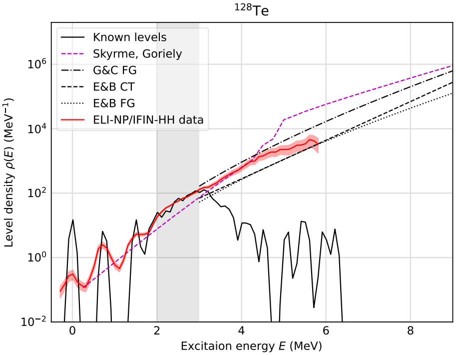
$$\tilde{\rho}(E_x - E_\gamma) = A_0 \exp[\alpha(E_x - E_\gamma)]\rho(E_x - E_\gamma), \quad (7)$$

$$\tilde{\mathcal{T}}(E_\gamma) = B_0 \exp(\alpha E_\gamma)\mathcal{T}(E_\gamma) \quad (8)$$

- Just need to determine A_0, B_0, and α

^{128}Te experiment at IFIN-HH

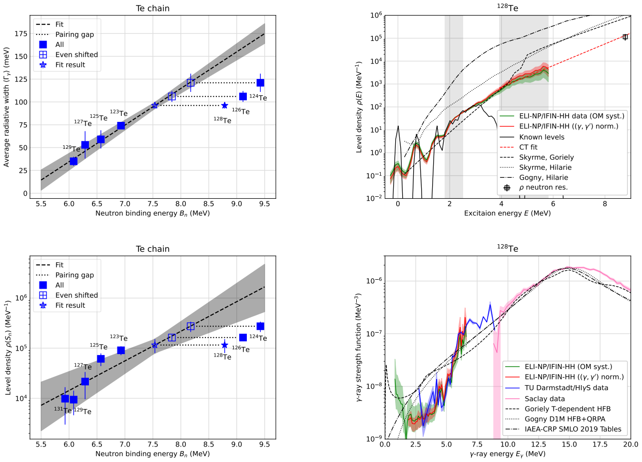




- Normalize γSF on the $(\gamma, \gamma'\gamma'')$ data from HIγS
- Use the normalization to fix the NLD slope

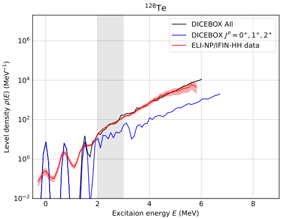
P.-A. Söderström, et al.: Phys. Scr. 100, 075301 (2025)

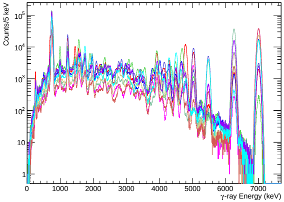
Comparison with neutron resonance normalization



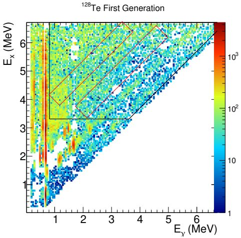
- (γ,γ') normalization reasonable?
- Typically Oslo-method normalization is performed on neutron capture data
- ^{127}Te unstable, no n-capture
- Estimate approximate quantities from systematics, interpolation between odd-A and even-A data corrected for pairing energy
- Agrees remarkably well!
- Massive difference between microscopic and experimental
- Cause of underestimated PT fluctuations in `DICEBOX`?

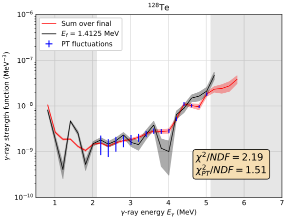
DICEBOX simulations

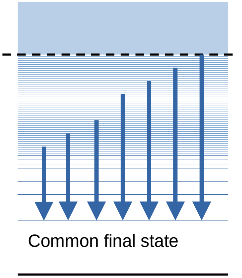


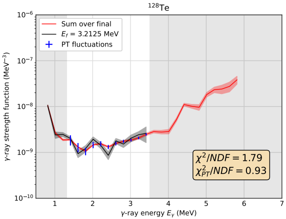


- DICEBOX calculations performed with the obtained experimental data
- The BSFG model with the spin cut-off factor by von Egidy and Bucurescu (2005), $a = 13.04$ MeV^{-1} and $E_1 = 0.68$ MeV
  J. Isaak, et al.: Phys. Lett. B 788, 225 (2019)
- Good agreement with current experiment
- Fluctuations of partial radiation widths according to Porter-Thomas distribution
- E1 PSF is given in a tabulated form from experiment
- Constant plus Lorentzian M1 PSF, Lorentzian E2 PSF
- 10 realisationsfrom the given NLD, decay widths from the average PSF with a Porter-Thomas probability distribution
- 10 typical expected Nuclear Resonance Fluorescence spectra and variations in unresolved strength



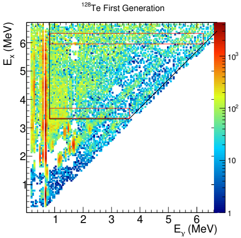


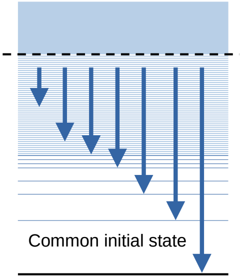


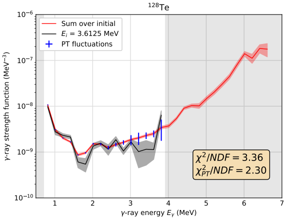


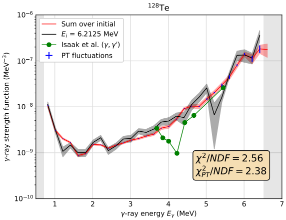
- Brink-Axel hypothesis: Strength function depends only on energy difference between initial and final states
- Must be violated on the level of the PT fluctuations (if PT distribution valid)
- $\sigma_{f,\mathrm{PT}}/f = \sqrt{2/n(E_\gamma, E_\mathrm{i})}$
- Analyze the matrix based on selected regions corresponding to common final state
- Approximately deviation of two from just statistical $\chi 2$. However, consistent if estimated Porter-Thomas fluctuations considered

Brink-Axel hypothesis: common initial states









- Brink-Axel hypothesis: Strength function depends only on energy difference between initial and final states
- Must be violated on the level of the PT fluctuations (if PT distribution valid)
- $\sigma_{f,\mathrm{PT}}/f = \sqrt{2/n(E_\gamma, E_\mathrm{i})}$
- Analyze the matrix based on selected regions corresponding to common initial state
- Approximately deviation of two from just statistical $\chi 2$. Including estimated Porter-Thomas fluctuations does not change the picture significantly!

Summary and conclusions

- We have started doing photon strength-function and nuclear level density measurements at the 9MV Tandem
- First experiment on ^{112}Sn and ^{114}Sn successful
- Photon strength-function, nuclear level density, microscopic structure, astrophysical reaction rates
- First experimental nuclear level density of ^{128}Te, normalized to (γ, γ') data
- Does not explain the observed departure from just Porter-Thomas violations of the Brink-Axel hypothesis

S. Aogaki, et al.: Nucl. Instrum. Methods Phys. Res. A 1056 (2023) 168628

P.-A. Söderström, et al.: Phys. Scr. 100 (2025) 075301

P.-A. Söderström, et al.: Phys. Rev. C 112 (2025) 024327

Collaboration

ELIGANT:

- Pär-Anders Söderström
- Aslı Kuşoğlu
- Andreea Ghitiu (Gavrilescu)

Special thanks:

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- Johann Isaak - Technische Universität Darmstadt
- Dimiter Balabanski - ELI-NP
- ... and all other colleagues that help

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