Comprehensive test of the Brink-Axel hypothesis in the energy range of the pygmy dipole resonance

[1]Markova Maria, [1]A.C. Larsen, [1] F.L.B.Garrote

[1]University of Oslo, Department of Physics, Nuclear Physics group

March 16, 2022

17th Russbach School on Nuclear Astrophysics

March 2022

Table of contents

UiO University of Oslo

Briefly about the gamma-ray strength function

- Gamma-ray strength function (GSF) is an average property of excited nuclei (by analogy with the level density).

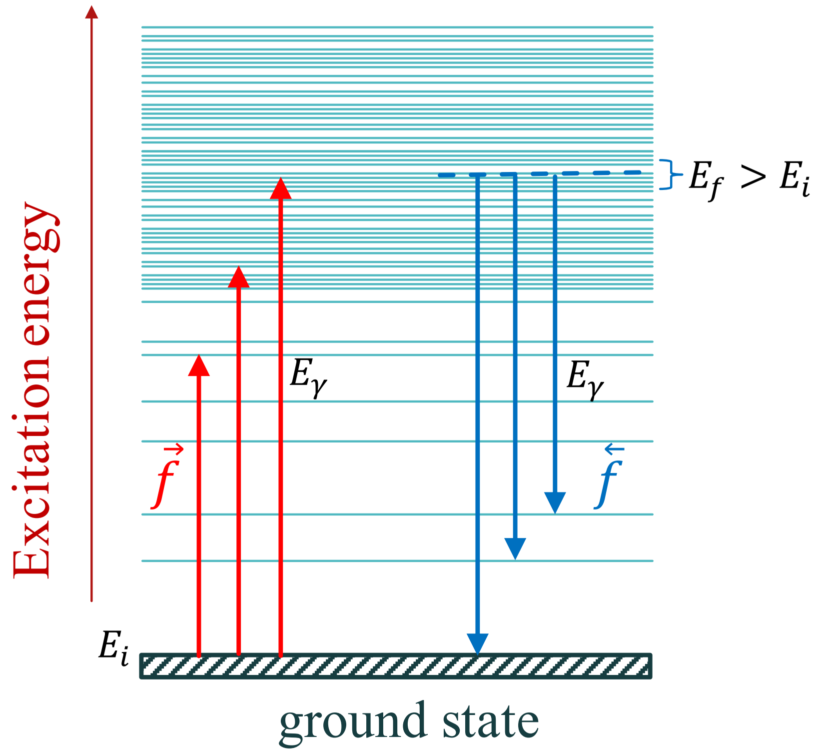
- By the general definition, the GSF $f_{XL}(E_\gamma)$ is the distribution of the average reduced width $\bar{\Gamma}$ for transitions of XL multipole type ($X = E$ for electric, $X = M$ for magnetic) over gamma-ray energies E_γ:

$$f^J_{i\to f,XL}(E_\gamma) = \frac{\bar{\Gamma}^J_{i\to f,XL}}{E_\gamma^{2L+1}} \cdot \rho^J(E_f),$$

  where we consider transition(s) from the state(s) i to the state(s) f of a certain spin and parity J, E_γ is the energy of an absorbed/emitted photon, $\rho^J(E_f)$ is the density of levels around excitation energy E_f.

- *i.e.* proportional to the reduced matrix element squared per unit excitation energy interval $\rightarrow$ **transition probability**.

- GSF from the photoabsorption experiments - "**upward**" $\overrightarrow{f}$ strength, from the γ-emission - "**downward**" $\overleftarrow{f}$ strength.



Schematic representation of the GSF in terms of γ-transitions.

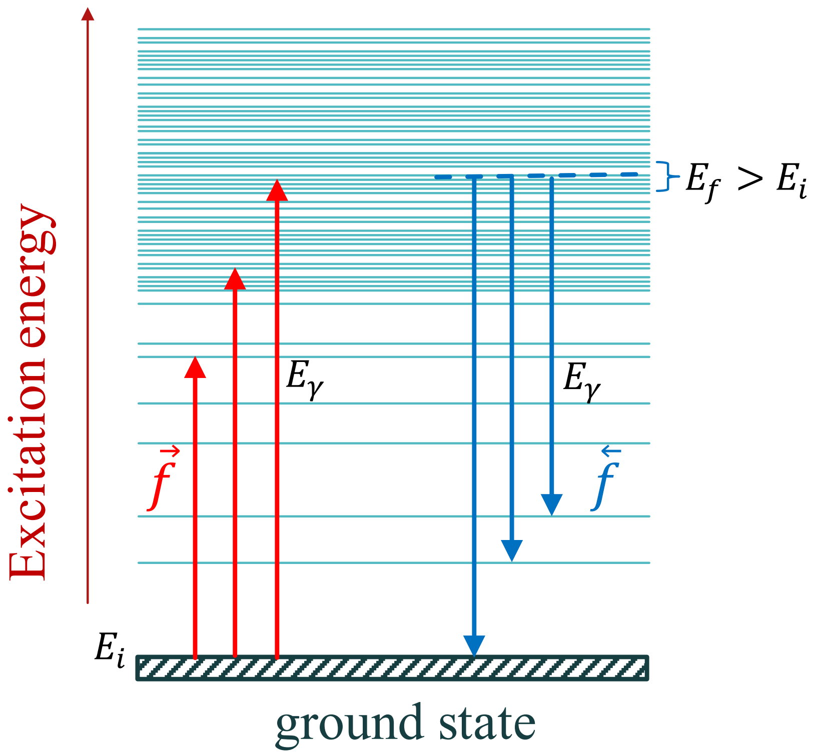
Generalized Brink-Axel hypothesis

- Photoabsorption cross section (and, therefore, GSF) of the giant electric dipole resonance (GDR) is independent of the detailed structure of the initial state (D. M. Brink).
- Further generalized to both γ-absorption and emission processes (P. Axel).
- Additional independence of the initial and final spins of the states involved (only dipole selection rules).

$\downarrow$

Generalized Brink-Axel hypothesis

- The "**upward** " $\overrightarrow{f}$ GSF should be identical to the "**downward** " $\overleftarrow{f}$ GSF.

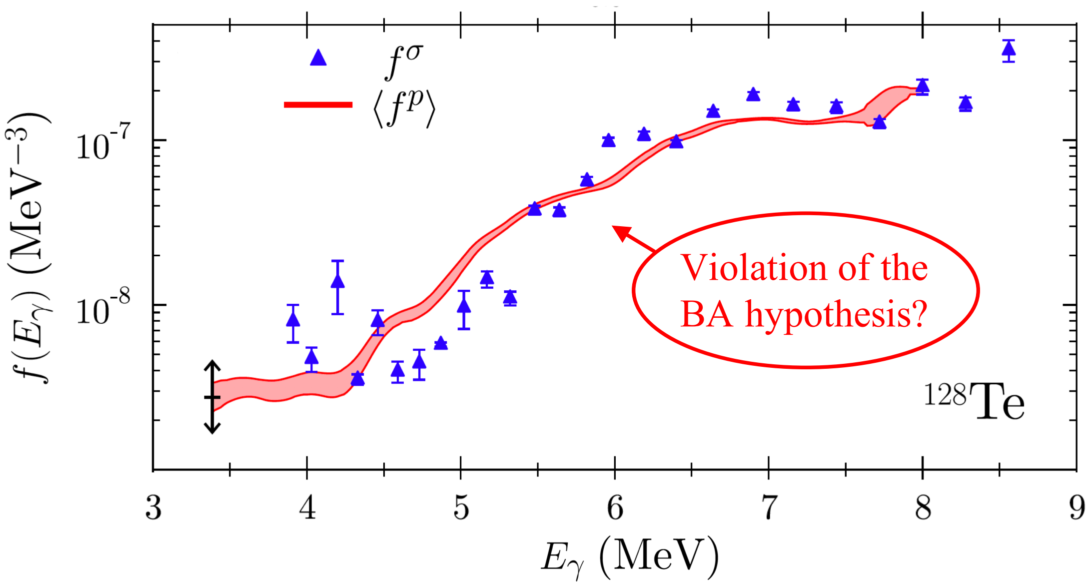


Schematic representation of the GSF in terms of γ-transitions.

Motivation: why is the Brink-Axel hypothesis important?

- Provides significant simplification of many problems in nuclear physics:
  - Widely used to calculate the low-energy $E1$ and $M1$ strengths (e.g. Oslo method).
  - Calculation of Gamow-Teller and Fermi transition strengths in β-decay and electron capture.
  - (n,γ) cross-section calculations for the astrophysical r-process in extreme environments and nuclear reactors.

The validity of the Brink-Axel hypothesis is still to be tested for different energy regions and systems!



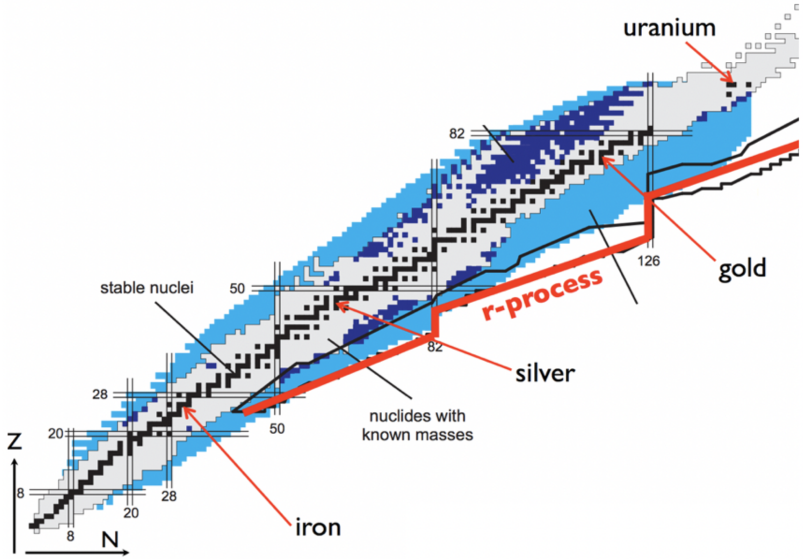
Comparison of the GSF from the photoabsorption cross section data f^{σ} and photon emission process $\langle f^{p} \rangle$.

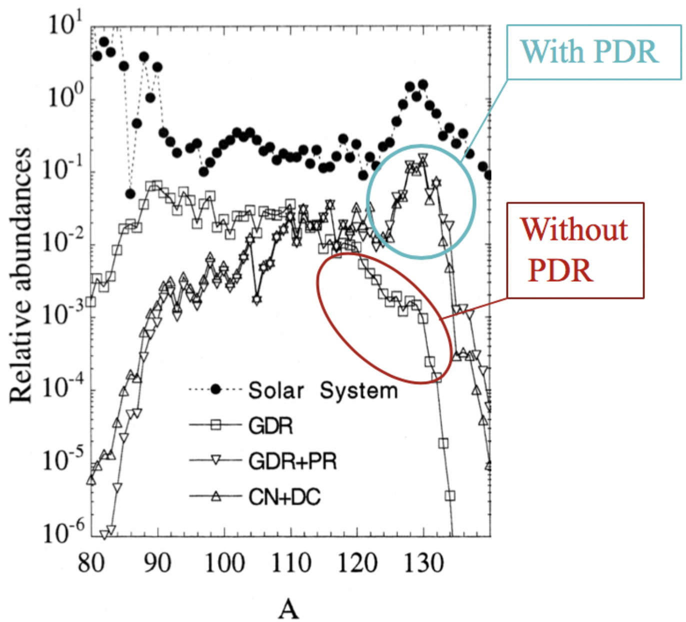
J. Isaak *et al.*, Physics Letters B 788 (2019) 225 - 230

.

Motivation: why PDR?

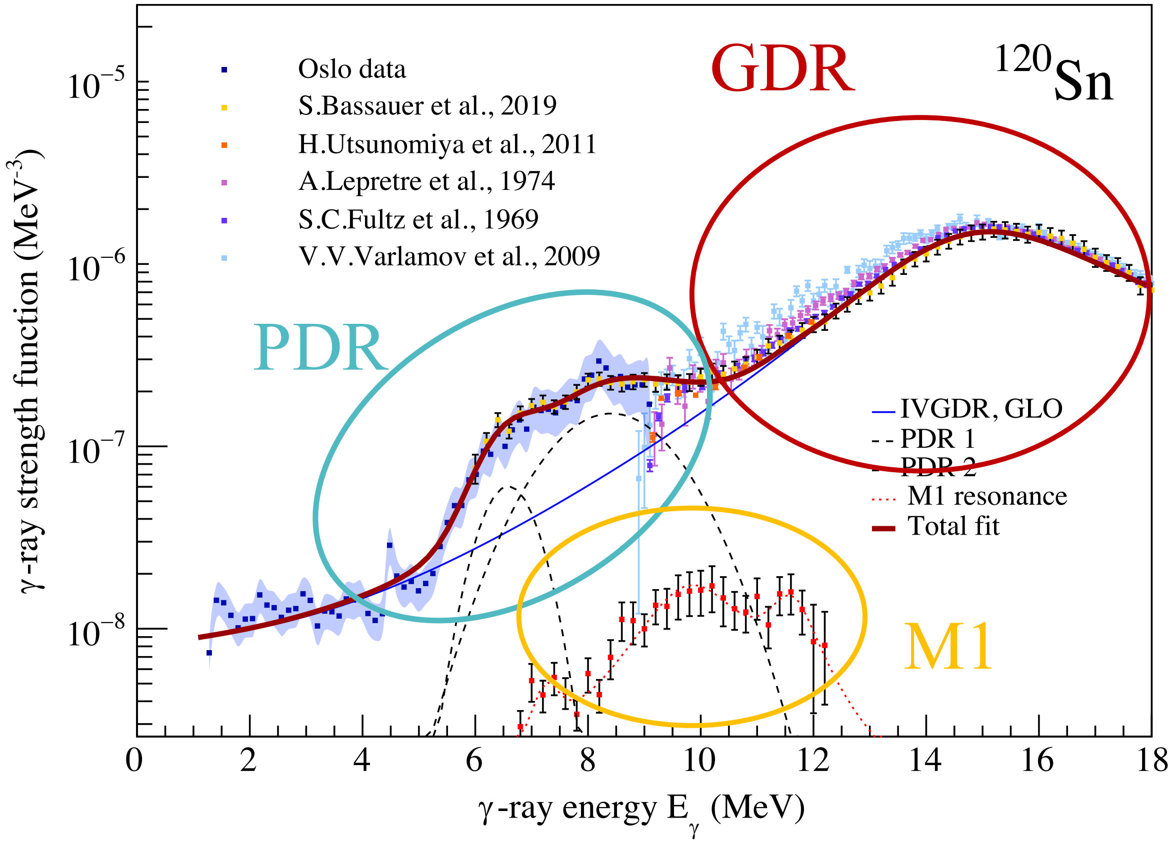
- The PDR has another particular astrophysical effect:
  - Influence of the PDR on neutron capture rates and resulting abundances in the r-process.
  - The r-process is responsible for the production of $\approx 50\%$ of elements heavier than iron in the Universe.
  - Appearance of the PDR increases probability of the (n, γ) reaction.





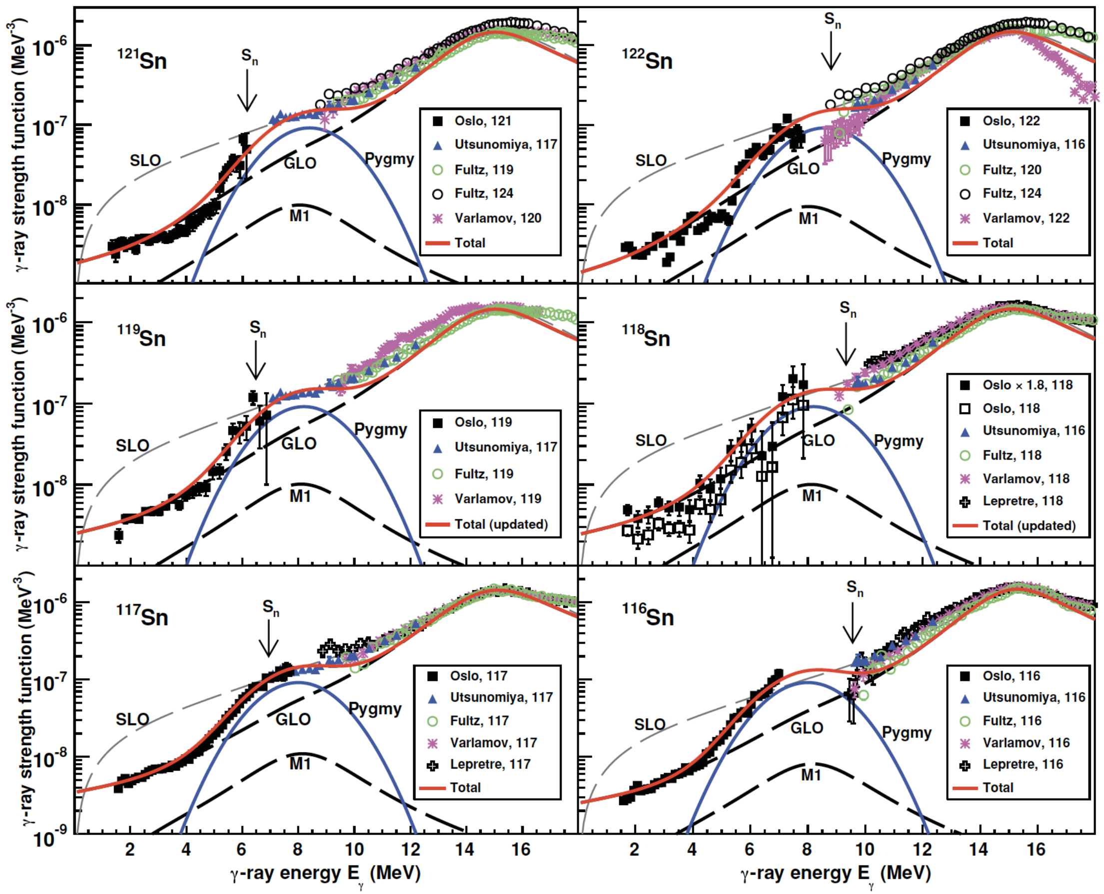
Left part: Probable pathway of the r-process.**Right part**: Abundances of elements produced in the r-process S. Goriely, Phys. Lett. B 436 (1998).

Motivation: why PDR?



GSF function for ^{120}Sn extracted from the Oslo-type of experiment (p,p′γ), (p,p′) and (γ, n) experiments

Motivation: why Sn?

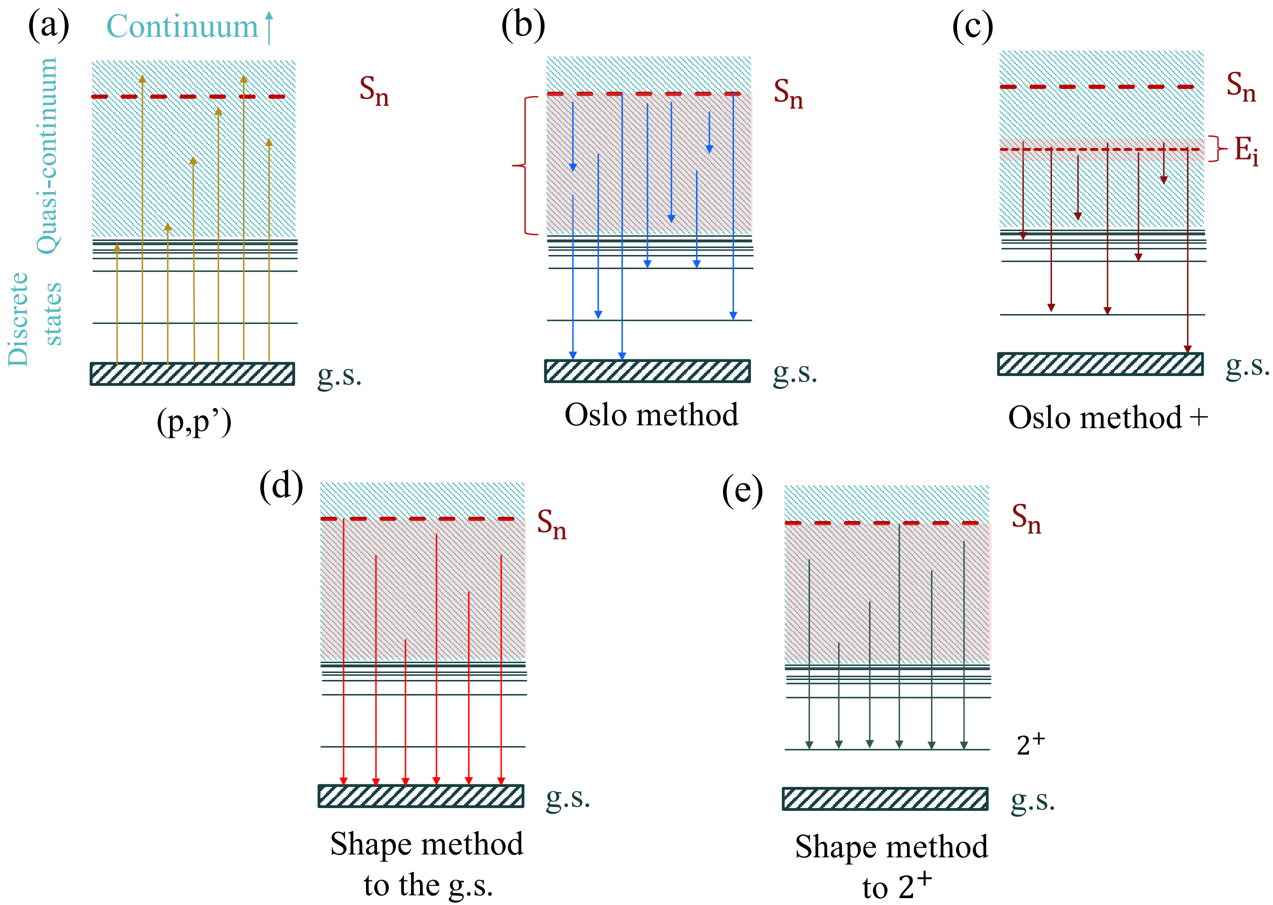


Comparison of the predictions for the total γ-strength functions with the OCL experimental measurements for $^{116-119,121,122}$Sn.

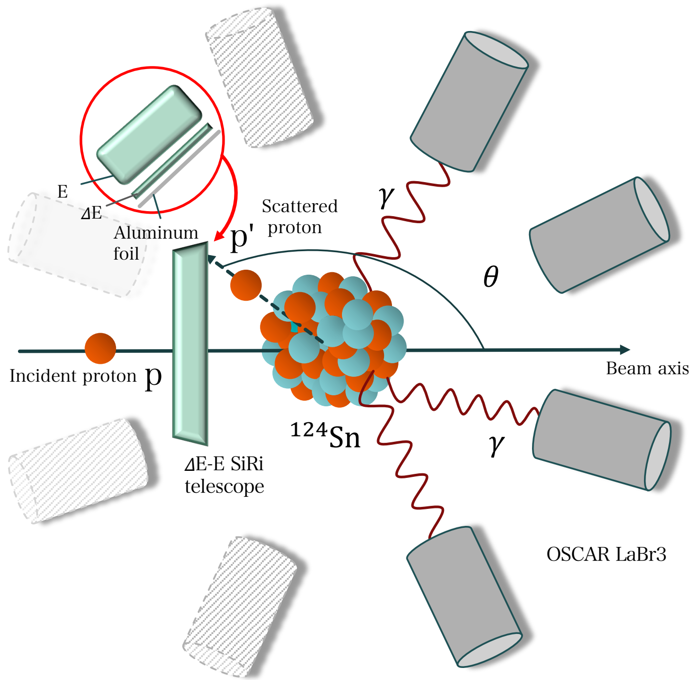
H. K. Toft *et al.*, Phys. Rev. C 83, 044320 (2011)

Experimental techniques used in the present work

The Brink-Axel hypothesis is tested in the energy range below the neutron separation energy for ^{116,120,124}Sn.



Oslo method: Experiment on ^{116,120,124}Sn at the Oslo Cyclotron Laboratory



The principal scheme of the experiment.

Principal goal of the experiment is to extract:

1. Nuclear level density: number of levels per unit energy
2. γ-ray strength function $\sim$ reduced transition probability

---

^{120,124}Sn:

- Performed in February-March, 2019 by means of OCL facilities with the OSCAR LaBr3(Ce)γ-detector array and charged particle SiRi detector.
- 126°-140° angles are covered.
- Study of the (p,p′γ) reaction with 16 MeV proton beam on highly pure ^{120,124}Sn target.
- proton-γ coincidences were extracted.

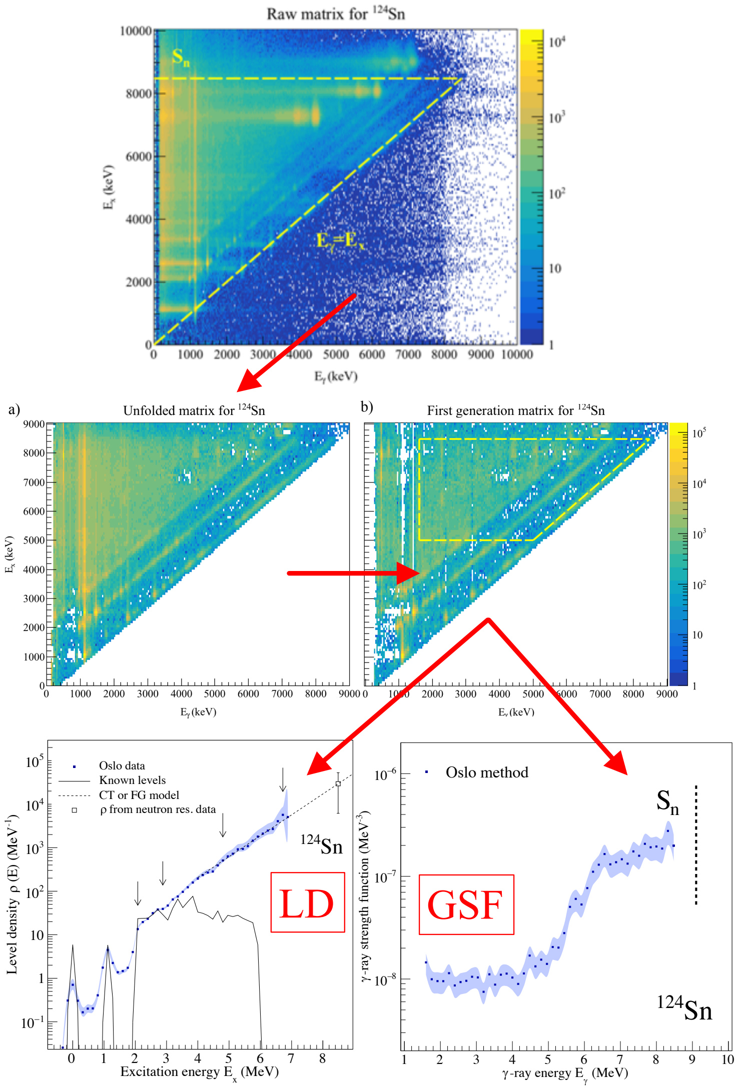
---

^{116}Sn:

- Older experiment with the previous setup: NaI scintillator detectors+silicon particle telescope, ^{117}Sn(^{3}He, $\alpha\gamma$)^{116}Sn reaction with 38 MeV ^{3}He beam.

UiO University of Oslo

The Oslo method



- Unfolding: extraction of the original spectra from the raw p-γ coincidence data on the base of the known detector response.

↓

- First generation method: subtraction of secondary and higher order γ-transitions.

↓

- Factorization of the first generation matrix P as
$$P(E_x, E_\gamma) \sim \rho(E_x - E_\gamma) \cdot \mathcal{T}(E_\gamma).$$

↓

- Subsequent extraction of the level density $\rho(E_x - E_\gamma)$ and radiative transmission coefficient $\mathcal{T}(E_\gamma)$ (Brink-Axel hypothesis).

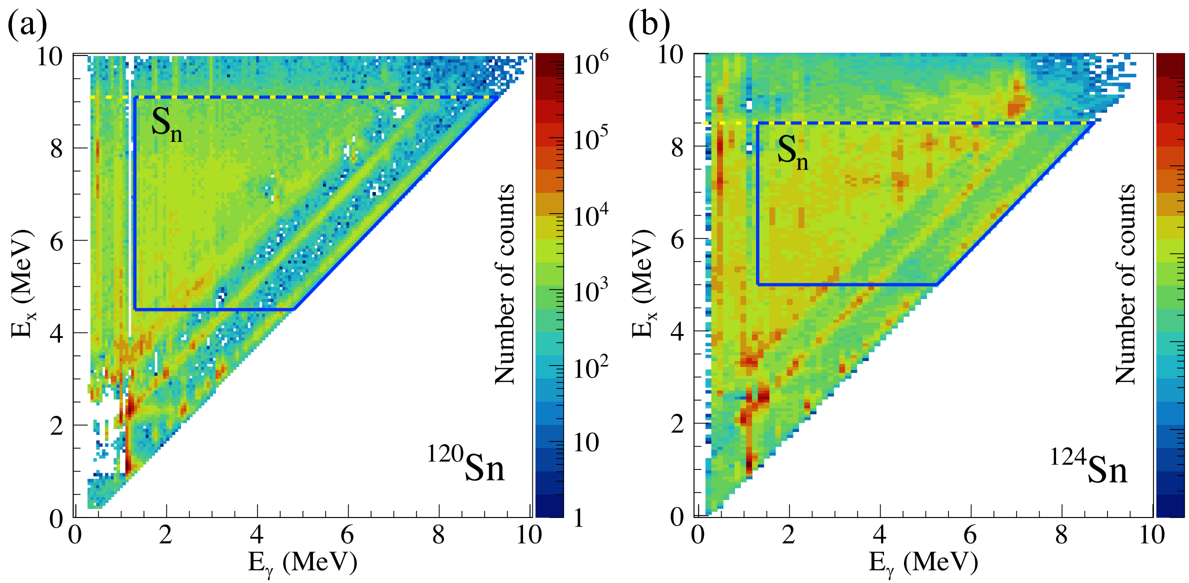
↓

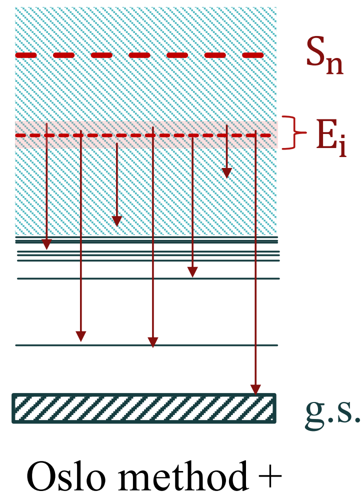
- $\mathcal{T}(E_\gamma)$ is used for estimation of the dipole γ-strength function
$$f(E_\gamma) = \mathcal{T}(E_\gamma)/2\pi E_\gamma^3$$

↓

- Normalization of the level density and γRSF.

Extraction of the GSF for a certain initial excitation energy





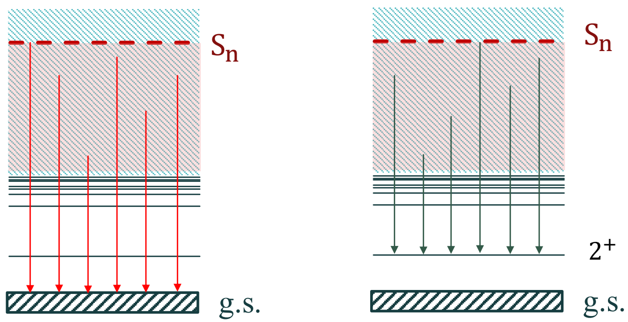
- Since the first generation matrix P is given by $P(E_x, E_\gamma) \sim \rho(E_x - E_\gamma) \cdot \mathcal{T}(E_\gamma)$, it is possible to map $\mathcal{T}(E_x, E_\gamma)$ and therefore $f(E_x, E_\gamma)$ as functions of initial excitation energy E_i:

$$f(E_i, E_\gamma) = \frac{N(E_i) \cdot P(E_i, E_\gamma)}{\rho(E_i - E_\gamma)},$$

where $N(E_i)$ is the normalization factor:

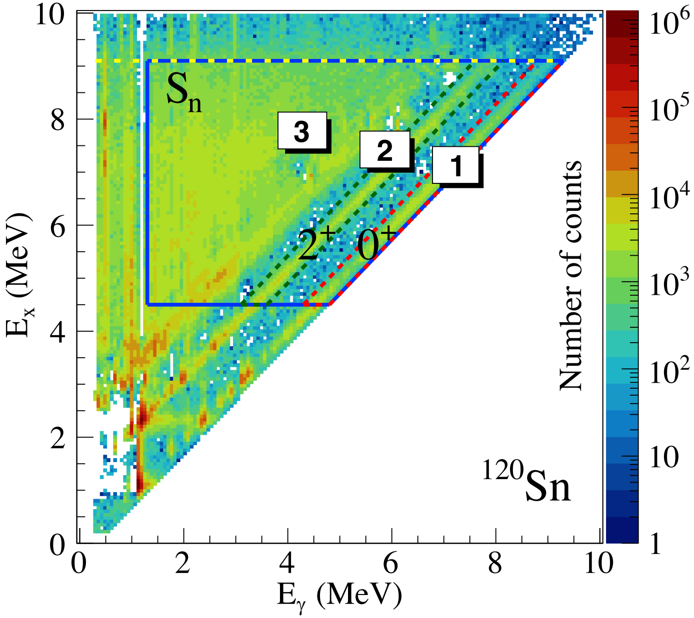
$$N(E_i) = \frac{\int_0^{E_i} \mathcal{T}(E_\gamma)\rho(E_i - E_\gamma)dE_\gamma}{\int_0^{E_i} P(E_i, E_\gamma)dE_\gamma}.$$

The Shape method



Shape method to the g.s.

Shape method to 2^+



- The number of counts in each diagonal is given by:

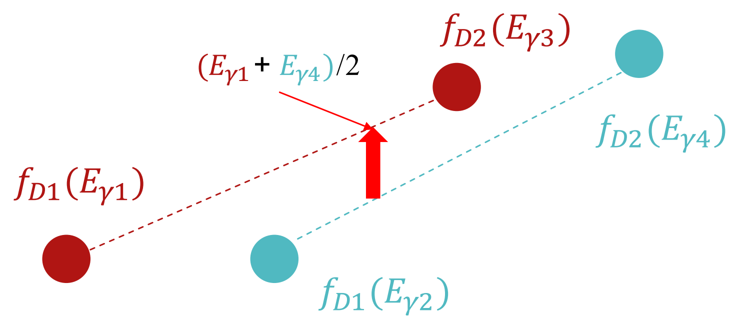
$$N_D \sim f(E_\gamma)E_\gamma^3 \sum_{J_i-J_f-1}^{J_i=J_f+1} \sigma(E_i, J_i)g(E_i, J_i),$$

  where $\sigma(E_i, J_i)$ is the cross-section to populate a certain initial state with spin J_i at a given excitation energy E_i, and $g(E_i, J_i)$ is a known spin distribution function.

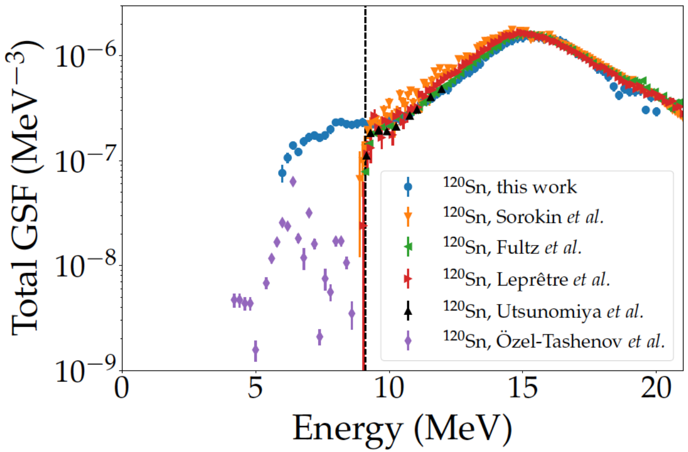
- For the current analysis the g.s. ($J_f^P = 0^+$) and 1st excited state diagonal ($J_f^P = 2^+$) are chosen (for the same E_i):

$$f(E_{\gamma 1,2})\frac{N_{D1,2}}{E_{\gamma 1,2}^3 \sum_{J_i-J_f-1}^{J_i=J_f+1}} g(E_i, J_i)$$

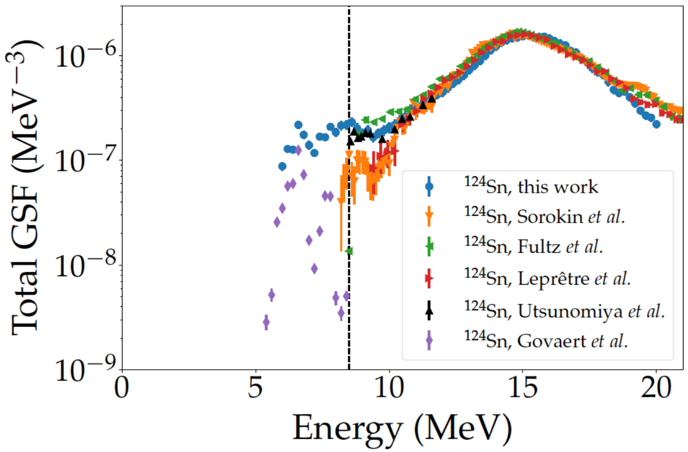
- Pairs of $f(E_{\gamma 1})$ and $f(E_{\gamma 2})$ for each excitation energy are "sewed "together:

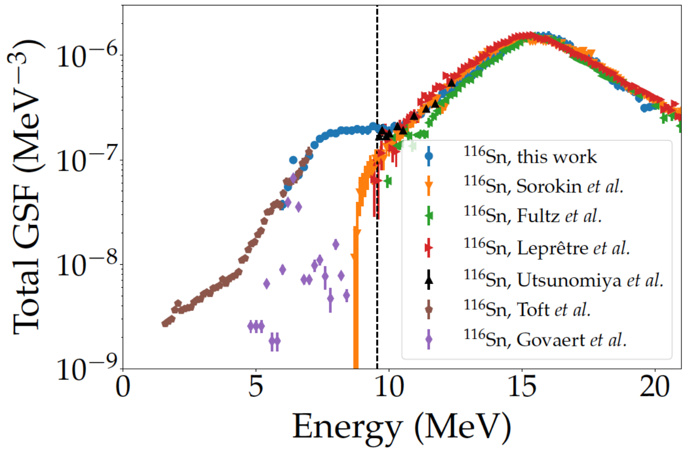


(p,p′) experiment at the RCNP

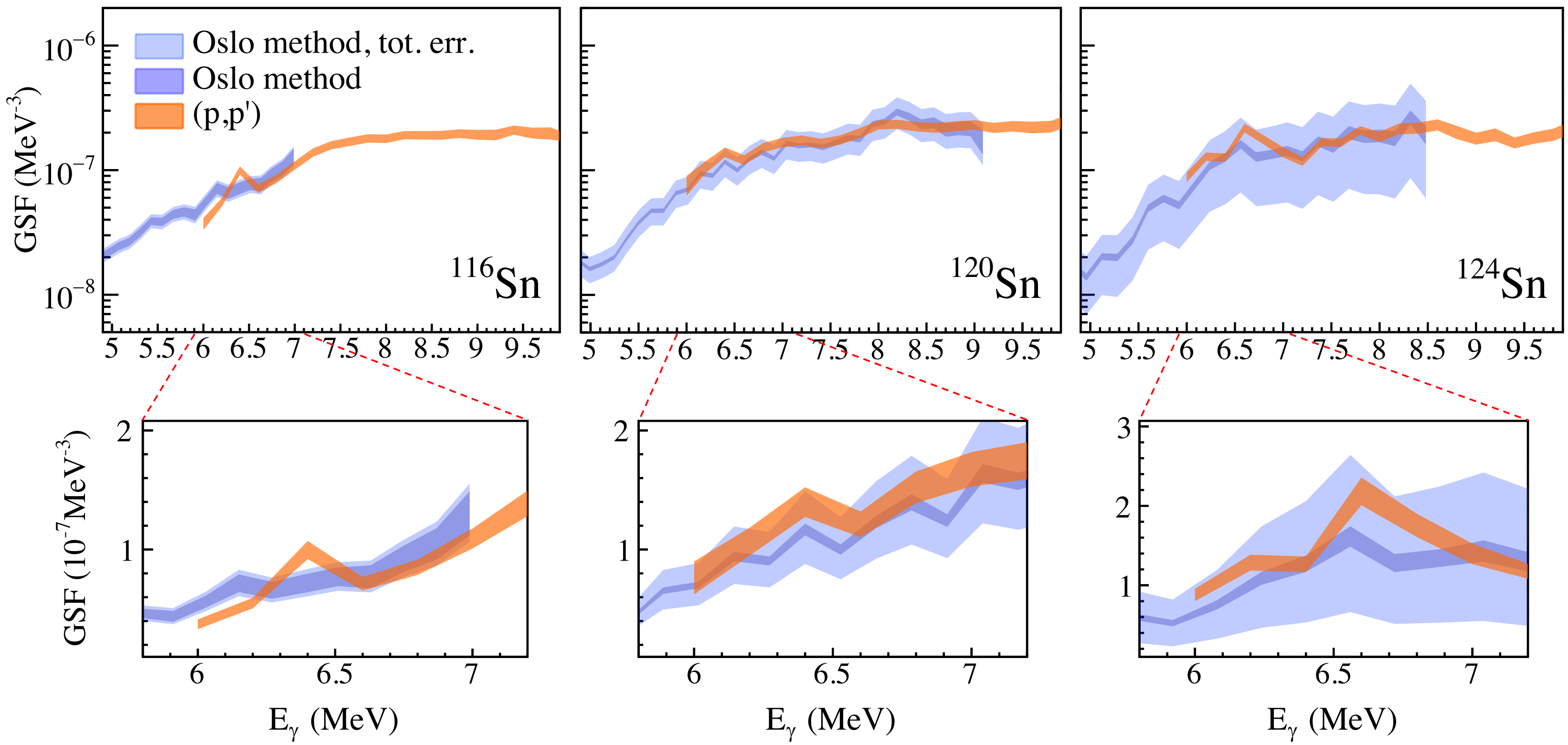


- Total gamma strength functions for stable tin isotopes were also extracted from the forward-angle inelastic proton scattering data at relativistic beam energies (295 MeV protons). Eperiment was performed at the Research Center for Nuclear Physics (RCNP) in Osaka, Japan. [S. Bassauer et al., Phys. Rev.C 102, 034327 (2020).]

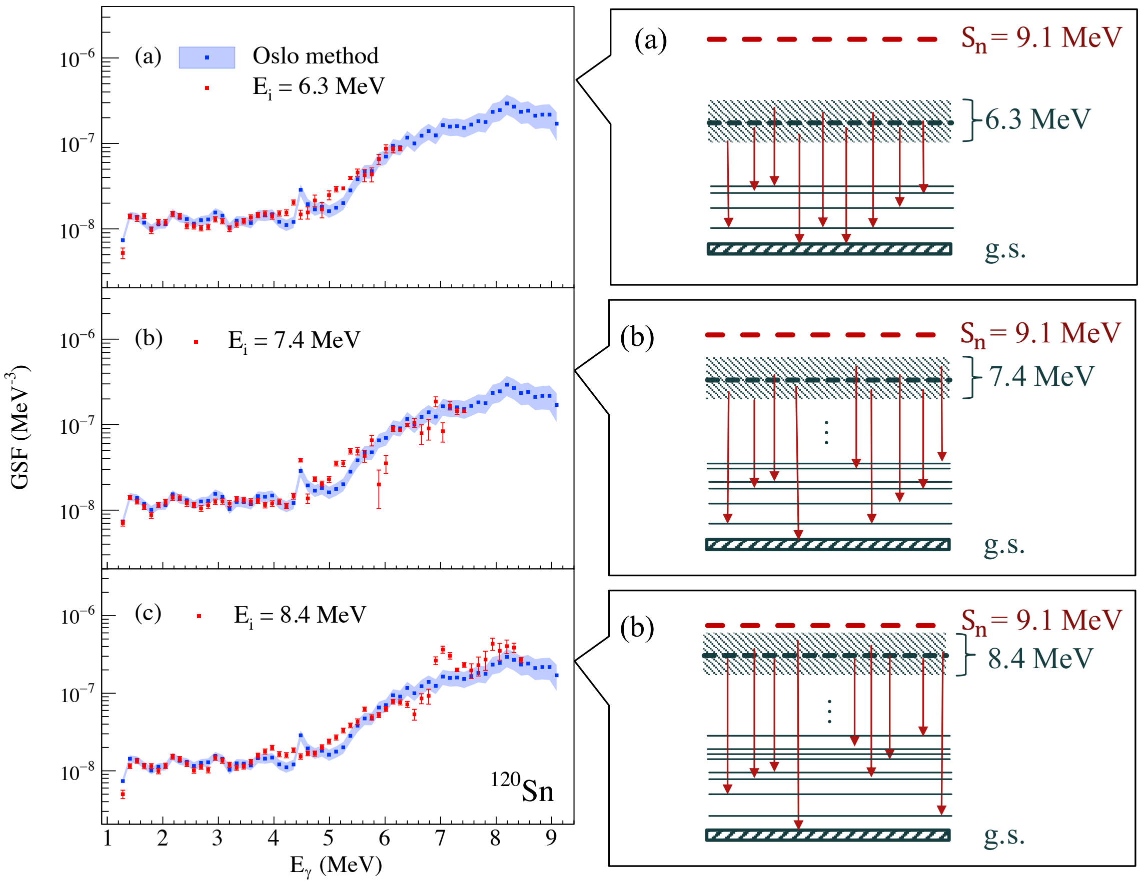




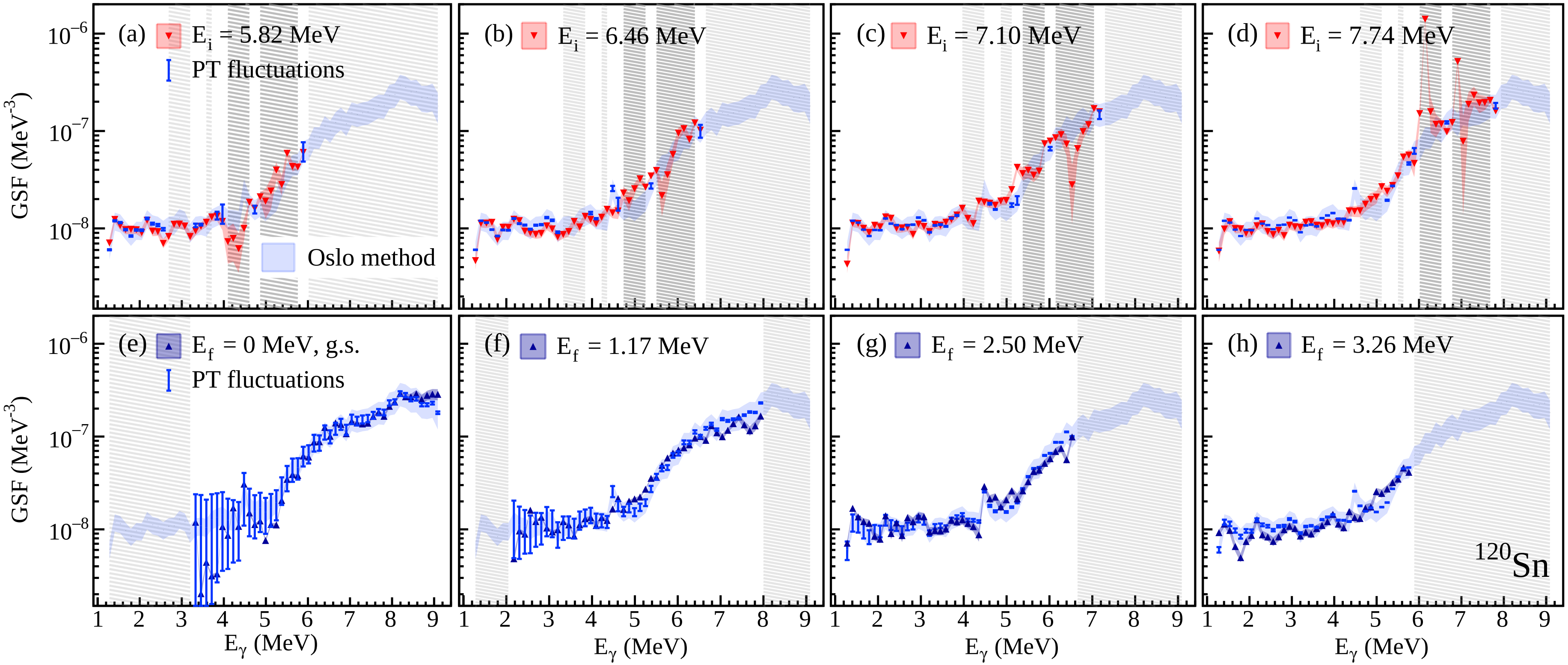
Main results: GSF for ^{116,120,124}Sn



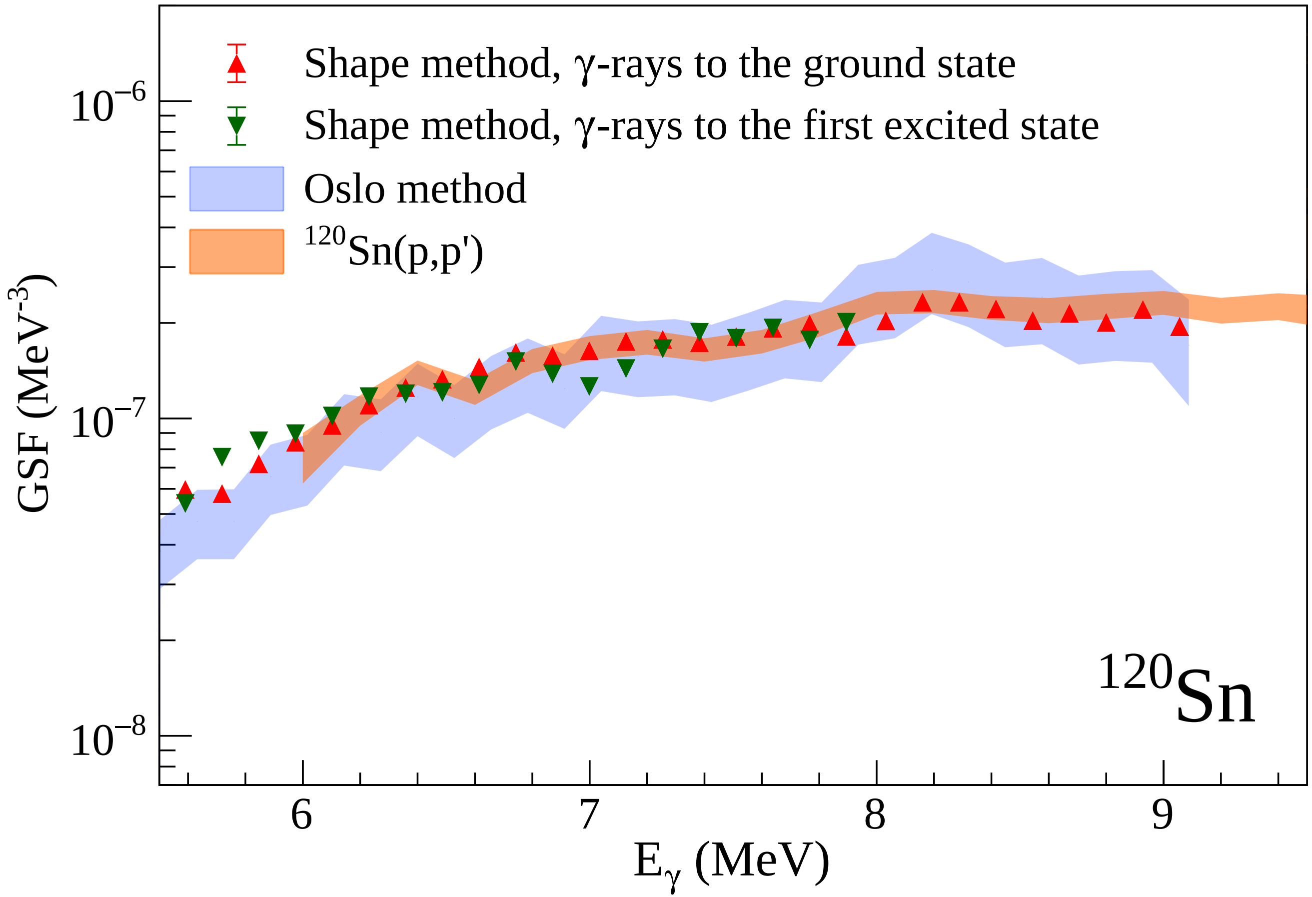
Main results: GSF extracted for several initial excitation energies for ^{120}Sn



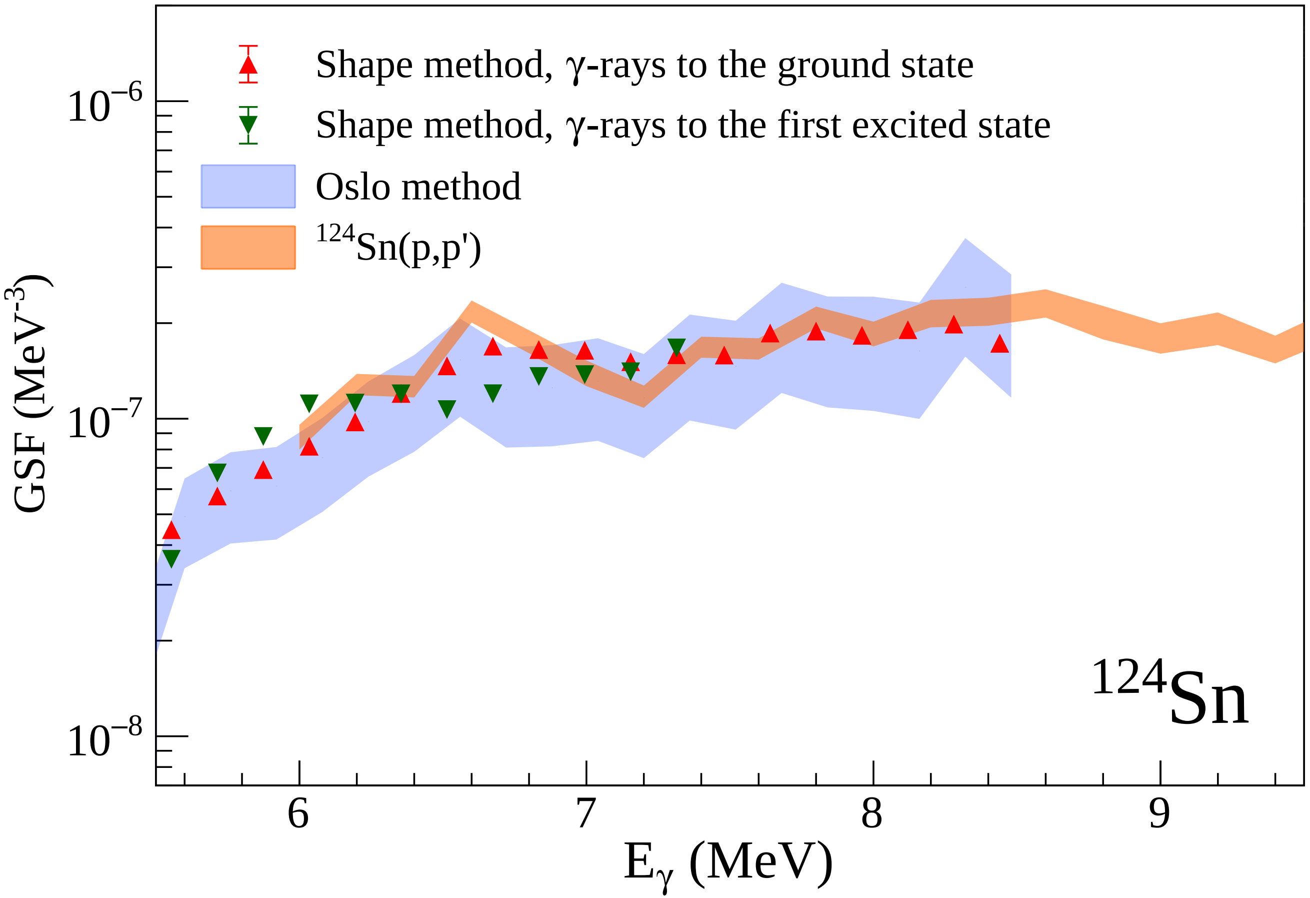
Main results: GSF extracted for several initial and final excitation energies for ^{120}Sn



Main results: Oslo method + Shape method + (p,p′) for ^{120}Sn



Main results: Oslo method + Shape method + (p,p′) for ^{124}Sn



Summary

- Comparison of the GSF extracted from the Oslo-type experiments and the relativistic Coulomb excitation experiment in forward-angle inelastic proton scattering demonstrates good agreement in the energy range between ≈ 5.5 MeV and the neutron separation energy.
- Experiments based on ground state photoabsorption provide the same information on GSFs in nuclei as Oslo-type experiments.
- The GSFs seem to be somewhat independent of the energies and spins of initial and final states (as shown by the Shape method).

$\downarrow$

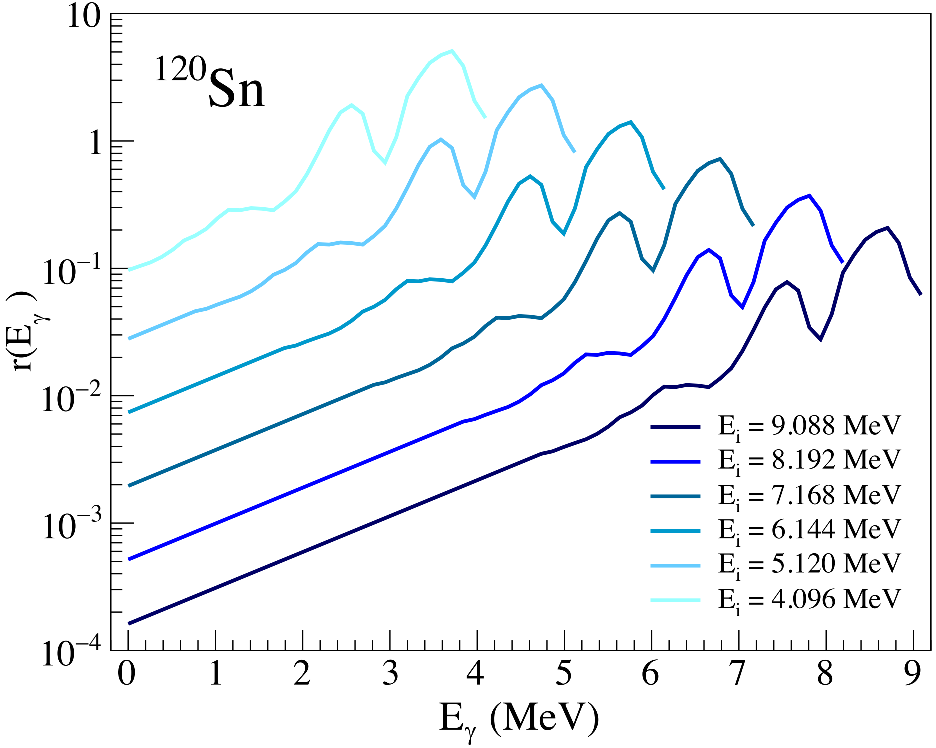
the generalized Brink-Axel hypothesis holds for ^{116,120,124}Sn isotopes in the energy range below the neutron separation energy!

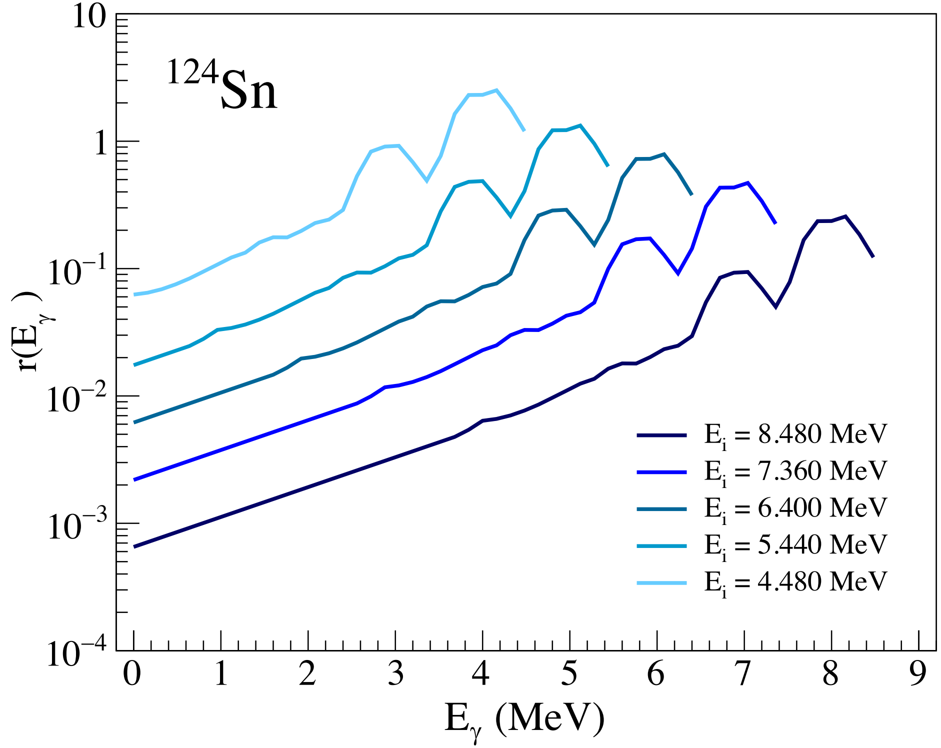
$\downarrow$

The assumptions made in the calculations of (n,γ) reactions relevant to r-process nucleosynthesis are verified.

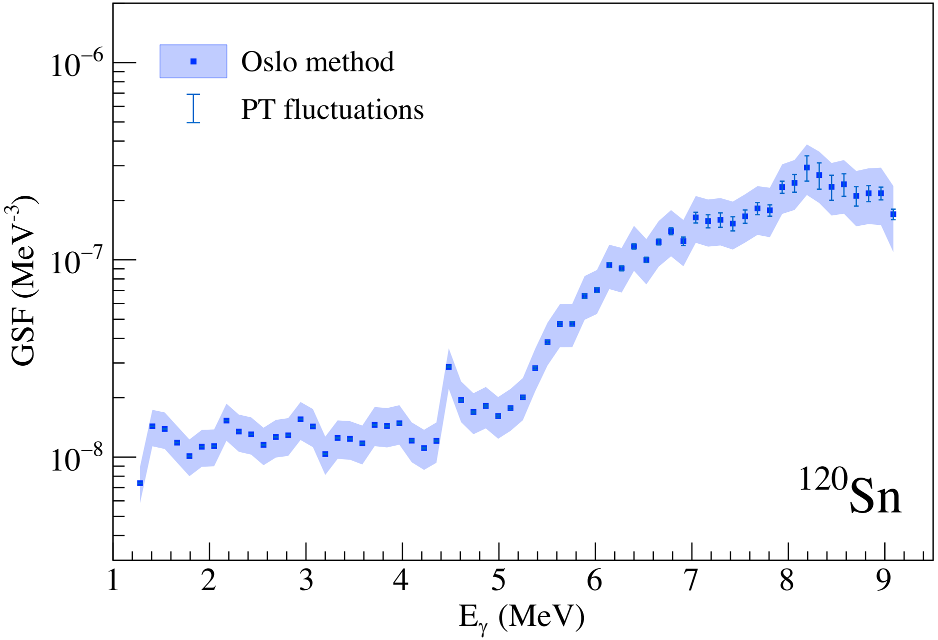
Thank you for your attention!

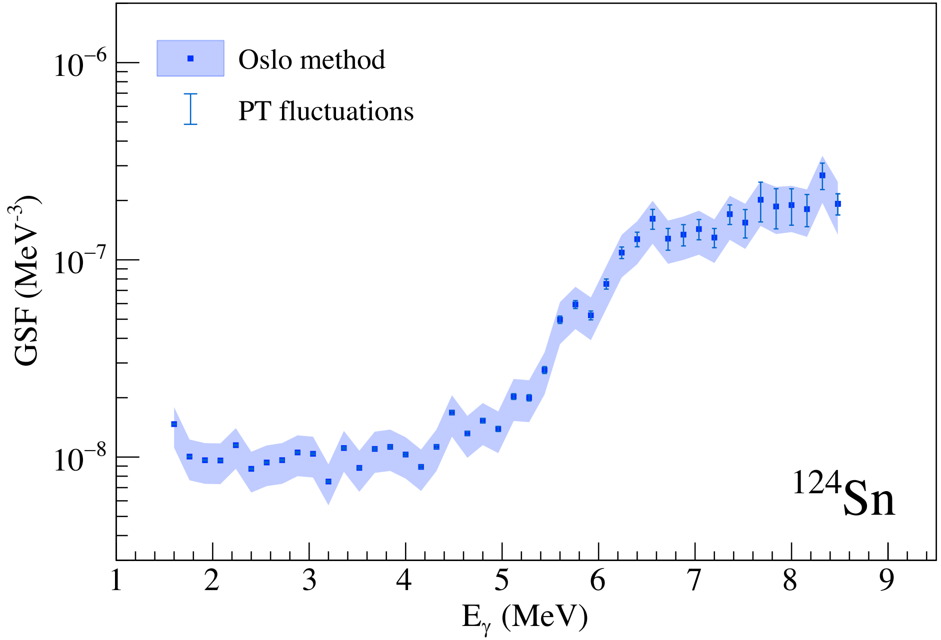
Porter-Thomas fluctuations





Porter-Thomas fluctuations





Porter-Thomas fluctuations