3rd Workshop on Level Density and Gamma Strength

Oslo, May 23-27 2011

γ-ray strength function method and applications

H. Utsunomiya (Konan University)

Outline

1. γSF method
2. Applications

(n,γ) cross sections
Nuclear Astrophysics : nucleosynthesis of heavy elements
Nuclear Engineering : basic data

Hauser-Feshbach cross section of raditaive neutron capture: $^{A}X(n,\gamma)^{A+1}X$

$$\sigma_{n\gamma}(E) = \frac{\pi}{k_n^2} \sum_{J,\pi} g_J \frac{T_\gamma(E,J,\pi)\, T_n(E,J,\pi)}{T_{tot}}$$

Total γ transmission coefficient

$$T_\gamma(E,J,\pi) = \sum_{\nu,X,\lambda} T^{\nu}_{X\lambda}(\varepsilon_\gamma) + \sum_{X,\lambda} \int T_{X\lambda}(\varepsilon_\gamma)\, \rho(E-\varepsilon_\gamma)\, d\varepsilon_\gamma$$

X=E, M
λ=1, 2, …

γ-ray strength function

$$T_{E1}(\varepsilon_\gamma) = 2\pi \langle \Gamma_{E1} \rangle / D$$

$$= 2\pi \varepsilon_\gamma^3 f_{E1}(\varepsilon_\gamma) \downarrow$$

γSF method

nuclear level density

$$\rho(E-\varepsilon_\gamma)$$

source of uncertainty

γSF method

The γ-ray strength function *$f_{X\lambda}(\varepsilon_\gamma)$ is a nuclear statistical quantity that interconnects photoneutron and radiative neutron capture cross sections within the HF model calculation.*

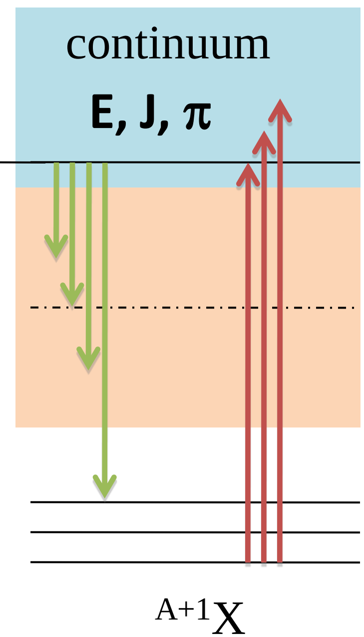
Radiative neutron capture

$^{A}X(n,\gamma)^{A+1}X$

$n+^{A}X$

$$f_{X\lambda}(\varepsilon_\gamma)\downarrow = \varepsilon_\gamma^{-(2\lambda+1)}\frac{\langle \Gamma_{X\lambda}(\varepsilon_\gamma)\rangle}{D}$$

$$\varepsilon_\gamma < S_n$$



Photoneutron emission

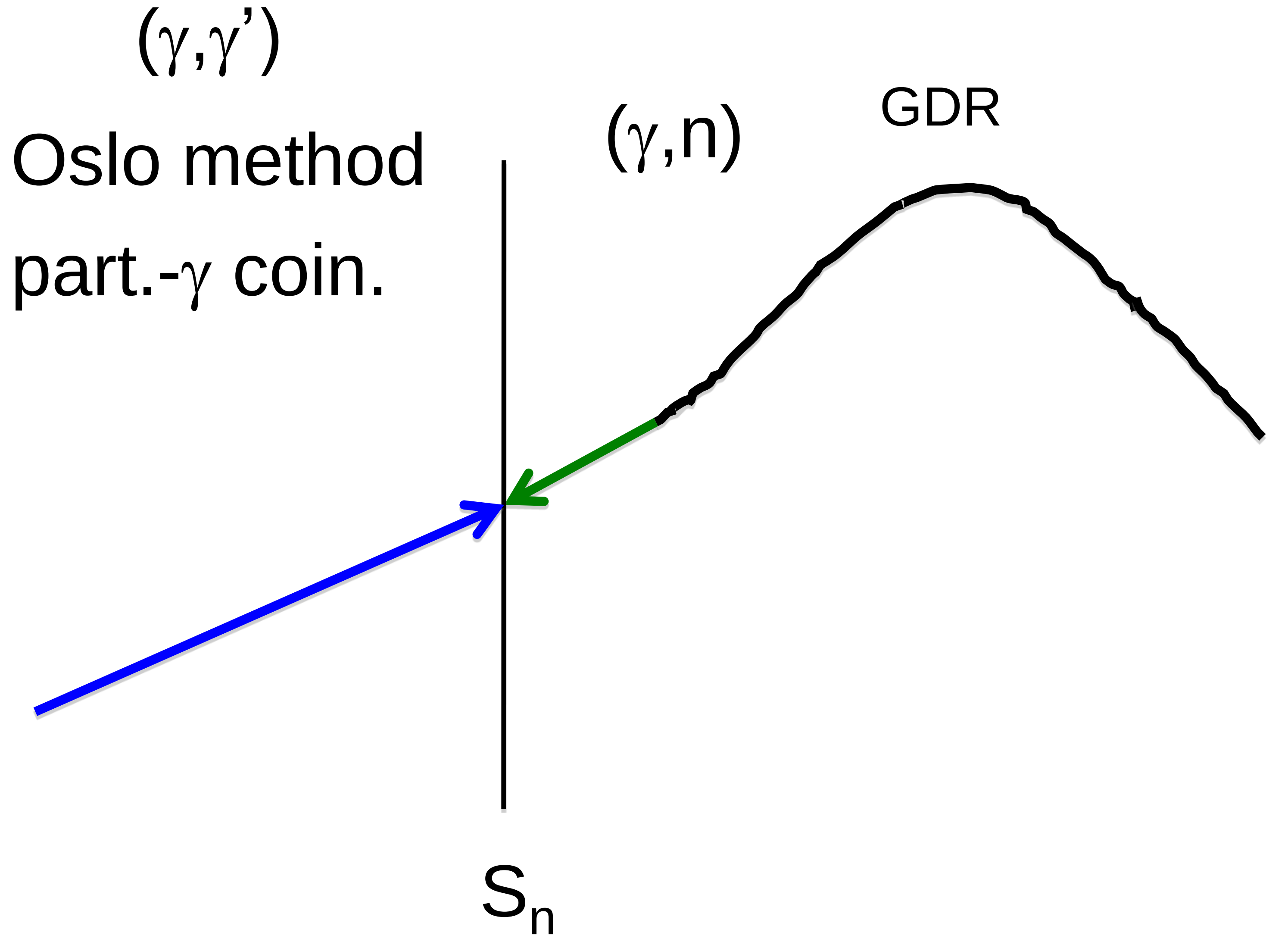
$^{A+1}X(\gamma,n)^{A}X$

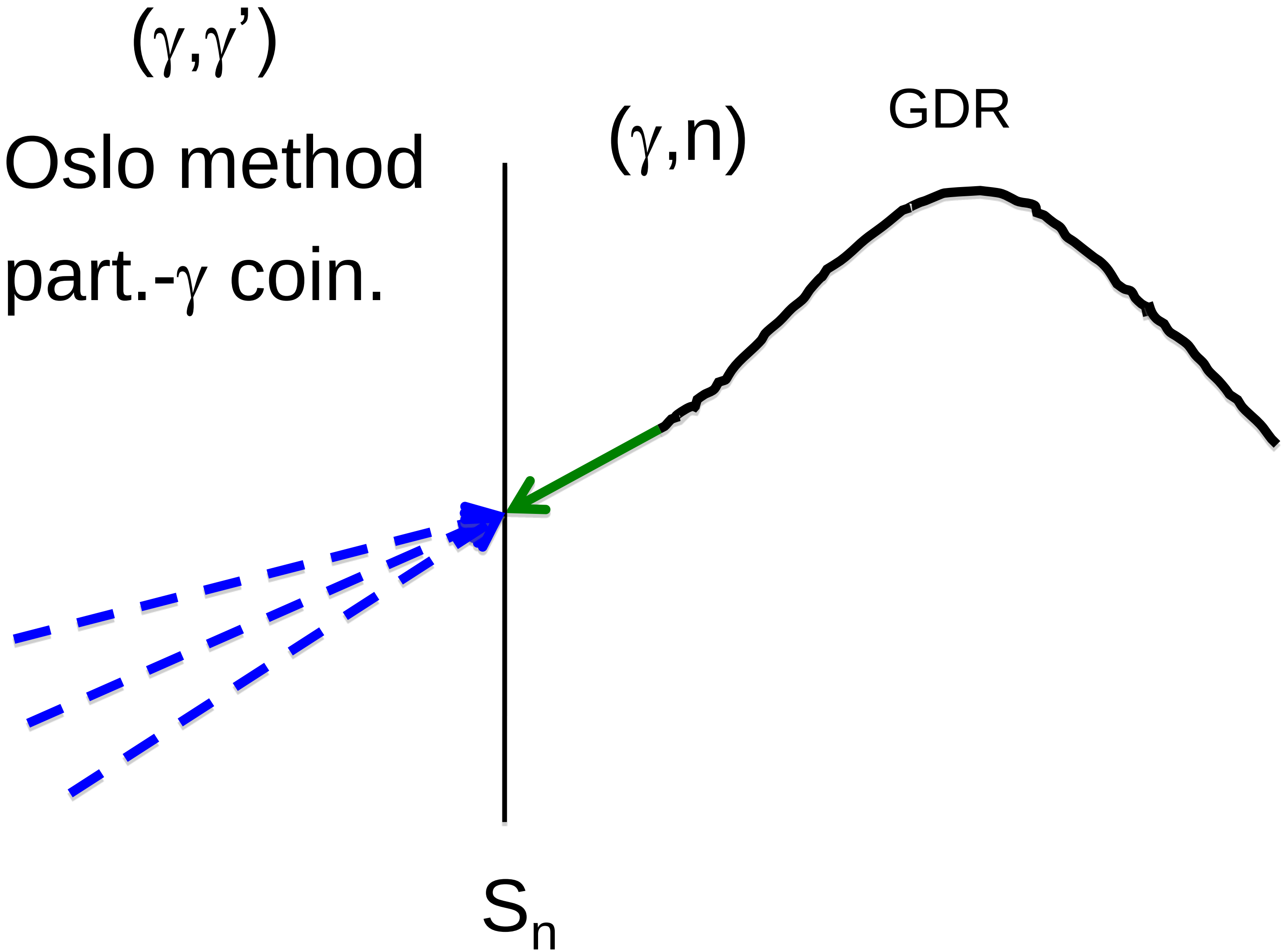
$$f_{X\lambda}(\varepsilon_\gamma)\uparrow = \frac{\varepsilon_\gamma^{-2\lambda+1}}{(\pi\hbar c)^2}\frac{\langle \sigma_{X\lambda}^{abs}(\varepsilon_\gamma)\rangle}{2\lambda+1}$$

$$\varepsilon_\gamma > S_n$$

$$\sigma_{X\lambda}^{\gamma n}(\varepsilon_\gamma) = \sigma_{X\lambda}^{abs}(\varepsilon_\gamma)\times\frac{T_n}{T_n+T_\gamma}$$

Brink Hypothesis $\boxed{f_{X\lambda}(\varepsilon_\gamma)\uparrow \cong f_{X\lambda}(\varepsilon_\gamma)\downarrow}$


(γ,γ')
Oslo method
part.-γ coin.
(γ,n)
GDR
S_n



(γ,γ')
Oslo method
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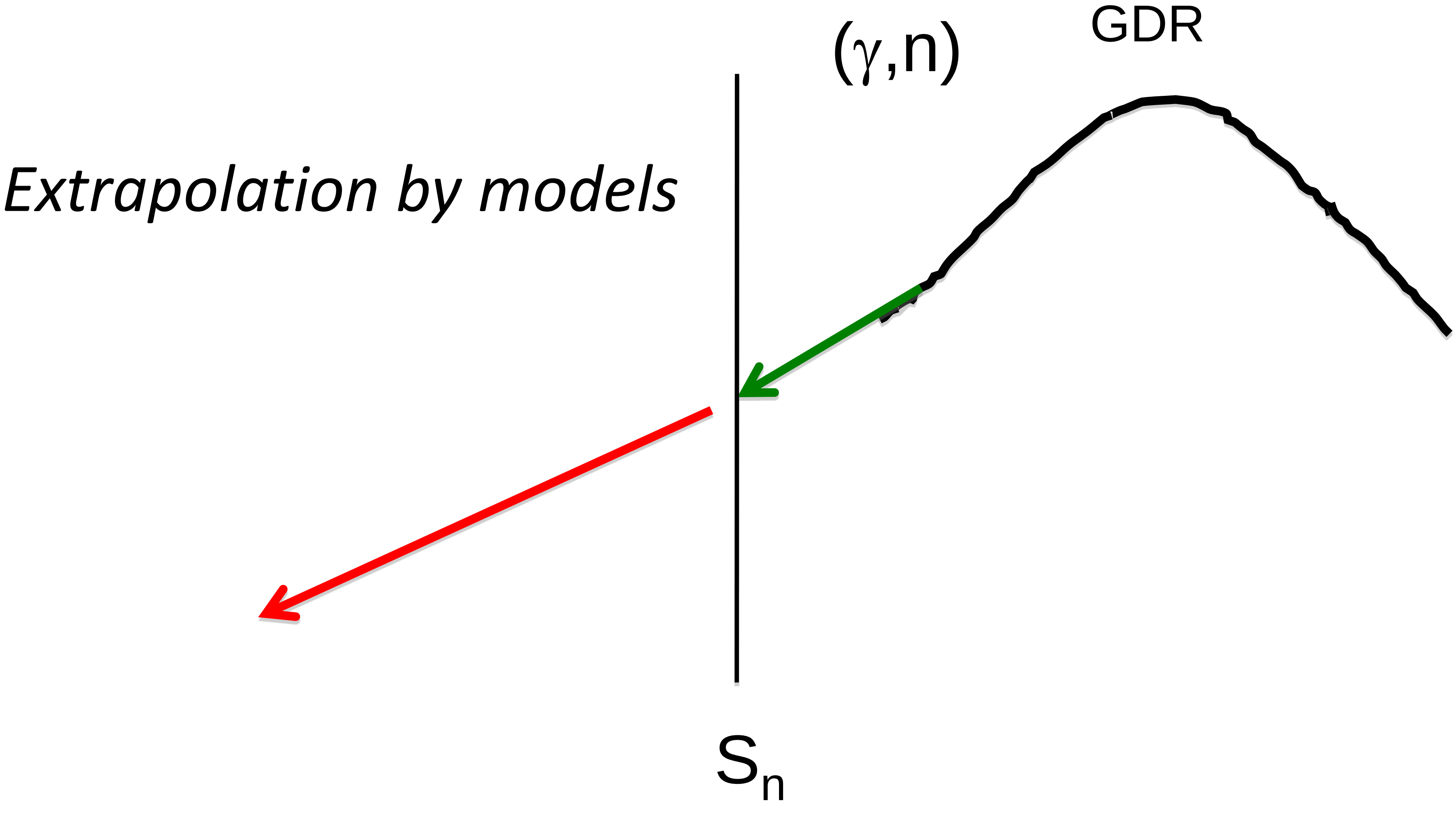
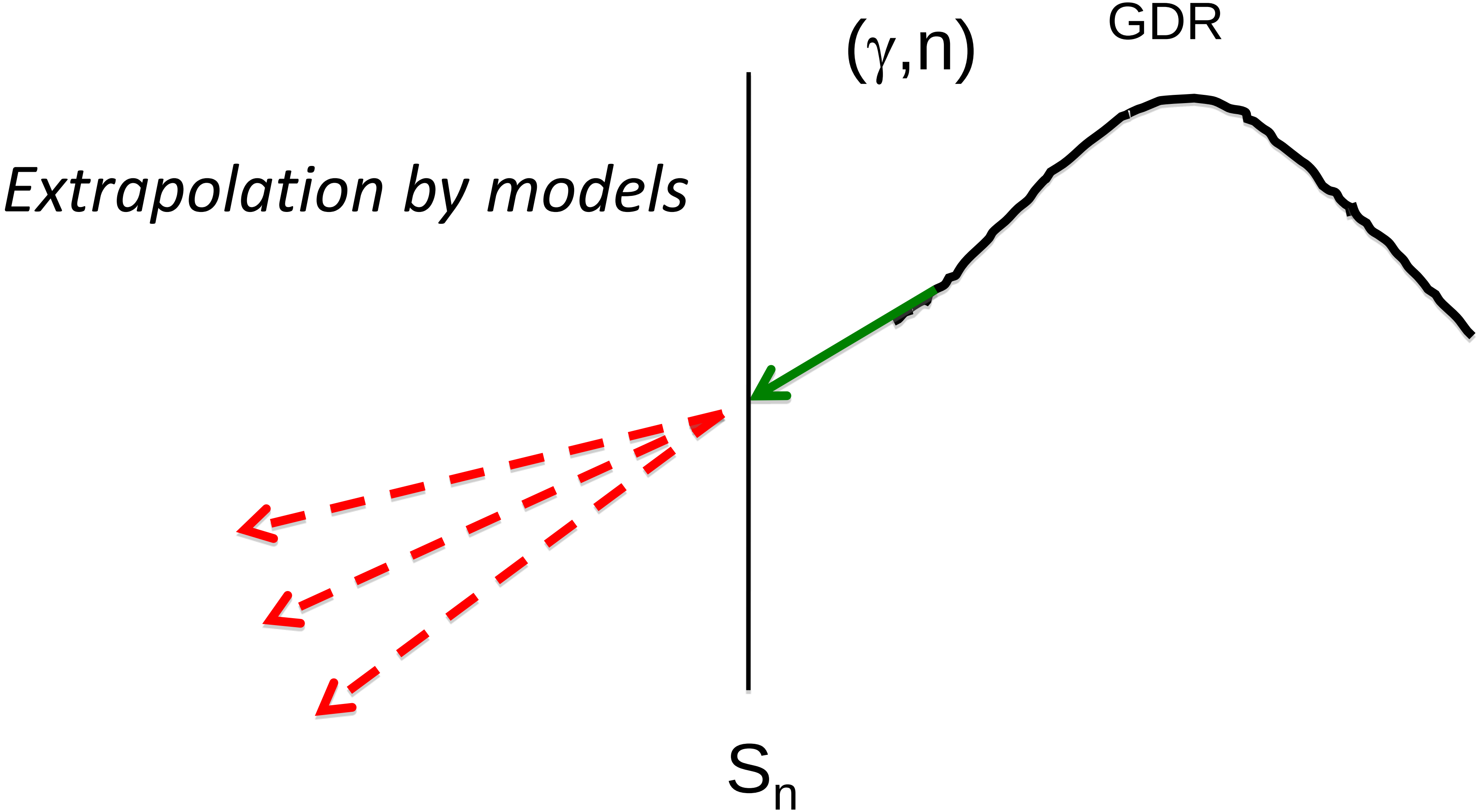
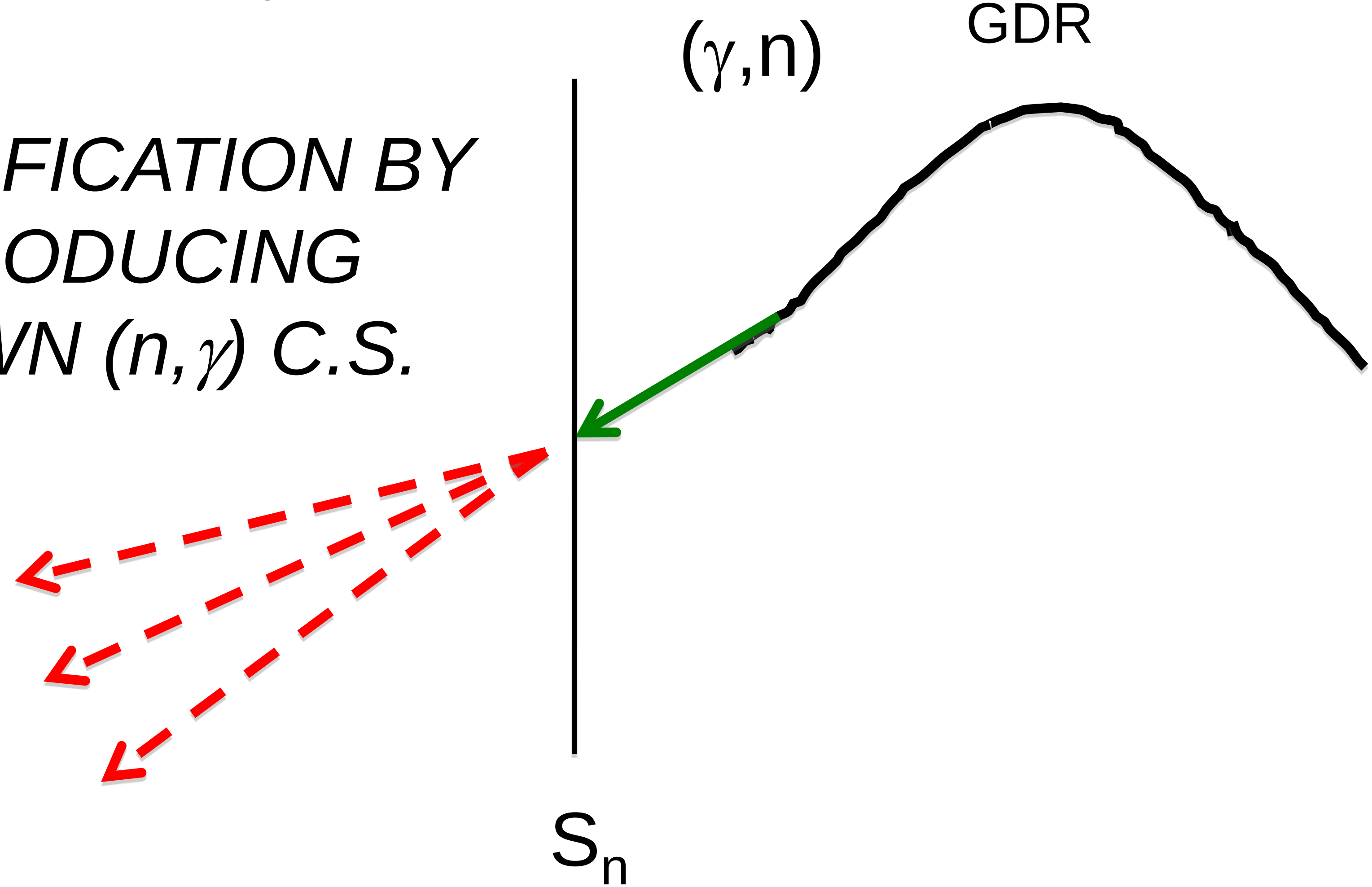

GDR
(γ,n)
Extrapolation by models
S
n



(γ,n)
GDR
Extrapolation by models
S
n

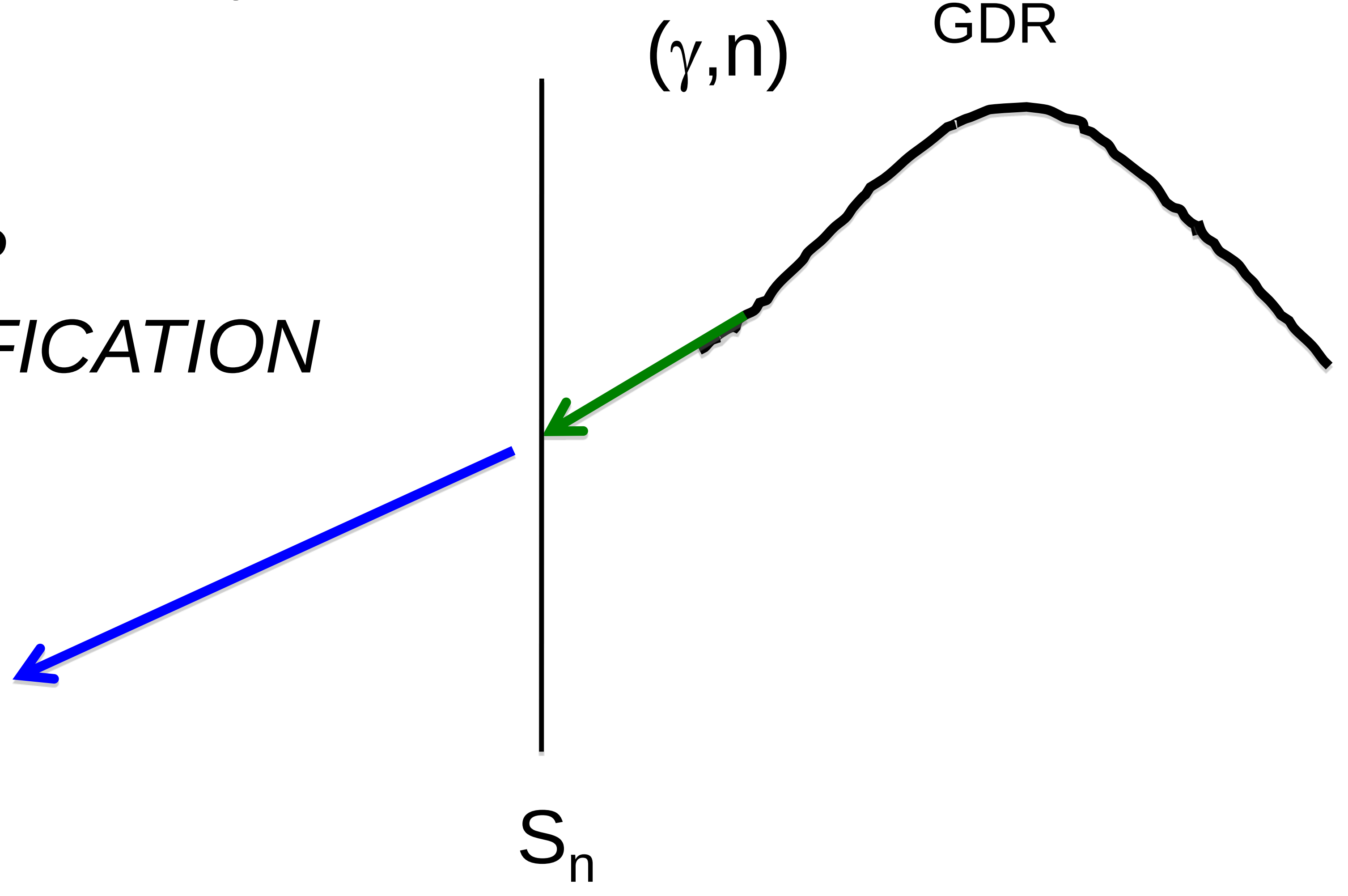
Extrapolation by models

JUSTIFICATION BY REPRODUCING KNOWN (n,γ) C.S.



Extrapolation by models

AFTER JUSTIFICATION



Methodology: γSF method

STEP 1

High precision measurements of (γ,n) cross sections near neutron threshold

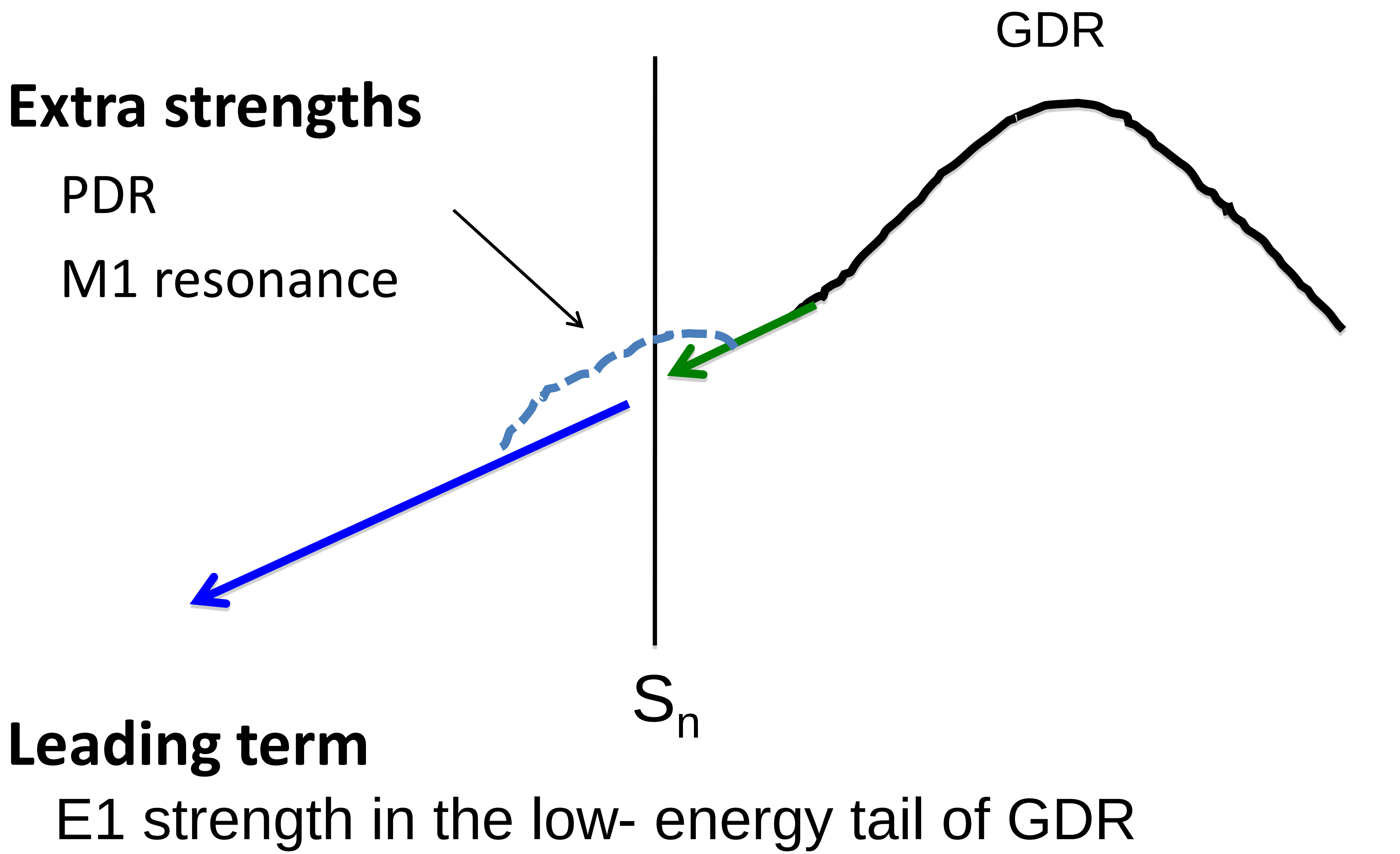
STEP 2

- Investigation of *γSF* that reproduces the measured *(γ,n) cross sections*
- *Extrapolation of γSF to the energy region below S_n with the help of nuclear physics models of γSF*
- *Justification of γSF by reproducing known (n,γ) cross section in the statistical model calculation*

STEP 3

Predictions of (n,γ) cross sections for unstable nuclei with γSF adopted in STEP 2 by the statistical model calculation

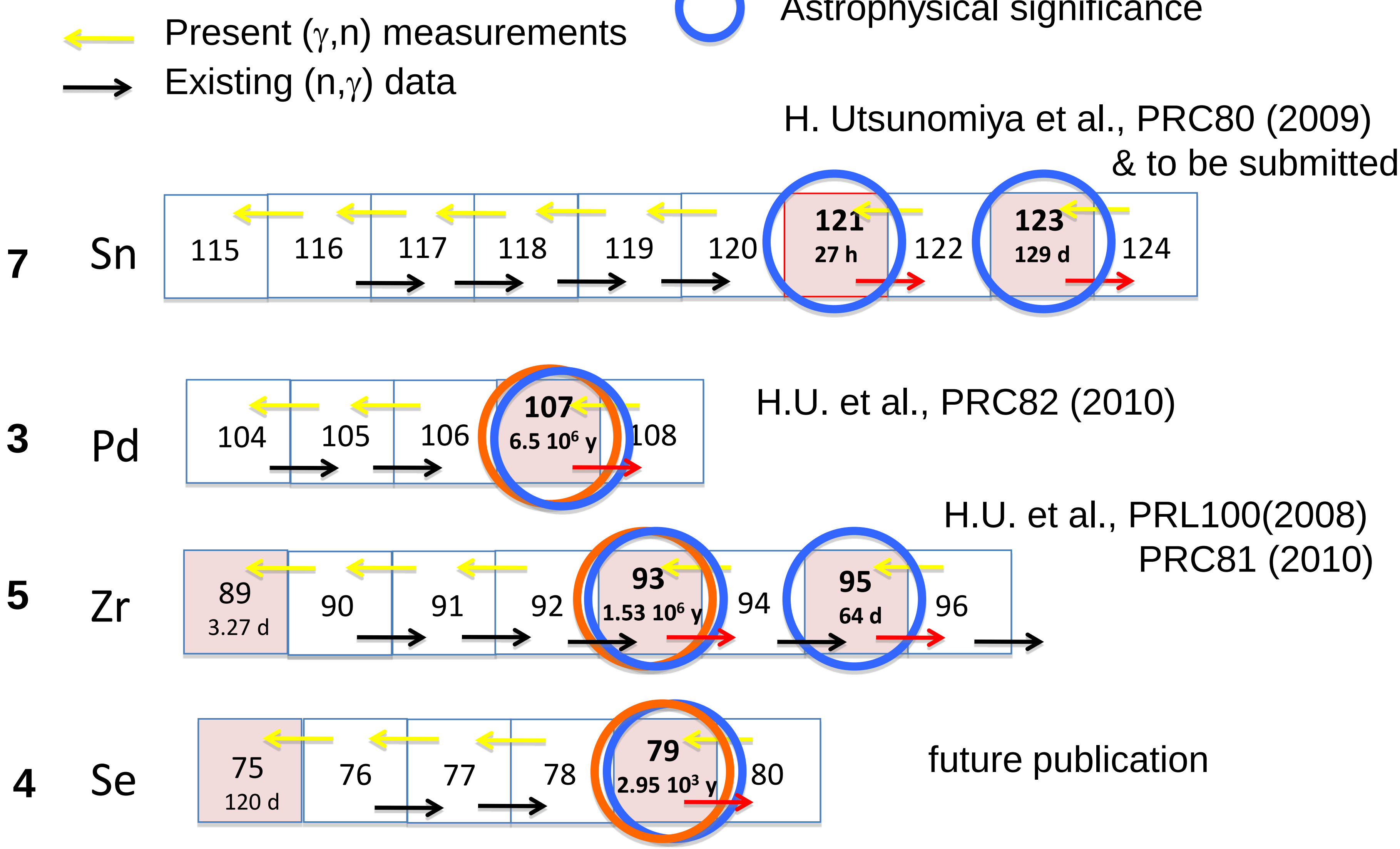
γ–ray strength function relevant to (n,γ) cross sections



Applications

LLFP (long lived fission products)
nuclear waste

Astrophysical significance



Applications

LLFP (long lived fission products) nuclear waste

Astrophysical significance

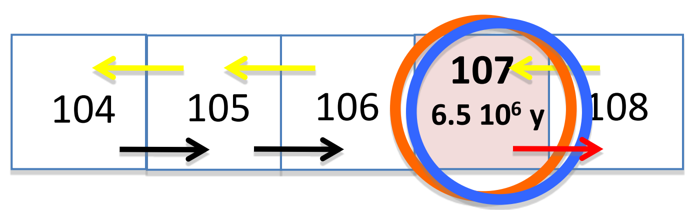
STEP 1 ⟵ Measurements of (γ,n) cross sections

STEP 2 Investigation of γSF that reproduces (γ,n) cross sections

Extrapolation of γSF below S_n

⟶ Justification of γSF by reproducing existing (n,γ) data

3 Pd

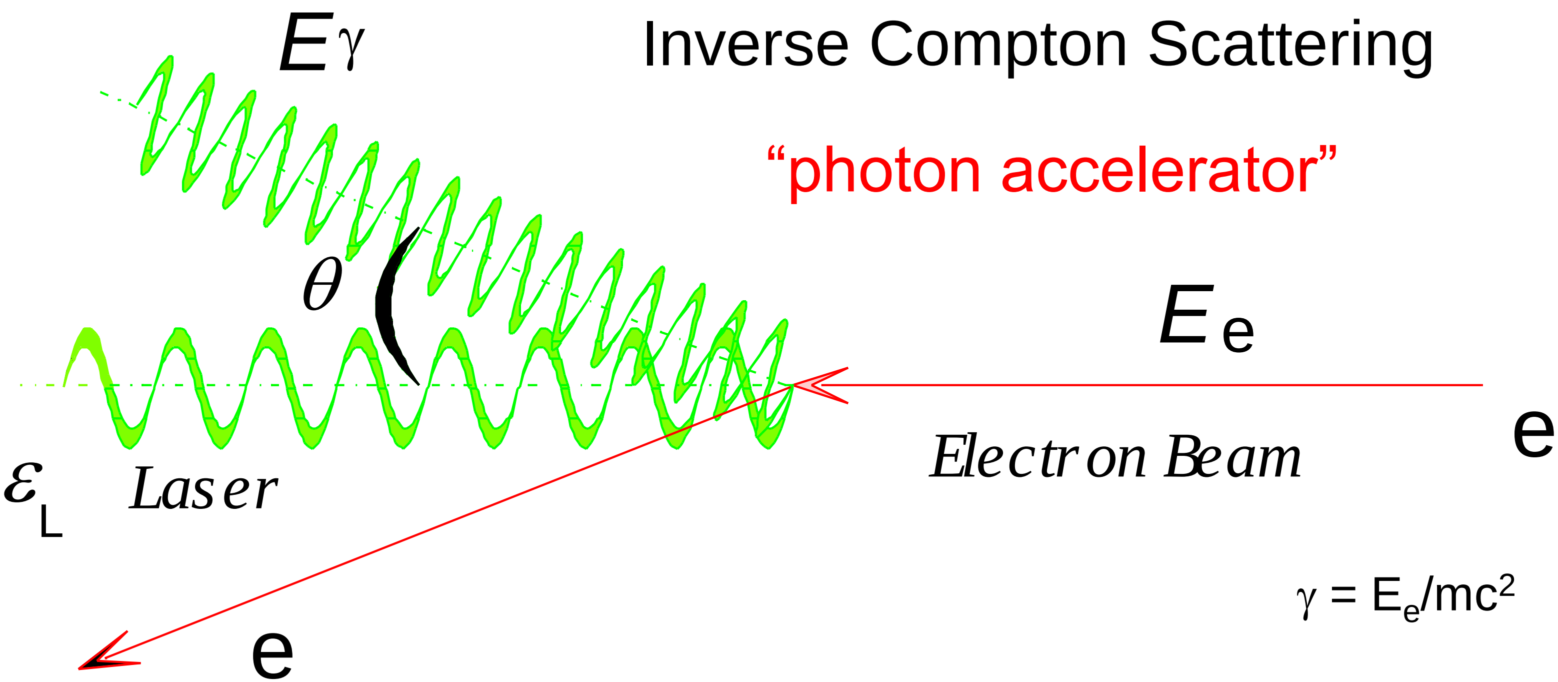


STEP 3 ⟶ Prediction of (n,γ) cross sections for ^{107}Pd

Laser Compton scattering γ-ray beam

Inverse Compton Scattering

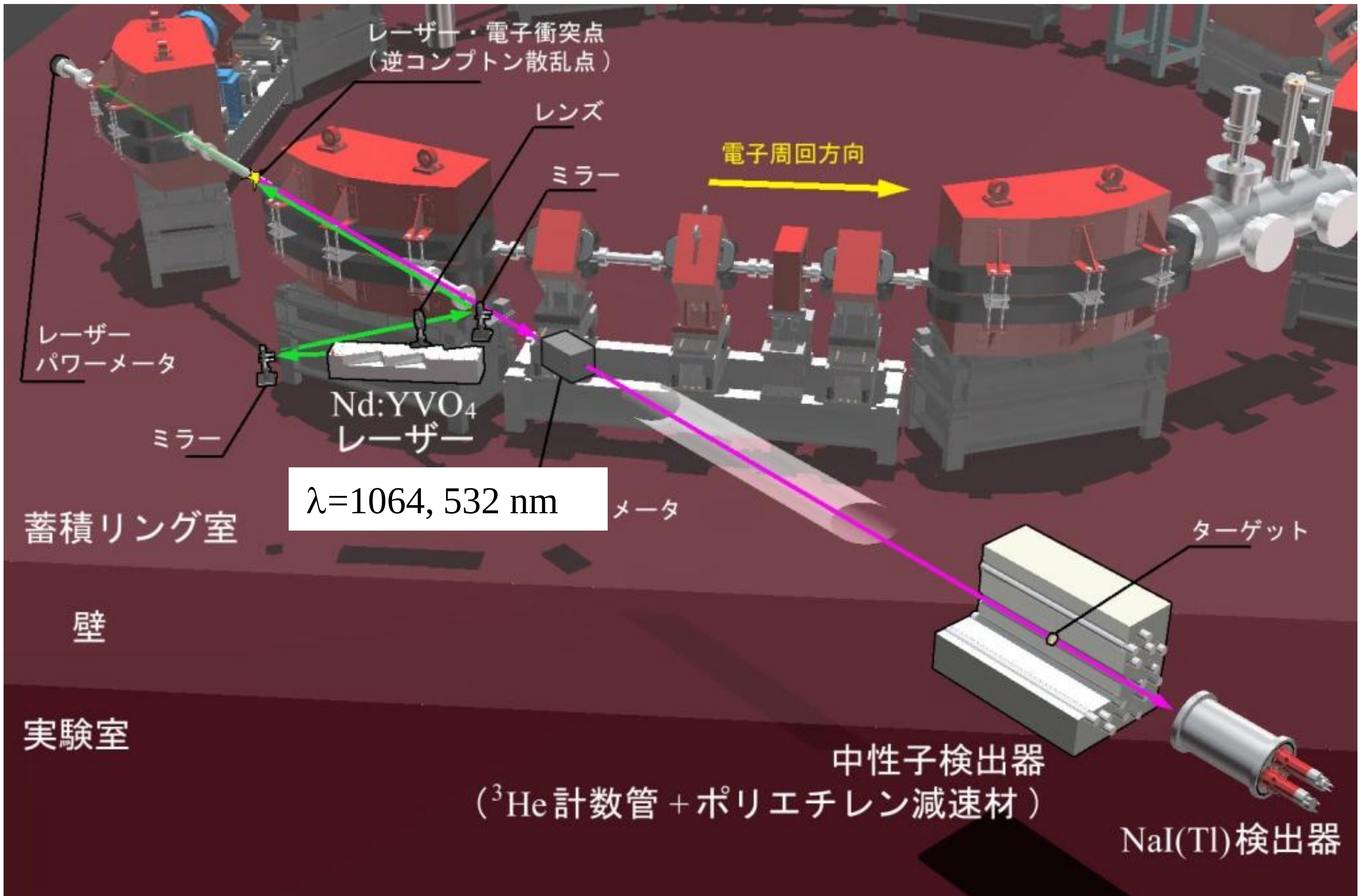
“photon accelerator”



$\gamma = E_e/mc^2$

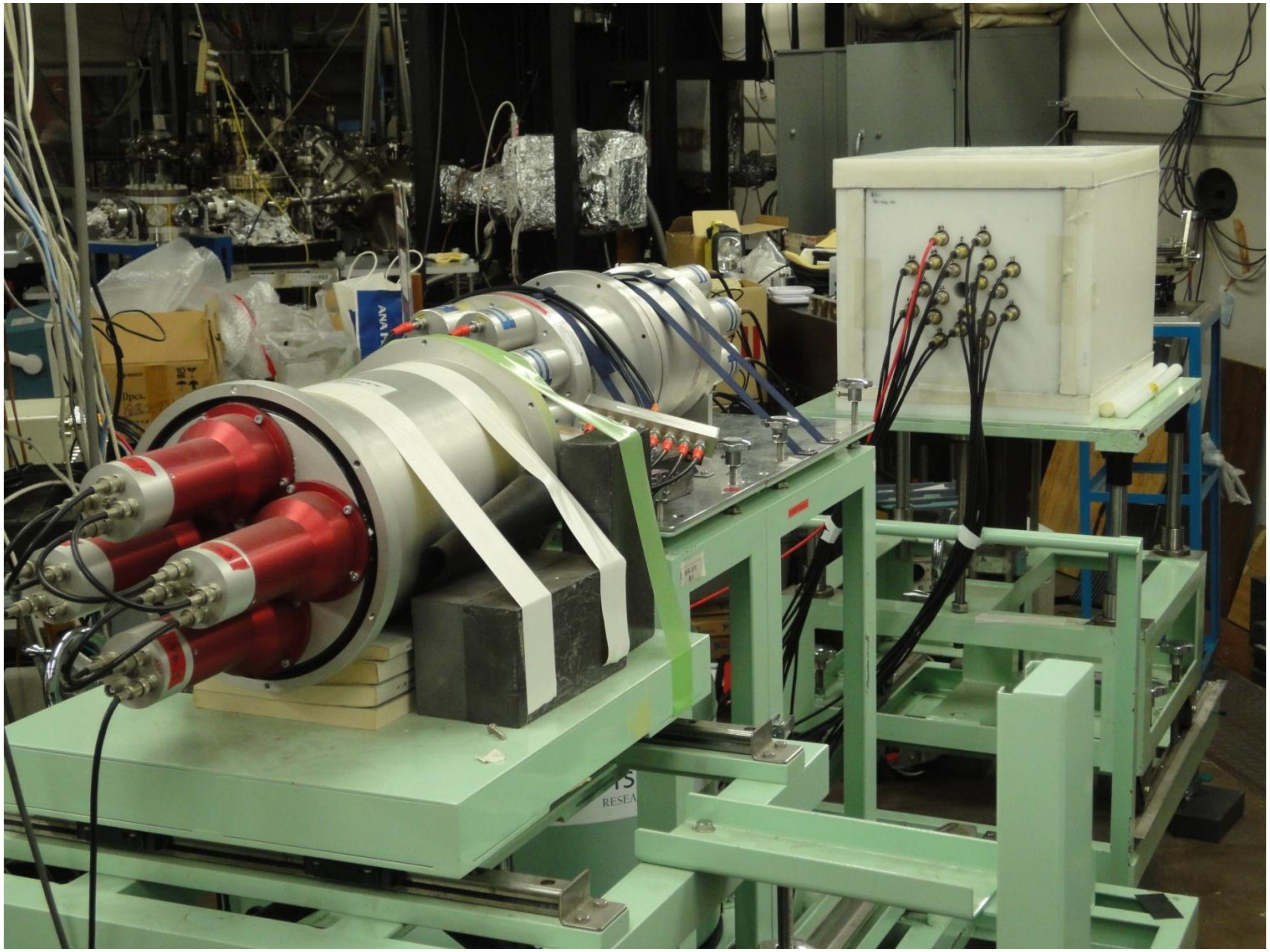
$$E_\gamma = \frac{4\gamma^2\varepsilon_L}{1 + (\gamma\theta)^2 + 4\gamma\varepsilon_L/(mc^2)}$$

AIST (National Institute of Advanced Industrial Science and Technology)



Neutron Detector System

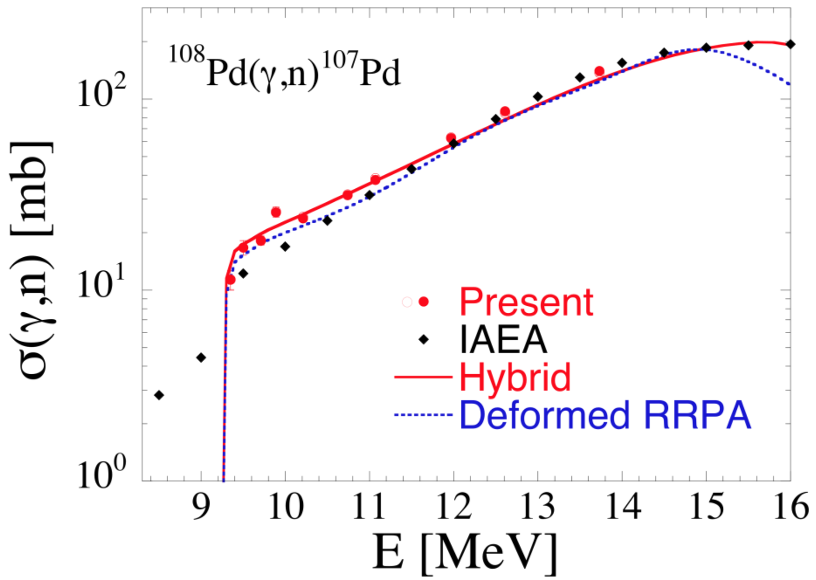
Triple-ring neutron detector
20 ^{3}He counters (4 x 8 x 8) embedded in polyethylene

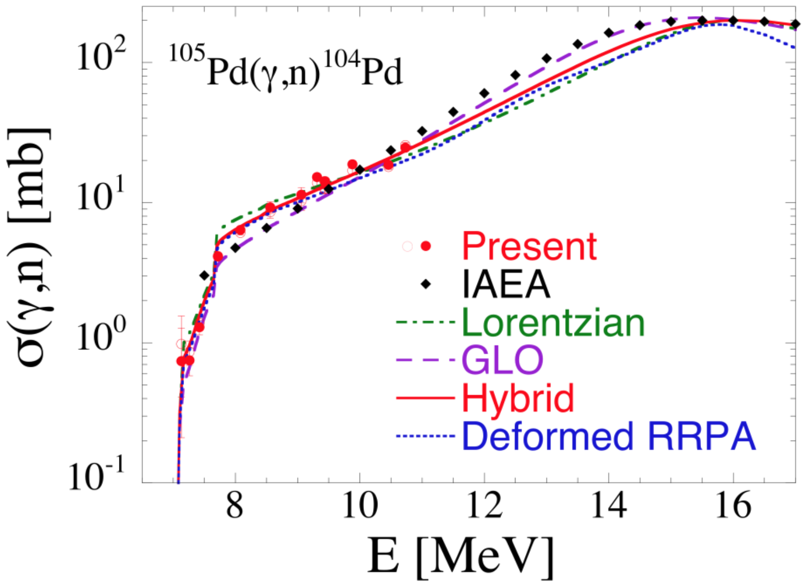


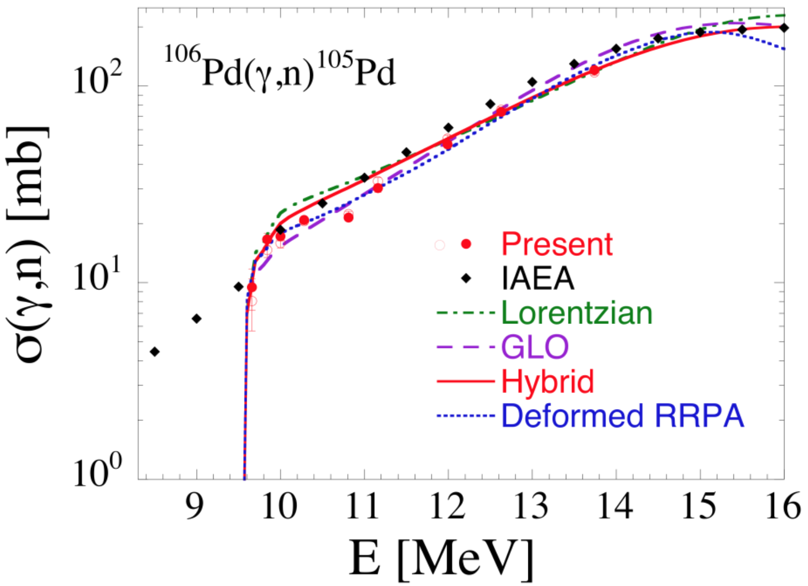
STEP 1

Measurement of (γ,n) cross section

Pd isotopes



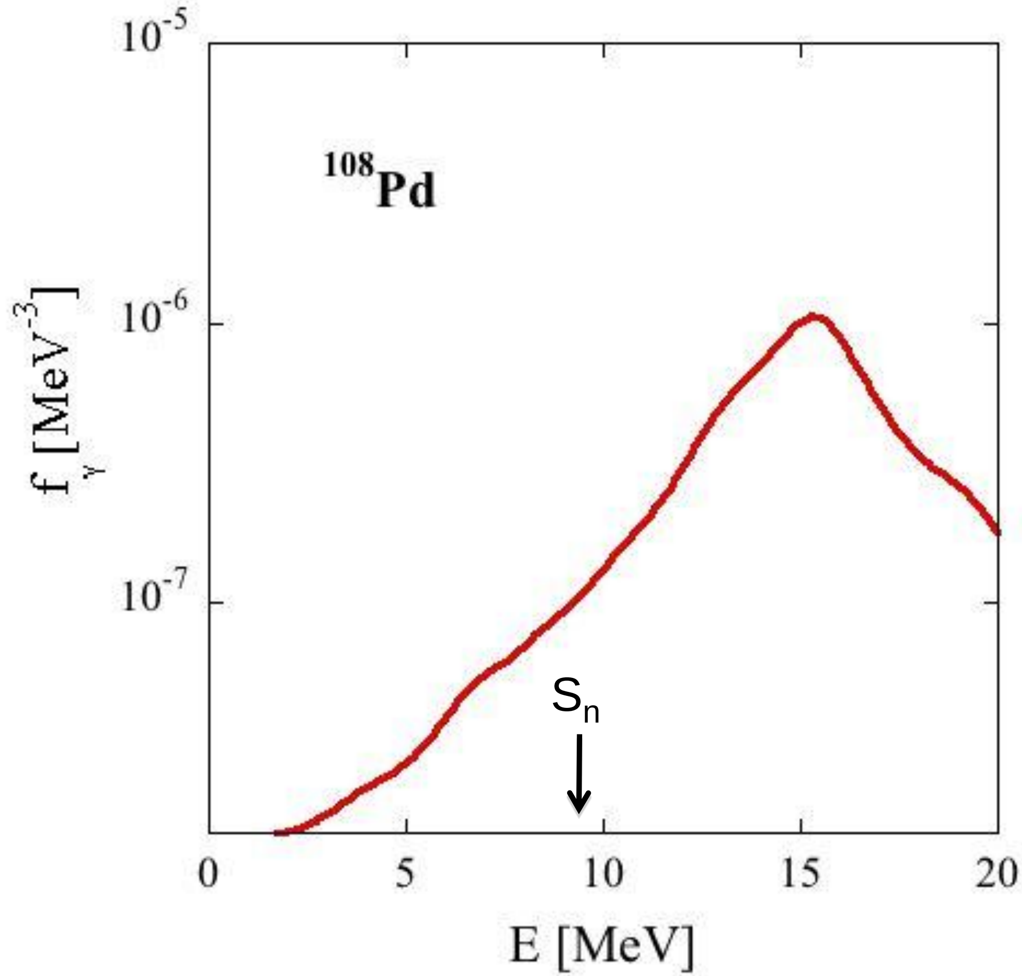




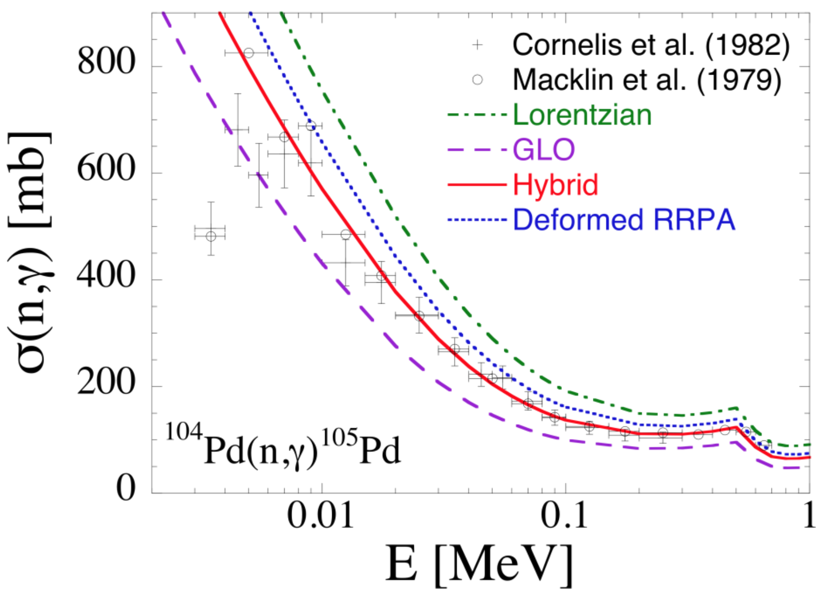
STEP 2 – Extrapolation of γSF

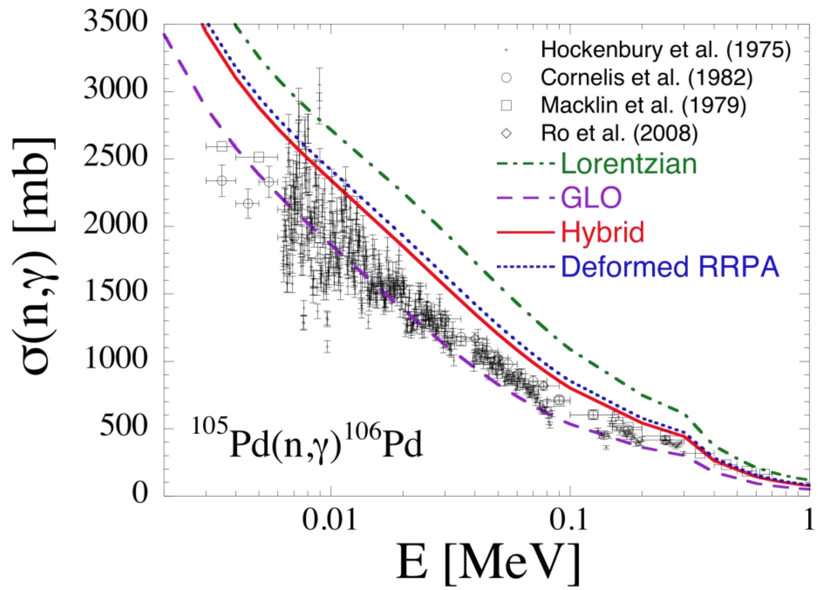
γSF for ^{108}Pd

RMF + QRPA D. P. Arteaga and P. Ring, Phys. Rev. C77, 034317 (2008)



STEP 2 – Justification of the adopted γSF



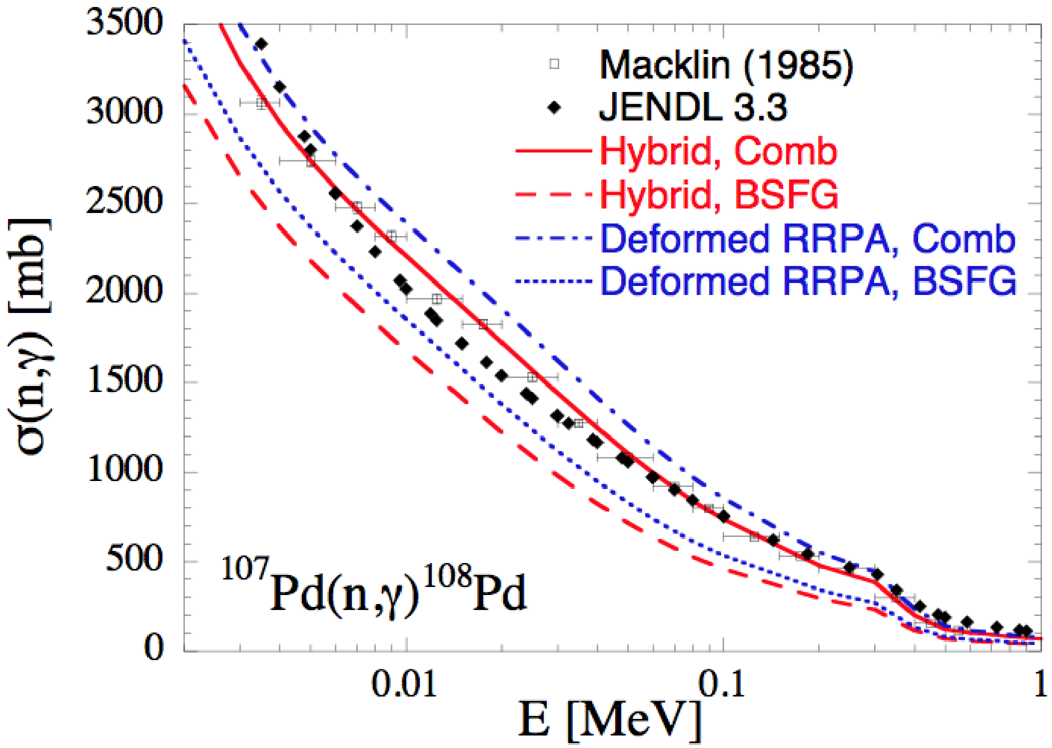


Hybrid S. Goriely, Phys. Lett. B436, 10 (1998).

Deformed RRPA D. P. Arteaga and P. Ring, Phys. Rev. C77, 034317 (2008).

STEP 3 – Statistical model calculations of (n,γ) cross sections for radioactive nuclei

$^{107}Pd[T_{1/2}=6.5\times10^{6}\ y]$



Applications

LLFP (long lived fission products) nuclear waste

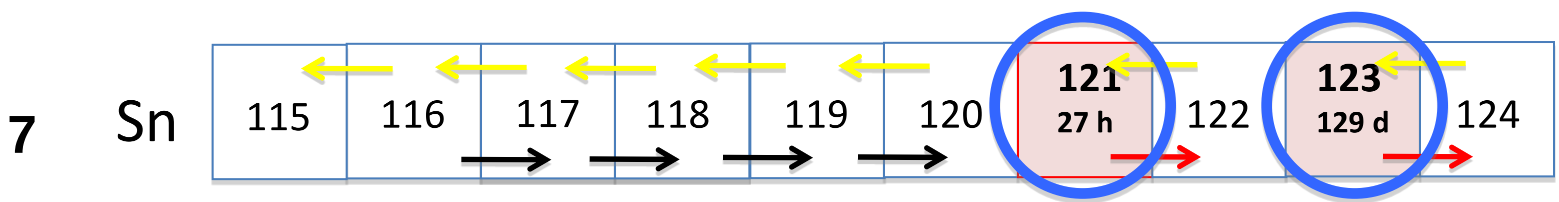
Astrophysical significance

STEP 1 Measurements of (γ,n) cross sections

STEP 2 Investigation of γSF that reproduces (γ,n) cross sections

Extrapolation of γSF below S_n

→ Justification of γSF with existing (n,γ) data



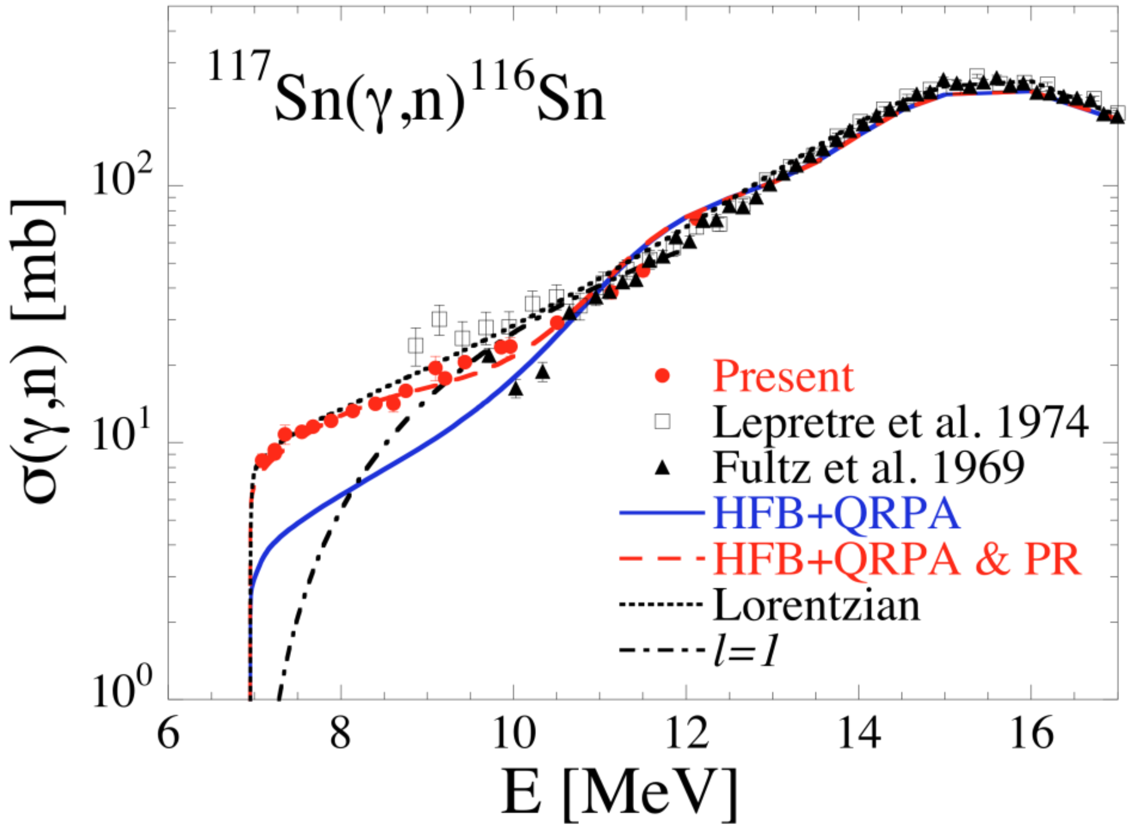
STEP 3 → Prediction of (n,γ) cross sections for ^{121}Sn and ^{123}Sn

Application

STEP 1 Measurement of (γ,n) cross section

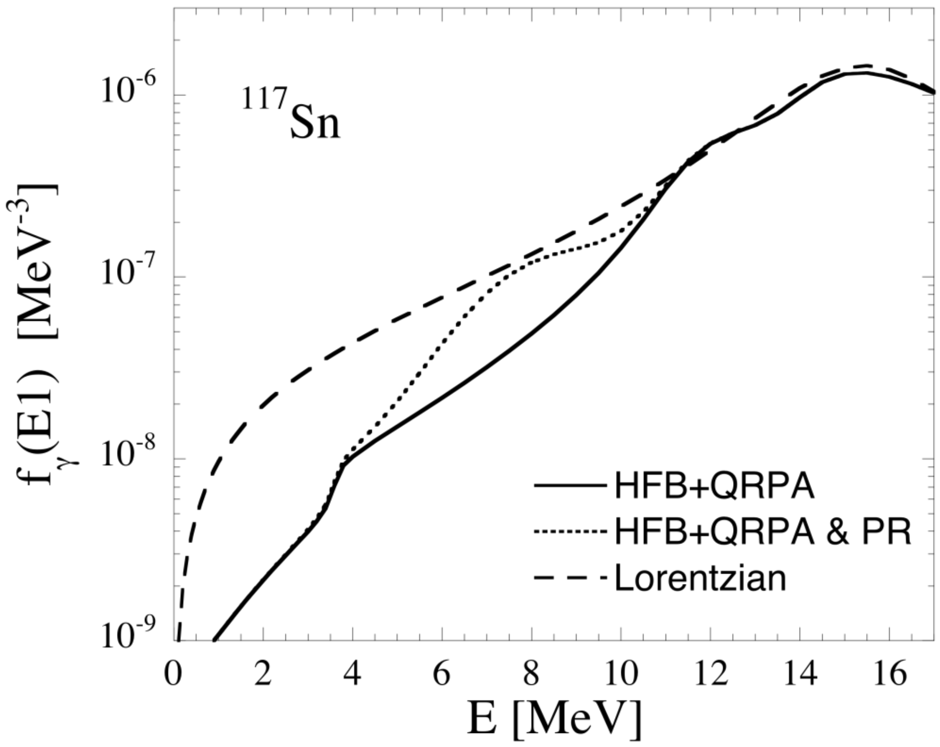
Sn isotopes

H. Utsunomiya et al., PRC80 (2009)



STEP 2 – Extrapolation of γSF to the low-energy region

HFB+QRPA
+ PDR



HFB+QRPA E1 strength supplemented with a pygmy E1 resonance in Gaussian shape

E_o ~ 8.5 MeV, Γ ~ 2.0 MeV, σ_o ~ 7 mb

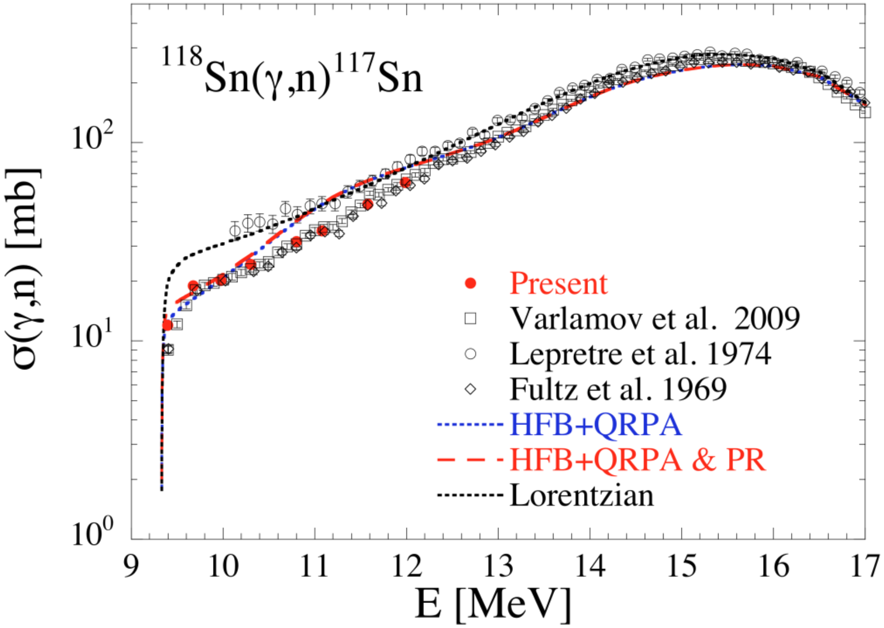
~ 1% of TRK sum rule of GDR

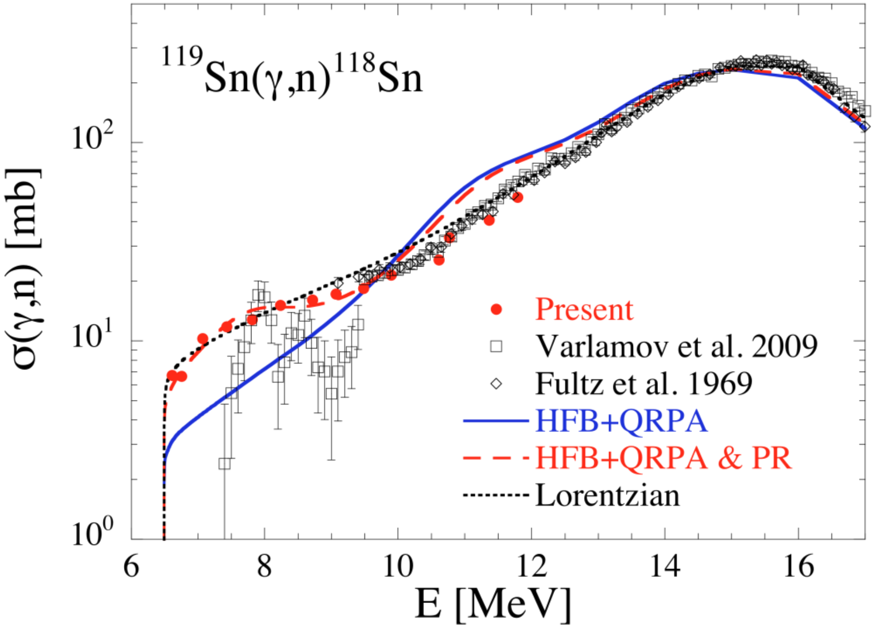
Application

STEP 1 Measurement of (γ,n) cross section

Sn isotopes

to be submitted

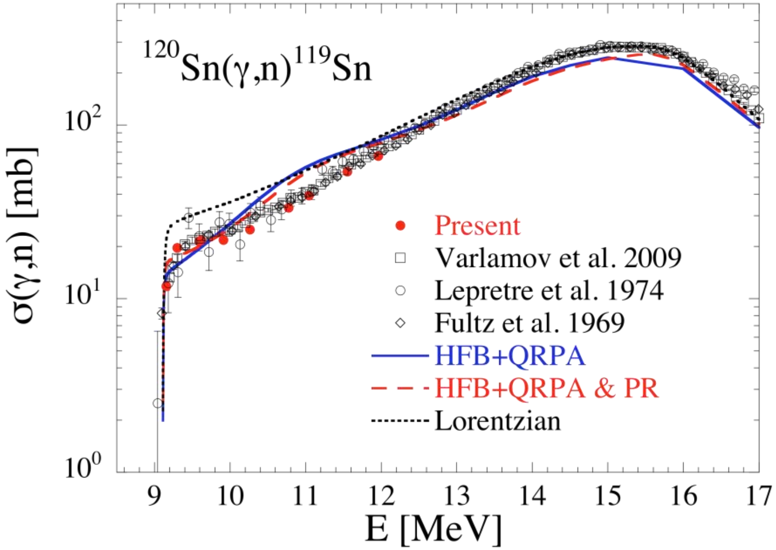


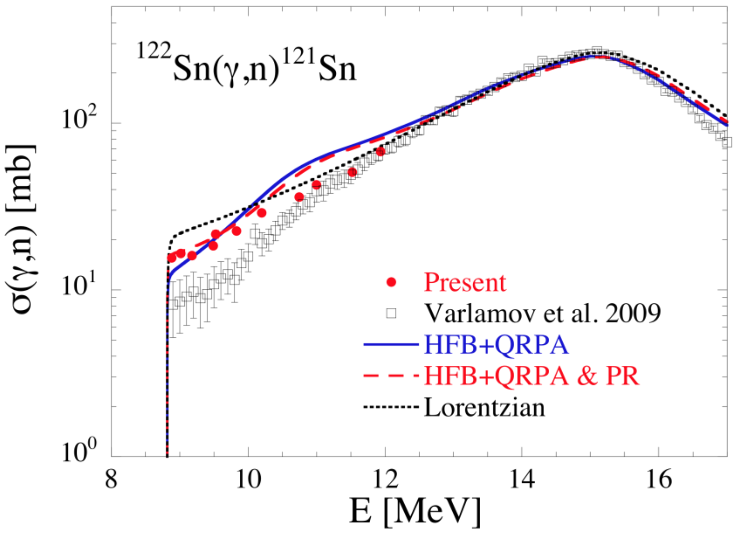


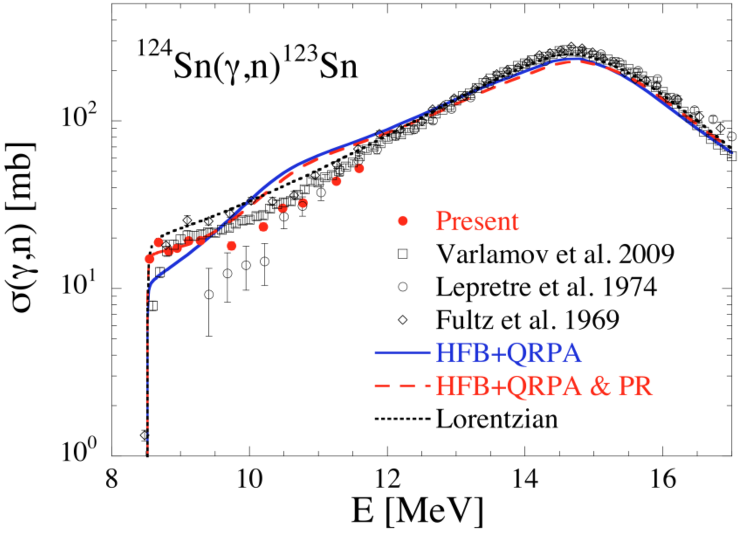
STEP 1

Measurement of
(γ,n) cross section

Sn isotopes

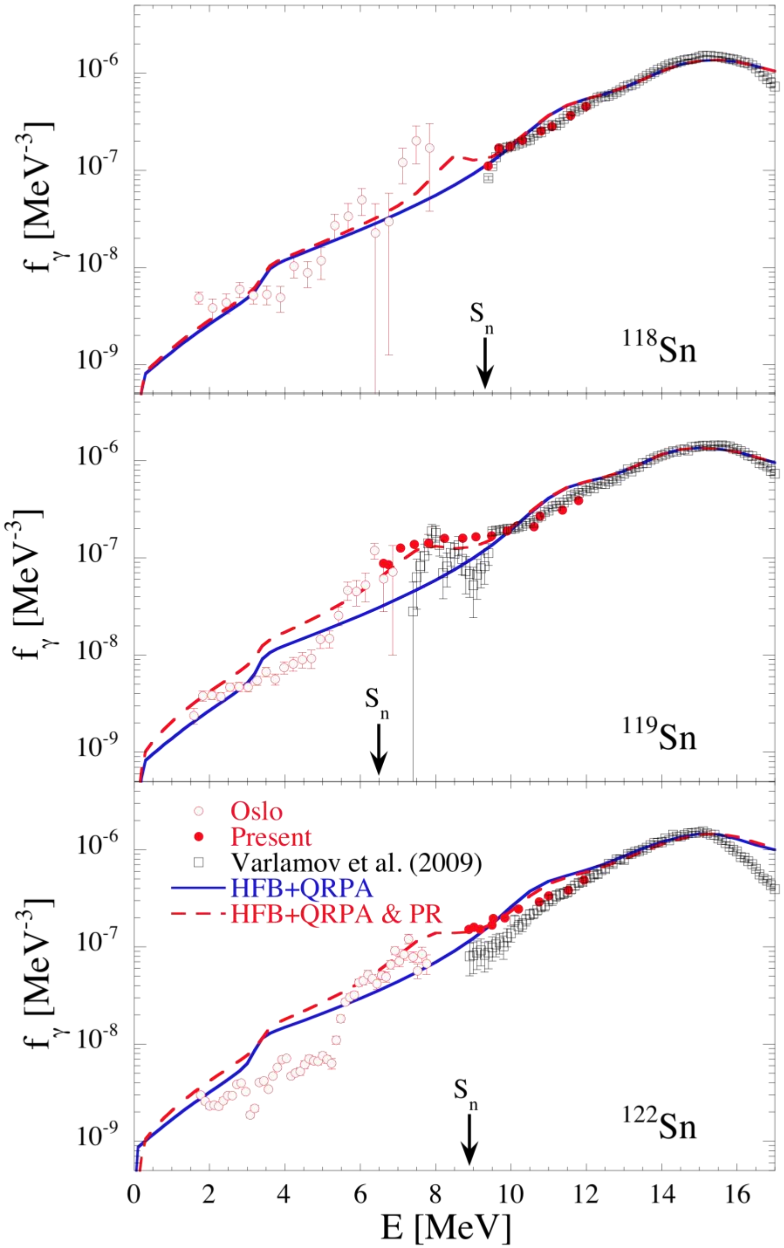




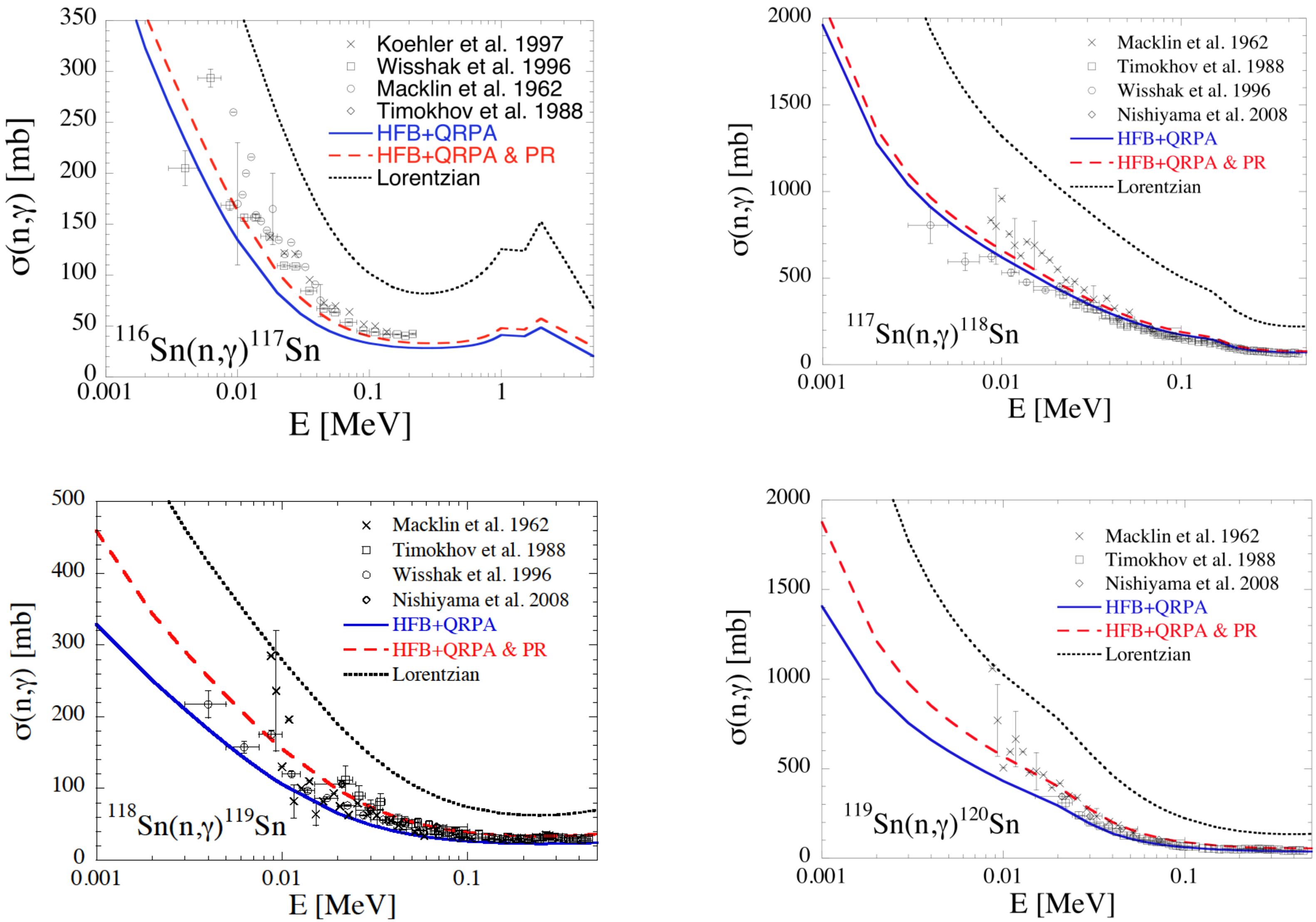


γSF for Sn isotopes -comparison with the Oslo method

Toft et al.,
PRC 81 (2010)
PRC 83 (2011)



STEP 2 – Justification of the adopted γSF

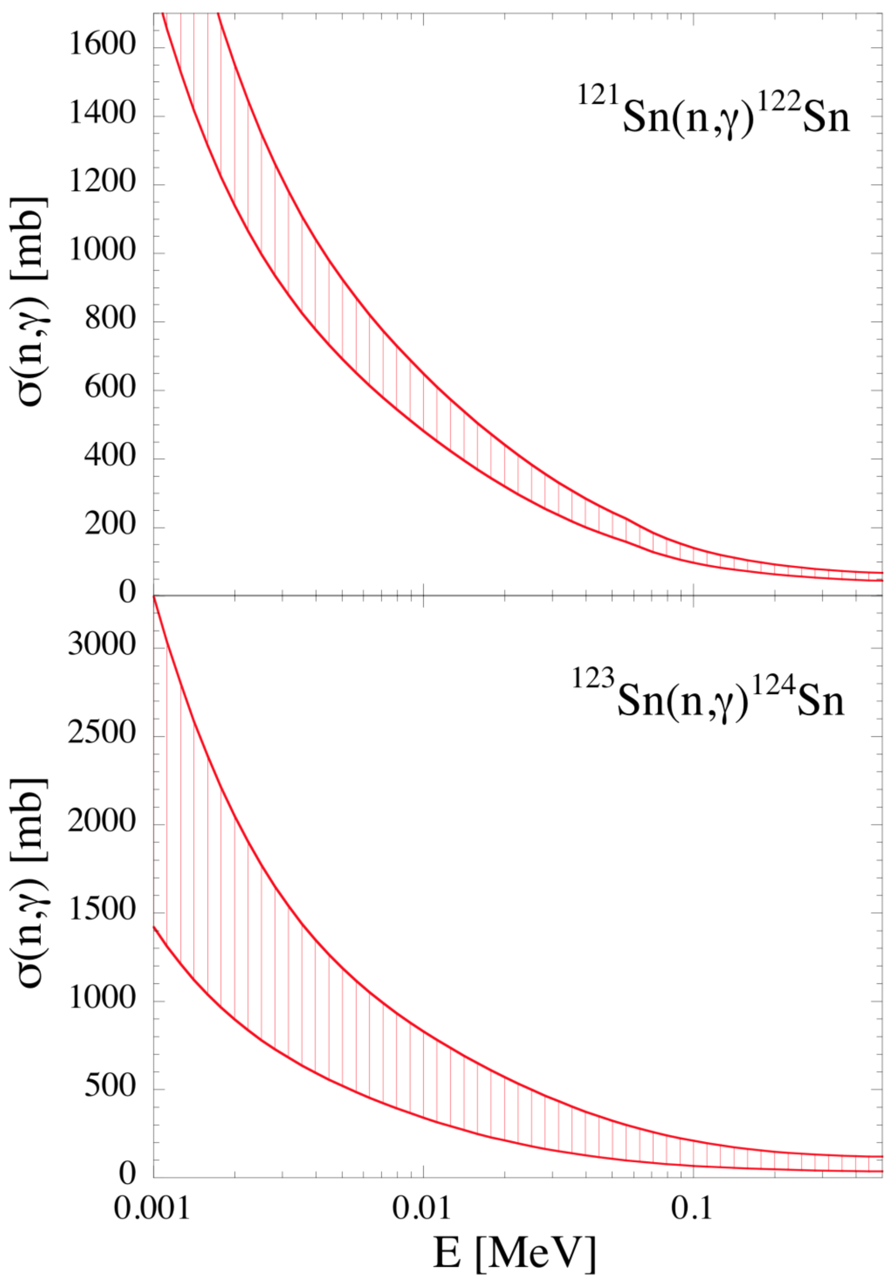


STEP 3 –

Statistical model calculations of (n,γ) cross sections for radioactive nuclei

$^{121}Sn[T_{1/2}=27\ h]$

$^{123}Sn[T_{1/2}=129\ d]$



Summary

1. The γ-ray strength function method (γSF method) to indirectly determine radiative neutron capture cross sections for unstable nuclei is devised.

2. We have applied the γSF method to deduce (n,γ) cross sections for ^{121,123}Sn, ^{107}Pd, ^{93,95}Zr and ^{79}Se.

3. The uncertainty of the method arises from the level density, being typically 30 – 40 %, if experimental data such as neutron resonance spacings are available.

4. There are many nuclei to apply γSF method throughout the chart of nuclides.

5. Key factors for a versatile application of the γSF method
- understanding PDR and M1 resonance throughout the chart of nuclides
- Refinement of γSF &NLD models

Collaborators

H. Utsunomiya[a)], S. Goriely[b)], H. Akimune[a)], T. Yamagata[a)], H. Toyokawa[c)],
H. Harada[d)], F. Kitatani[d)], Y. -W. Lui[e)], I. Daoutidis[b)], D. P. Arteaga[f)],
S. Hilaire[g)], and A. J. Koning[h)]

a) Department of Physics, Konan University, Okamoto 8-9-1, Higashinada, Kobe 658-8501, Japan
b) [b)] Institut d'Astronomie et d'Astrophysique, ULB, CP 226, B-1050 Brussels, Belgium
c) National Institute of Advanced Industrial Science and Technology, Tsukuba 305-8568, Japan
d) Japan Atomic Energy Agency, Tokai, Naka-gun, Ibaraki 319-1195, Japan
e) Cyclotron Institute, Texas A&M University, College Station, Texas 77843, USA
f) Institut de Physique Nucléaire, Université Paris-Sud, IN2P3-CNRS, F-91406 Orsay Cedex, France
g) CEA,DAM, DIF, F-91297 Arpajon, France
h) Nuclear Research and Consultancy Group, P.O. Box 25, NL-1755 ZG Petten, The Netherlands

Applications

Present (γ,n) measurements

LLFP (long lived fission products) nuclear waste

Astrophysical significance

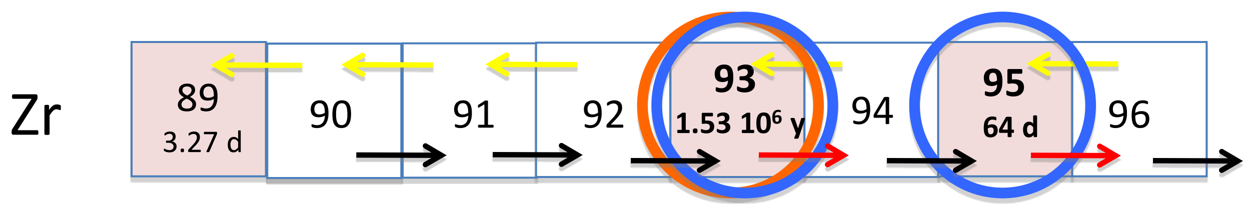
STEP 1 Measurements of (γ,n) cross sections

STEP 2 Investigation of γSF that reproduces (γ,n) cross sections

Extrapolation of γSF below S_n

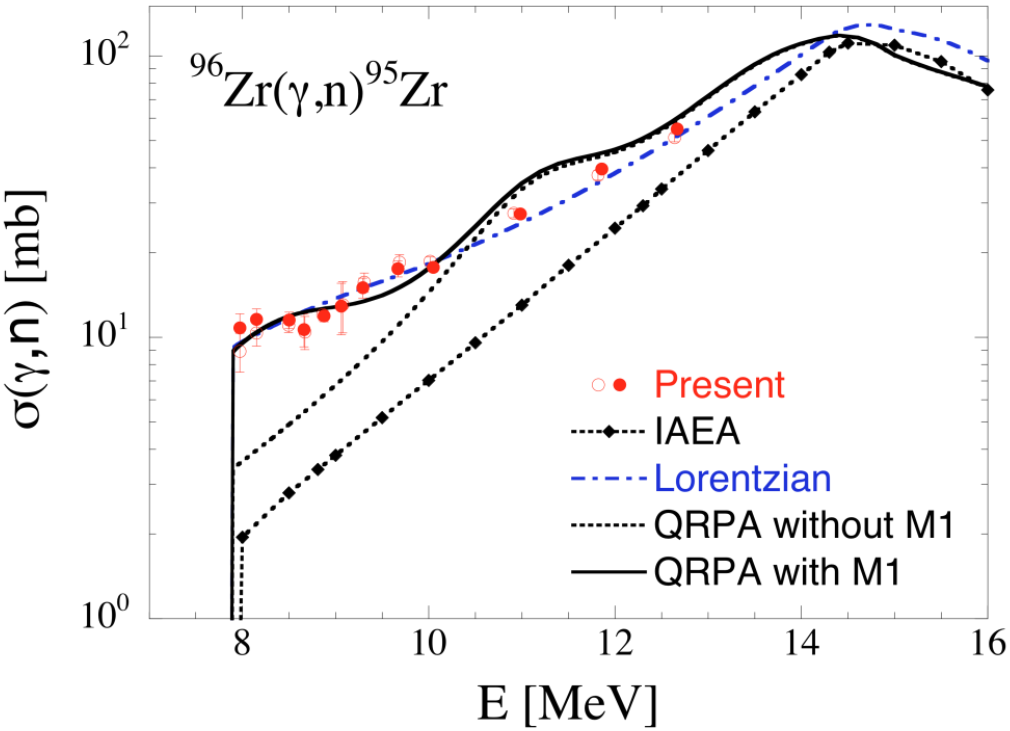
→ Justification of γSF with existing (n,γ) data

5



STEP 3 → Prediction of (n,γ) cross sections for ^{93}Zr and ^{95}Zr

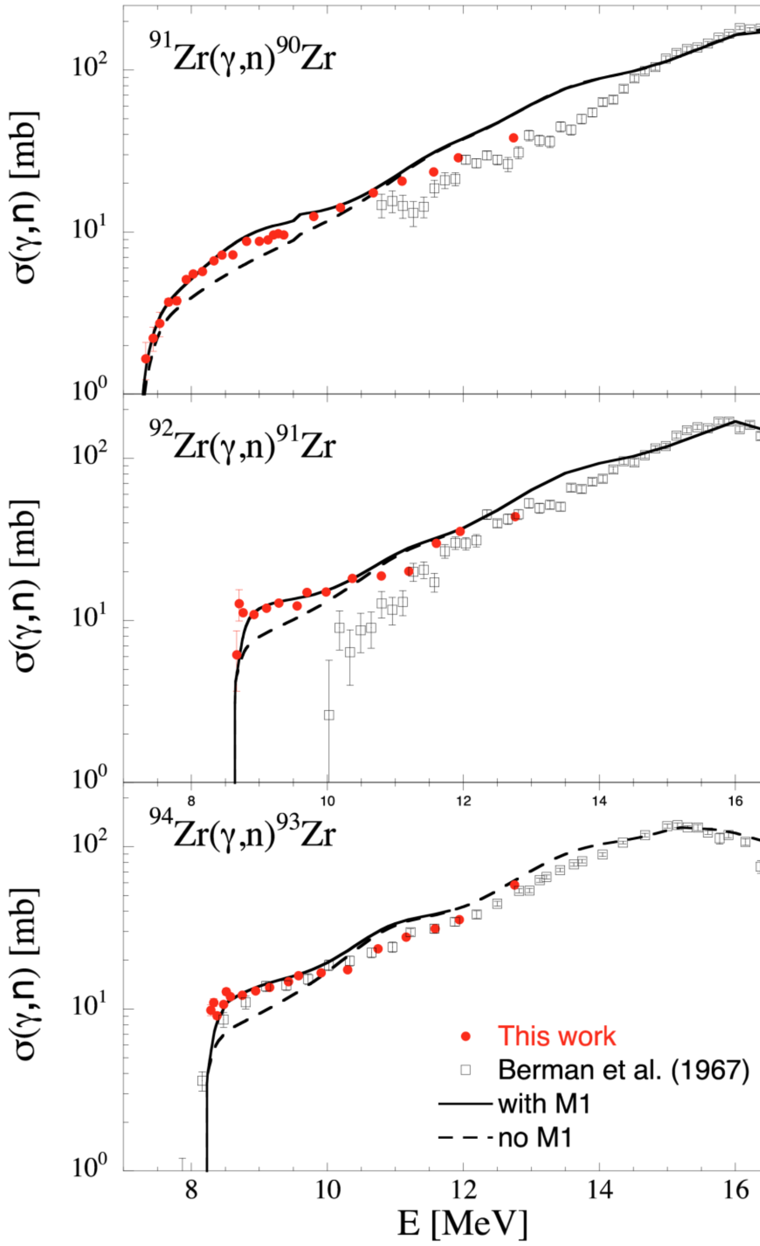
STEP 1 – Measurement of (γ,n) cross section



STEP 1

Measurement of
(γ,n) cross section

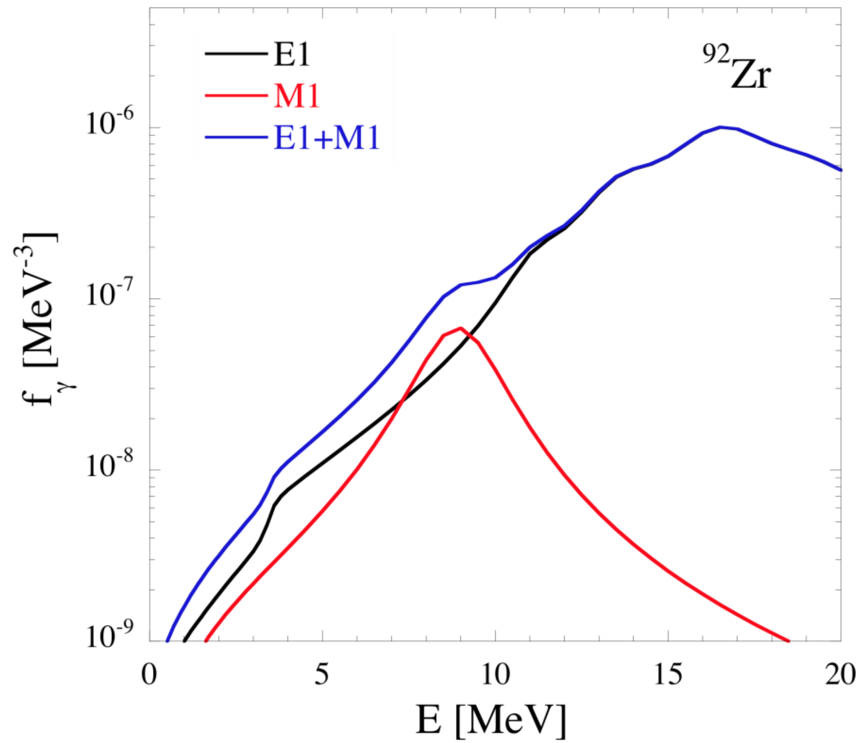
Zr isotopes



Application

STEP 2 – Extrapolation of γSF to the low-energy region

HFB+QRPA
+ Giant M1



HFB+QRPA E1 strength supplemented with a giant M1 resonance in Lorentz shape

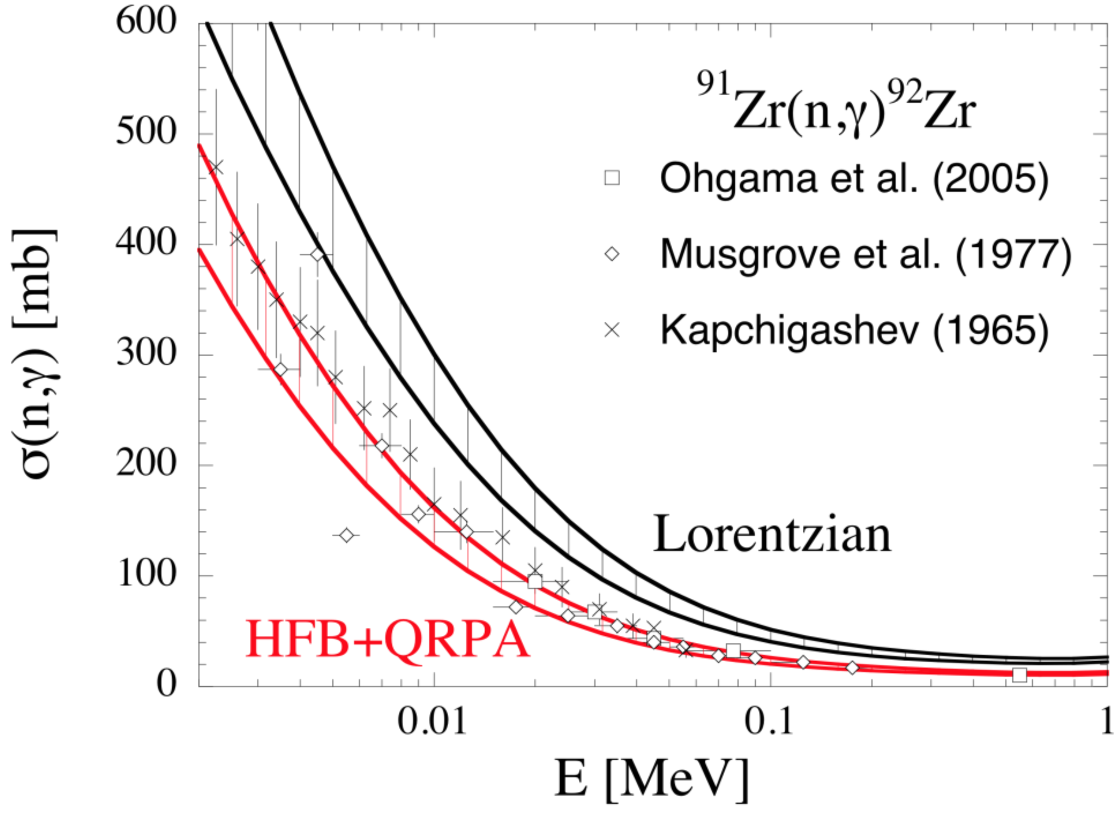
E_o ~ 9 MeV, Γ ~ 2.5 MeV, σ_o ~ 7 mb

~ 2% of TRK (Thomas-Reiche-Kuhn) sum rule of GDR

Application

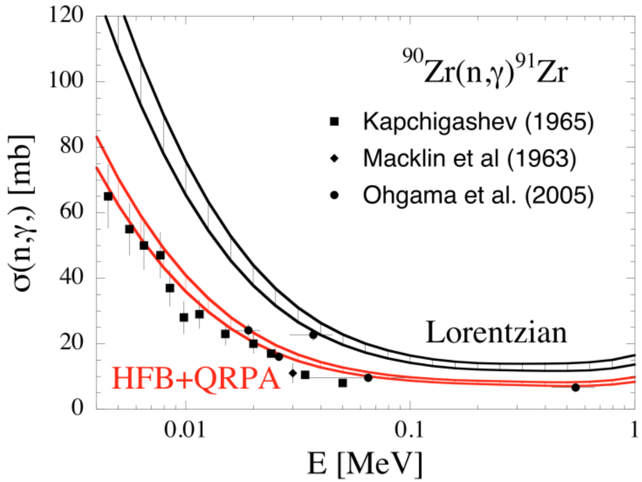
STEP 2 – Justification of the adopted γSF

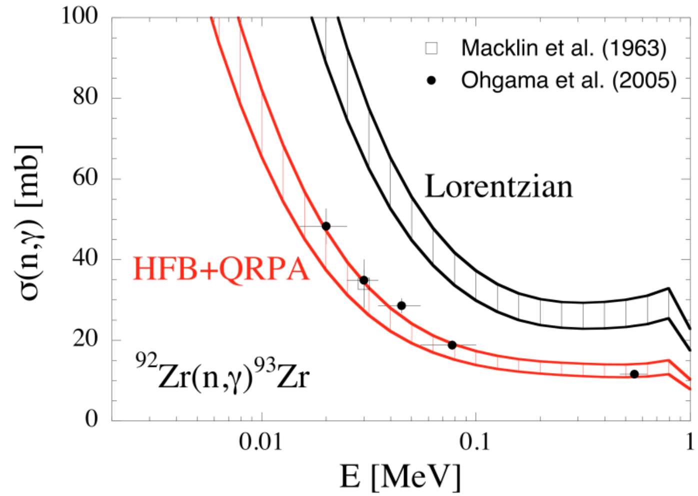
TALYS code of the HF model

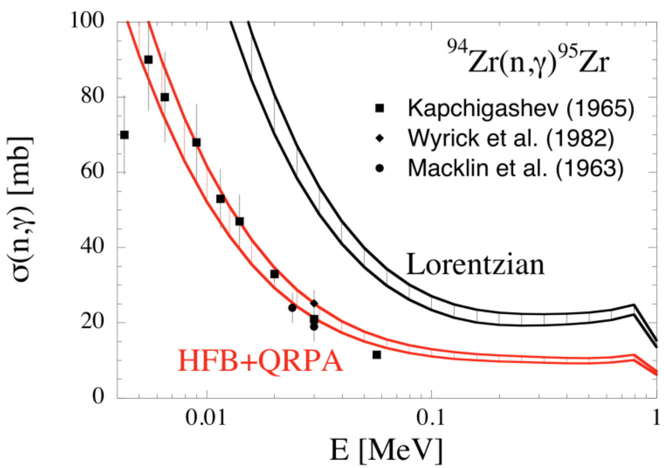


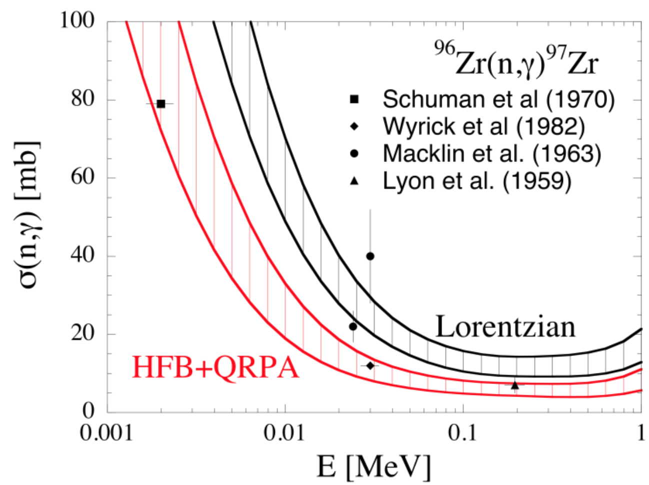
Application

STEP 2 – Justification of the adopted γSF





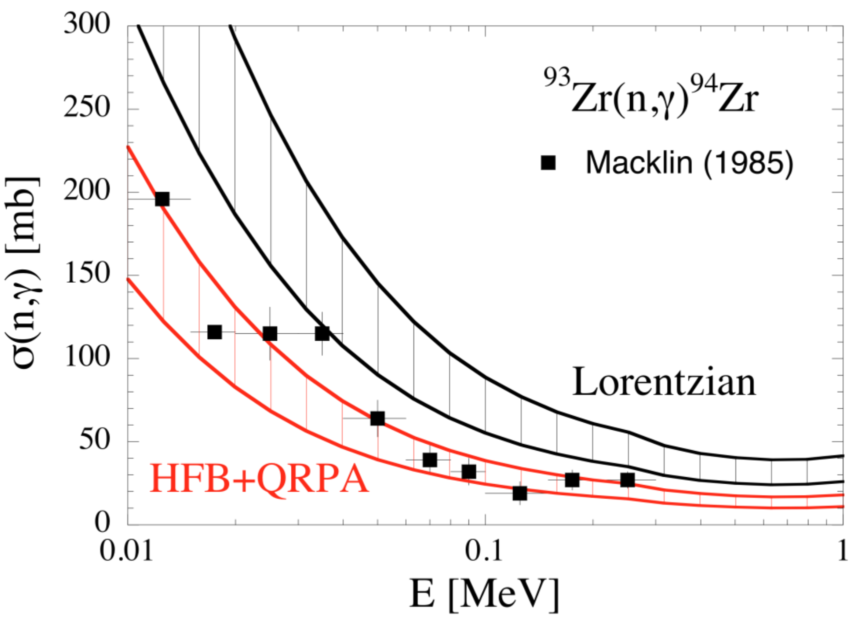




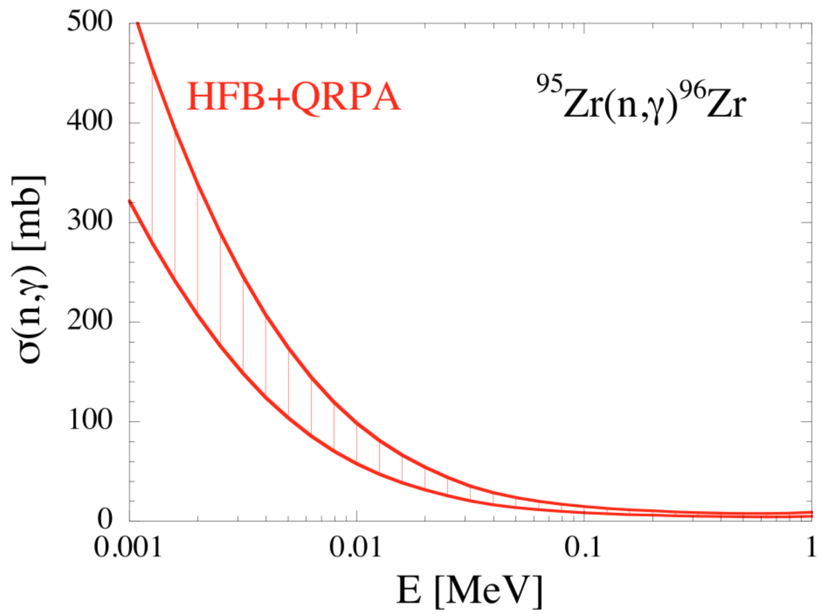
Application

STEP 3 – Statistical model calculations of (n,γ) cross sections for radioactive nuclei

^{93}Zr[$T_{1/2}$=1.5 × 10^6 y]



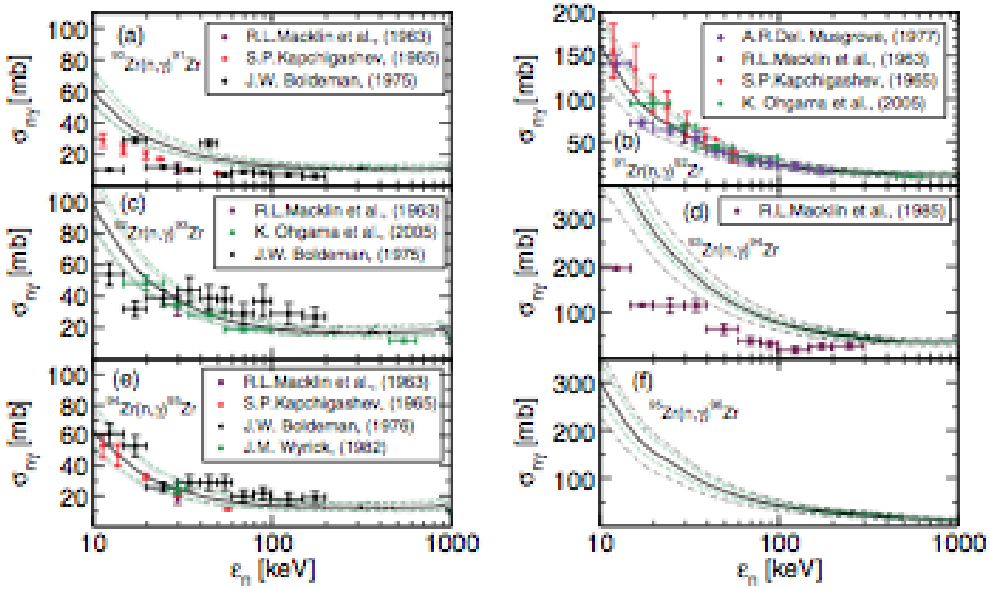
^{95}Zr[$T_{1/2}$=64 d]



Comparison with the surrogate reaction technique

Forssèn et al., PRC75, 055807 (2007)

Zr isotopes



93Zr(n,γ)94Zr

95Zr(n,γ)96Zr

1. The surrogate reaction technique gives larger cross sections by a factor of ~ 3 than the γSF method.

The surrogate reaction technique gives similar cross sections to those given by the γSF method provided that a choice is made of the Lorentian type of γSF.