Experiments of photoreaction cross sections: what has been done so far and left for a future development

THERRAA, November 24 - 25 2011, Athens, Greece

H. Utsunomiya (Konan University)

Outline

1. Photoreaction studies in the last decade
2. Future perspectives

Historical aspects

<u>1960s～1980s</u>

Nuclear Physics: GDR by (γ,n) measurements

E1, M1 excitations by (γ,γ') measurements

γ-ray sources: bremsstrahlung

positron annihilation in flight @ LLNL, Saclay

<u>1990s～Present</u>

Nuclear Astrophysics: Nucleosynthesis

P. Mohr et al., Phys. Lett. B 488 (2000) 127

Nuclear Physics: PDR, M1

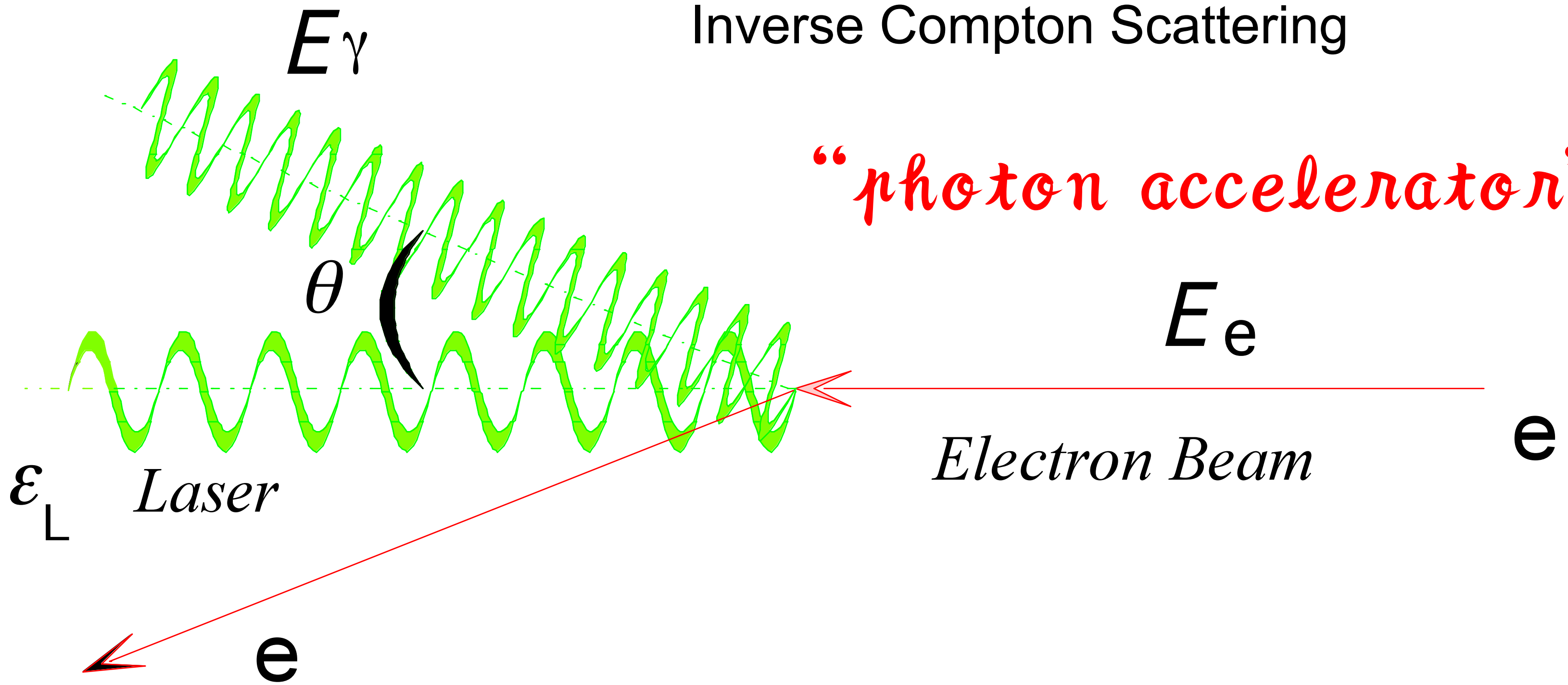
γ-ray sources: bremsstrahlung @ Darmstadt, ELBE

laser-Compton scattering @ AIST, Duke-HIγS

• Energy

Inverse Compton Scattering

“photon accelerator”



E_γ = 1 – 40 MeV @ AIST

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

$\gamma = E_e/mc^2$

Personal View of Photoreactions in Astrophysics
(γ,n) (γ,γ') (γ,p) (γ,α)

1. **The reciprocity theorem** to determine radiative capture cross sections for light nuclei

2. γSF of direct relevance to p-process

3. Isomer as a probe of NLD

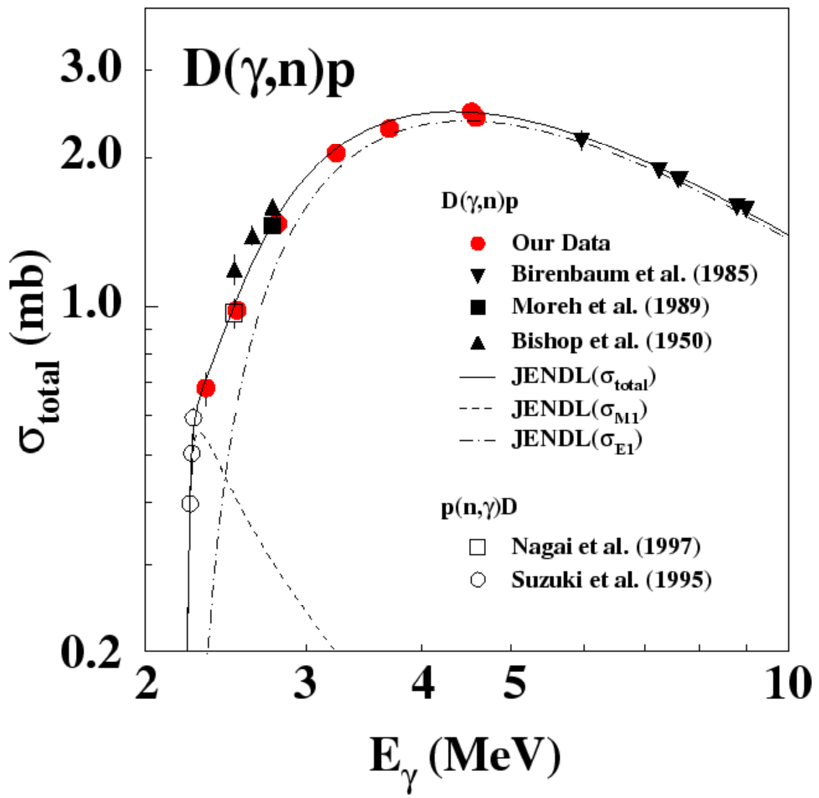
4. The γSF method to determine radiative neutron capture cross sections for unstable nuclei

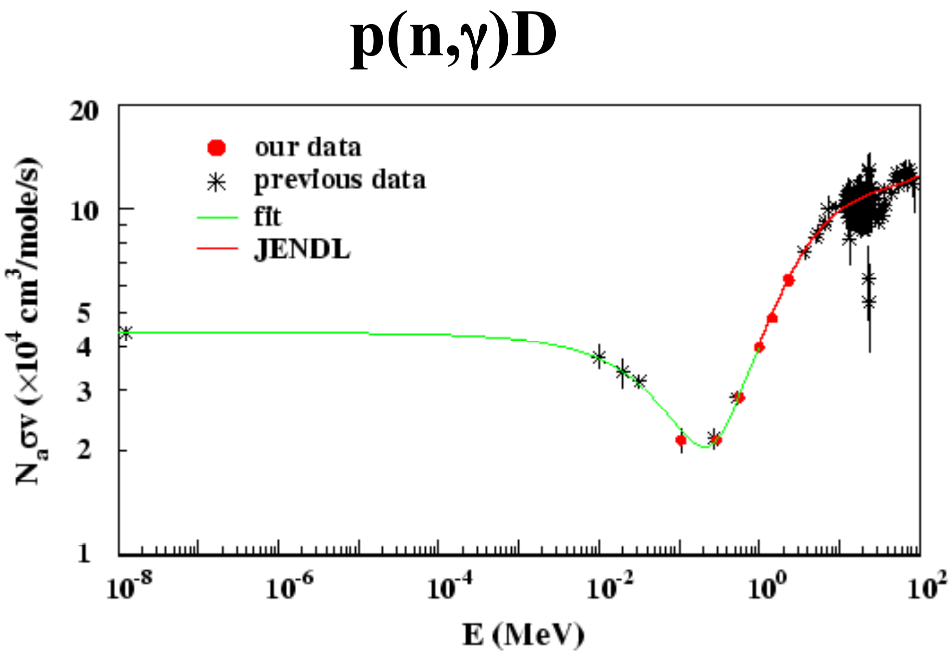
5. Nuclear structure: PDR, M1

Reciprocity theorem   A + n ⇄ B + γ + Q

$$\frac{\sigma(\gamma \rightarrow n)}{(2I_A+1)2p_n^2} = \frac{\sigma(n \rightarrow \gamma)}{(2I_B+1)2p_\gamma^2} \qquad p_\gamma = \hbar k = \frac{E_\gamma}{c} \qquad p_n^2 = 2\mu E_n$$

K.Y. Hara et al., PRD 68 (2003)





Personal View of Photoreactions in Astrophysics
(γ,n) (γ,γ') (γ,p) (γ,α)

1. The reciprocity theorem to determine radiative capture cross sections for light nuclei

2. **γSF** of direct relevance to p-process

3. Isomer as a probe of NLD

4. The γSF method to determine radiative neutron capture cross sections for unstable nuclei

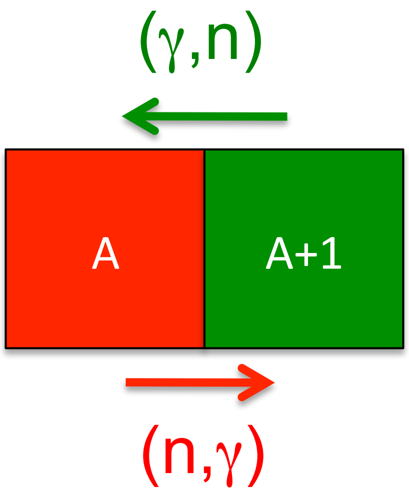
5. Nuclear structure: PDR, M1

Stellar photodisintegration rates can be determined from stellar capture rates by the reciprocity theorem.

$$\lambda_\gamma = \left(\frac{A_i A_j}{A_m}\right)^{3/2} \frac{(2J_i+1)(2J_j+1)}{(2J_m+1)} \frac{G_i(T^*)}{G_m(T^*)} \qquad i(j,\gamma)m$$

$$\times (T^*)^{3/2} F e^{-Q/kT^*} N_A \langle \sigma_i v \rangle^*$$

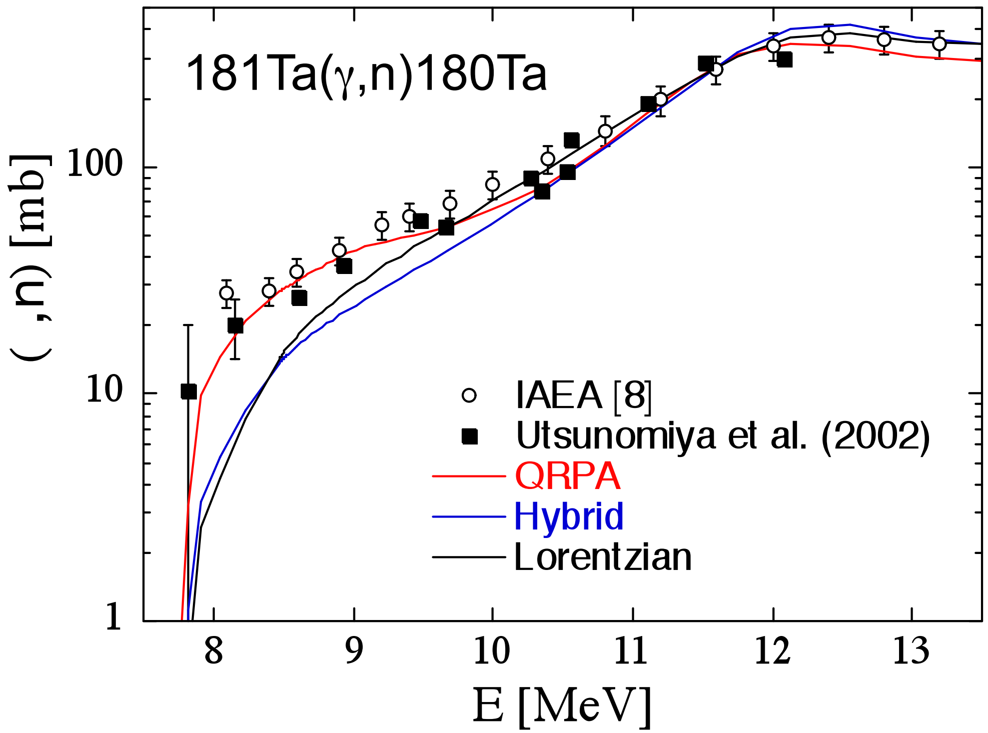
However, this does not apply to the p-process nuclei with low natural abundances and unstable nuclei with short half-lives.



Extra strength was found around Sn in the γSF of 181Ta.

γSF > Sn photoreaction rate for the g.s.

γSF < Sn photoreaction rates for excited states



Personal View of Photoreactions in Astrophysics
(γ,n) (γ,γ') (γ,p) (γ,α)

1. The reciprocity theorem to determine radiative capture cross sections for light nuclei

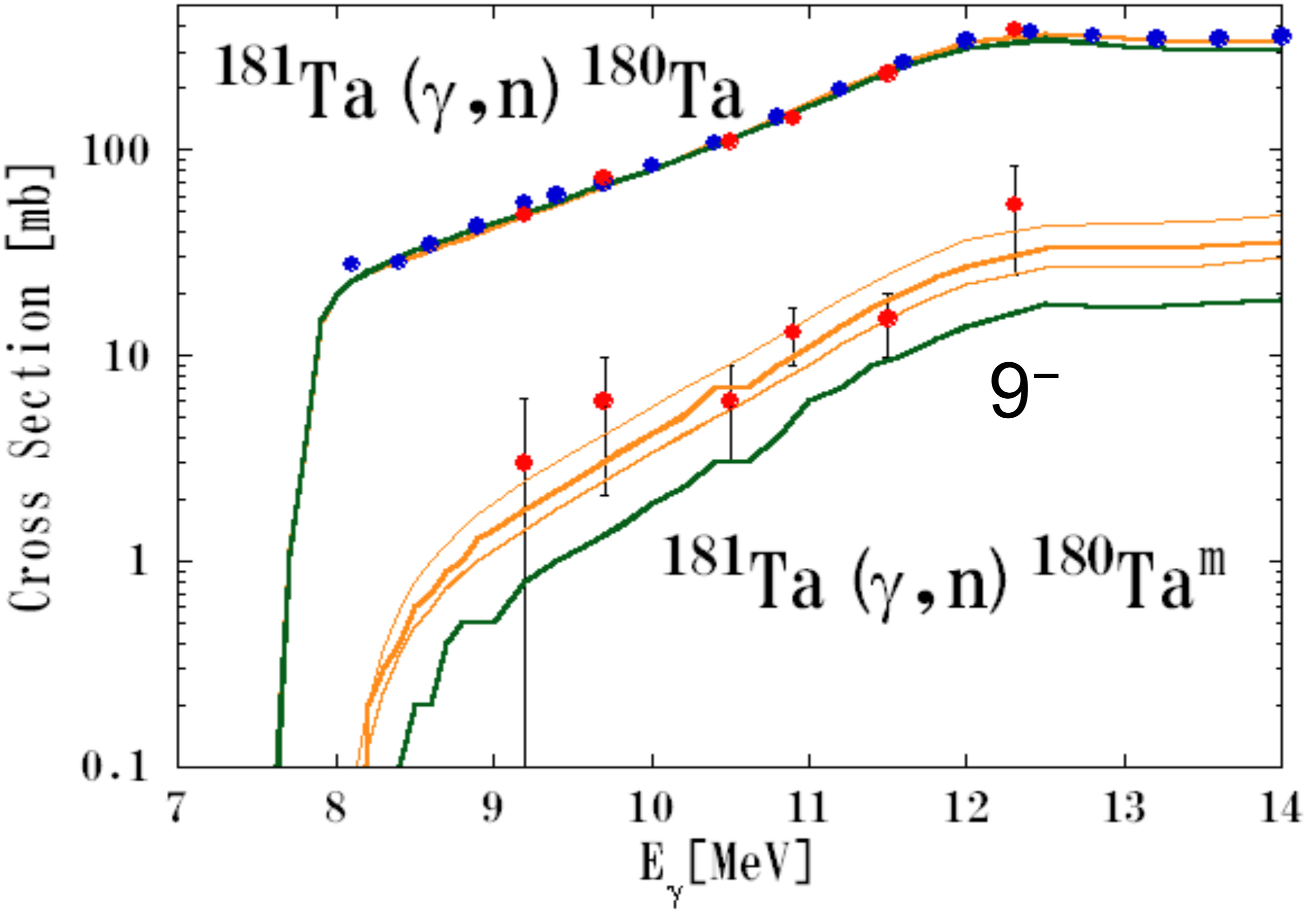
2. γSF of direct relevance to p-process

3. **Isomer** as a probe of NLD

4. The γSF method to determine radiative neutron capture cross sections for unstable nuclei

5. Nuclear structure: PDR, M1

Goko et al. Phys. Rev. Lett. 96 (2006)



Combinatorial NLD model

Hilaire & Goriely, NPA779 (2006)

Statistical NLD model

Personal View of Photoreactions in Astrophysics
(γ,n) (γ,γ') (γ,p) (γ,α)

1. The reciprocity theorem to determine radiative capture cross sections for light nuclei

2. γSF of direct relevance to p-process

3. Isomer as a probe of NLD

4. **The γSF method** to determine radiative neutron capture cross sections for unstable nuclei

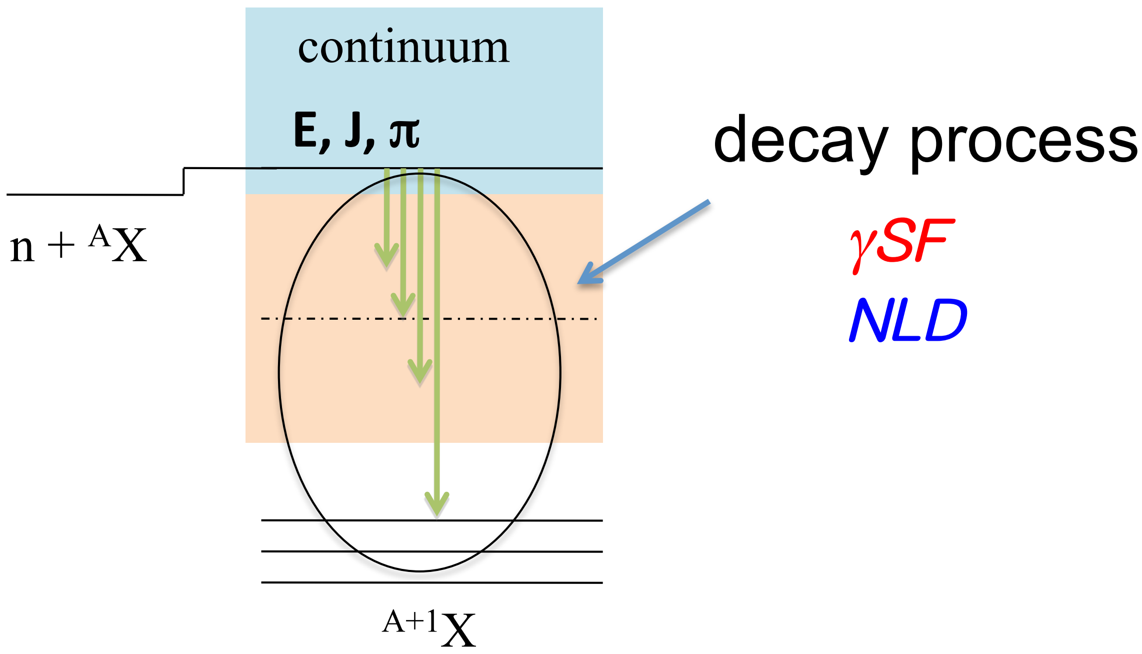
5. Nuclear structure: PDR, M1

γ-ray strength function method

H. Utsunomiya et al., PRC80 (2009)

follows *the statistical model of the radiative neuron capture in the formation of a compound nucleus and its gamma decay*

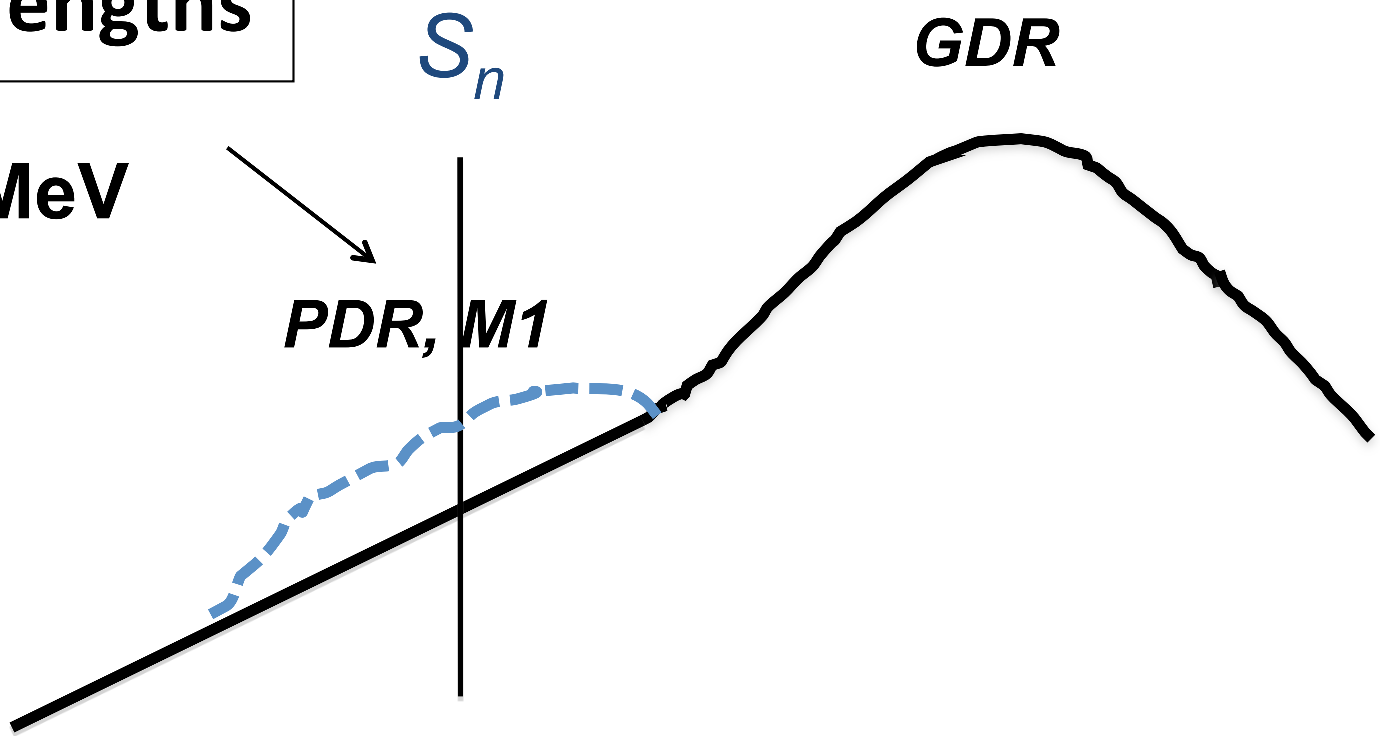
Radiative neutron capture $^{A}X(n,\gamma)^{A+1}X$



Structure of γ-ray strength function

Extra strengths

6 – 10 MeV



Primary strength

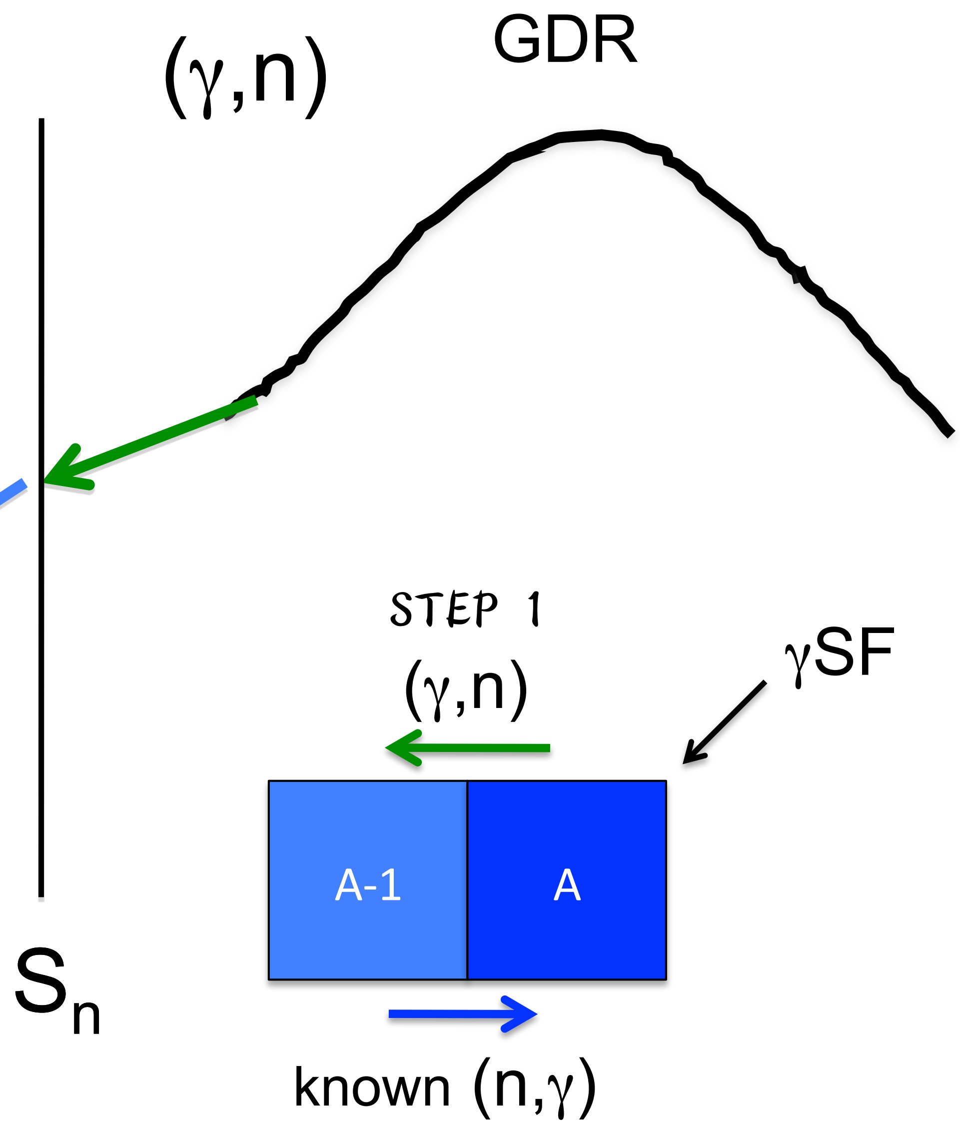
E1 strength in the low- energy tail of GDR

Methodology of γSF method

(γ,n) CS measurement

Extrapolation of γSF by microscopic models

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

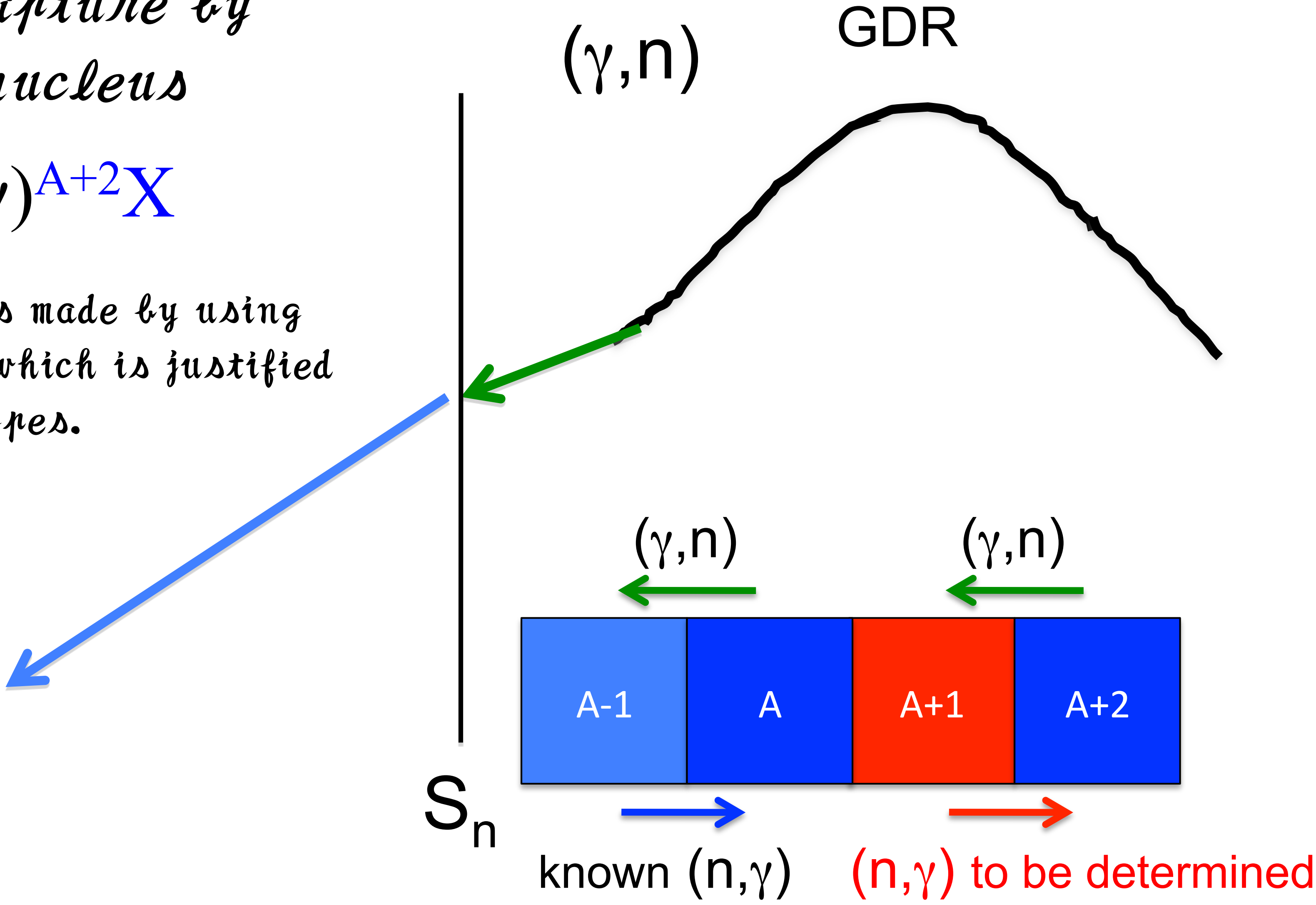


Methodology of γSF method

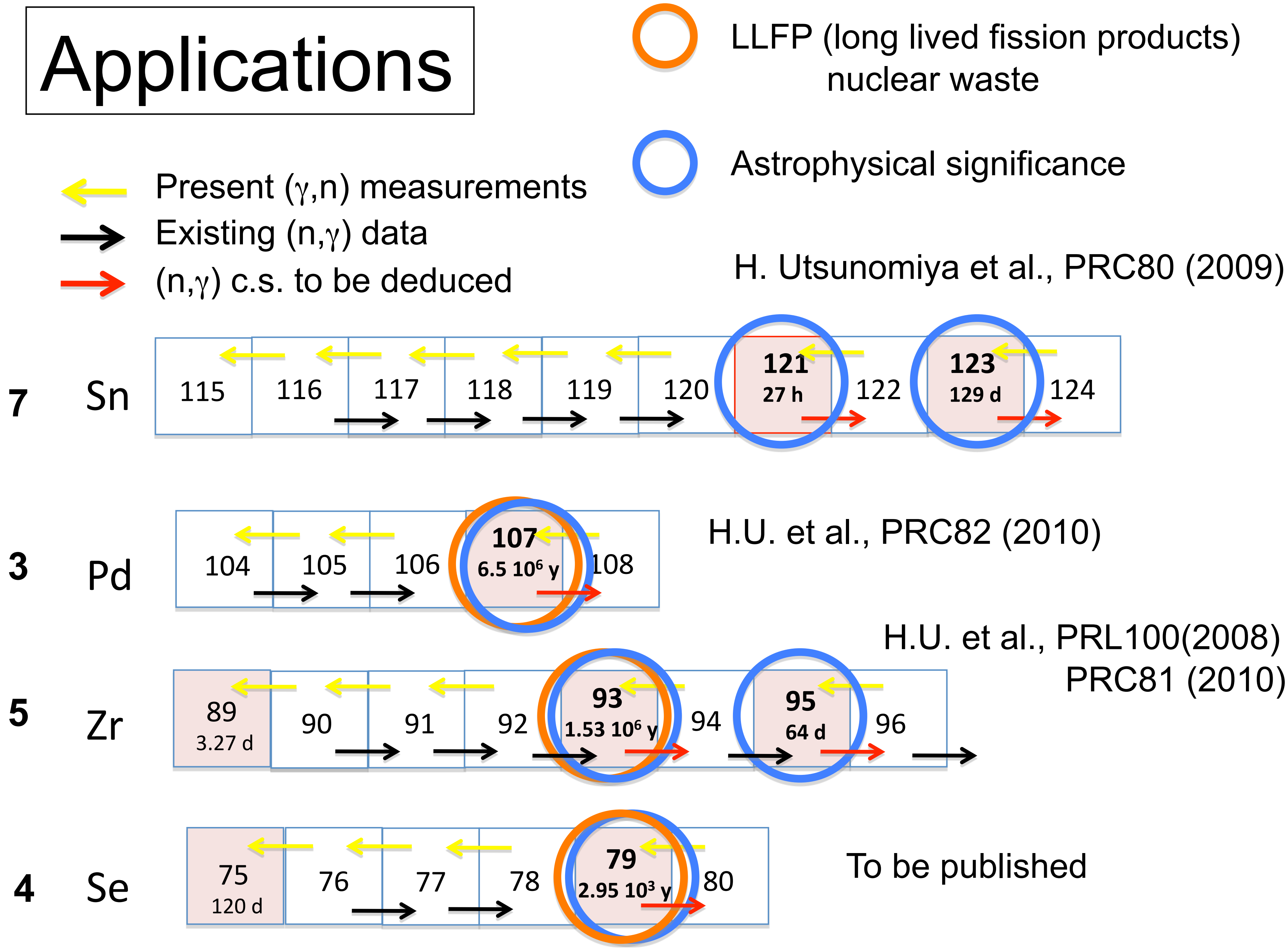
neutron capture by unstable nucleus

$^{A+1}X(n,\gamma)^{A+2}X$

Extrapolation is made by using the same model which is justified for stable isotopes.

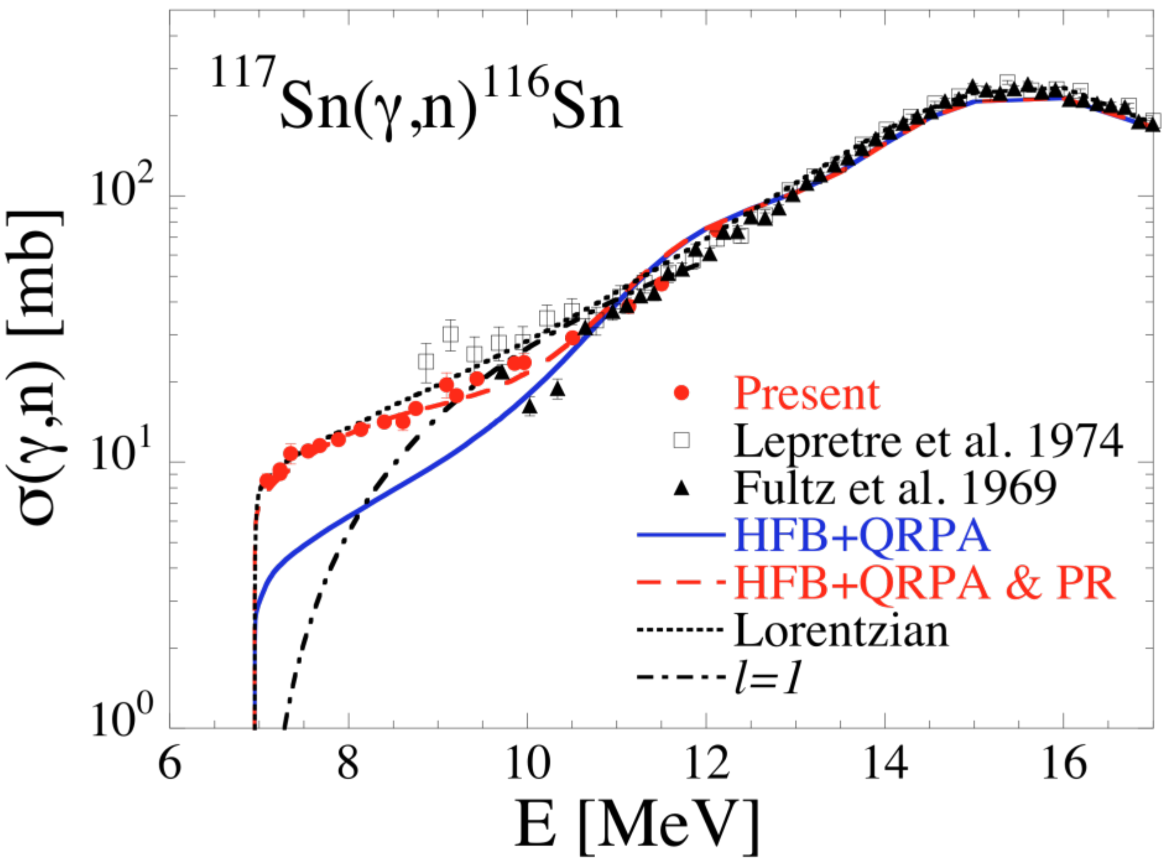


Applications



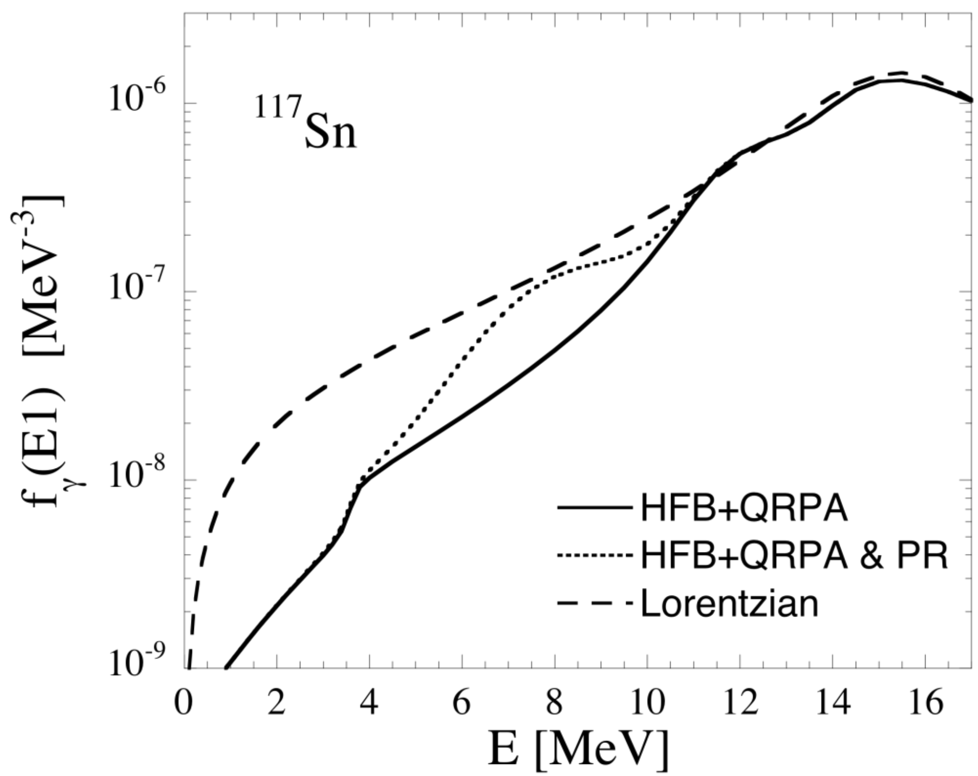
Sn isotopes

STEP 1 *Measurement of (γ,n) cross sections*



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

HFB+QRPA
+ PDR

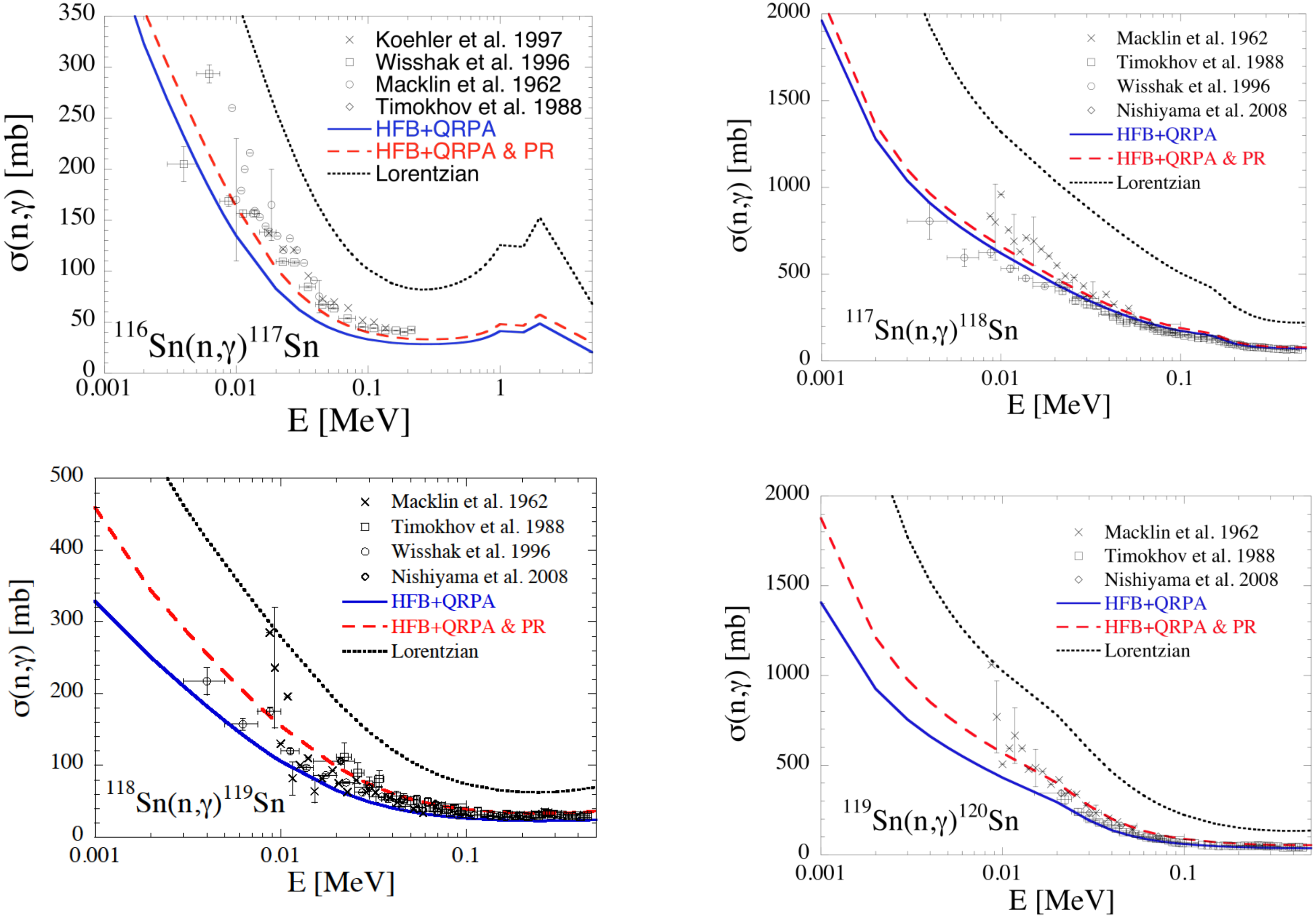


HFB+QRPA E1 strength supplemented with a pygmy E1 resonance in Gaussian shape

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

~ 1% of TRK sum rule of GDR

STEP 2 – Justification of the extrapolated γSF

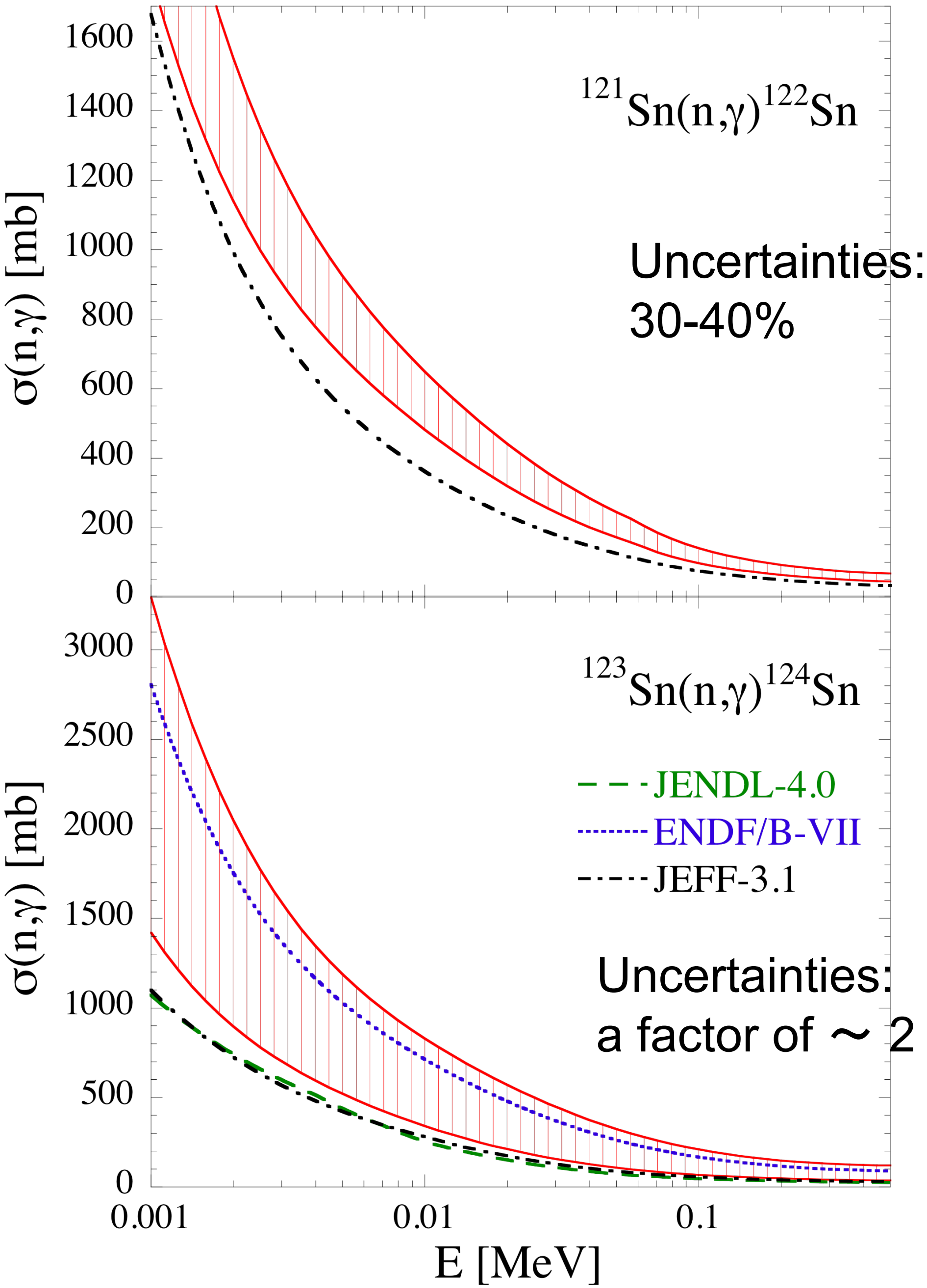


STEP 3 –

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

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

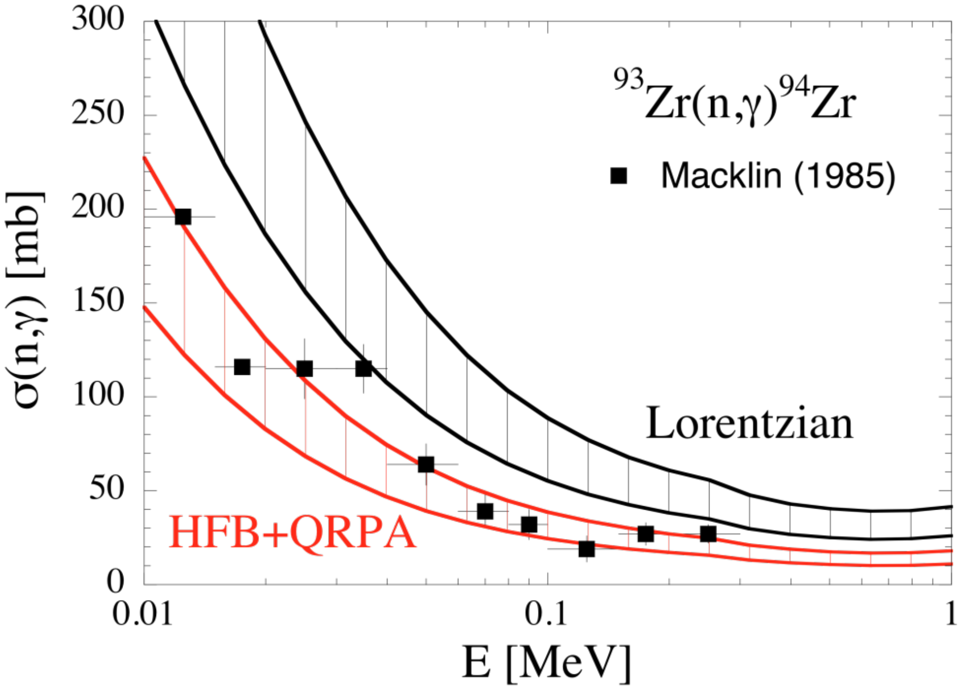
$^{123}Sn[T_{1/2}=129\ d]$



Results for Zr isotopes

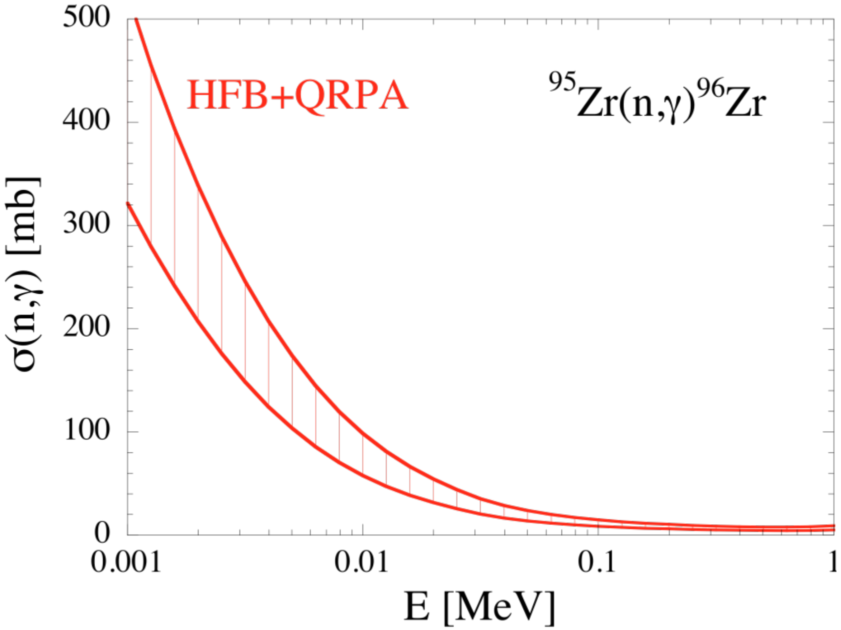
^{93}Zr[$T_{1/2}$=1.5×10^{6} y]

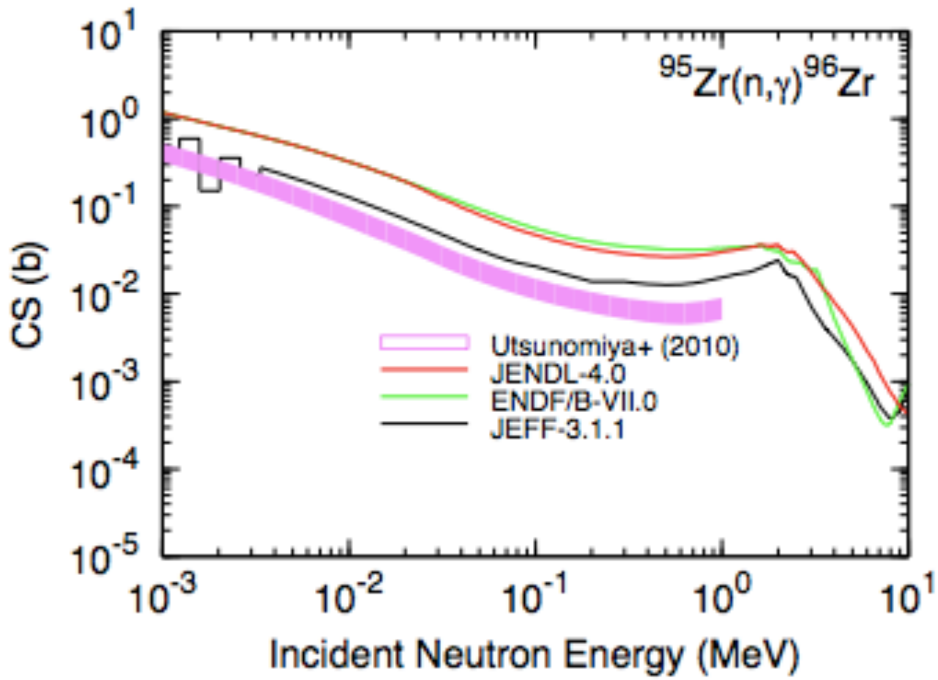
long-lived fission product
nuclear waste



$^{95}Zr[T_{1/2}=64\ d]$ *s-process branching*

30-40% uncertainties

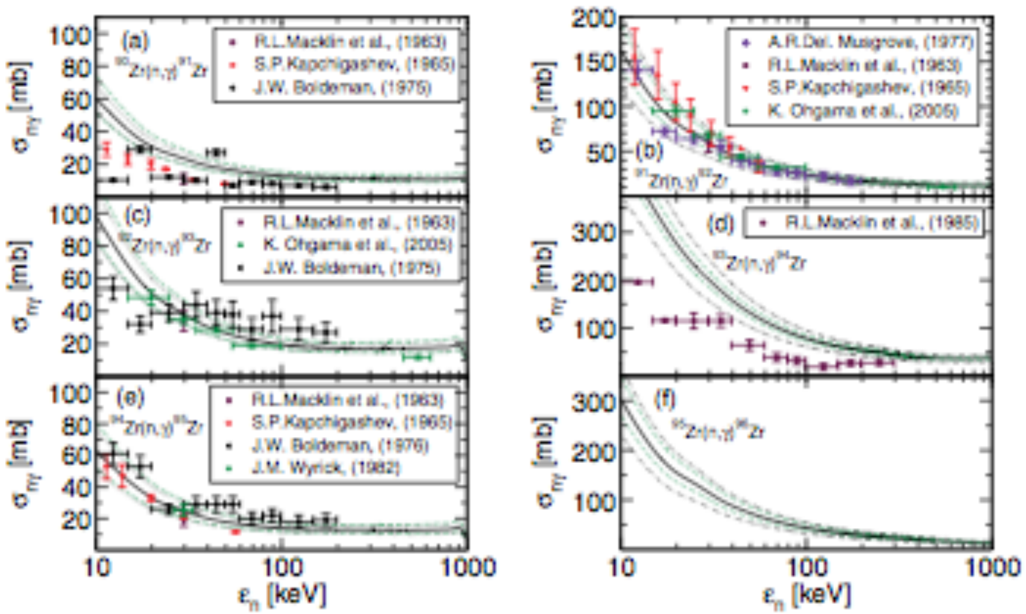




Comparison with the surrogate reaction technique

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.

Personal View of Photoreactions in Astrophysics
(γ,n) (γ,γ') (γ,p) (γ,α)

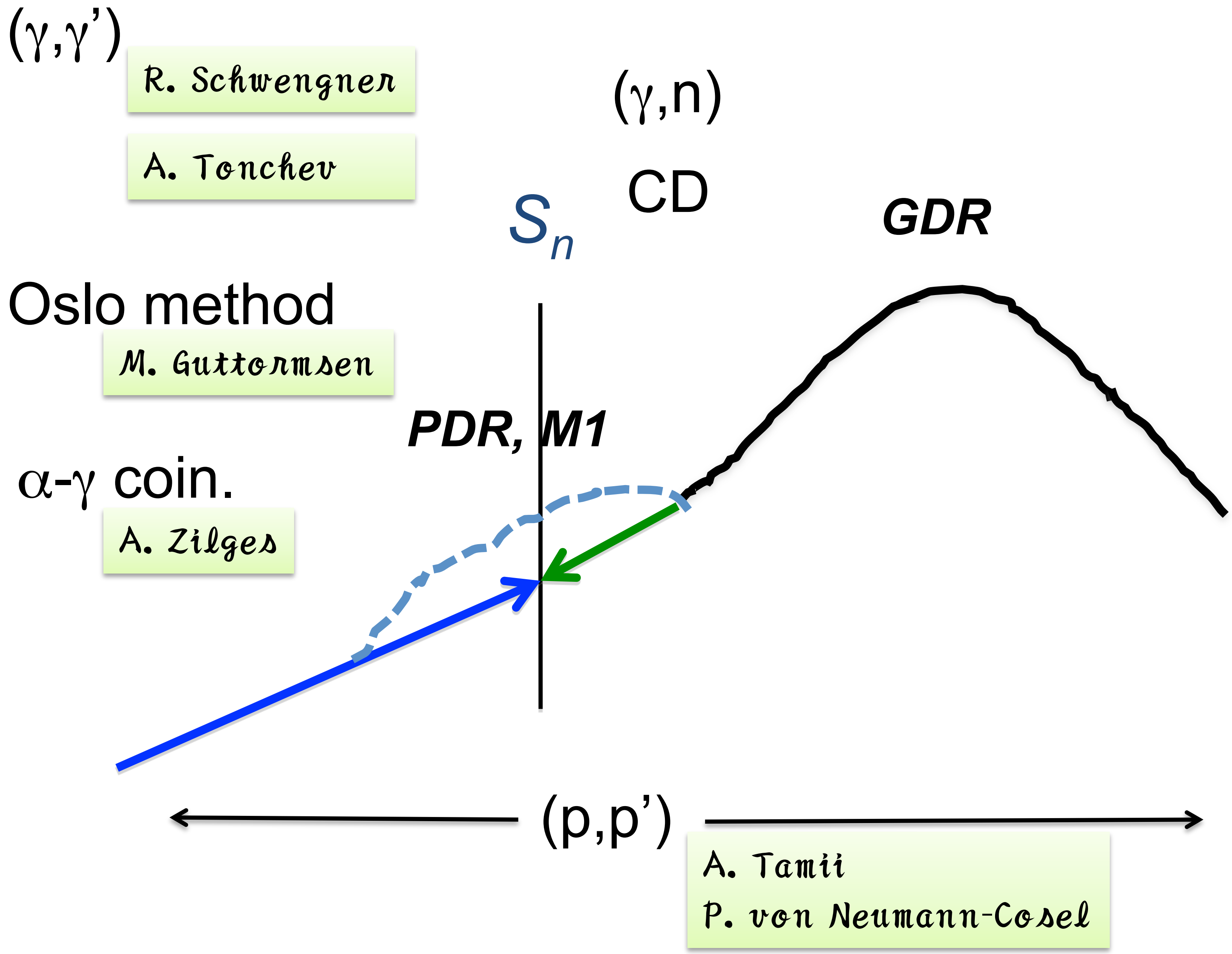
1. The reciprocity theorem to determine radiative capture cross sections for light nuclei

2. γSF of direct relevance to p-process

3. Isomer as a probe of NLD

4. The γSF method to determine radiative neutron capture cross sections for unstable nuclei

5. **Nuclear structure**: PDR, M1


(γ,γ')
R. Schwengner
A. Tonchev
(γ,n)
CD
S_n
GDR
Oslo method
M. Guttormsen
PDR, M1
α-γ coin.
A. Zilges
(p,p')
A. Tamii
P. von Neumann-Cosel

Future of (γ,n)

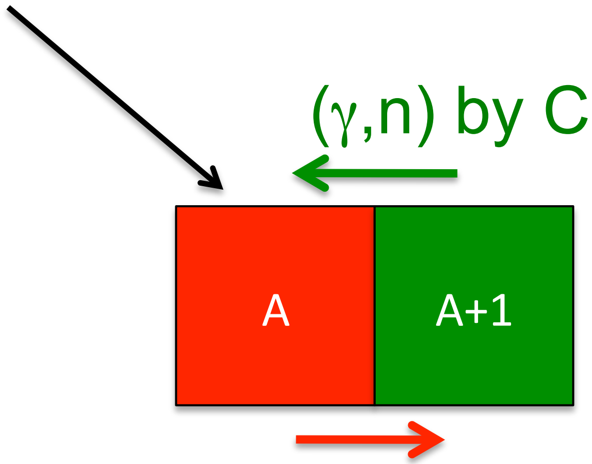
SPring-8 大型放射光施設
（8 GeV電子蓄積リング）
1 GeV直線加速器
8 GeVシンクロトロン加速器
NewSUBARU facility

Future of (γ,n)

The γSF method @ RIKEN-RIBF and GSI

unstable nucleus

(γ,n) by Coulomb dissociation



(n,γ) to be determined by γSF method

Coulomb dissociation experiments

F. Käppeler *et al.*, Rev. Mod. Phys. **83**, 157 (2011)

11 unstable nuclei

18 Coulomb dissociations

s-process branching nuclei	halflife (yr)	Coulomb dissociation	(n, γ) data
134Cs,135Cs	2.0652, 2.3× 10^6	136Cs,135Cs,134Cs	133Cs
152Eu*	13.537	153Eu, 152Eu	151Eu
154Eu,155Eu	8.593, 4.753	156Eu,155Eu,154Eu	153Eu
160Tb	0.198	161Tb,160Tn	159Tb
163Ho	4570	164Ho,166Ho	165Ho
170Tm,171Tm	0.352, 1.921	172Tm,171Tm,170Tm	169Tm
179Ta	1.82	180Ta,182Ta	181Ta
204Tl	3.78	205Tl,204Tl	203Tl

Application of the γSF method to the r-process

$^{131}Sn(n,\gamma)^{132}Sn$ cross sections in *the r-process nucleosynthesis*

The astrophysical significance is controversial !

BUT this would be the first application to a very neutron-rich nucleus.

A pioneering work is in progress. *Nadia Tsoneva @ Giessen.*

1) A systematic study of the γSF for Sn isotopes

116Sn ,...., 124Sn (7 stable) → → → 132Sn

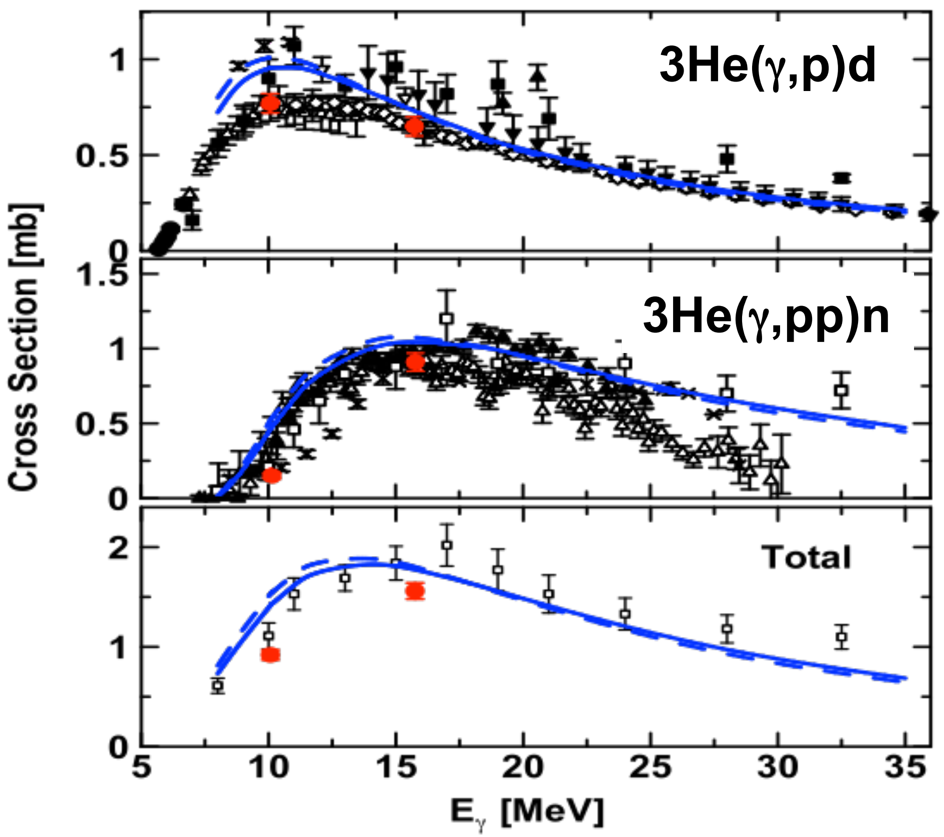
132Sn(γ,n) data: GSI Coulomb dissociation data for 132Sn

Present of (γ,p) (γ,α)

Only a few cases

● S. Naito et al. @AIST
PRC73, 034003 (2006)

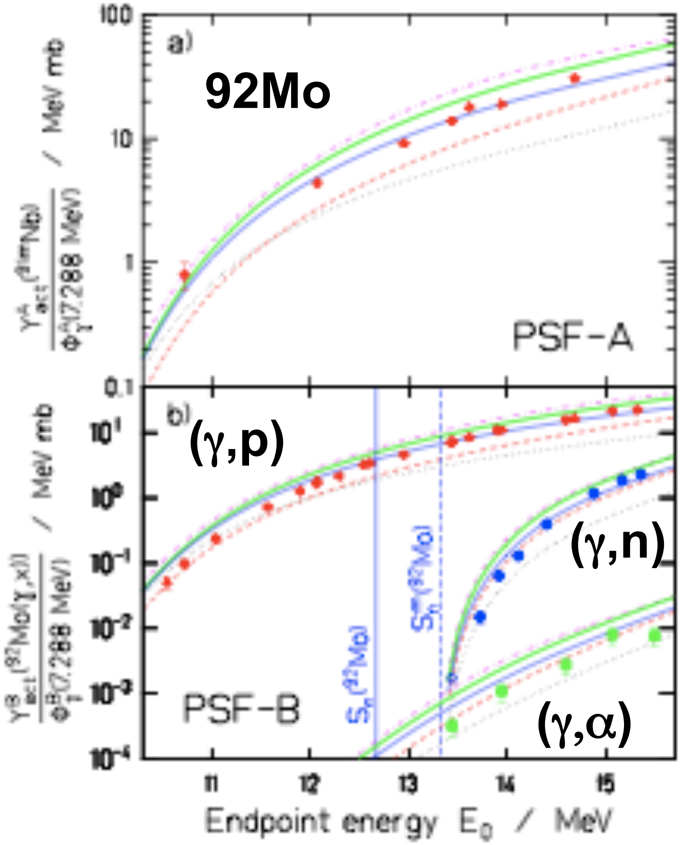
TPC



M. Erhard et al., Journal of Physics Conf. Ser. 202 (2010)

Photoactivation

@ ELBE



Future of (γ,p) (γ,α)

Efforts were made and being made …., but lack accuracy to address a few-body problem.

D, 3He, 4He:	cloud chamber
3He, 4He:	liquid He scintillator
12C:	emulsion chamber

16O(γ,α)12C: STAR bubble chamber
O-TPC @ HIγS

Achievements are yet to come.

Summary

We continue to study γSF in the context of nucleosynthesis.

1. Nuclear Physics Experiment

a. (γ,n) (γ,γ') c.s. measurements

real photons for stable nuclei: NewSUBARU, HIγS, ELBE etc.

ELI-NP (Bucharest-Magurele, Romania)

virtual photons for unstable nuclei (CD): RIKEN-RIBF, GSI

b. (γ,p) (γ,α) c.s. measurements

Future prospect is unclear, depending on …

2. Nuclear Theory

a. good models of γSF

primary strength: low-energy E1 of GDR

extra strengths: PDR, M1

b. good models of NLD