重元素合成における原子核の電磁応答

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宇核連第2回研究戦略ワークショップ

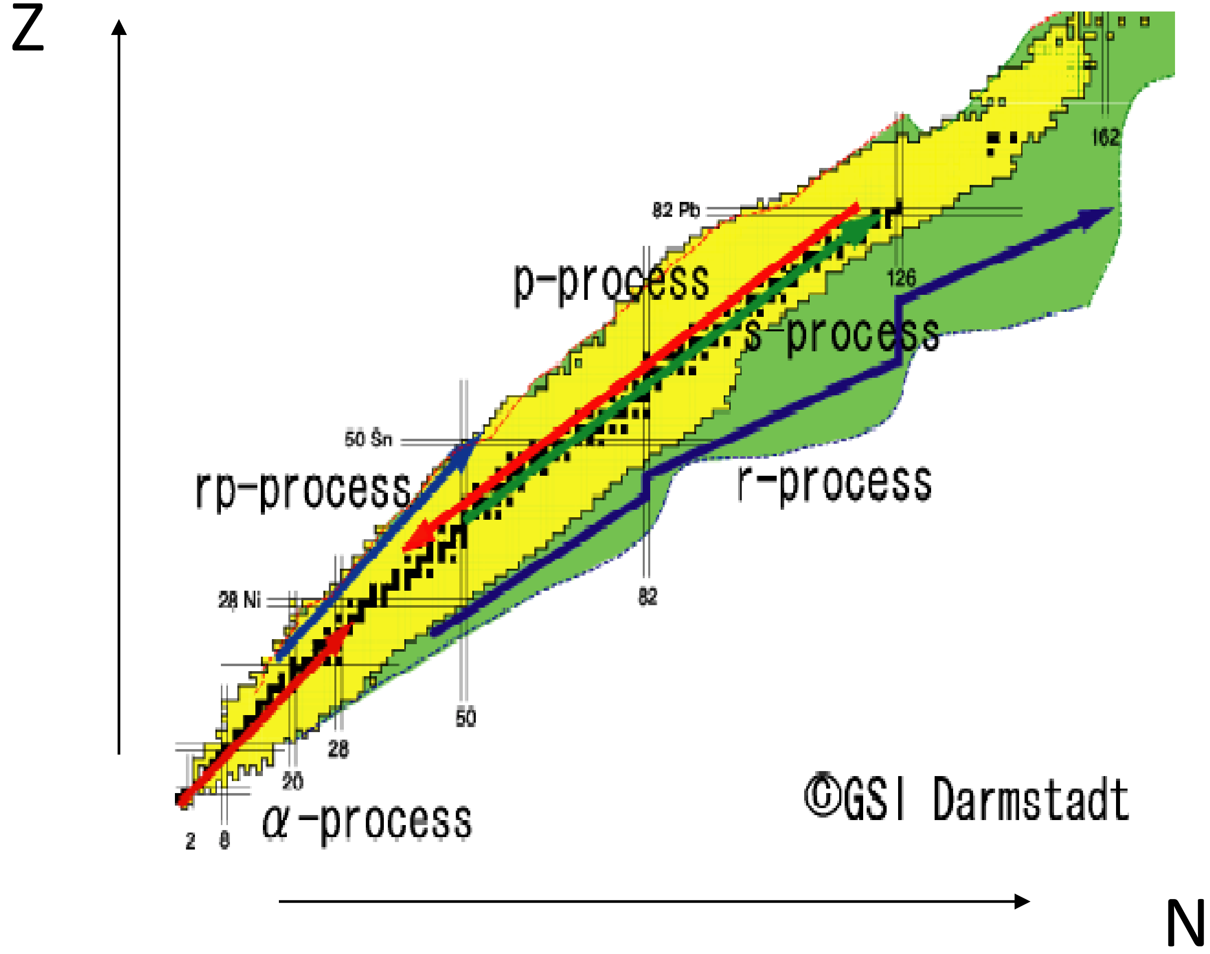
2009年7月27日 ー29日　理研

１．中性子捕獲反応とガンマ線強度関数
２．ガンマ線強度関数
３．ＧＤＲとＰＤＲ
４．まとめ

The present study includes the result of “Study on nuclear data by using a high intensity pulsed neutron source for advanced nuclear system” entrusted to Hokkaido University by the Ministry of Education, Culture, Sports, Science and Technology of Japan (MEXT).

Nucleosynthesis of elements heavier than Fe

s, r-processes: neutron capture



中性子捕獲反応に対する Hauser-Feshbach の公式

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

共鳴領域　En = 0.1 – 数十keV
連続領域　En > 数十keV

仮定　compound nuclear reactions under $\Delta E \gg D$
ΔE: energy spread of incident particles
D: average level spacing

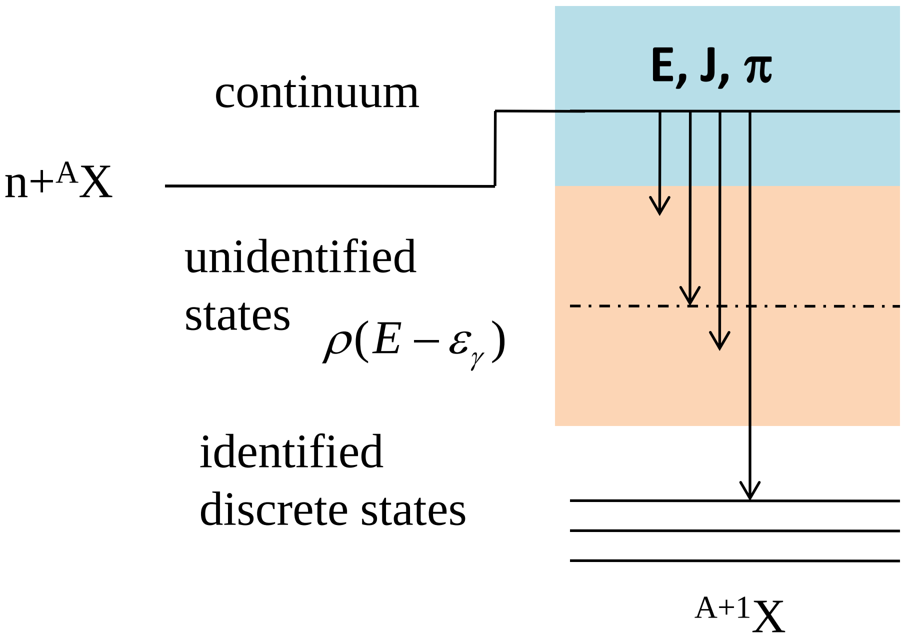
$$\sigma_{n\gamma}(E) = \frac{\pi}{k_n^2} \sum_{J,\pi} g_J \frac{T_\gamma(E,J,\pi) T_n(E,J,\pi)}{T_{tot}}$$

statistical factor

$$g_J = \frac{2J+1}{2(2J_A+1)}$$

J, π: 複合核状態のスピン・パリティ

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



γ-ray strength function

$$\overleftarrow{f}_{E1}(\varepsilon_\gamma) = \varepsilon_\gamma^{-3}\langle\Gamma_{E1}\rangle / D$$

D: average level spacing

γ-ray transmission coeff.

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

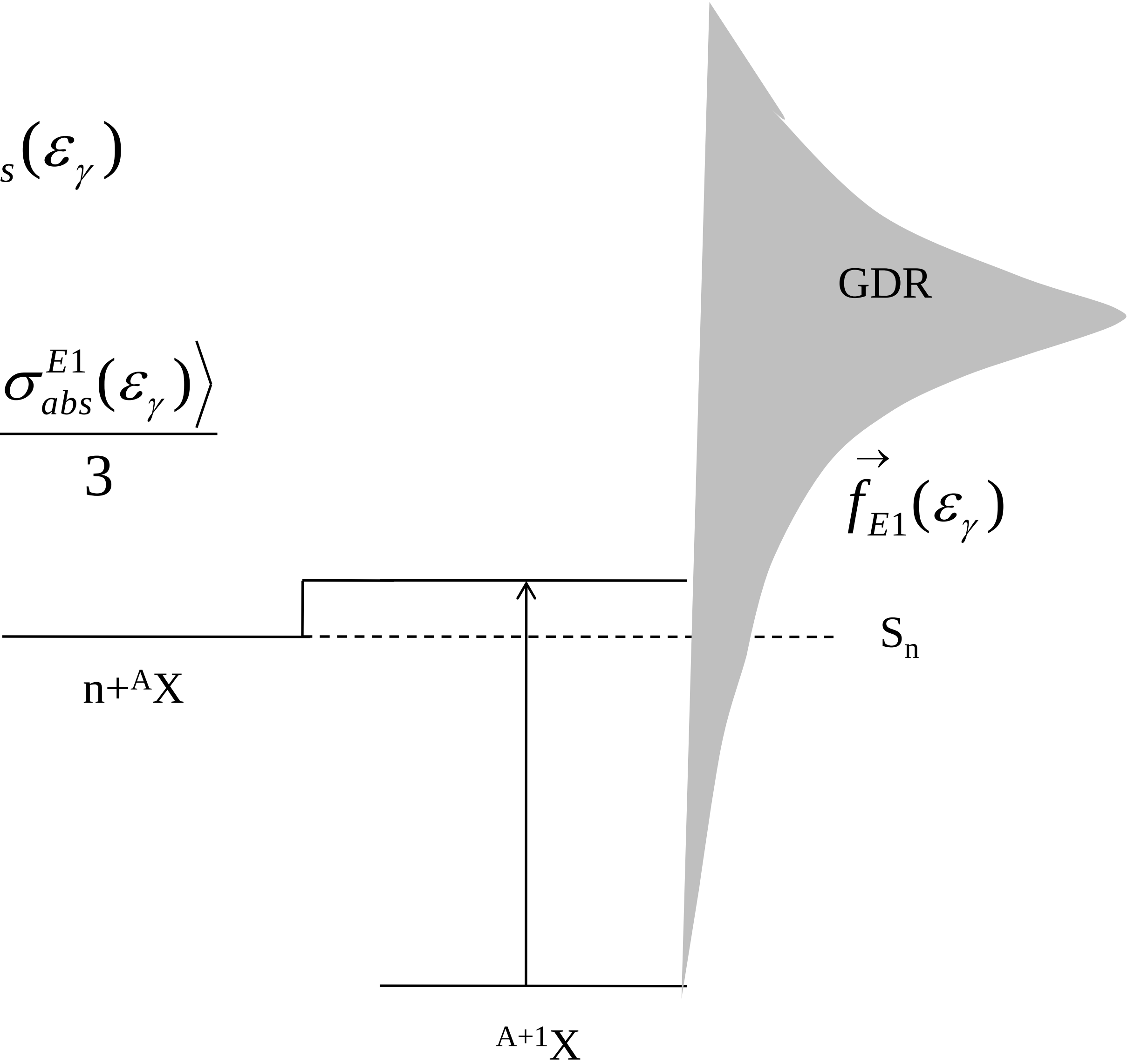
$$= 2\pi\varepsilon_\gamma^3\ \overleftarrow{f}_{E1}(\varepsilon_\gamma)$$

$$T_{E1}(E,J,\pi) = \sum_\nu T_{E1}^\nu(\varepsilon_\gamma) + \int T_{E1}(\varepsilon_\gamma)\rho(E-\varepsilon_\gamma)d\varepsilon_\gamma$$

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

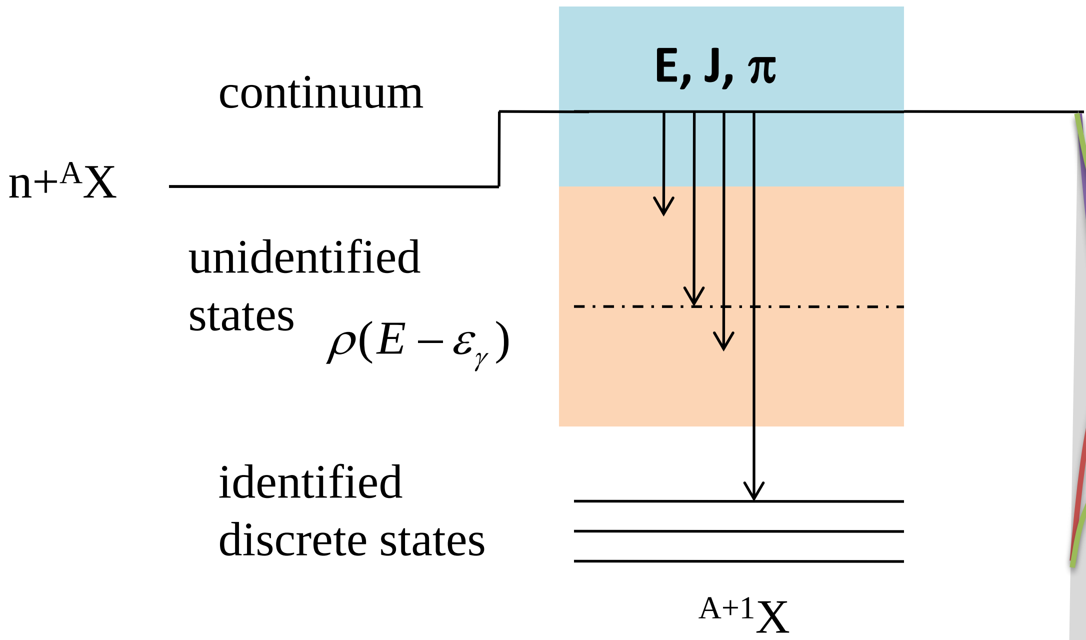
$$\sigma_{\gamma n}(\varepsilon_\gamma) = \frac{T_n}{T_{tot}}\sigma_{abs}(\varepsilon_\gamma)$$

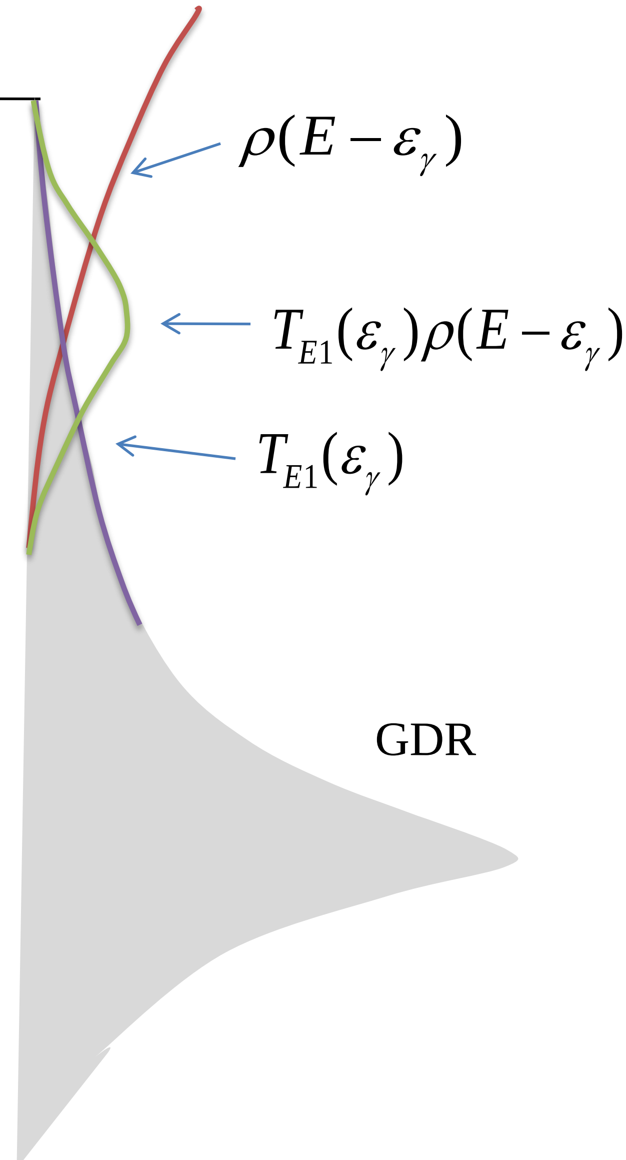
$$\vec{f}_{E1}(\varepsilon_\gamma) = \frac{\varepsilon_\gamma^{-1}}{(\pi\hbar c)^2}\frac{\left\langle \sigma_{abs}^{E1}(\varepsilon_\gamma)\right\rangle}{3}$$



Brink Hypothesis

$$\vec{f}_{E1}(\varepsilon_\gamma) = \overleftarrow{f}_{E1}(\varepsilon_\gamma)$$





$$T_{E1}(E, J, \pi) = \sum_{\nu} T_{E1}^{\nu}(\varepsilon_\gamma) + \int \boxed{T_{E1}(\varepsilon_\gamma)\rho(E-\varepsilon_\gamma)}\, d\varepsilon_\gamma$$

Standard Lorentzian

$$\overleftarrow{f}_{E1}(\varepsilon_\gamma) = 8.68\times10^{-8}(mb^{-1}MeV^{-2})\frac{\sigma_o \varepsilon_\gamma \Gamma^2}{(\varepsilon_\gamma^2 - E^2)^2 + \varepsilon_\gamma^2\Gamma^2}$$

Three corrections for

1. Spreading into two-particle two-hole states
2. Finite temperature effect
3. Zero energy limit $(\varepsilon_\gamma \to 0)$

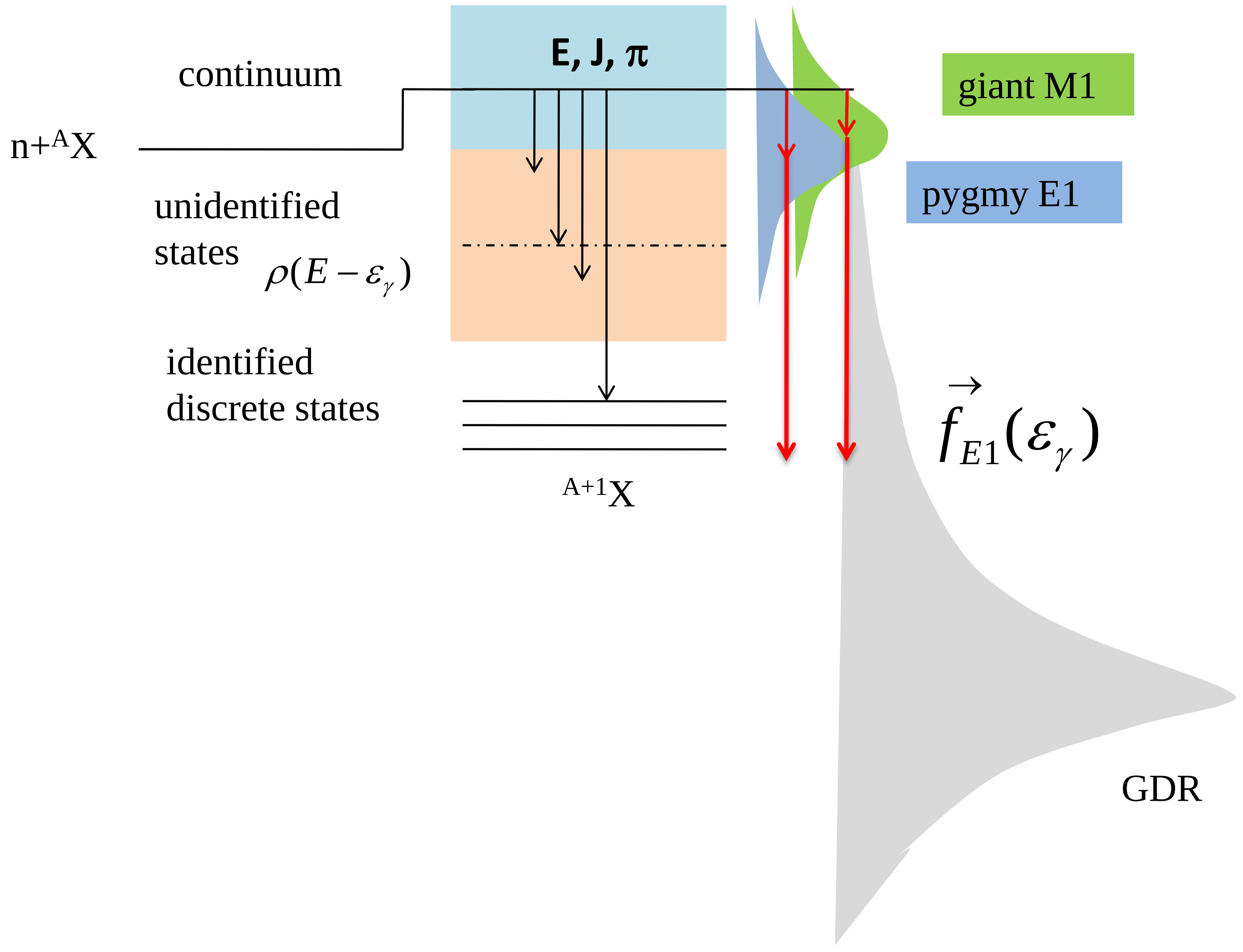
Generalized Lorentzian

$$\overleftarrow{f}_{E1}(\varepsilon_\gamma, T) = 8.68\times 10^{-8}(mb^{-1}MeV^{-2})$$

$$\times\left[\frac{\varepsilon_\gamma \Gamma(\varepsilon_\gamma)}{(\varepsilon_\gamma^2 - E^2)^2 + \varepsilon_\gamma^2 \Gamma(\varepsilon_\gamma)^2} + \underbrace{\frac{0.7\Gamma 4\pi^2 T^2}{E^5}}_{3}\right]\sigma_o \Gamma$$

$$\Gamma(\varepsilon_\gamma) = \Gamma\frac{\overbrace{\varepsilon_\gamma^2}^{1} + \overbrace{4\pi^2 T^2}^{2}}{E^2} \qquad T = \sqrt{(B_n - \varepsilon_\gamma)/a}$$

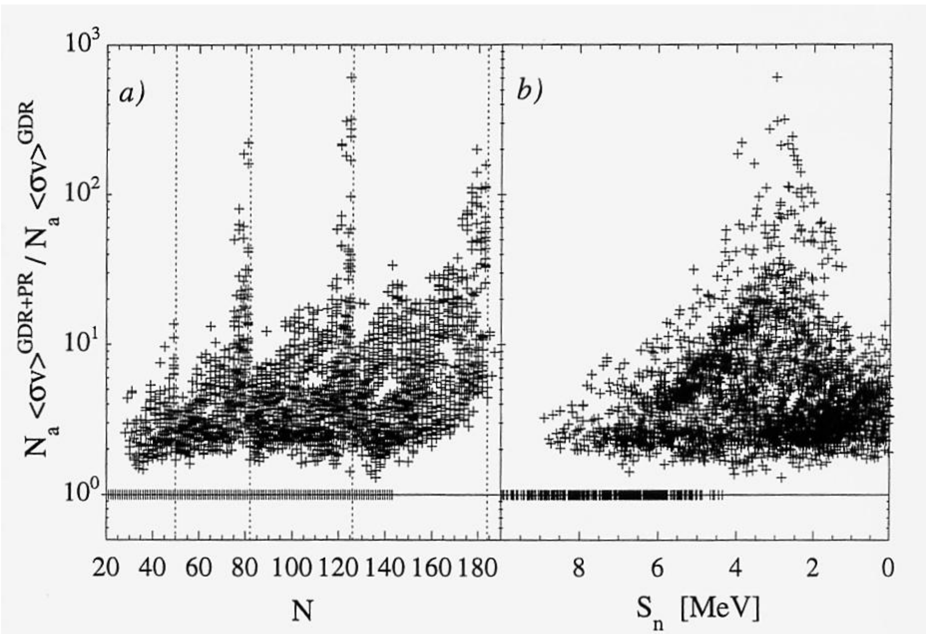
extra contributions

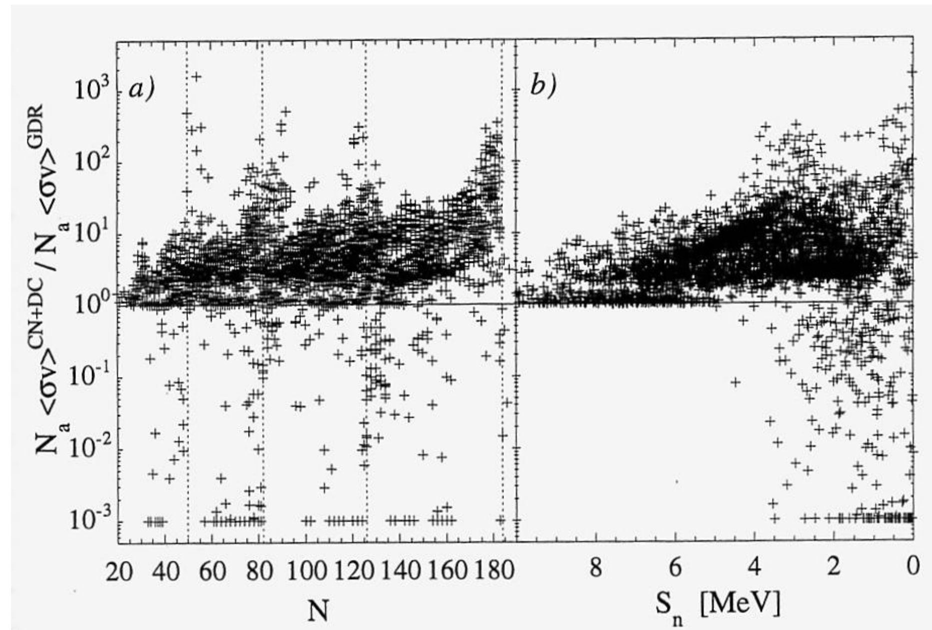


Goriely, PLB (1998)

GDR vs GDR+PDR

CN vs CN+DC





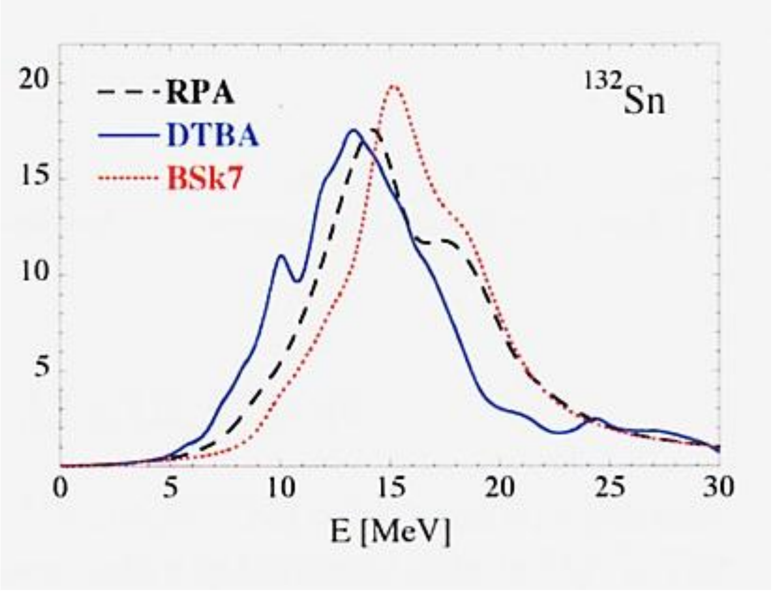
Closed-shell nuclei
with $2 \leq S_n$ [MeV] ≤ 4

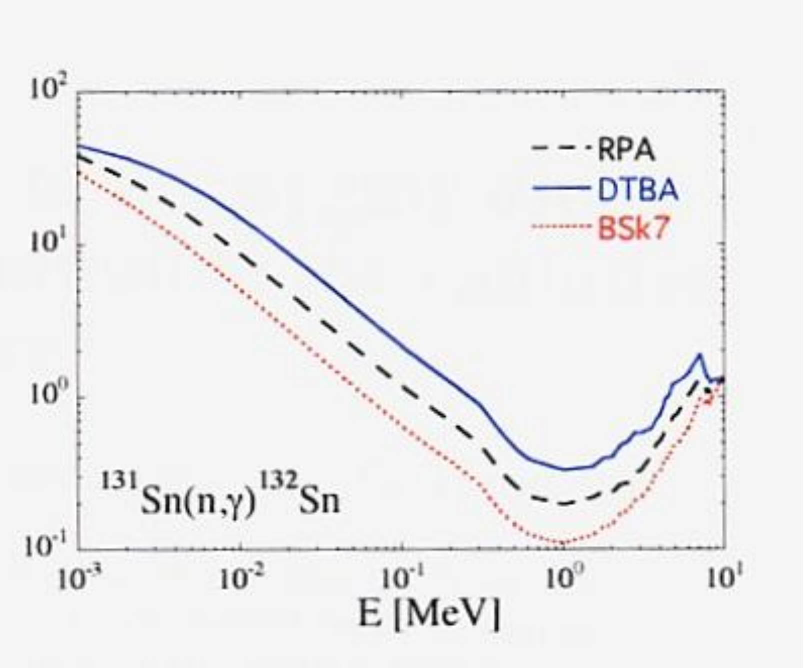
$1 \leq S_n$ [MeV] ≤ 3

DTBA (Discrete Time Blocking Approximation)

Avdeyenkov, Goriely, Kamerdzhiev, Tertychny (2008)

Key ingredients
Single particle continuum
Phonon coupling

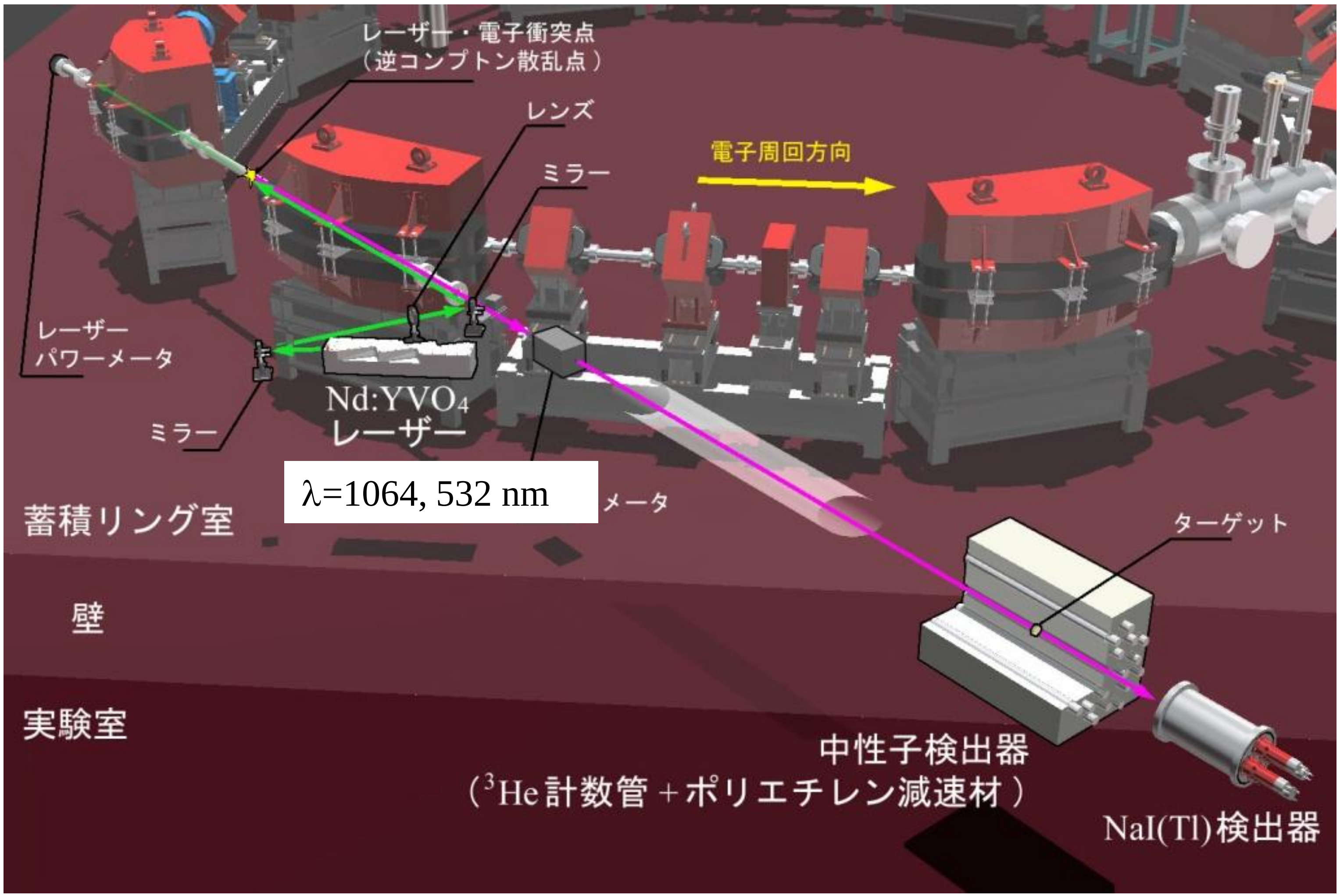




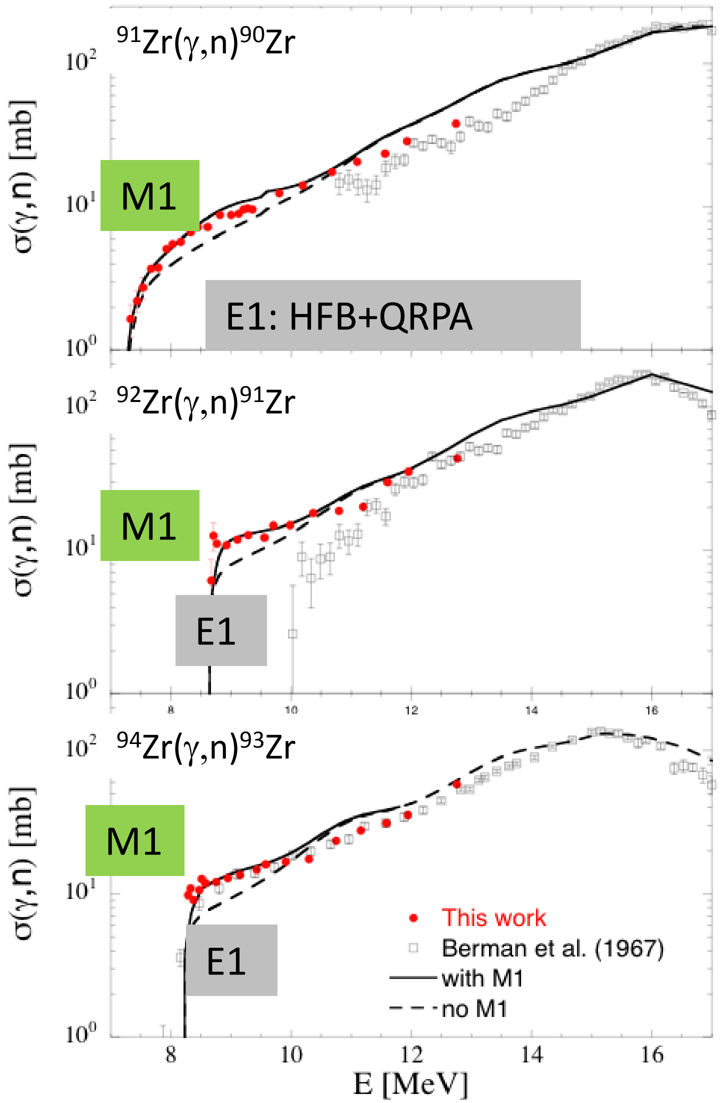
Correct prediction of PDR in ^{132}Sn at 9.8 MeV

Phonon coupling increases (n,γ) cross sections by a factor of 2-3.

Tsukuba Electron Ring for Acceleration and Storage (TERAS) at AIST



M1 strength in Zr isotopes in the photoneutron channel



H. Utsunomiya PRL100 (2008)

E1 γSF (HFB+QRPA)

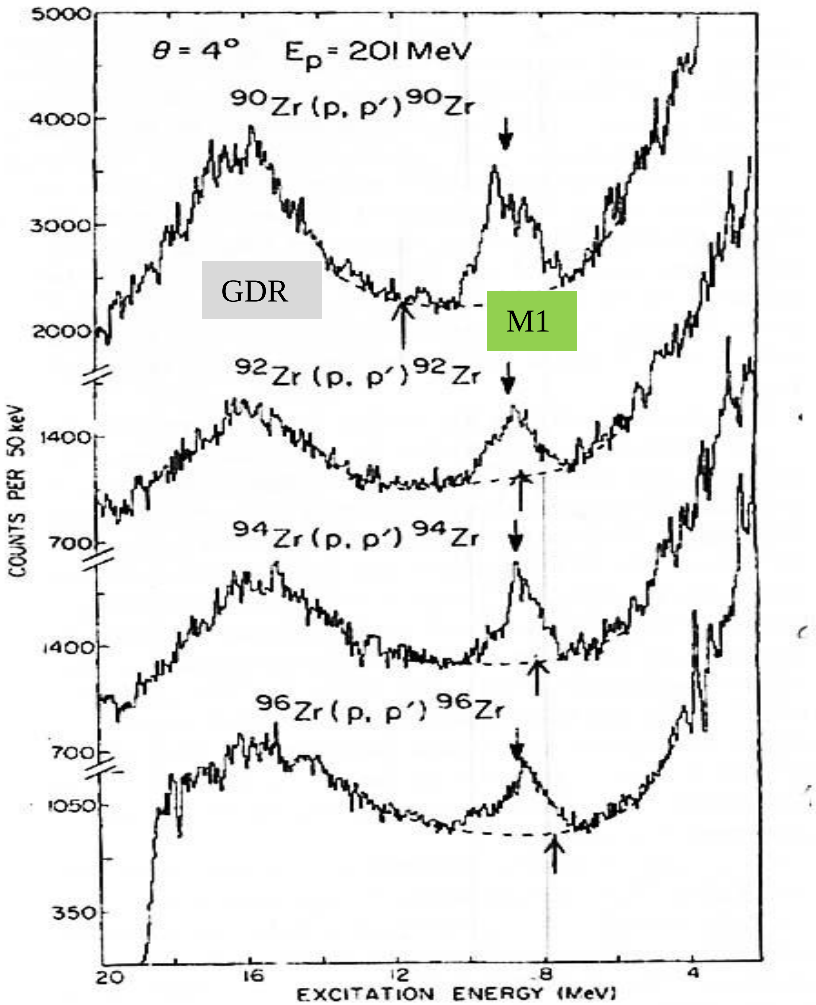
M1 resonance

E_o= 9 MeV, σ_0=7.5mb,

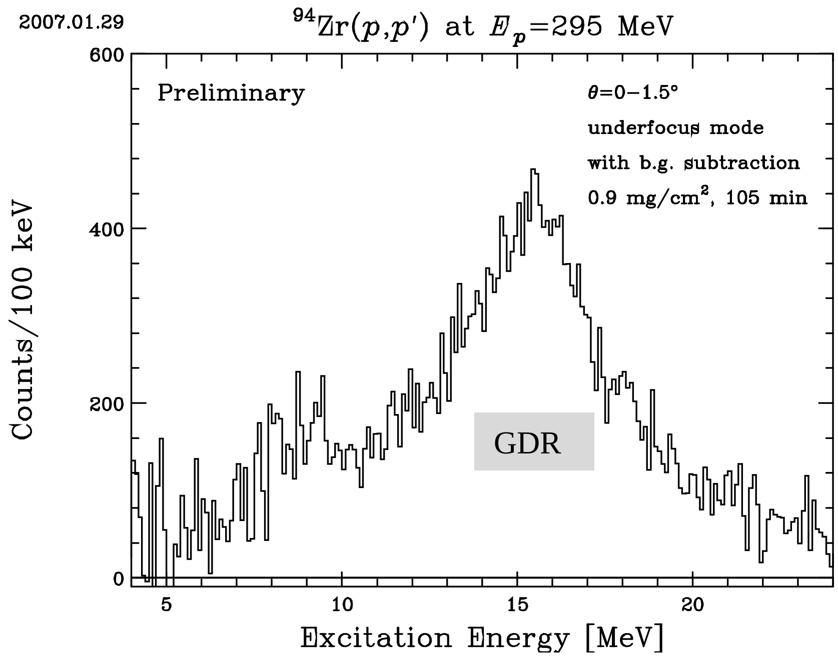
Γ=2.5MeV in Lorentz shape

(p,p') data

Crawley PRC26 (1982)

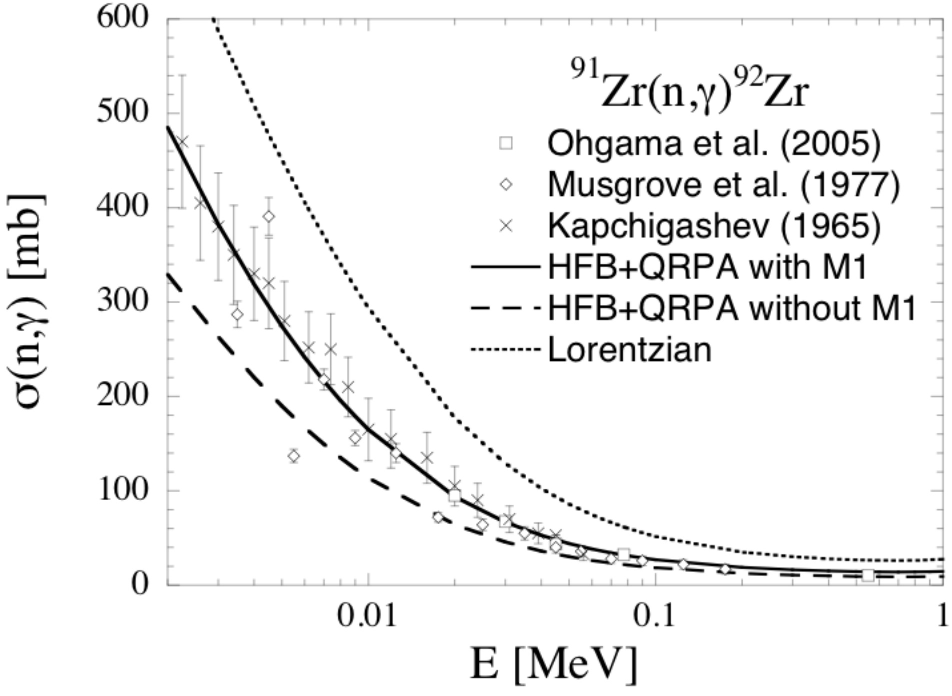


Tamii (priv. comm.)

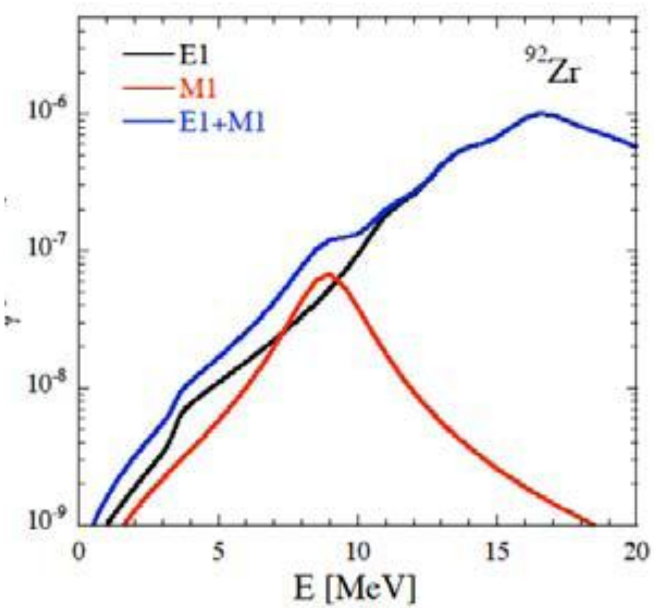


Coherent analysis of (γ,n) and (n,γ) cross sections

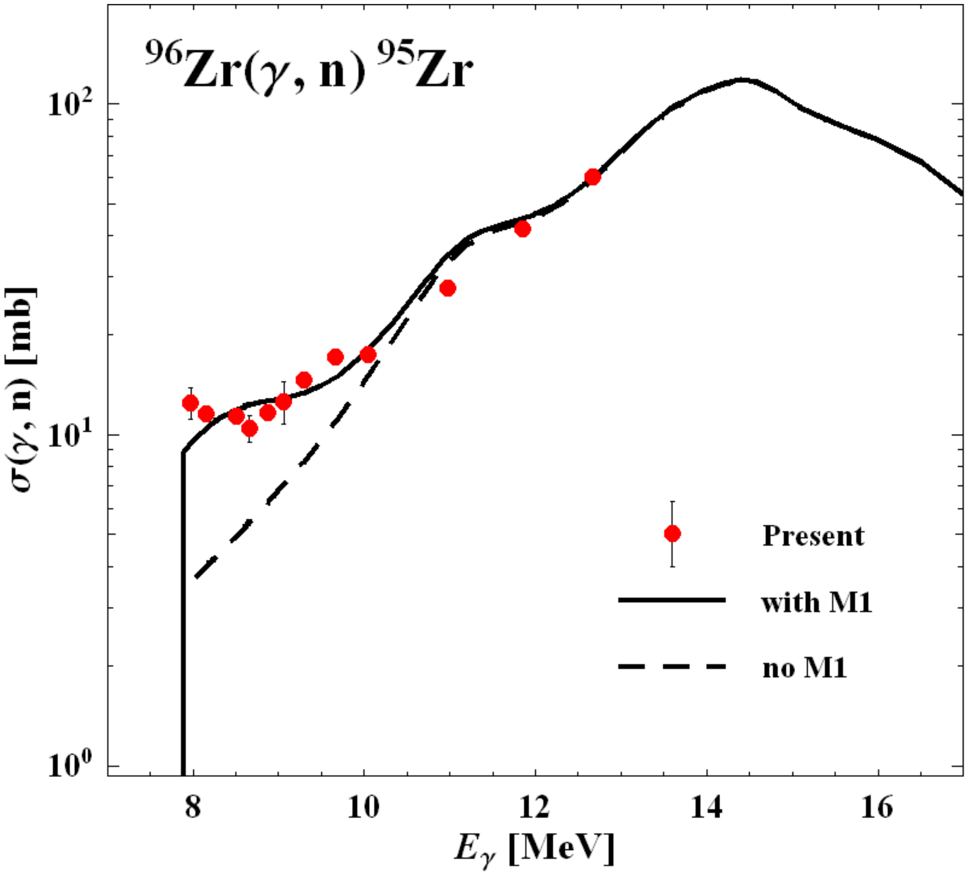
^{91}Zr(n,γ) cross sections



γ-ray strength function for ^{92}Zr

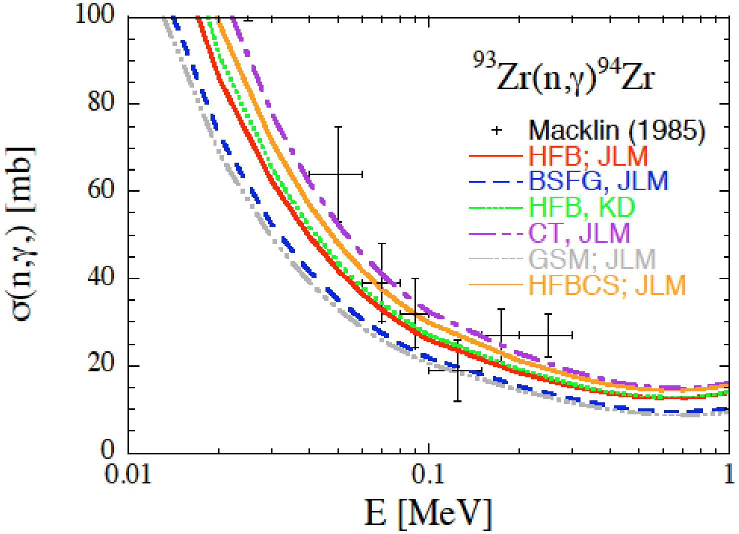


$^{96}Zr(\gamma,n)^{95}Zr$ cross sections



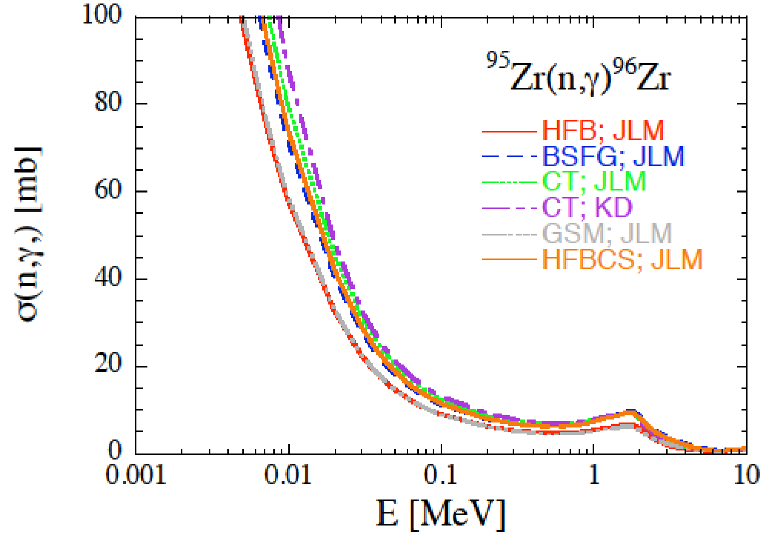
γ-ray strength functions
E1 : HFB+QRPA
plus
M1 resonance in Lorentz shape
E_o = 8.5 MeV
(9.0 MeV for $^{91,92,94}Zr$)
σ_0 =7.5mb
Γ=2.5 MeV

^{93}Zr[$T_{1/2}$=1.5 × 10^{6} y](n, γ)^{94}Zr
Transmutation of nuclear waste



Uncertainties : 40 – 50%
in 0.01 – 1 MeV

^{95}Zr[$T_{1/2}$=64 d](n, γ)^{96}Zr
s-process branching



Uncertainties : 30 – 40%
in 0.01 – 1 MeV

Source of uncertainties

<u>NLD models</u>

1. HFB+Combinatorial
2. BSFG
3. CT (Constant Temp.)
4. GSM (Gen. Superfluid)

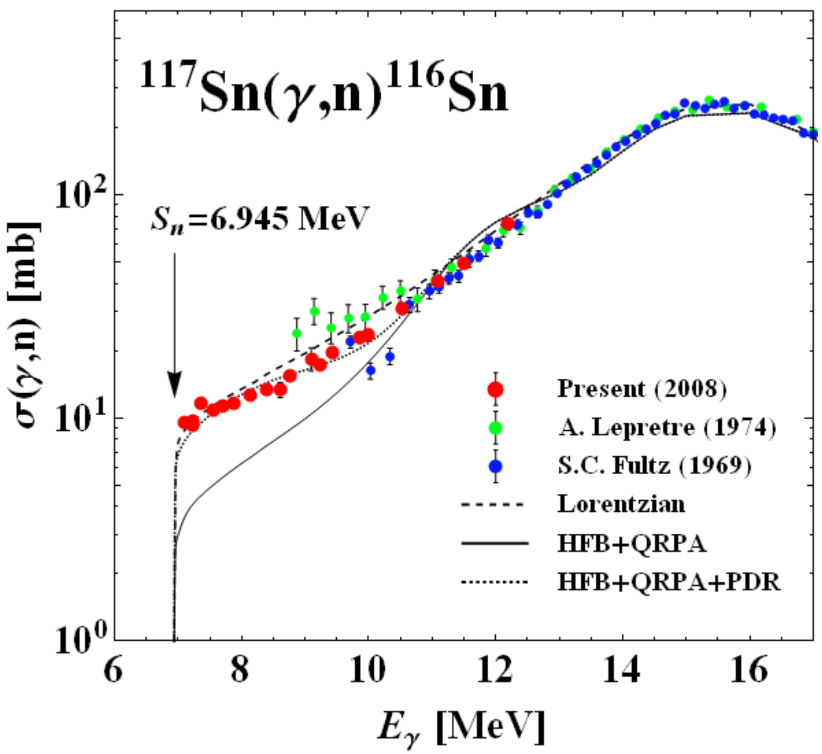
<u>Optical potential models</u>

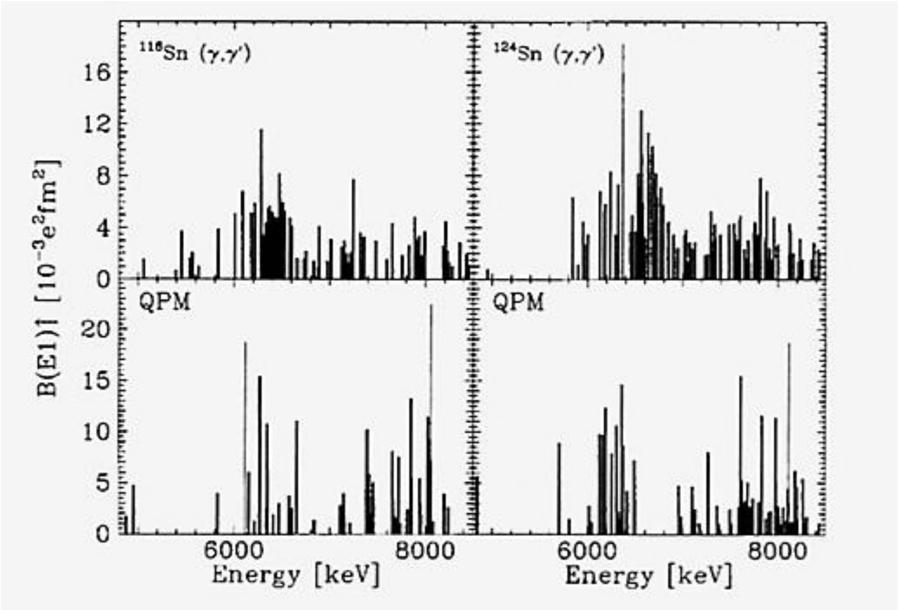
1. KD (Koning & Delaroche 2003)
2. JLM (Bauge et al. 2001)

Pygmy E1 resonance in ^{117}Sn

GDR (HFB+QRPA) + PDR

(E_o=8.5 MeV, Γ=2 MeV, s_o=7 mb in Gaussian shape)

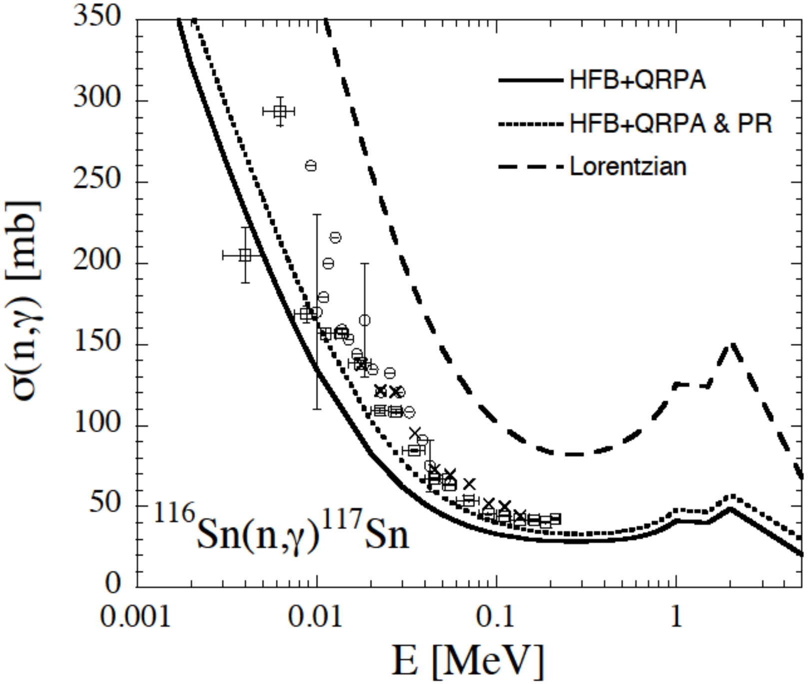




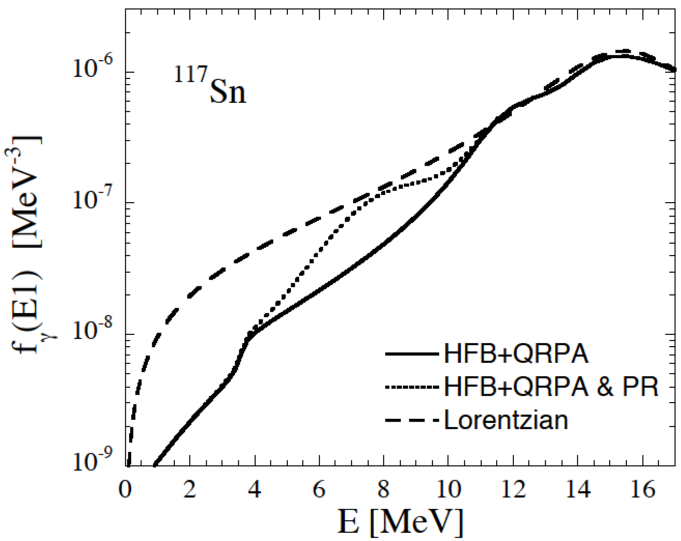
Kovaert et al., PRC57 (1998)

γ-ray strength function for ^{117}Sn

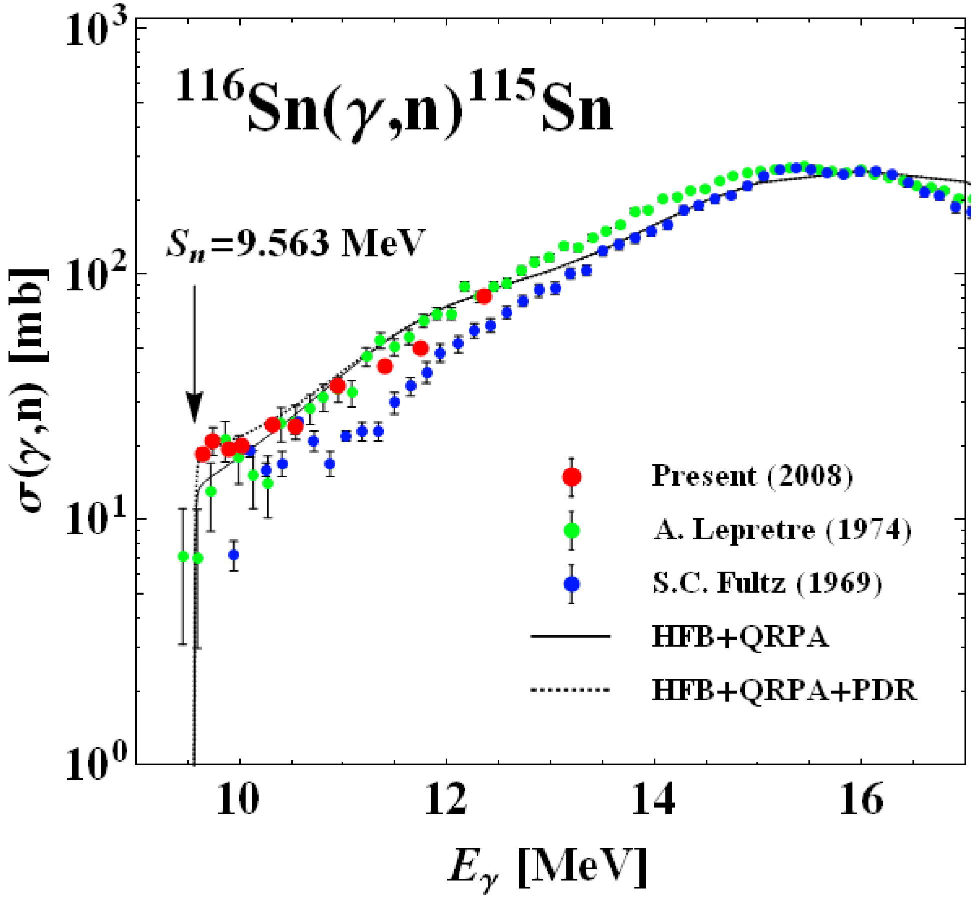
^{116}Sn(n,γ)^{117}Sn



γ-ray strength function



Pygmy dipole resonance in ^{116}Sn



まとめ

1. (γ,n)チャンネルでの余剰ガンマ線強度関数の実験的導出の処方箋を示した。

・(HFB+QRPA E1 + 余剰)強度関数

・Coherent analysis of (γ,n) and (n,γ) cross sections

2. Pygmy E1 共鳴の実験的理論的研究が急務

・いろいろな実験的プローブによる安定・不安定核の研究 (γ,n)(γ,γ')(p,p') 他

・核構造の理論的理解:集団運動モード、一粒子励起モード

・Systematics(E_o, Γ)の確立