Pygmy E1 and giant M1 resonances in the nucleosyntheis of heavy elements

H. Utsunomiya (Konan University)

Workshop on "Level Density and Gamma Strength"
Oslo, Norway, 11. - 15. May 2009.

Outline

1. **Basics of the statistical model with emphasis on γ-ray strength function in (n,γ) and (γ,n) reactions**
2. **(γ.n) data indicative of extra γ-ray strengths (pygmy E1 & giant M1)**
3. **HF model predictions of (n,γ) cross sections with γ-ray strength function**
4. **Summary**

Collaborators

Konan U.	**H. Utsunomiya, H. Akimune, T. Yamagata**
AIST	**K. Yamada, H. Toyokawa, T. Matsumoto, H. Harano**
JAEA	**H. Harada, F. Kitatani, S. Goko**
RCNP	**T. Shima**
NewSUBARU	**S. Miyamoto**
Texas A&M, USA	**Y.-W. Lui**

ULB, Brussels, Belgium	**S. Goriely**
CEA-Bruyères-le-Châtel, France	**S. Hilaire, S. Peru**
ZG Petten, The Netherlands	**A.J. Koning**

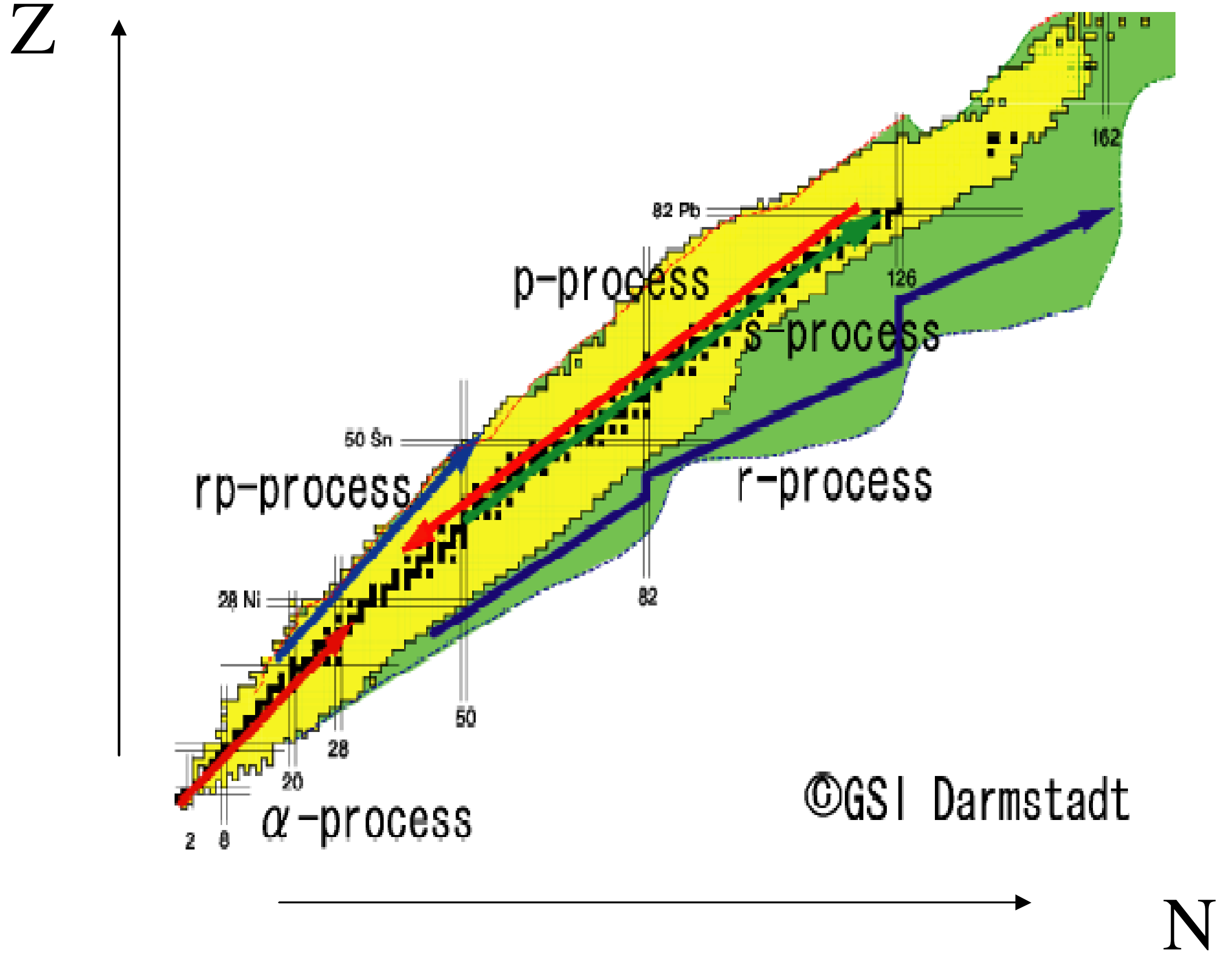
The present study includes the result of "Study on nuclear data by using a high intensity pulsed neutron source for advanced nuclear system" entrusted to Hokkaido University by the Ministry of Education, Culture, Sports, Science and Technology of Japan (MEXT).

Nucleosynthesis of elements heavier than Fe

Leading reactions

s, r-processes: neutron capture

p-process: photodisintegration, [proton capture]



Experimentalist's view of the statistical model

Assumption: compound nuclear reactions under ΔE□D

ΔE: energy spread of incident particles

D: average level spacing

or high $\rho(U)$

Hauser-Feshbach model A(a,b)B

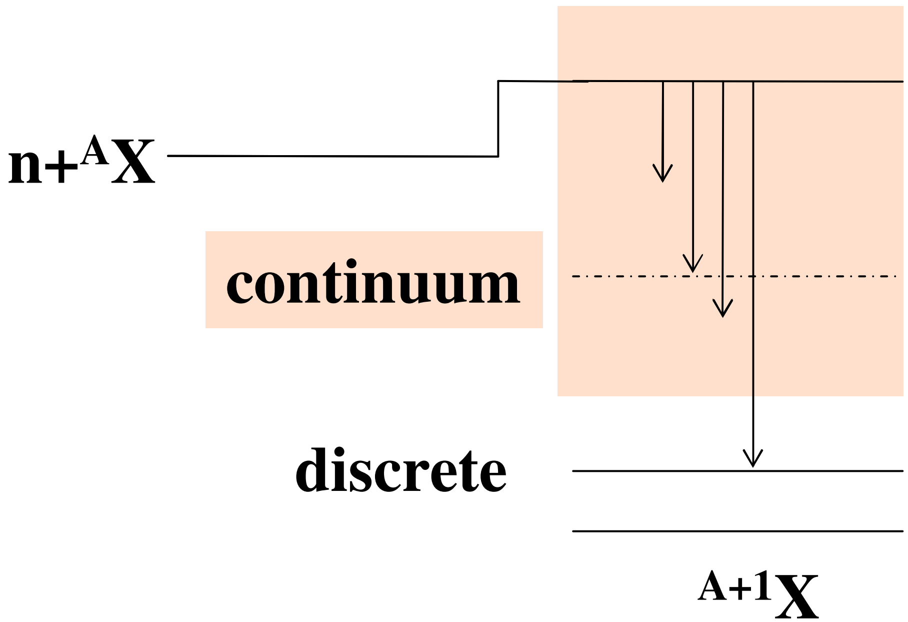
$$\sigma_{\beta\alpha} = \frac{\pi}{k_a^2} \sum_{J,\pi} g_J \frac{T_\beta T_\alpha}{T_{tot}}$$

α=a+A, β=b+B

statistical factor

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

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



γ-ray strength function

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

γ-ray transmission coeff.

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

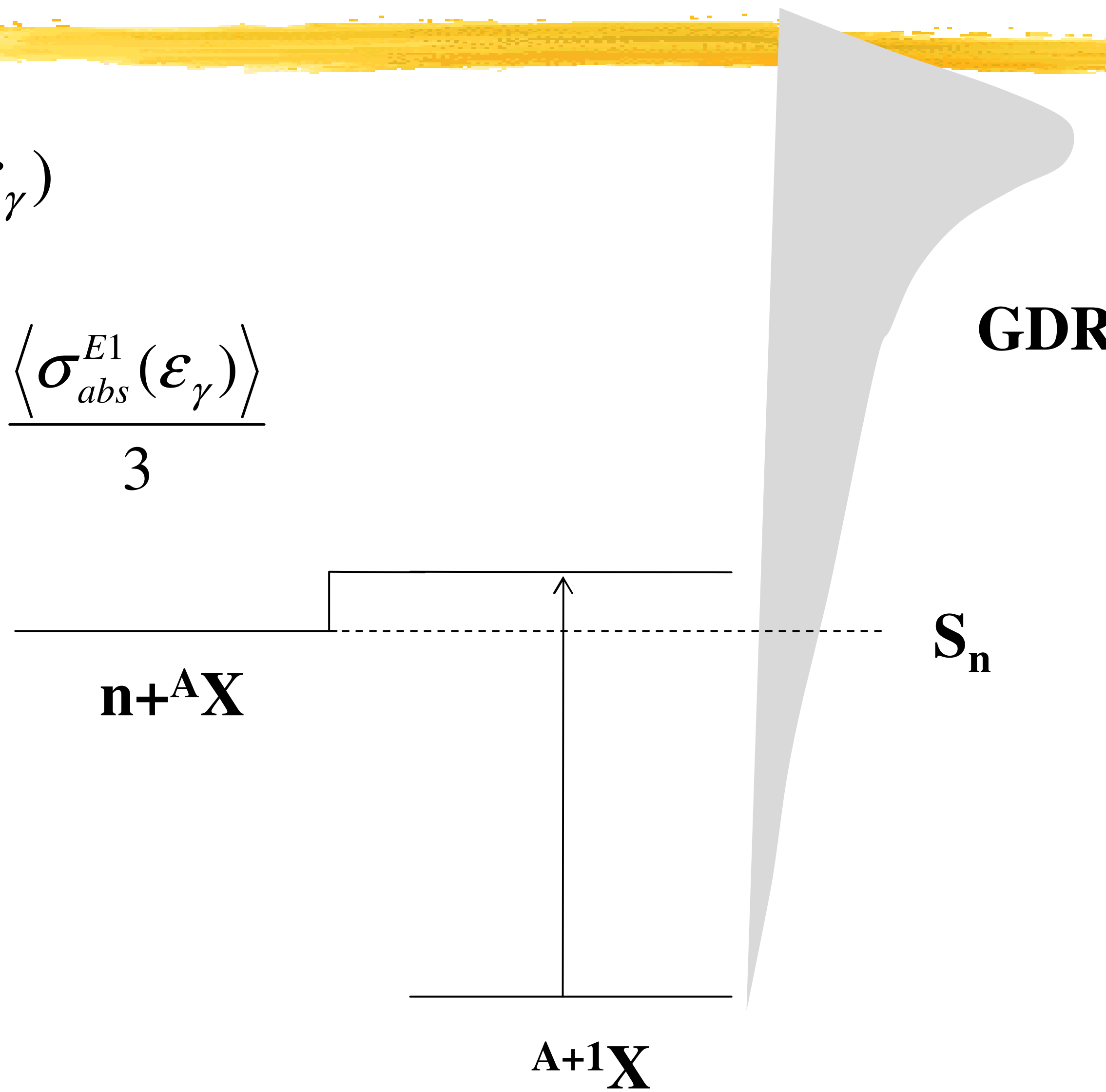
$$= 2\pi \varepsilon_\gamma^{3} \overleftarrow{f}_{E1}(\varepsilon_\gamma)$$

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

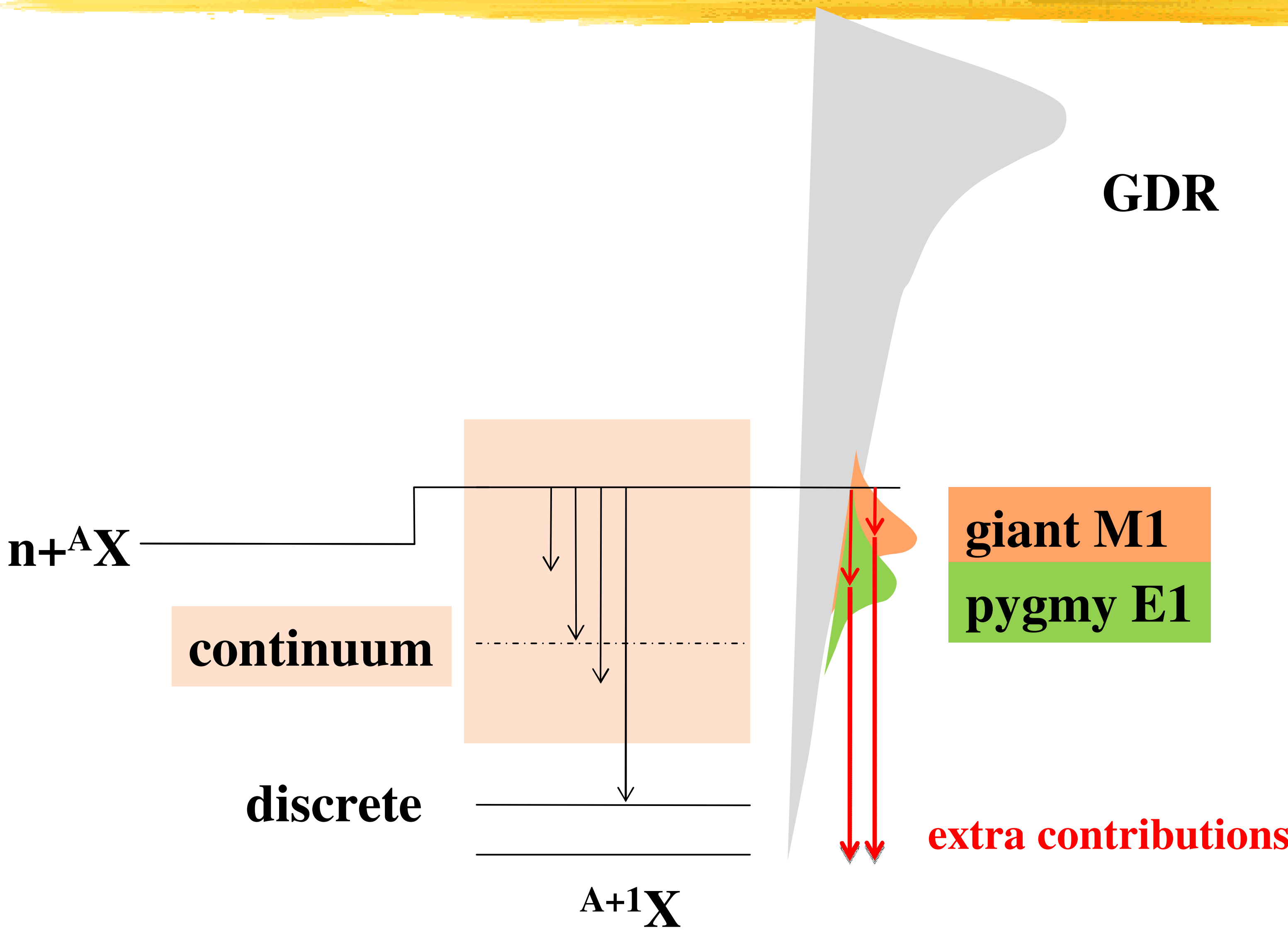
Photonuclear reactions: $^{A+1}X(\gamma,n)^{A}X$

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

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



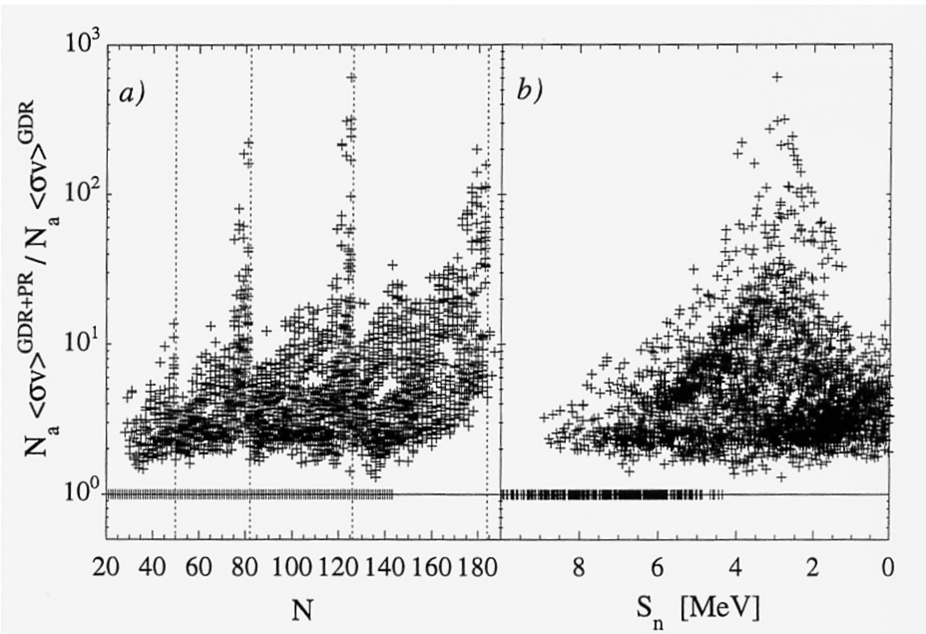
Enhancements of neutron capture via pygmy E1 and giant M1 resonances

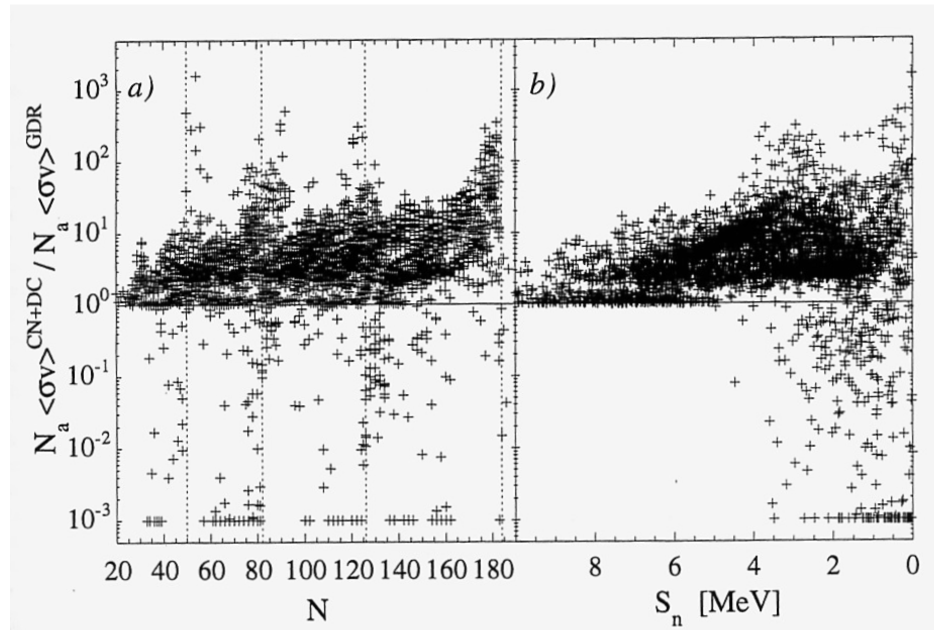


Goriely, PLB (1998)

GDR vs GDR+PDR

CN vs CN+DC





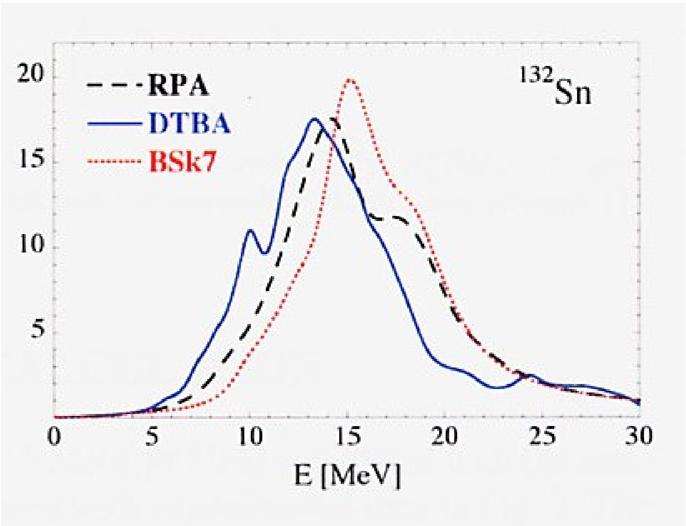
Closed-shell nuclei
with $2 \leq S_n$ [MeV] ≤ 4

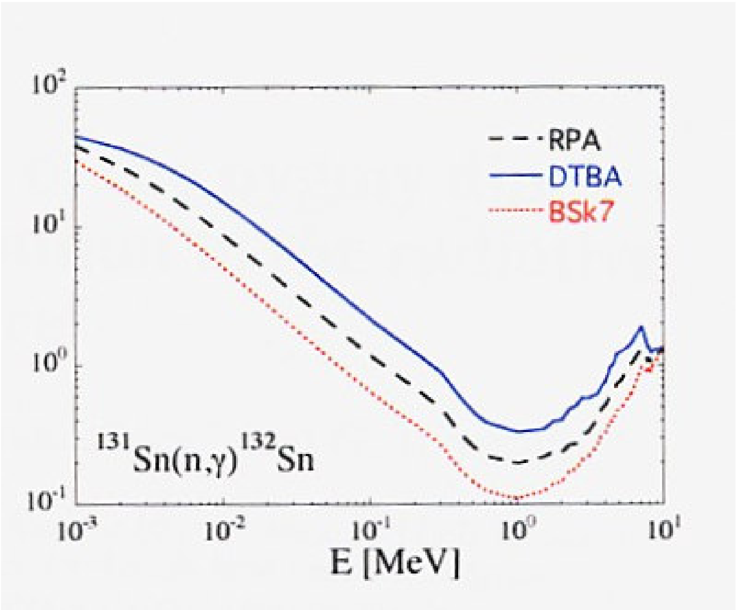
$1 \leq S_n$ [MeV] ≤ 3

DTBA (Discrete Time Blocking Approximation)

Avdeyenkov, Goriely, Kamerdzhiev, Tertychny (2008)

Key ingredients
Single particle continuum
Phonon coupling

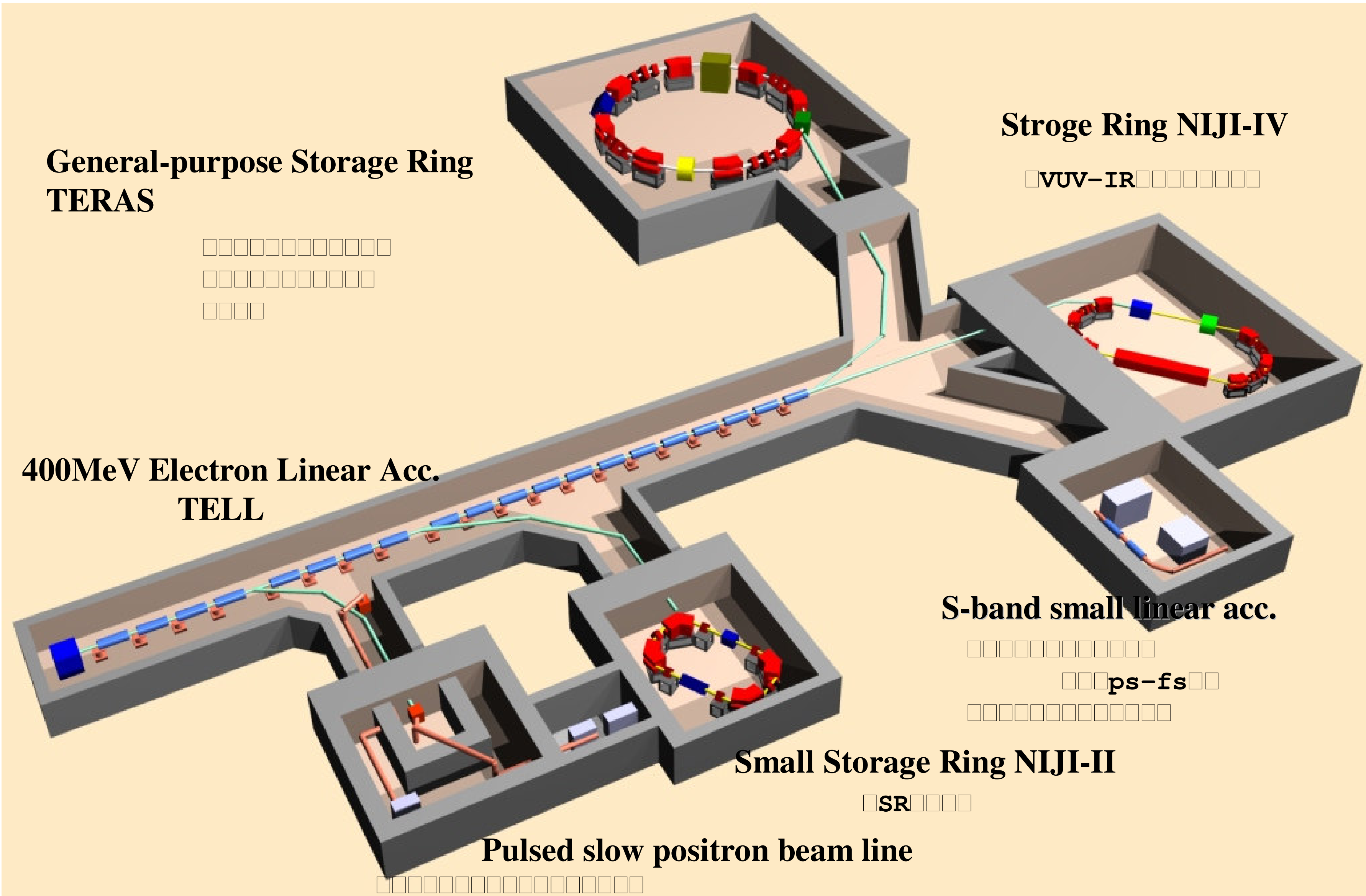




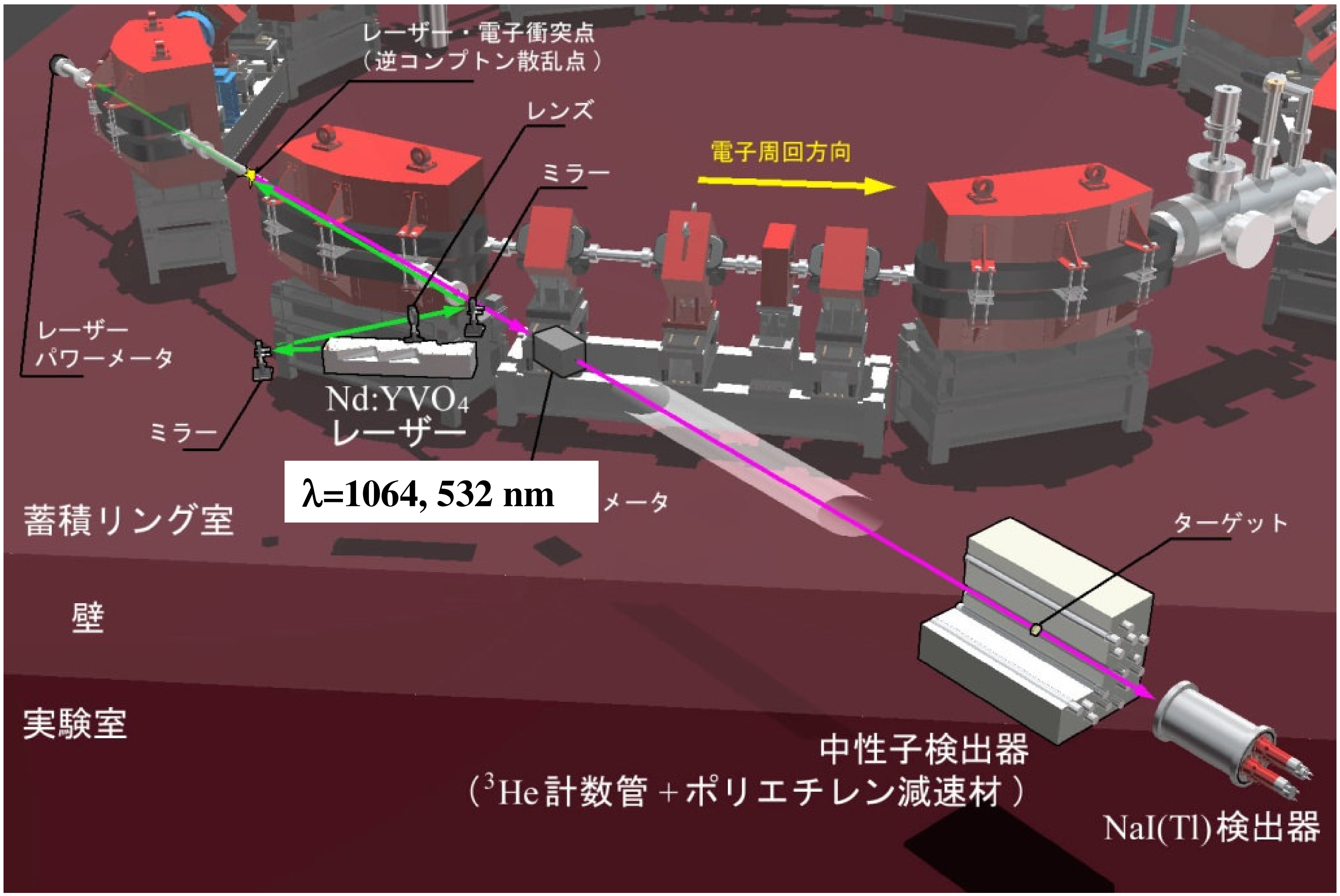
Correct prediction of PDR in ^{132}Sn at 9.8 MeV

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

AIST Electron Accelerator Facility; National Institute of Advanced Industrial Science and Technology (AIST)



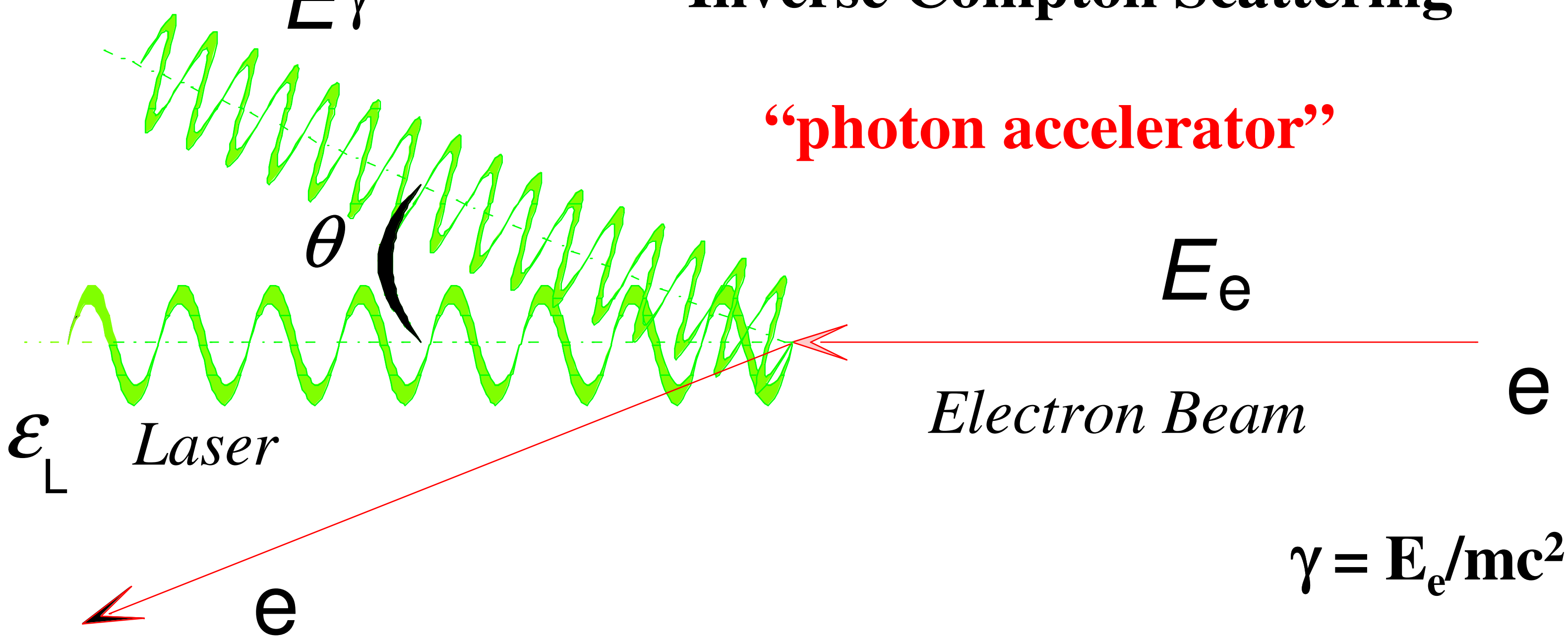
Tsukuba Electron Ring for Acceleration and Storage (TERAS) at AIST



• Energy $\quad E_\gamma = 1 – 40$ MeV

Inverse Compton Scattering

"photon accelerator"

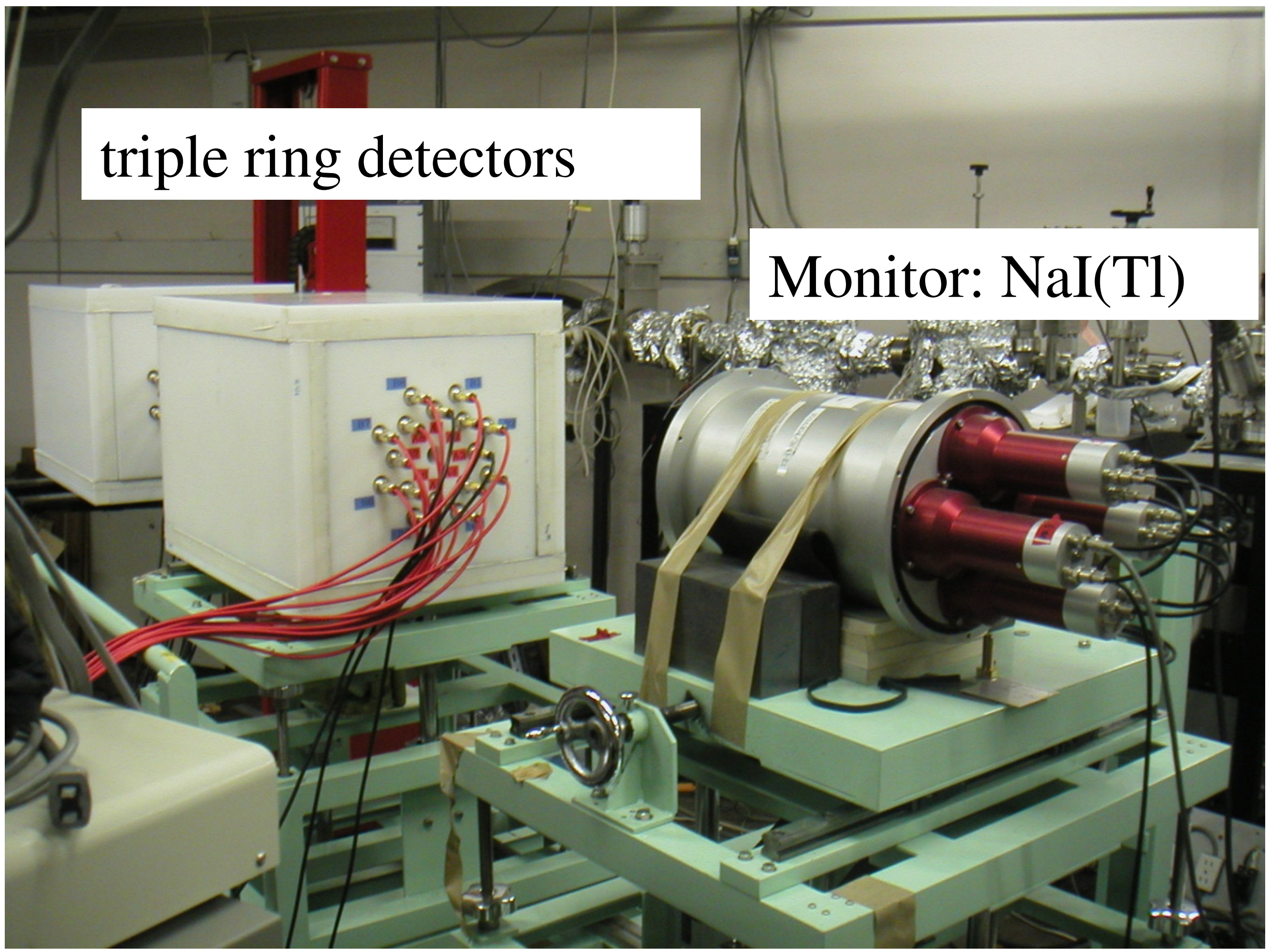


$\gamma = E_e/mc^2$

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

Neutron Detector System

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



Ingredients in the Talys code

Talys code: Koning, Hilaire, Duijvestijn, Proc. Int. Conf. on Nuclear Data for Science and Technology, AIP Conf. Proc. 769, 1154 (2005).

- **GDR γ-ray strength function**

Lorentzian models: Axel, PR126 (1962), Kopecky & Uhl, PRC41 (1990)

HFB+QRPA model: Goriely, Khan, Samyn, NPA739 (2006)

- **Spin-flip giant M1 γ-ray strength function**

Global systematics in RIPL Handbook (Bohr & Mottelson)

Lorentzian function : $E_o=41A^{-1/3}$ MeV, Γ_o = 4 MeV,

$f_{M1}=1.58\ 10^{-9}\ A^{0.47}\ MeV^{-3}$ at 7 MeV

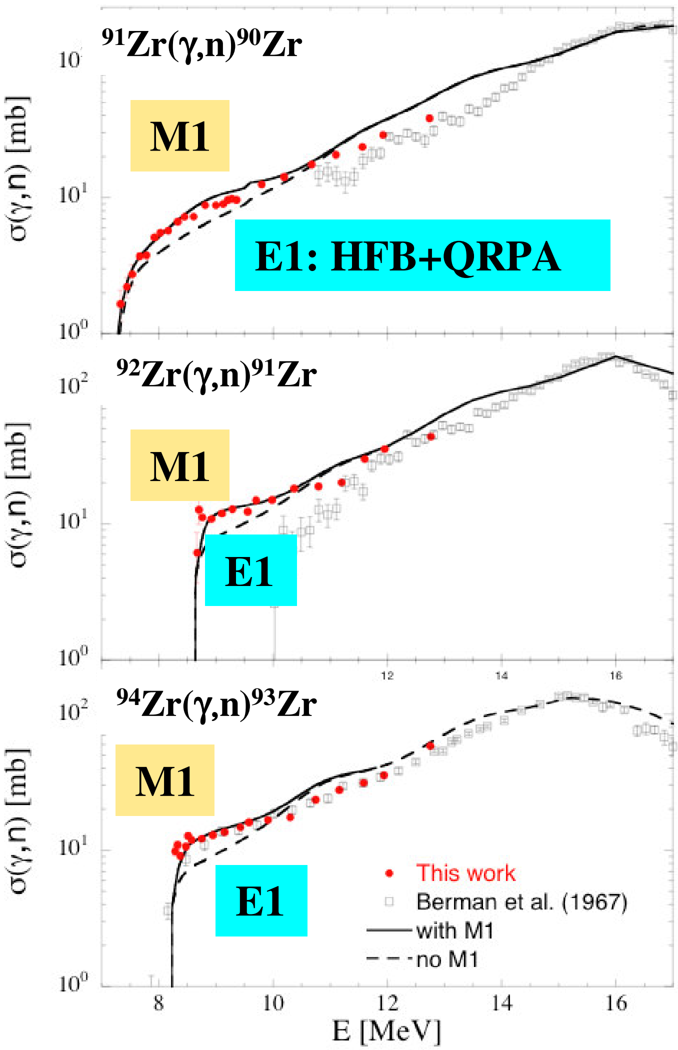
- **Pygmy E1: No global systematics**

- **Nuclear Level density**

HFB+ Combinatorial model: Hilaire & Goriely, NPA779 (2006)

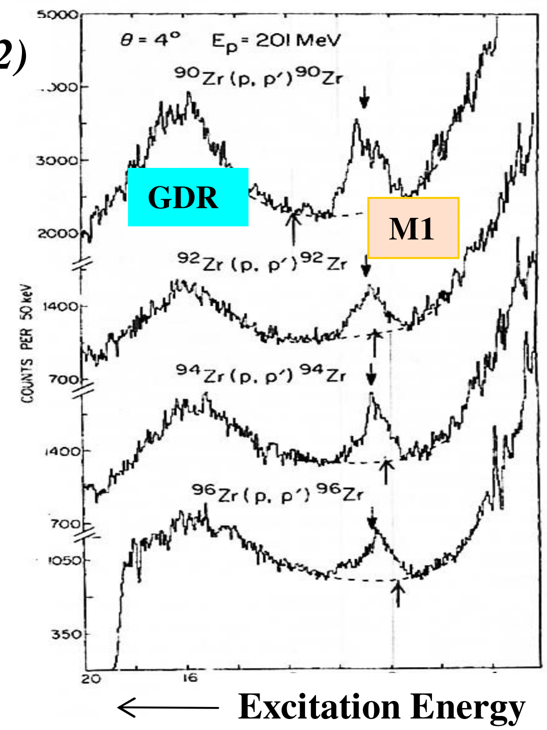
M1 strength in Zr isotopes in the photoneutron channel

H. Utsunomiya PRL100 (2008)

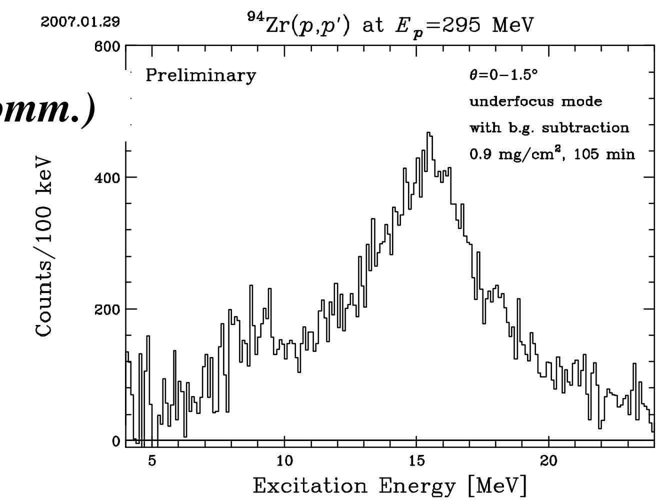


E1 γSF (HFB+QRPA)
M1 resonance
E_0= 9 MeV, σ_0=7.5mb, Γ=2.5MeV in Lorentz shape.

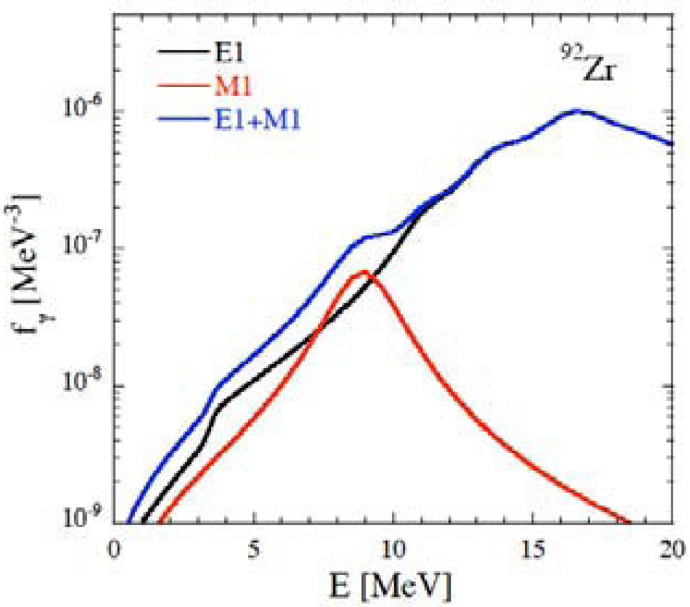
Crawley PRC26 (1982)

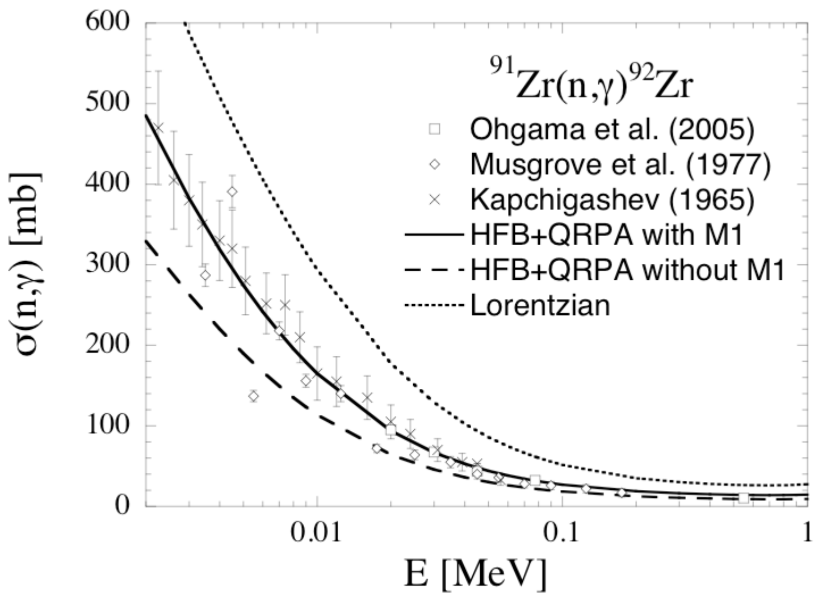


Tamii (priv. comm.)



γ-ray strength function for ^{92}Zr



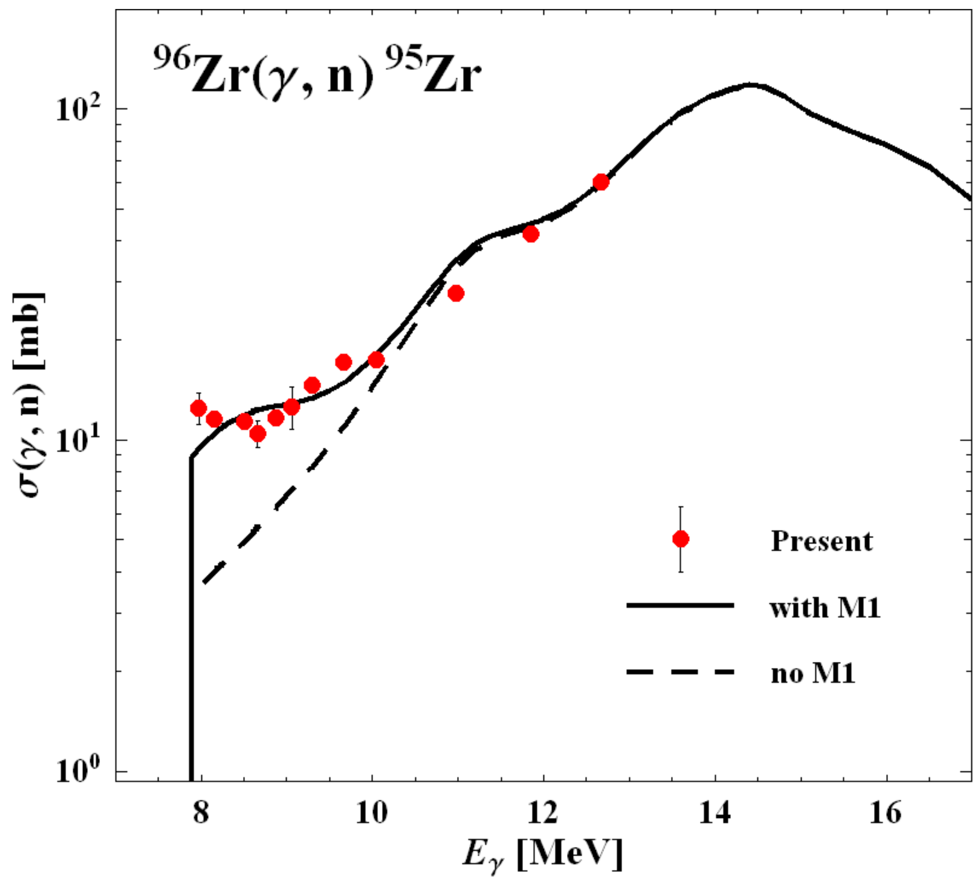


$^{96}Zr(\gamma,n)^{95}Zr$

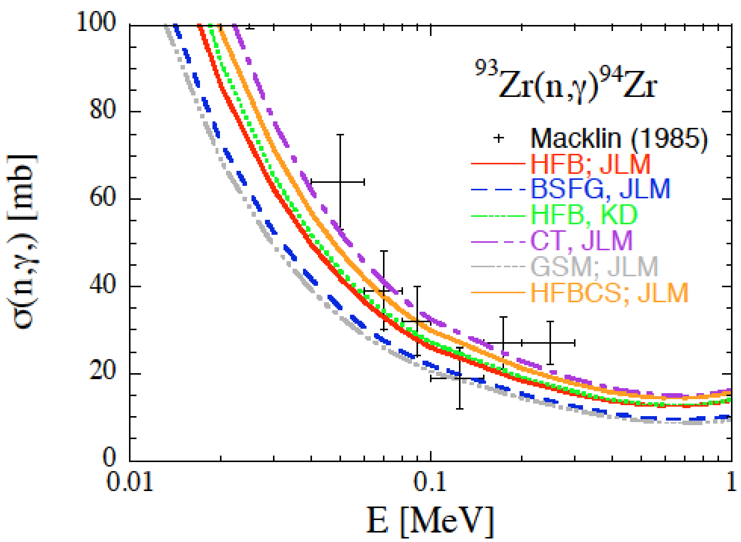
γ-ray strength functions
E1 : HFB+QRPA
plus
M1 resonance in Lorentz shape
E_o = 8.5 MeV (9.0 MeV for $^{91,92,94}Zr$)
σ_0 =7.5mb
Γ=2.5 MeV

NLD
HFB+ Combinatorial
Goriley & Hilaire (2008)

Optical potential
Koning & Delaroche (2003)

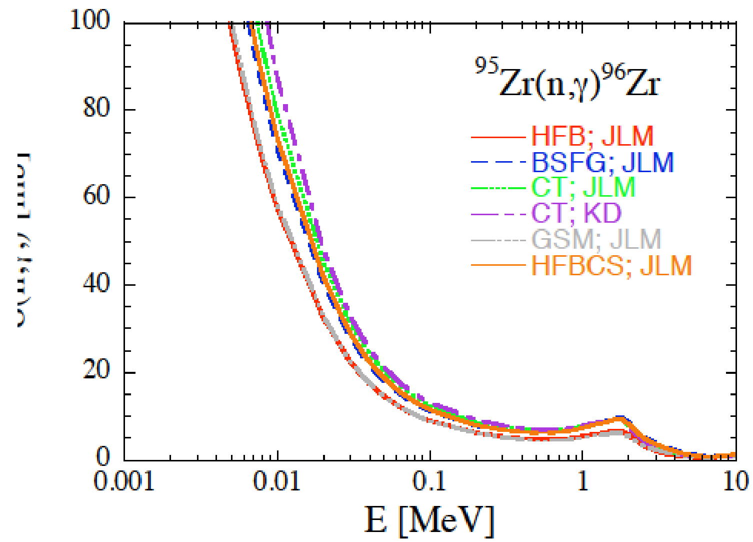


^{93}Zr[$T_{1/2}$=1.5 ×10^{6} y](n, γ)^{94}Zr
Transmutation of nuclear waste



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

NLD models

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

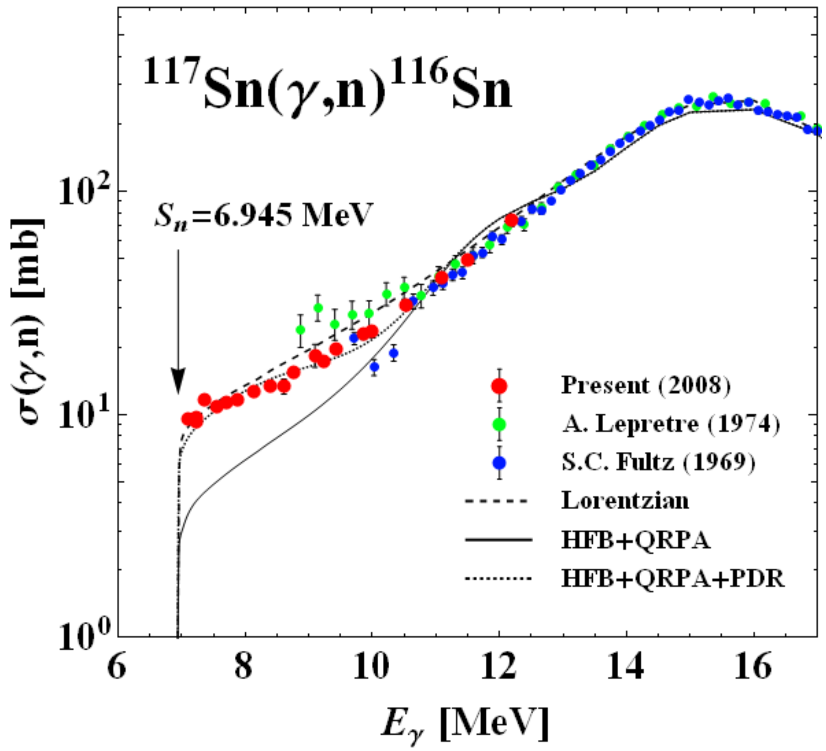
Optical potential models

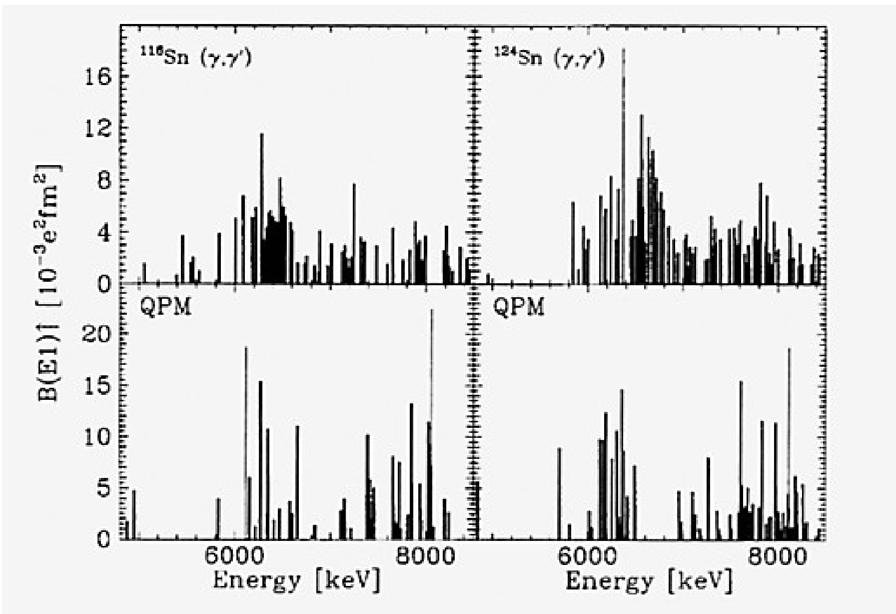
1. KD (Koning & Delaroche 2003)
2. JLM (Bauge et al. 2001)

Pygmy dipole resonance in ^{117}Sn

GDR (HFB+QRPA) + PDR

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

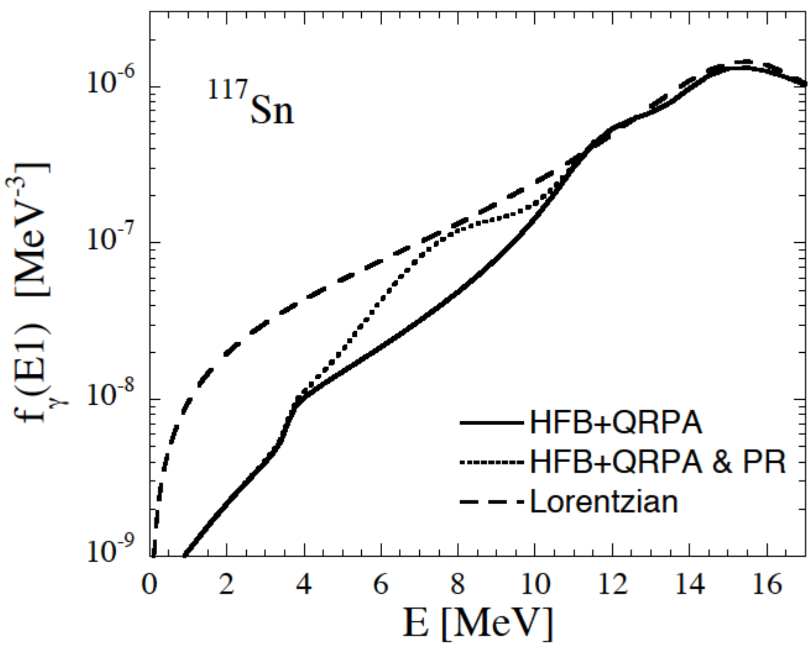




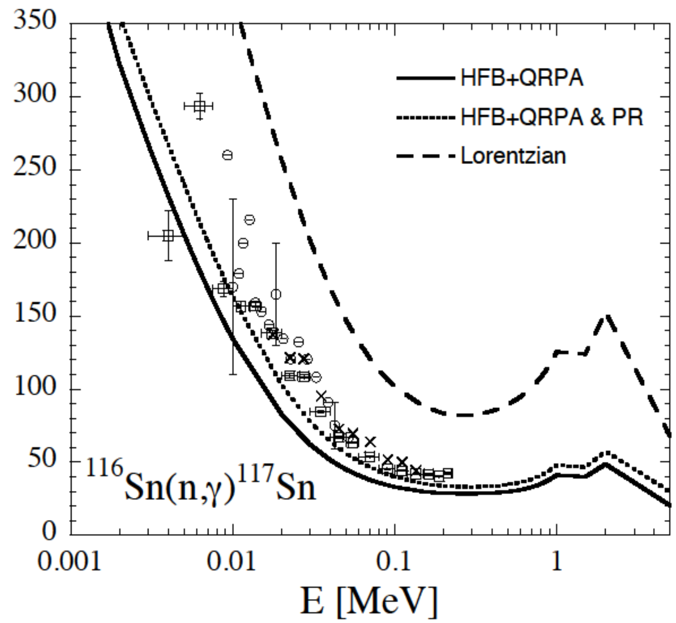
Kovaert et al., PRC57 (1998)

γ-ray strength function for ^{117}Sn

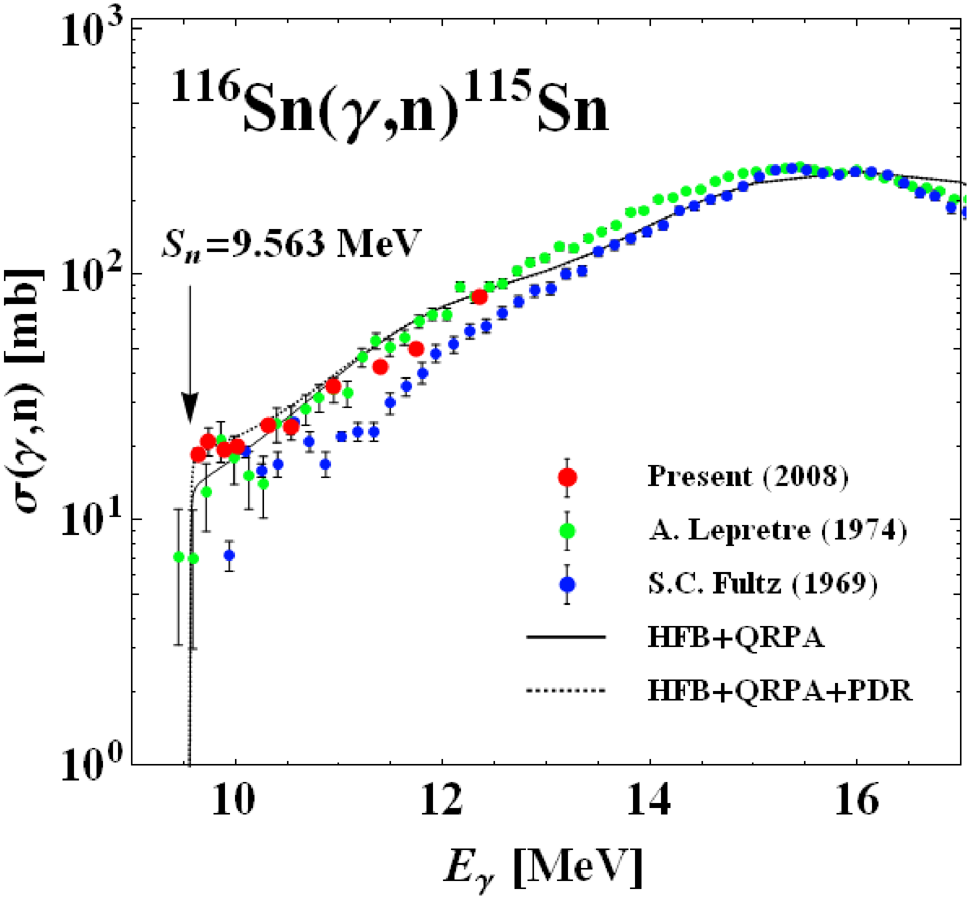
γ-ray strength function



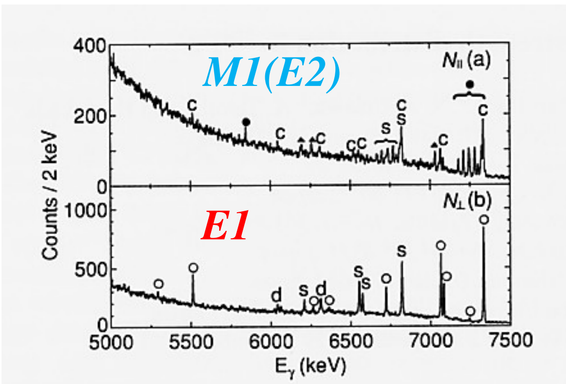
^{116}Sn(n,γ)^{117}Sn



Pygmy dipole resonance in ^{116}Sn

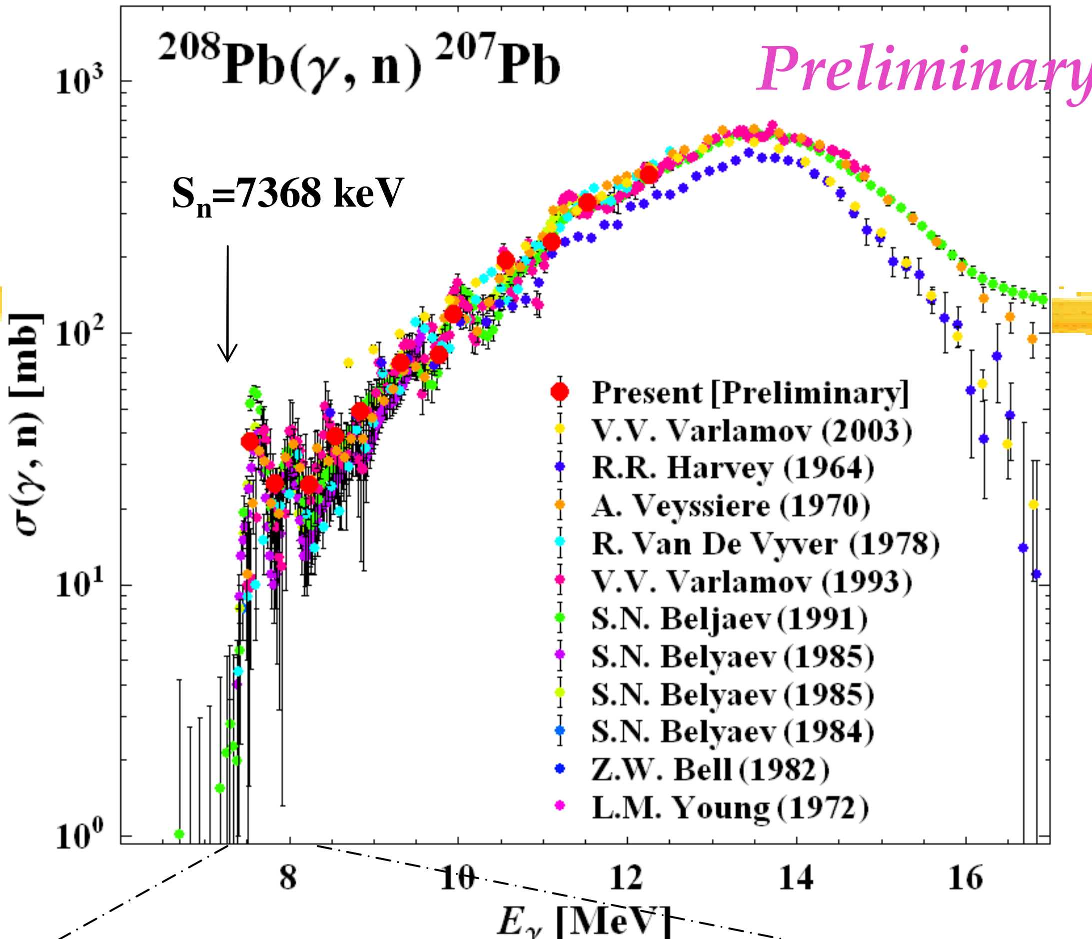


^{208}Pb



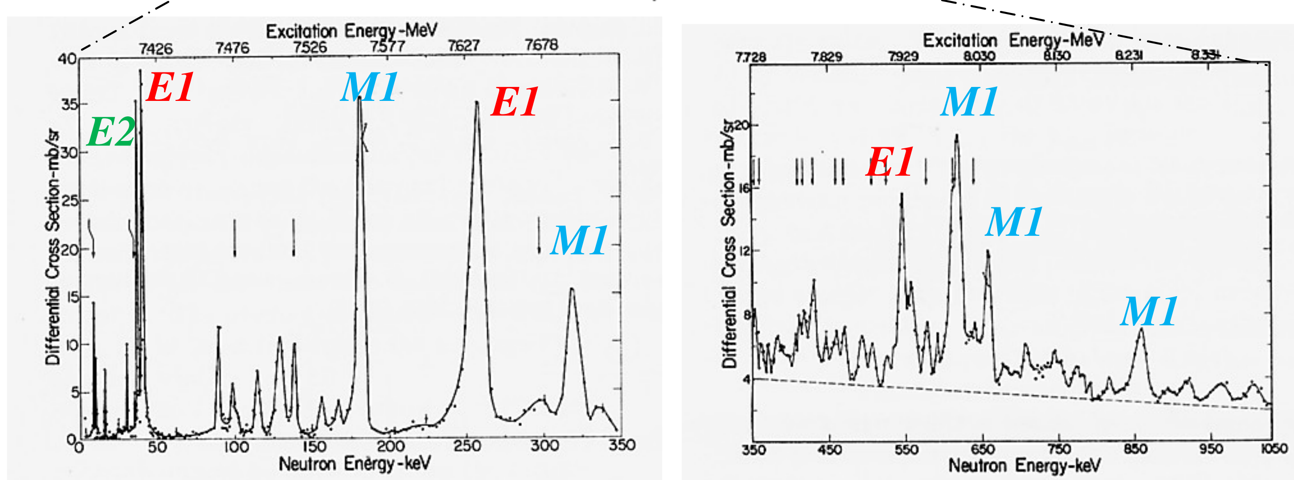
Shizuma PRC78 (2008)

$(\vec{\gamma},\gamma)$ **100% lin. pol.**

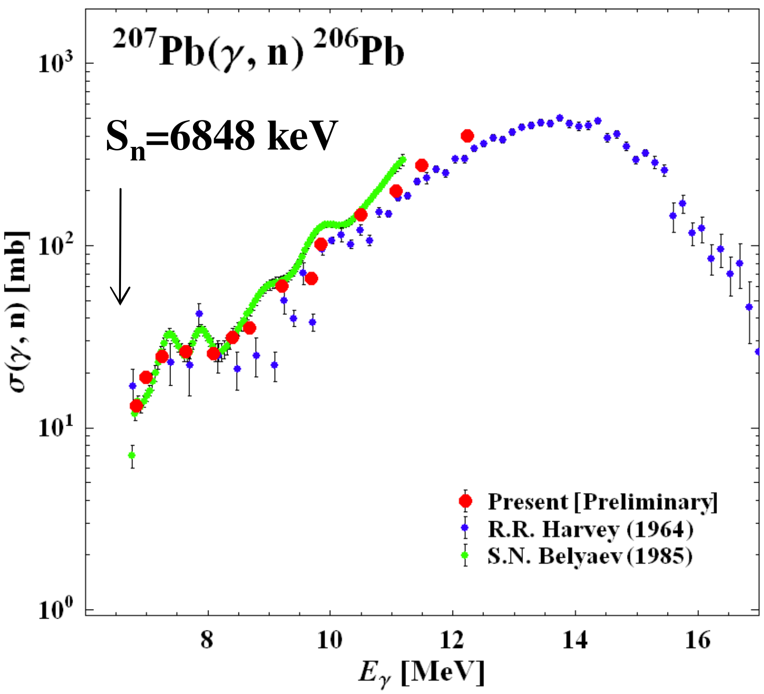


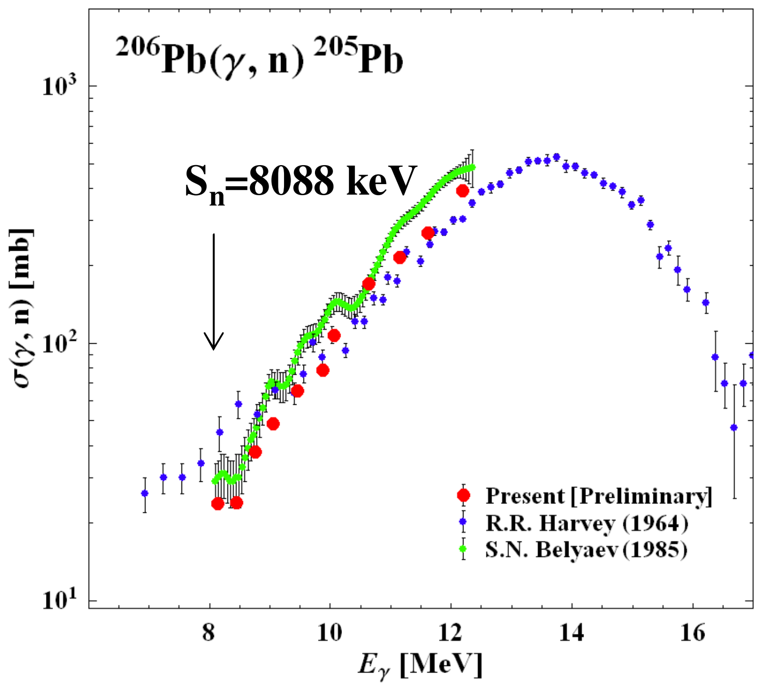
Bowman PRL25 (1970)

n-TOF spectra



^{207}Pb *Preliminary* ^{206}Pb





Summary

- The γ strength function is a key nuclear ingredient in the Hauser-Feshbach model calculations of neutron capture rates.

- It is important to investigate the low-energy E1 γ-ray strength function of GDR as a leading factor and pygmy E1 and giant M1 resonances as extra strengths .

- In particular, it is necessary to investigate experimentally and theoretically the nuclear structure and the global systematics of PDR by combining different probes of *γ, p*, ^{3}He, *e,* and others.

- After all, we still have lots of work to do for E1, M1, E2, …