Probing Nuclear Statistical Quantities by Photodisintegration

光核反応による統計的核物理量の研究

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RIKEN Workshop, 25-26 September

Outline

1. Japan synchrotron radiation facilities
2. Photodisintegration for nuclear statistical quantities
3. Systematic study of E1 & M1 γ strength functions for Zr isotopes
4. Pigmy E1 resonance for Sn isotopes
5. Nuclear level density
6. Summary

Collaborators

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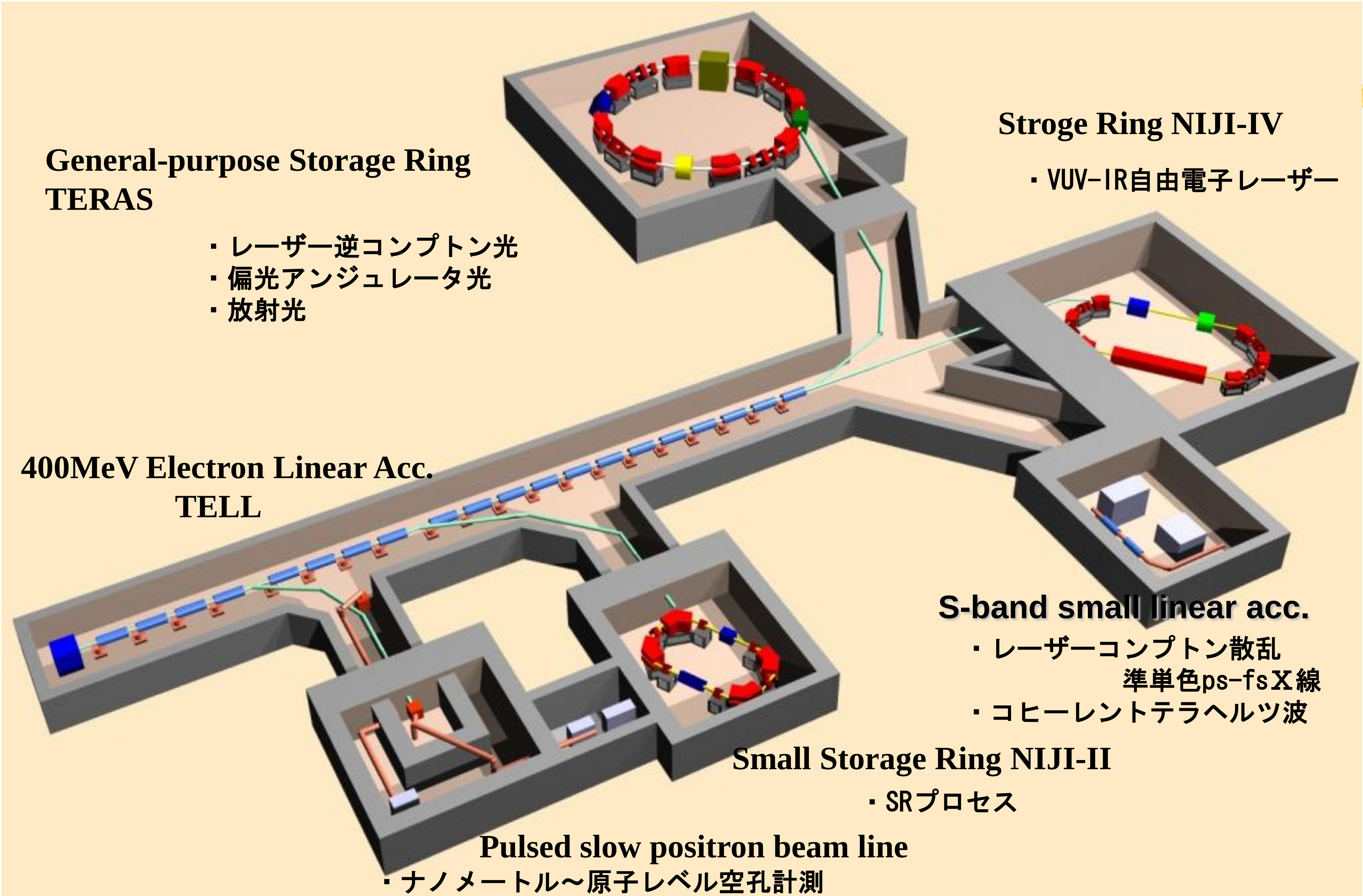
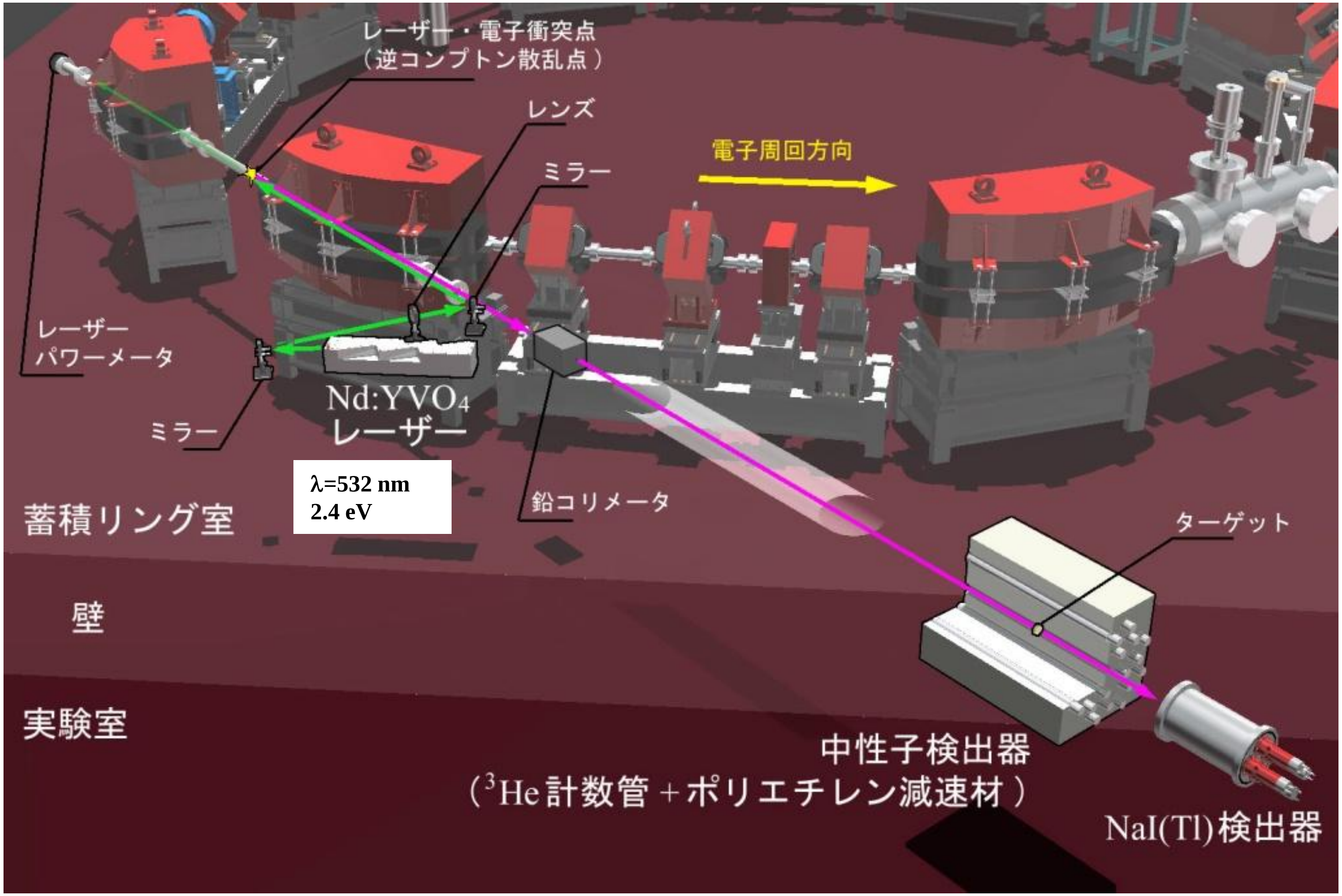
この研究発表は、旧電源開発促進対策特別会計法及びに特別会計に関する法律（エネルギー対策特別会計）に基づく文部科学省からの受託事業として、北海道大学が実施した平成20年度「高強度パルス中性子源を用いた革新的原子炉用核データの研究開発」の成果を含みます。

AIST Electron Accelerator Facility



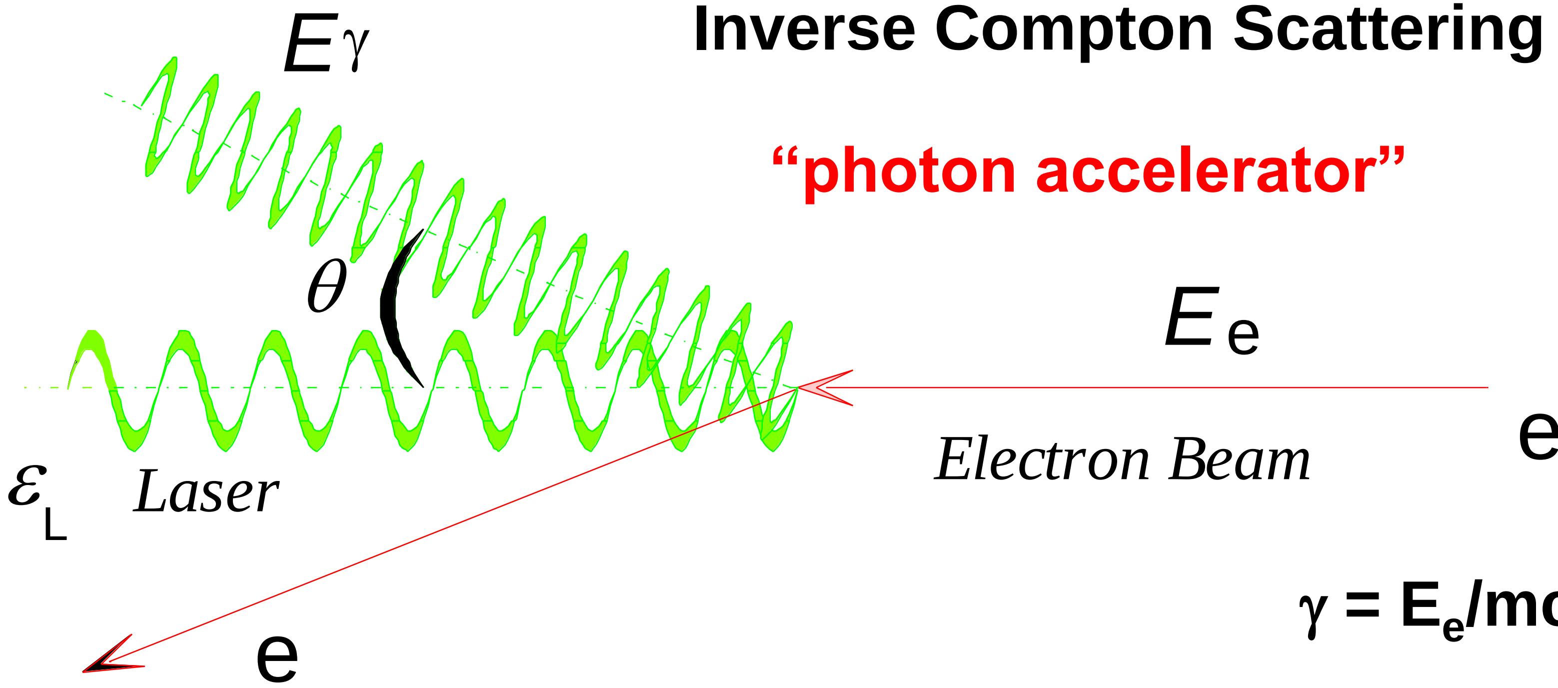
Tsukuba Electron Ring for Acceleration and Storage (TERAS)



• Energy $E_\gamma = 1 – 40\ \text{MeV}$

Inverse Compton Scattering

“photon accelerator”

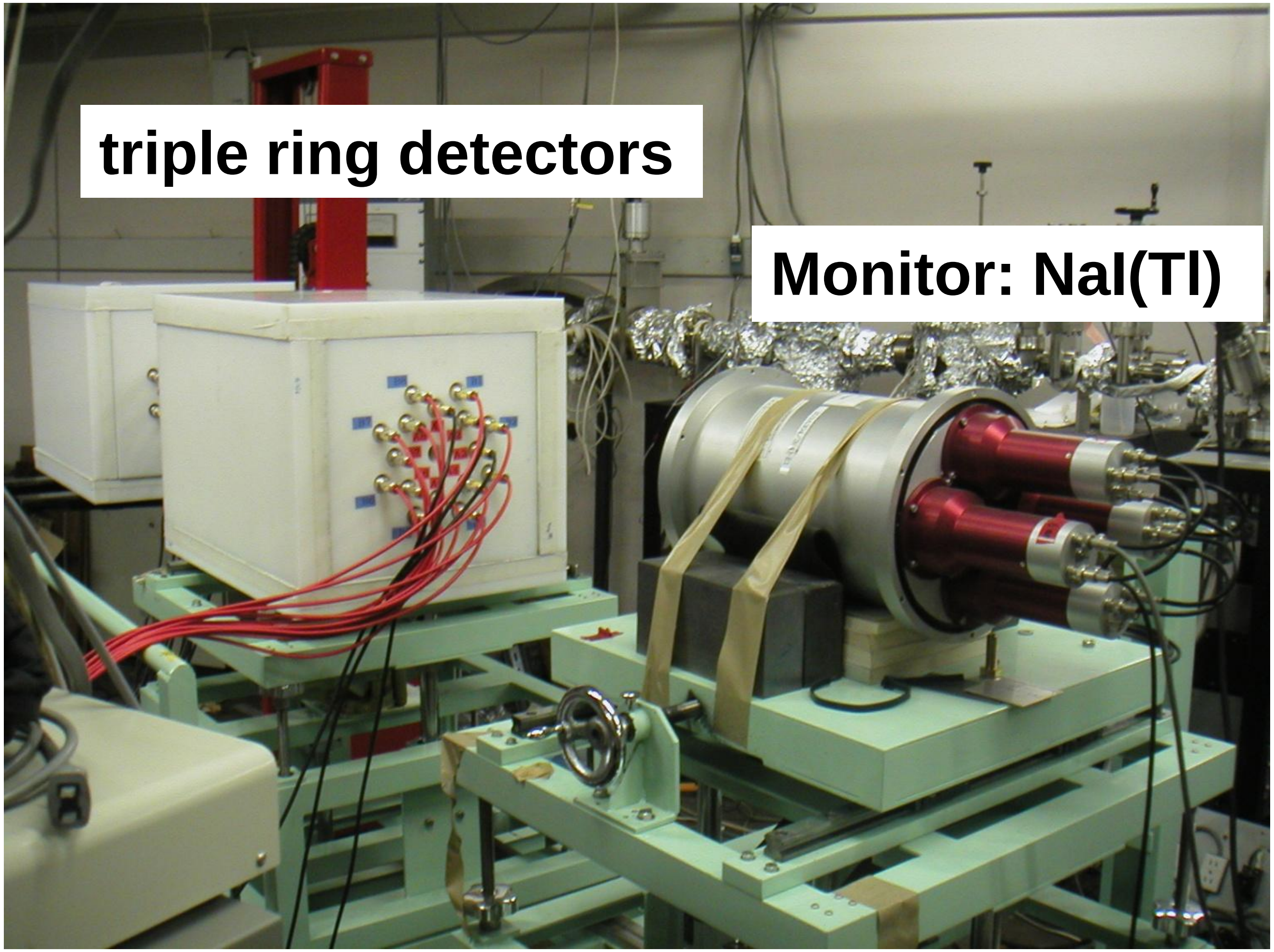


$\gamma = E_e/mc^2$

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

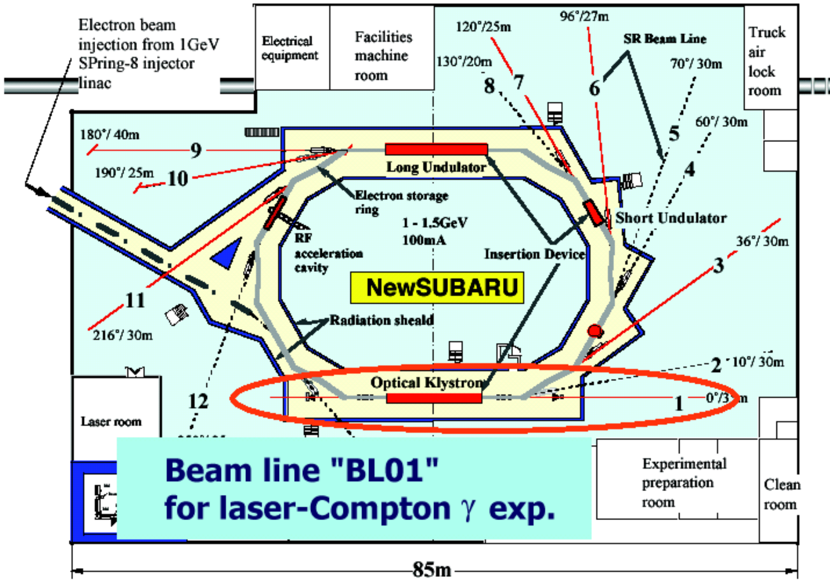
Neutron Detector System

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

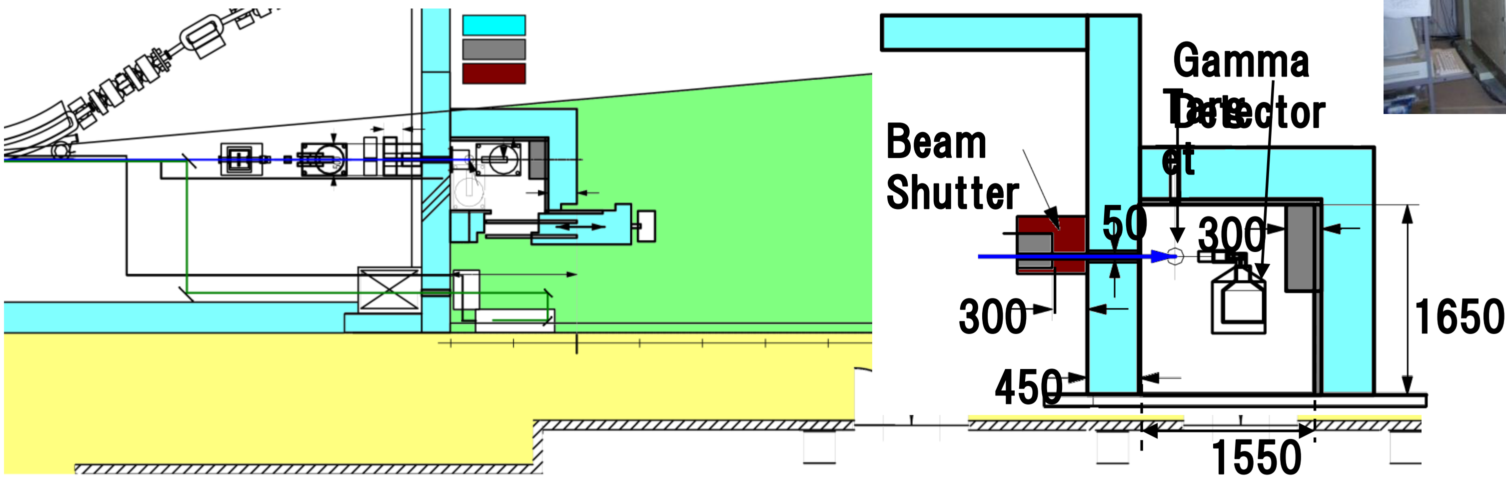


New SUBARU facility

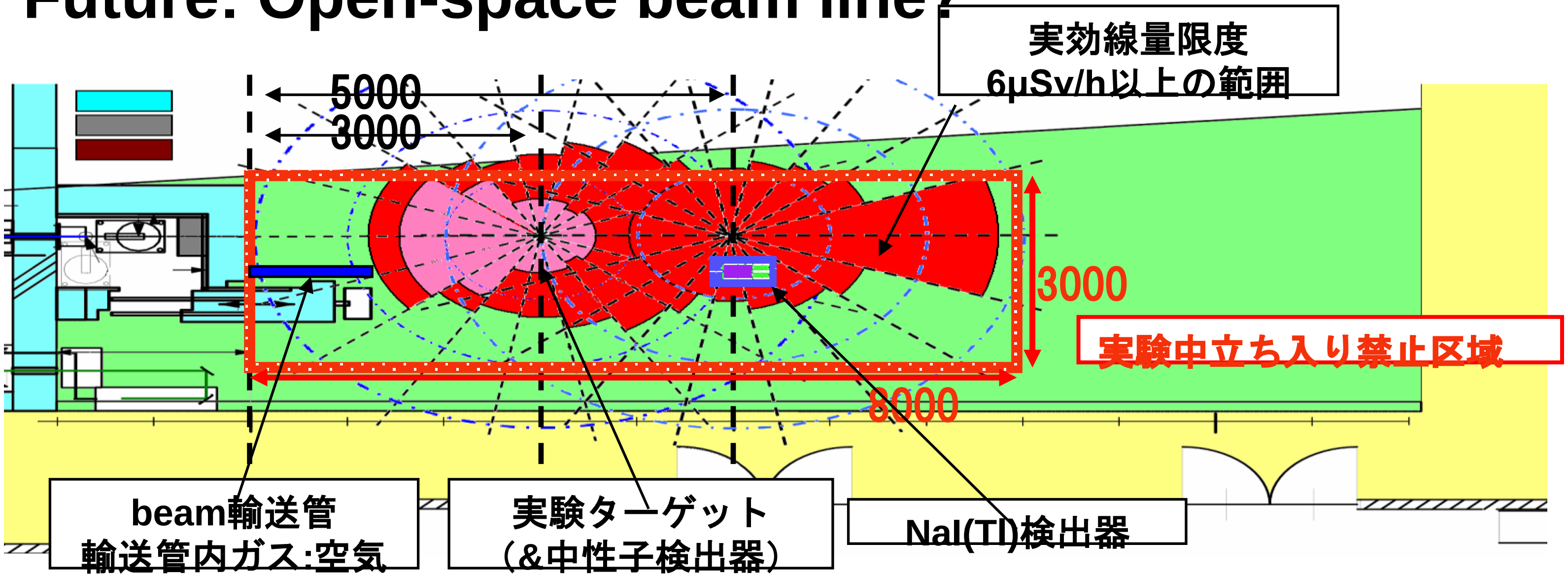
兵庫県立大
高度研



Present: limited space



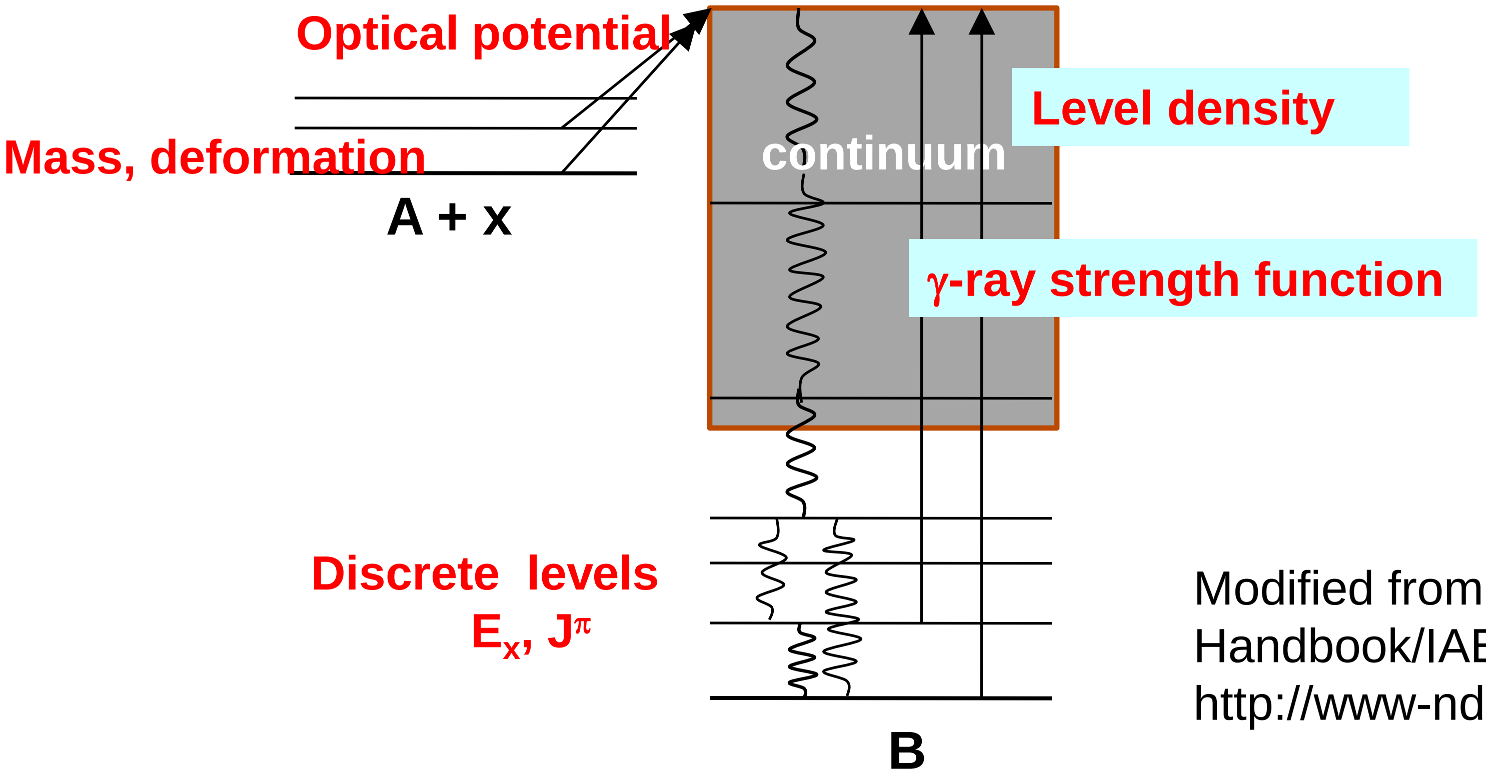
Future: Open-space beam line?



Radiative Capture and Photodisintegration

Nuclear Statistical Quantities in the Hauser-Feshbach model

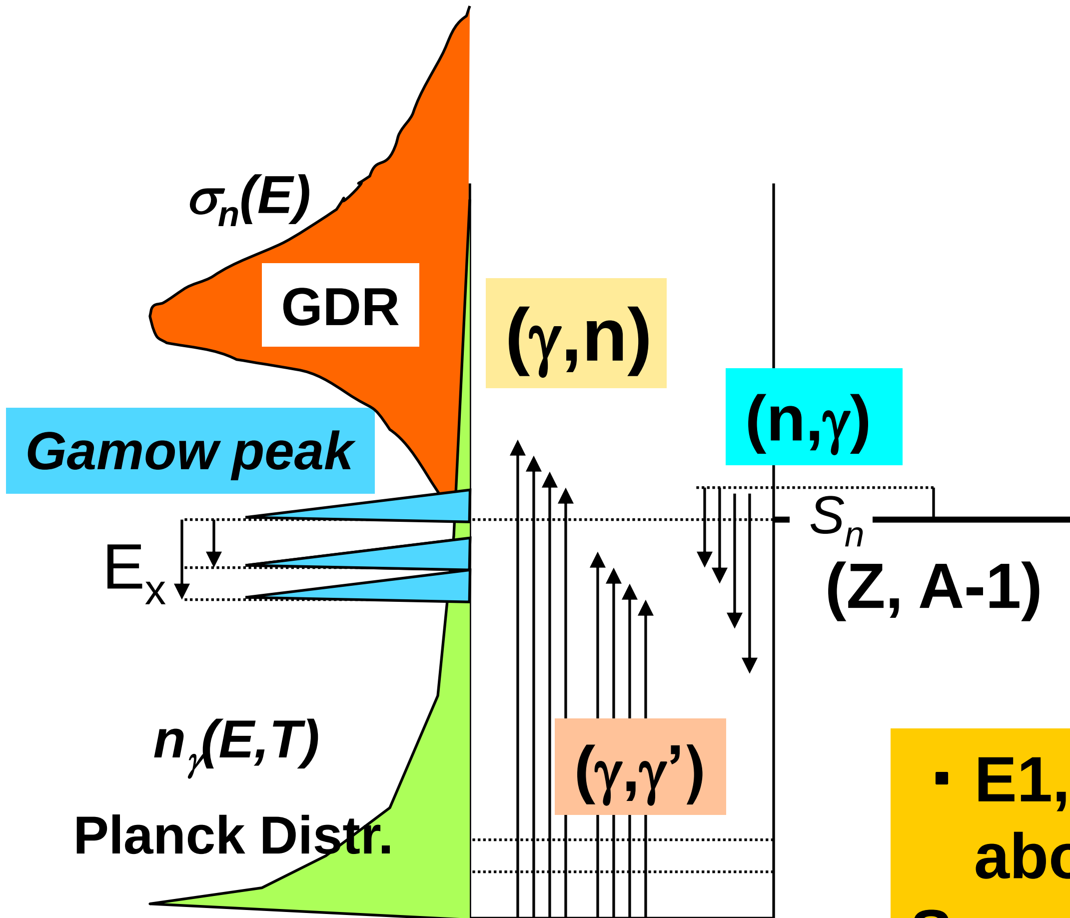
A(x, γ)B (x= n, p, d, t, ^{3}He, α) x= n: s & r processes



Modified from RIPL1 Handbook/IAEA-TECDOC
http://www-nds.iaea.org/ripl/

Neutron Capture and Photodisintegration

Brink hypothesis: GDR is built on excited states.



$$\lambda_{\gamma n} = c \int_0^\infty n_\gamma(E,T)\sigma_n^\mu(E)dE$$

(Z,A)

Key issues

- **E1, M1 γ SF above and below Sn**
- **NLD**

Main 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).

- **E1 γ strength function**

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

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

- **Nuclear Level density**

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

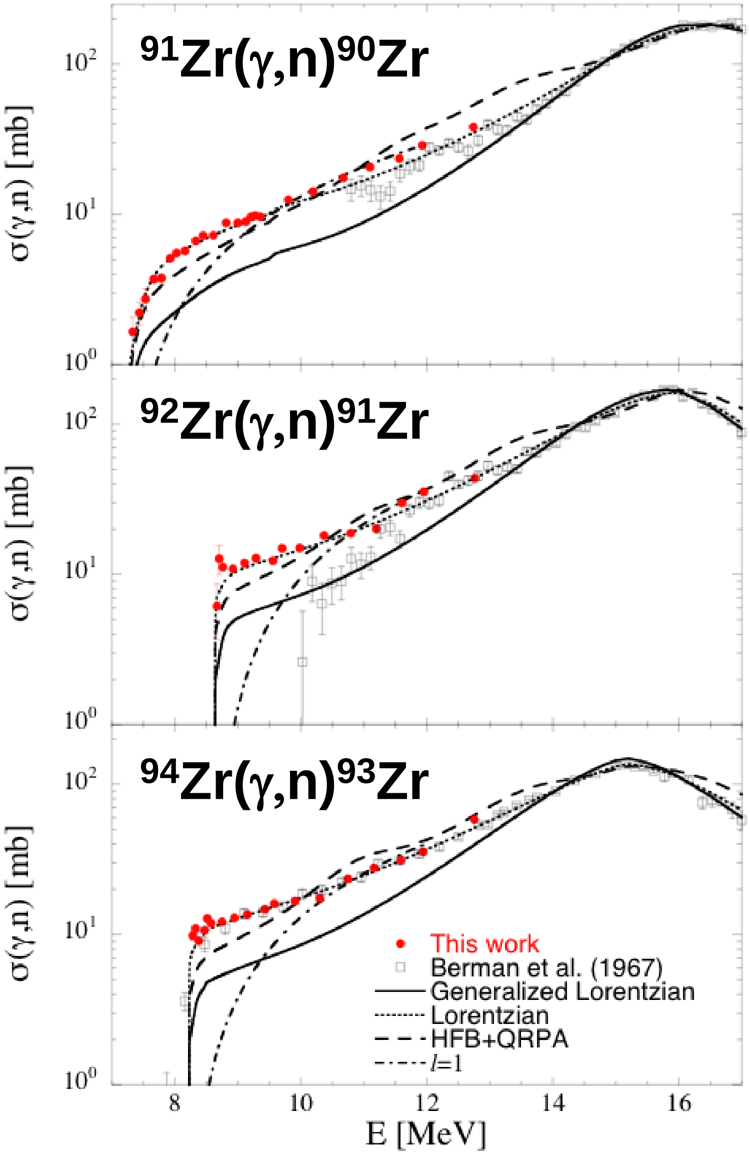
- **Spin-flip giant M1 γ strength function by Bohr & Mottelson**

Global systematics in RIPL Handbook

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

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

(γ,n) cross sections on Zr isotopes



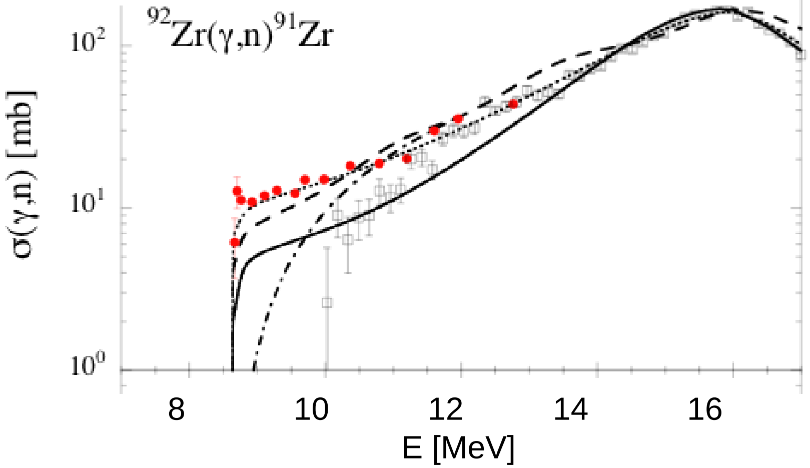
Threshold behavior of (γ,n) cross sections is given by

$$\sigma(E) = \sigma_o \left(\frac{E - S_n}{S_n} \right)^{\ell + 1/2} .$$

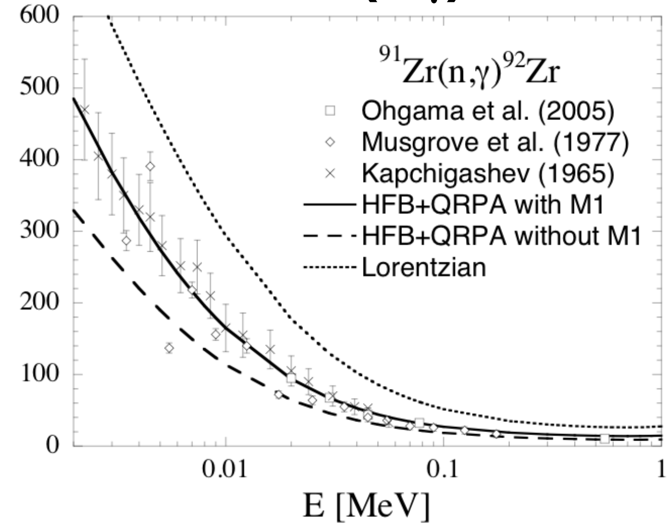
In the E1 photo-excitation, $\ell = 1$ is allowed. However, the experimental cross sections are strongly enhanced from the expected $\ell = 1$ behavior.

The Lorentzian parametrization of the E1 γ-ray strength function

^{92}Zr(γ,n)^{91}Zr



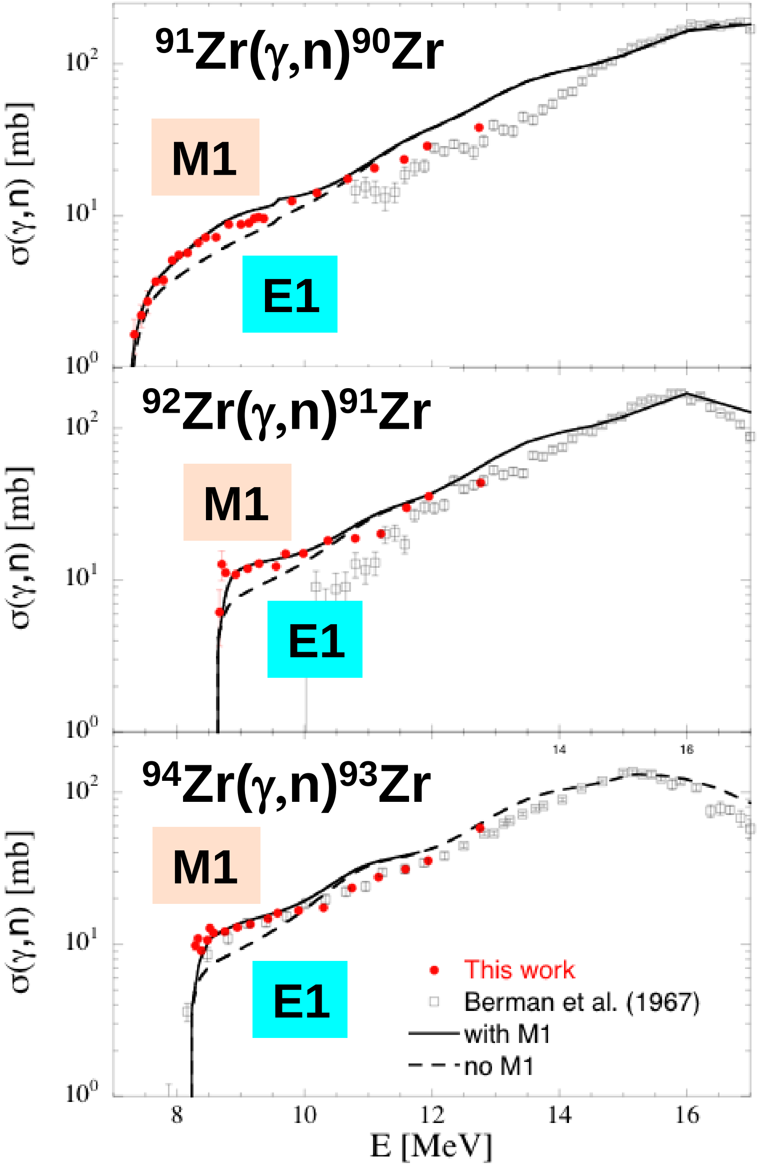
^{91}Zr(n,γ)^{92}Zr



The generalized Lorentzian parametrization of the E1 γ-ray strength function significantly underestimates the cross sections .

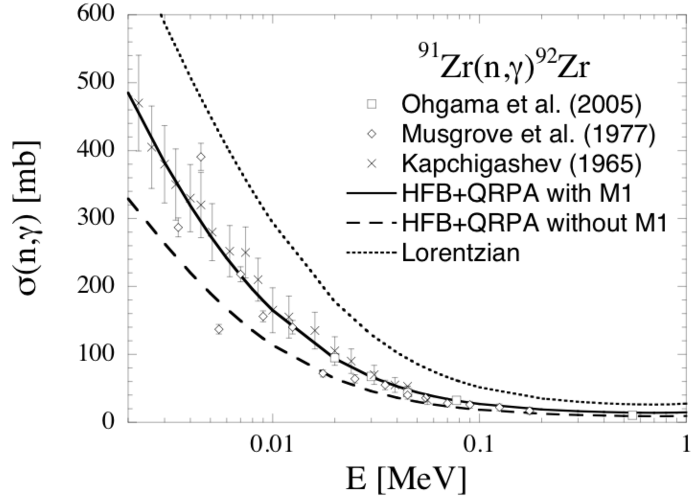
The standard Lorentzian parametrization of the E1 γ-ray strength function for ^{92}Zr can fit the (γ,n) data, but strongly overestimates (n,γ) cross sections.

M1 strength in Zr isotopes in the photoneutron channel



H. Utsunomiya et al., PRL100 (2008)

$^{91}Zr(n,\gamma)^{92}Zr$



The HFB+QRPA E1 γSF
Plus
M1 resonance
E_o= 9 MeV, σ_0=7.5mb, Γ=2.5MeV in Lorentz shape.

M1 strength in Zr isotopes

(p,p’): giant M1 resonance

Crawley et al., PRC26, 87 (1982)

Nanda et al., PRL51 (1982)

Anantaraman et al., PRL46 (1981)

Bertrand et al., PL103B (1981)

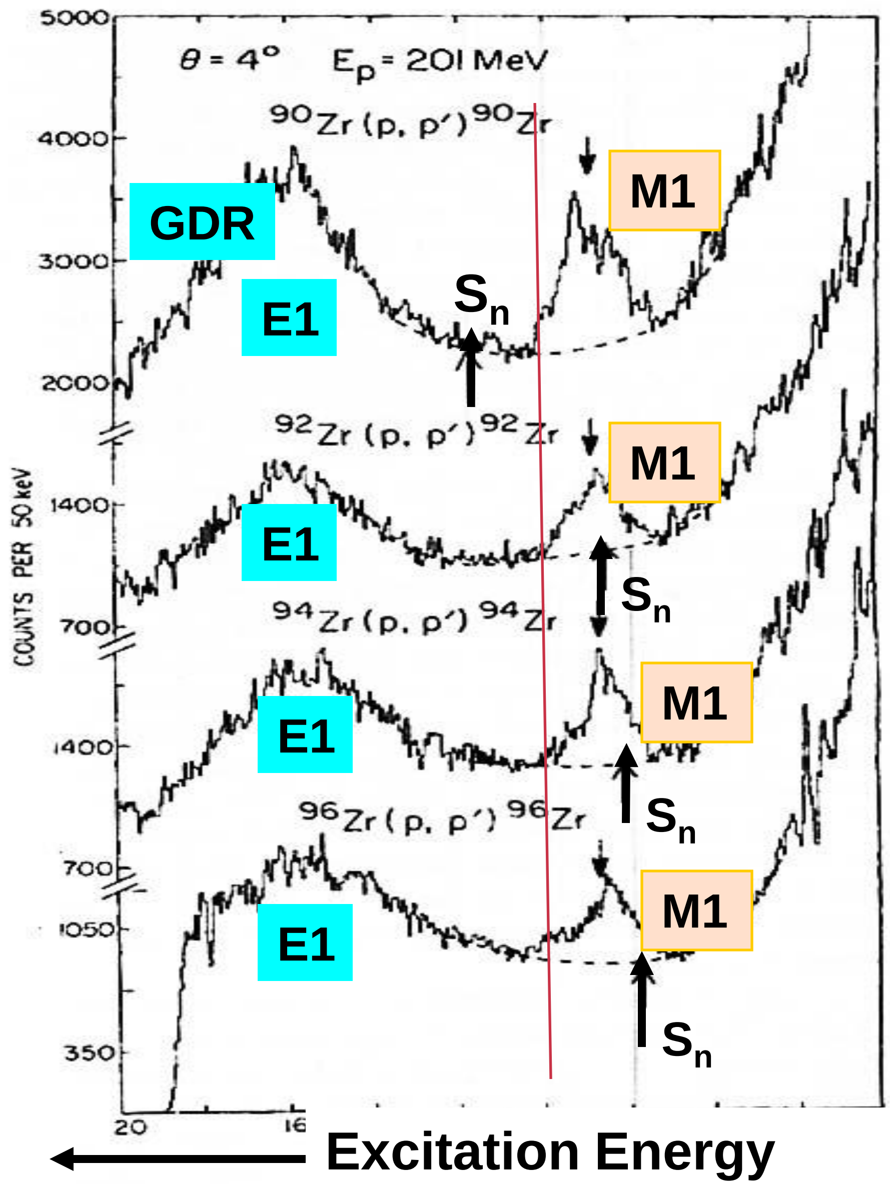
Other probes

(γ,γ’): giant M1 resonance

Laszewski et al., PRL59 (1987)

(e,e’) weak & fragmented

Meuer et al., NPA 1980



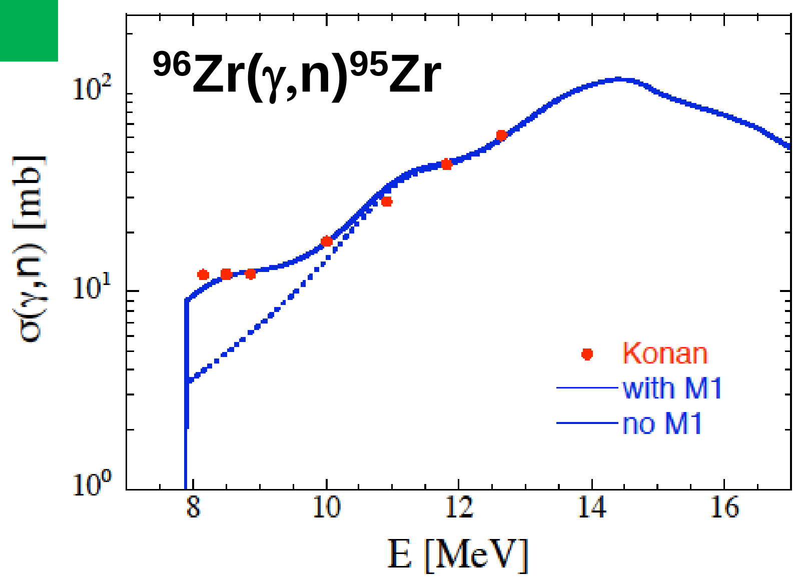
$^{96}Zr(\gamma,n)^{95}Zr$

γ-ray strength functions
E1 : HFB+QRPA, Goriely et al. (2004)
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

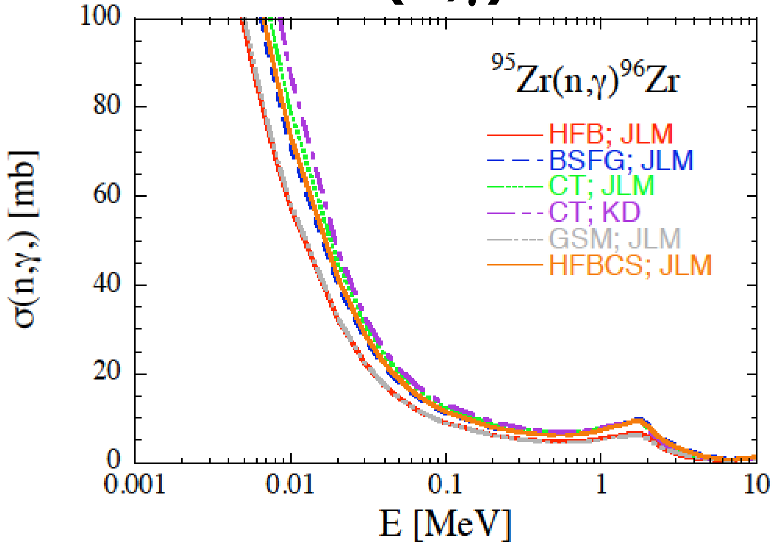
Preliminary



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

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

Uncertainties : 30 – 40%
in 0.01 – 1 MeV



Preliminary

Sources of uncertainties

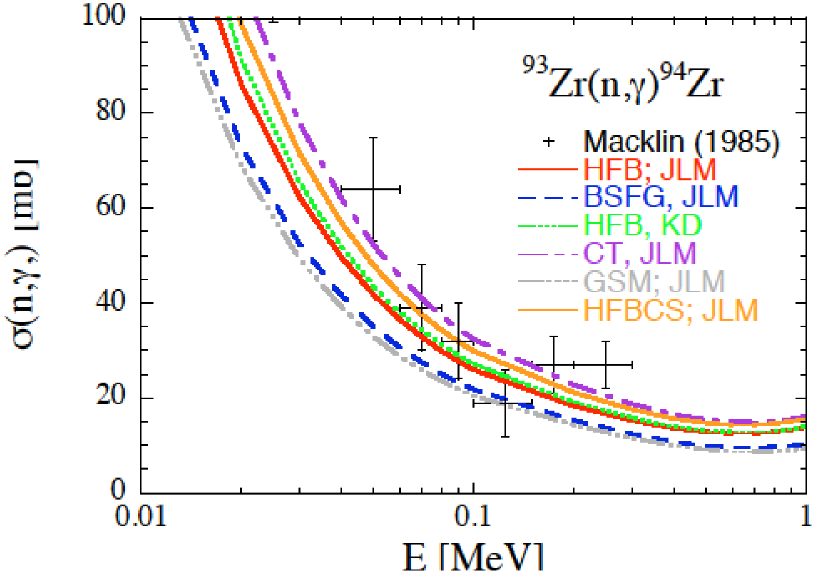
<u>NLD models</u>
1. **HFB+Combinatorial**
2. **BSFG**
3. **CT (Constant Temp.)**
4. **GSM (Gen. Superfluid)**
5. **HFBCS+statisticales**

<u>Optical potential models</u>
1. **KD (Koning & Delaroche 2003)**
2. **JLM (Bauge et al. 2001)**

$^{93}Zr(n,\gamma)^{94}Zr$

$^{93}Zr[T_{1/2}=1.5\times10^{6}$ y]$(n,\gamma)^{94}Zr$
Transmutation of nuclear waste ^{93}Zr known as LLFP (long-lived fission products)

$^{93}Zr(n,\gamma)^{94}Zr$



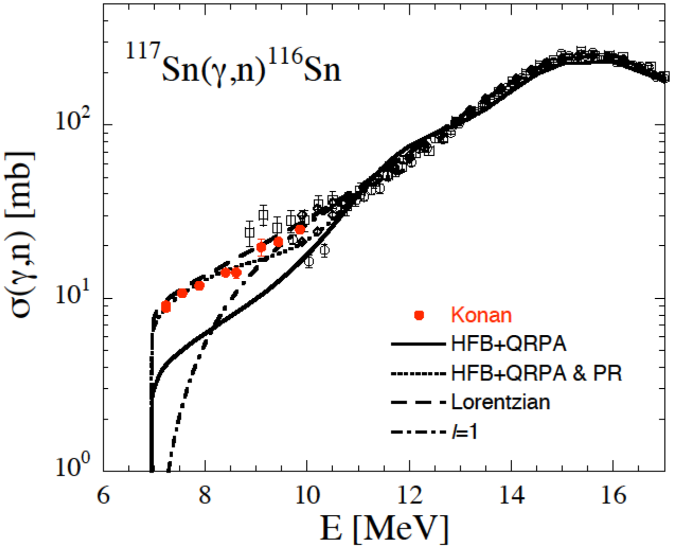
Preliminary

Uncertainties : 40 – 50% in 0.01 – 1 MeV

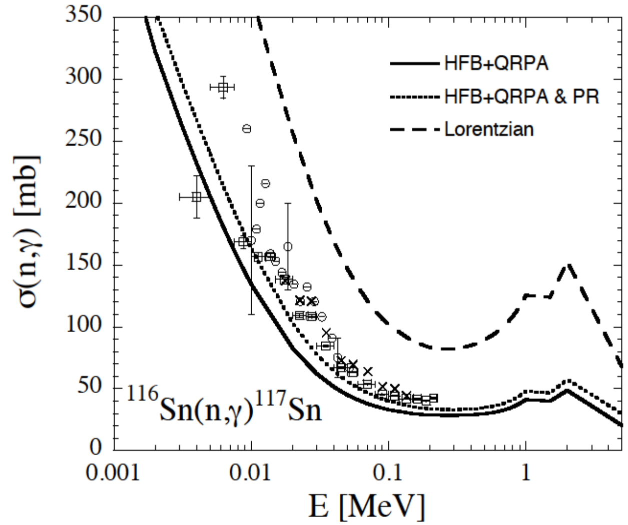
Sources of uncertainties
NLD & Optical pot. models

Pigmy E1 resonance in ^{117}Sn

^{117}Sn(γ,n)^{116}Sn



^{116}Sn(n,γ)^{117}Sn



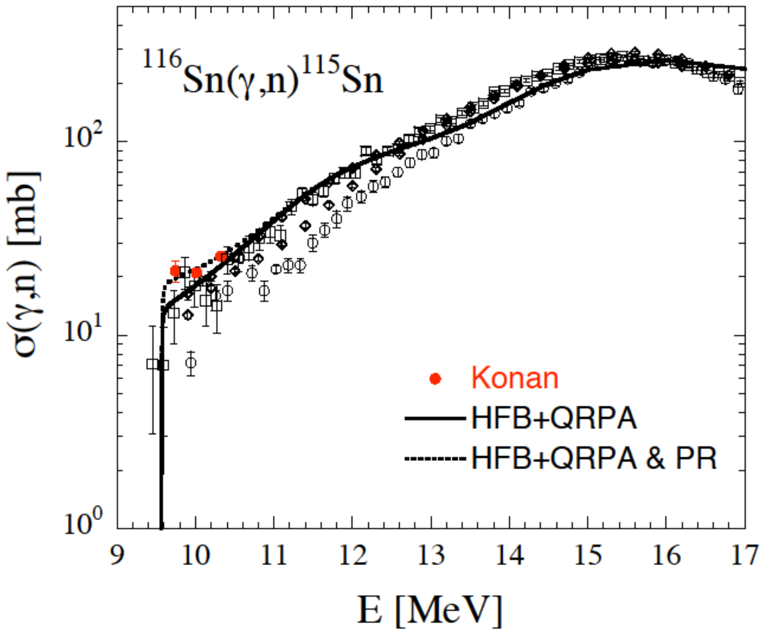
断面積のしきい値振る舞い（1点鎖線、l=1）に従わない。

$$\sigma(E) = \sigma_o \left(\frac{E - S_n}{S_n} \right)^{\ell + 1/2}$$

Lorentz型のガンマ線強度関数（破線）で^{117}Sn(g,n)断面積はフィットできるが、^{116}Sn(n,g)断面積はoverestimateする。

解： HFB+QRPAガンマ線強度関数（点線）にPigmy resonance（E_o=8.5 MeV, Γ=2 MeV, s_o=7 mb in Gaussian shape） を導入すれば、^{117}Sn(γ,n)断面積だけでなく^{116}Sn(n,γ)断面積もほぼ再現できる。

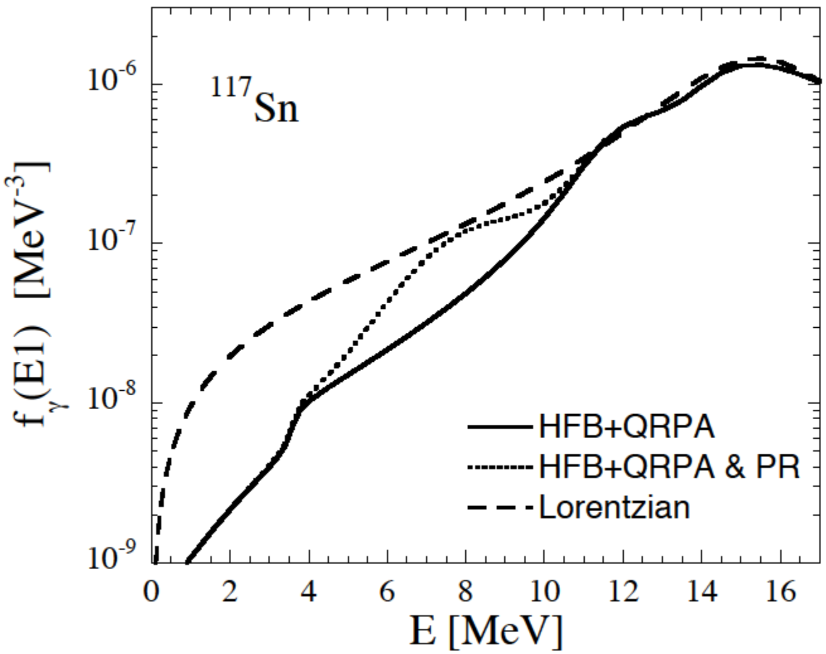
Pigmy resonance in ^{116}Sn

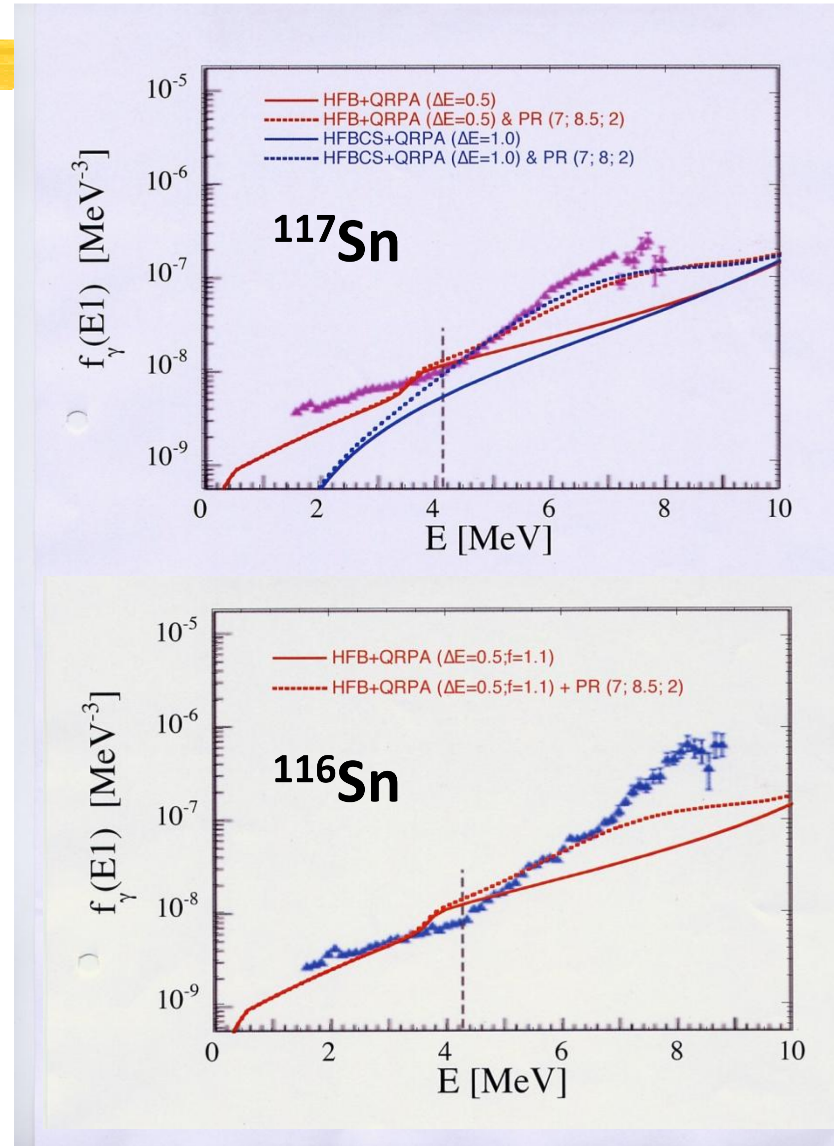


しきい値が高いeven-A核である^{116}Snの場合は、pigmy resonanceのhigh energy partが(g,n)断面積に寄与していると考えられる。

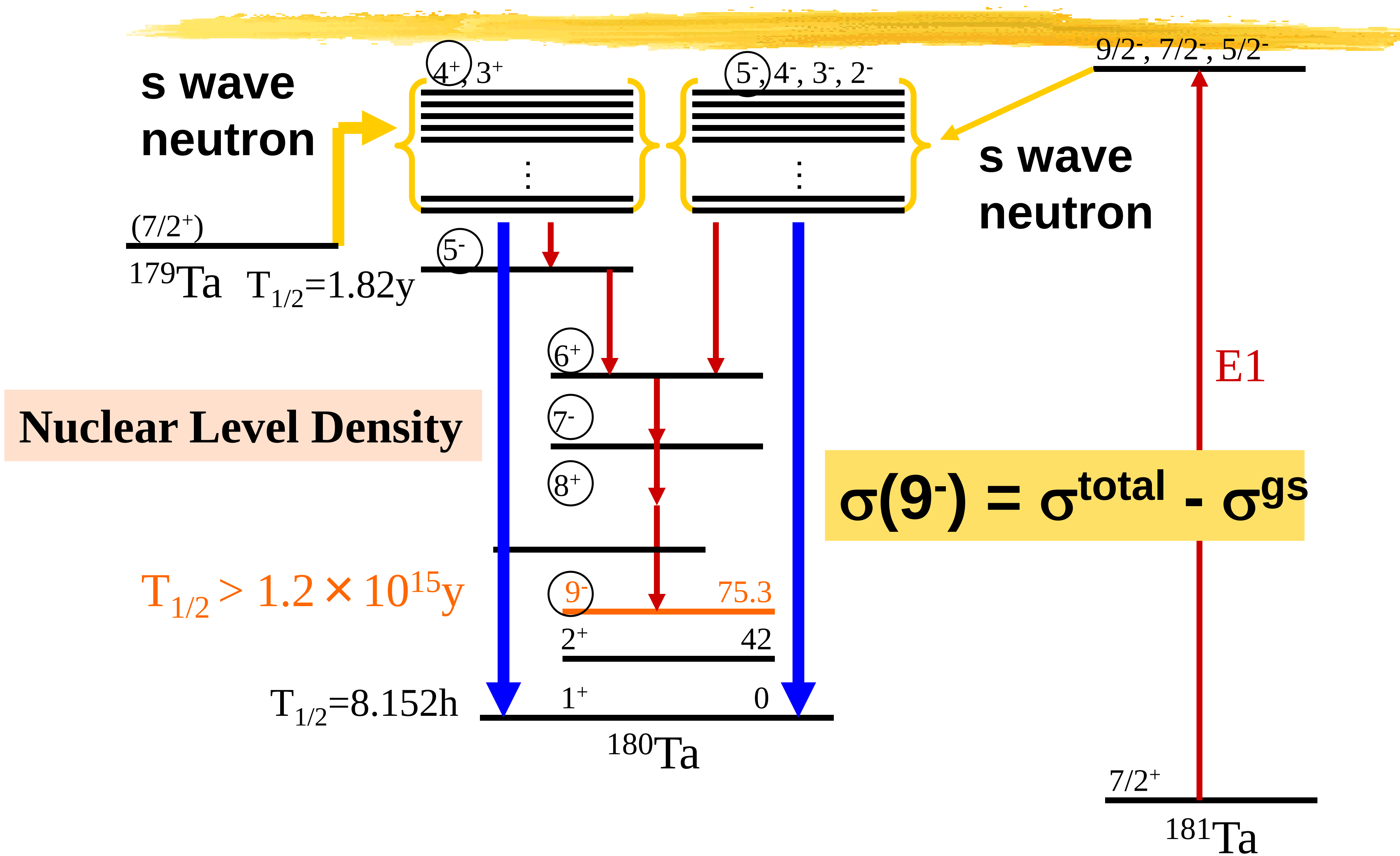
γ-ray SF for $^{117,116}Sn$

Osloデータとの比較



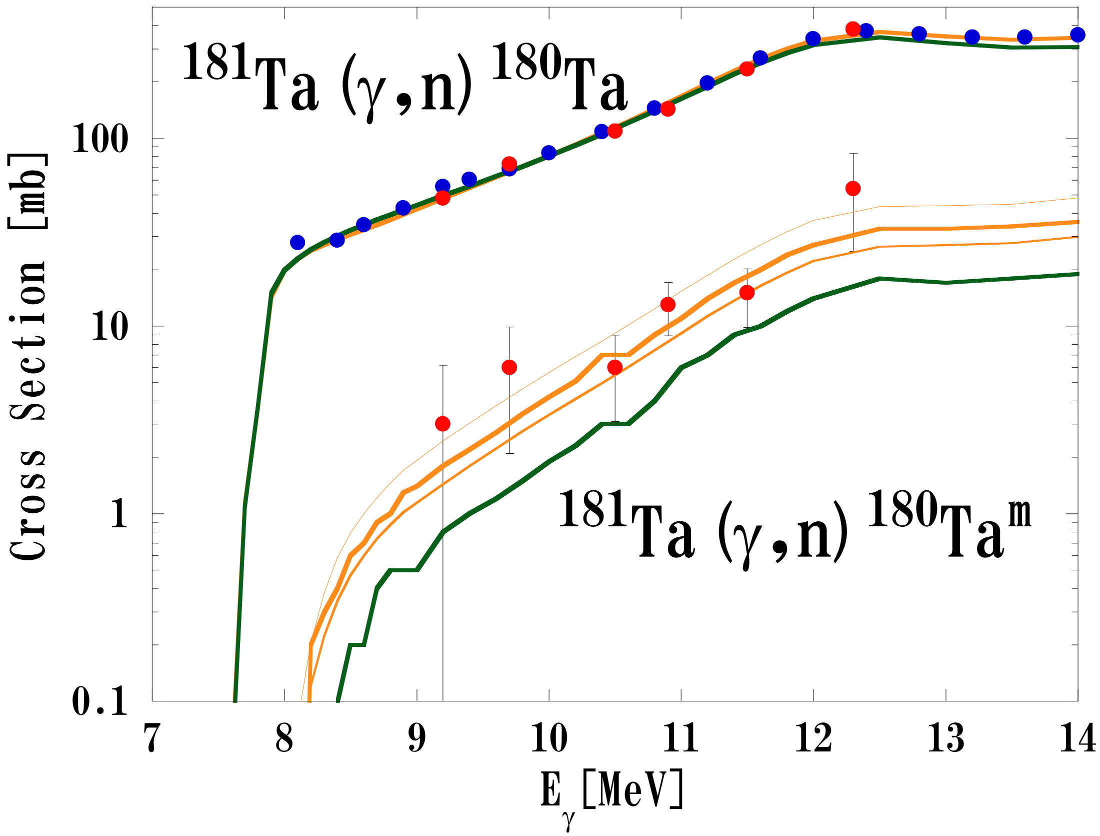


s-process production of $^{180}Ta^m$



Experimental results, and comparison with theoretical models

Goko et al. Phys. Rev. Lett. 96, 192501 (2006)



Combinatorial NLD

Hilaire & Goriely, NPA779 (2006)

HF + BCS NLD

- Present work (2006)
- IAEA : Lee et al. (1998)

High-spin states with $J \geq 5$ are needed in Ex < 5 MeV.

Summary

- The γSF and NLD are key nuclear statistical quantities in the Hauser-Feshbach model calculations of reaction rates of direct relevance to the nucleosynthesis of heavy elements.

- Systematic studies of extra γ-ray strength arising from M1 and pigmy E1 resonance in the low-energy tail of GDR are important to improve the predictive power of the Hauser-Feshbach model for the nucleosynthesis of heavy elements.

- The unique spin and parity of isomeric states can be a good probe of NLD by measuring relevant partial cross sections