核異性体^{180}Ta^{m}の
光核生成部分断面積

後神進史

甲南大学理工学部

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- **核異性体**$^{180}Ta^{m}$**の性質**
- ^{180}Ta**の天体生成起源**
- **中性子直接計数による** $^{181}Ta(\gamma,n)^{180}Ta$ **全光核反応断面積**σ^{tot}**の測定**
- **放射化法による** $^{181}Ta(\gamma,n)^{180}Ta^{gs}$ **部分光核反応断面積**σ^{gs}**の測定**
- $^{181}Ta(\gamma,n)^{180}Ta^{m}$ **部分光核反応断面積**σ^{m}**の決定**
- $^{180}Ta^{m}$ **天体生成起源に関する考察**
- **まとめ**

Natural Isomer $^{180}Ta^{m}$

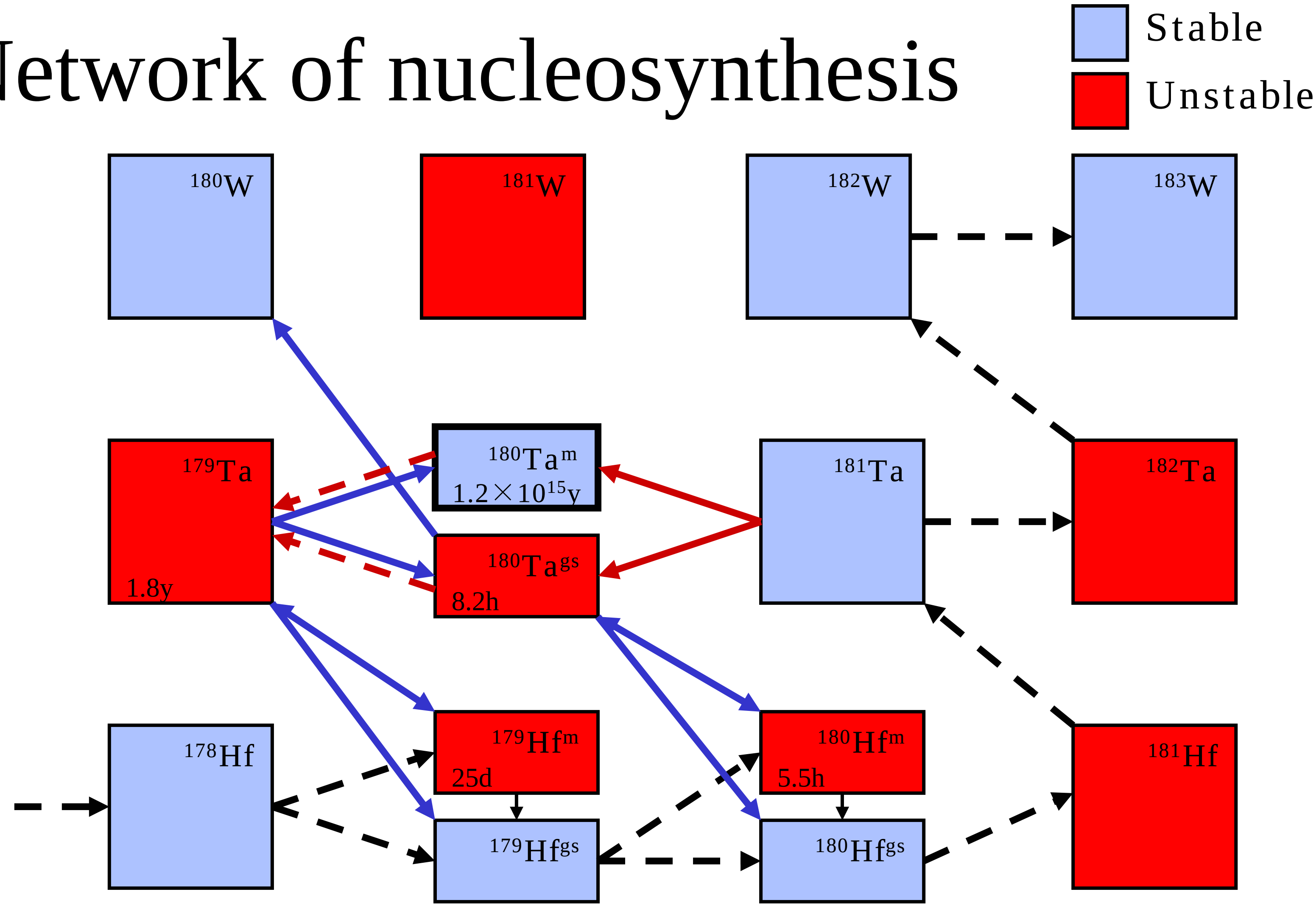
- Odd-odd Nuclei (Z=73, N=107)
- Proton rich nuclei (p-nuclei)
- Solar Abundance ; 0.012% (the rarest)
- Half Life > 1.2×10^{15}y
- E_x = 75keV
- $J^{\pi} = 9^{-}$

$^{180}Ta^{gs}$

•Half Life = 8.152h

•$J^{\pi} = 1^{+}$

Network of nucleosynthesis



Primary s-process flow $^{A}_{Z}X\,(n,\gamma)\,^{A+1}_{Z}X\,(\beta^{-})\,^{A+1}_{Z+1}X'$

p-process (photodisintegration) $^{181}Ta(\gamma,n)^{180}Ta^{gs,m}$

Weak branching s-process

Nucleosynthesis of $^{180}Ta^{m}$

• p-process in the pre-supernova phase of massive stars or during their explosions as type-Ⅱ supernovae

Temperature ; $1.8 \leqq T[10^{9}K] \leqq 3.0$

Typical photon energy ; 300[keV]

$^{181}Ta(\gamma,n)^{180}Ta^{m}$

• s-process in the Low-mass AGB star

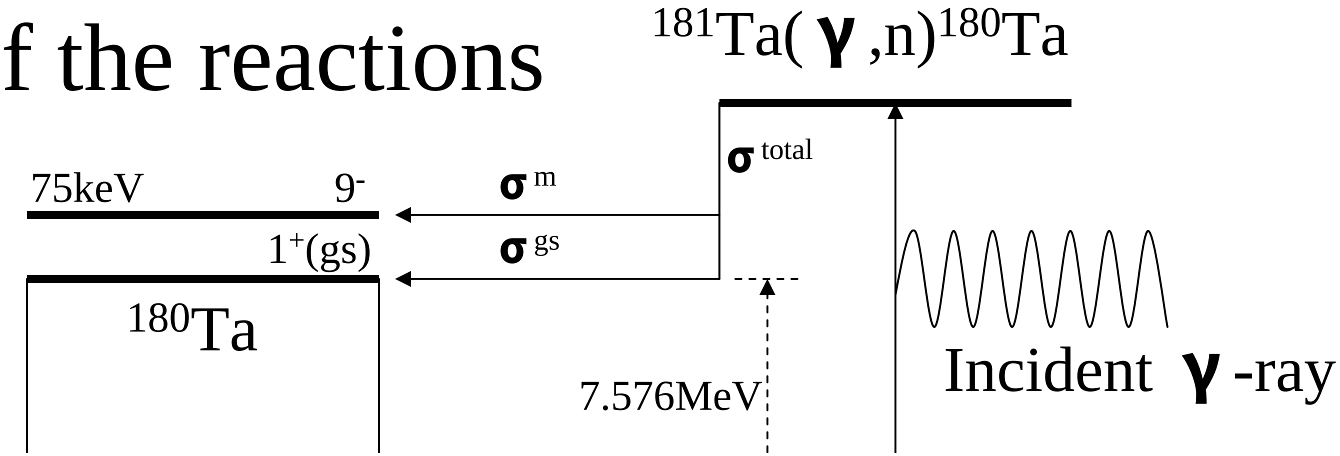
Temperature ; $2.9 \leqq T[10^{8}K] \leqq 3.3$

Typical photon energy ; 30[keV]

$^{179}Hf(\beta)^{179}Ta(n,\gamma)^{180}Ta^{m}$

Progress of the reactions

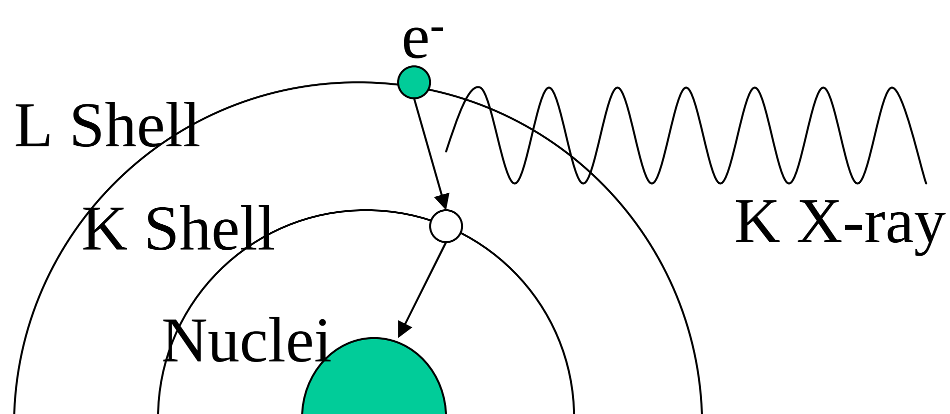
$T_{1/2} > 1.2 \times 10^{15}$y
$T_{1/2} = 8.152$h



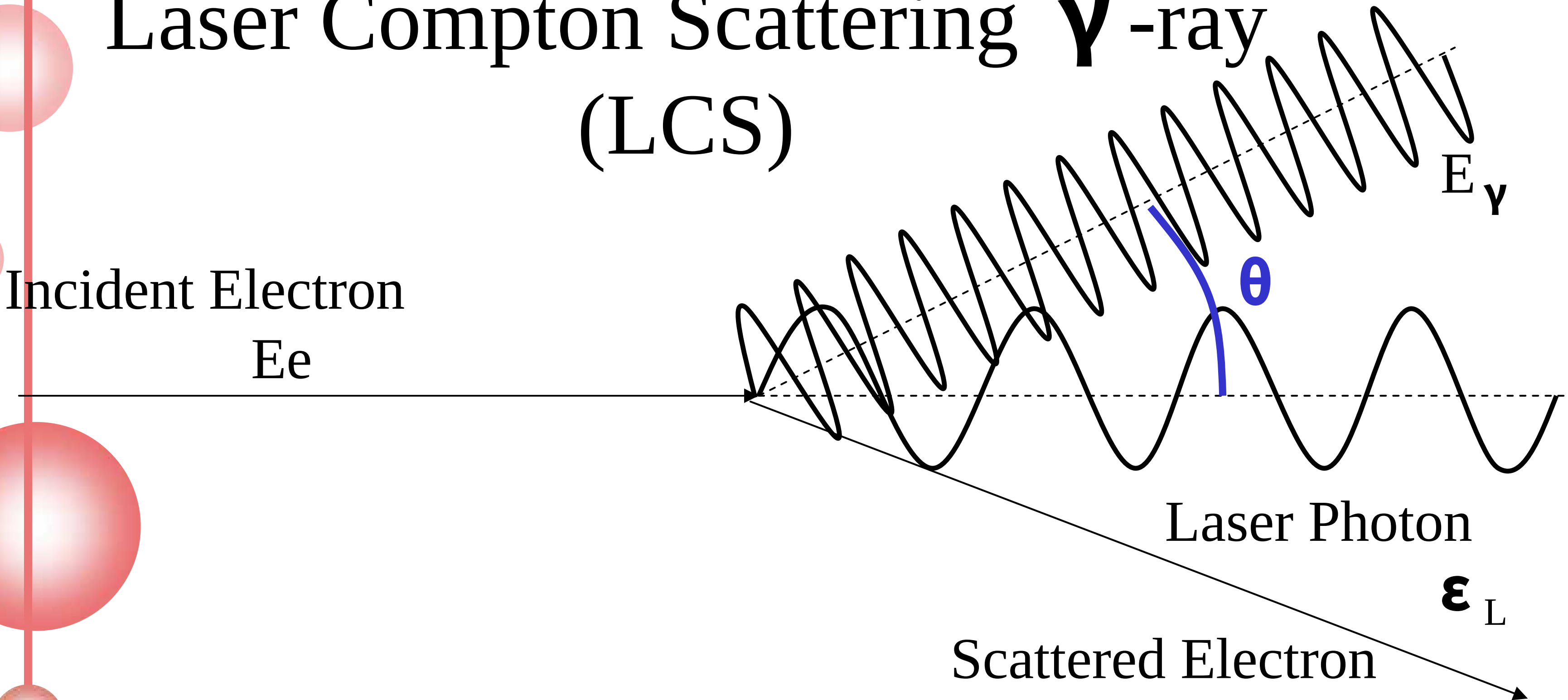
$$\sigma^{m} = \sigma^{total} - \sigma^{gs}$$

et)

$^{180}Ta^{gs}$の1decayあたり
93keV γ-ray 4.665%
55.8keV $K_{\alpha 1}$ 33.12%
54.6keV $K_{\alpha 2}$ 19.20%



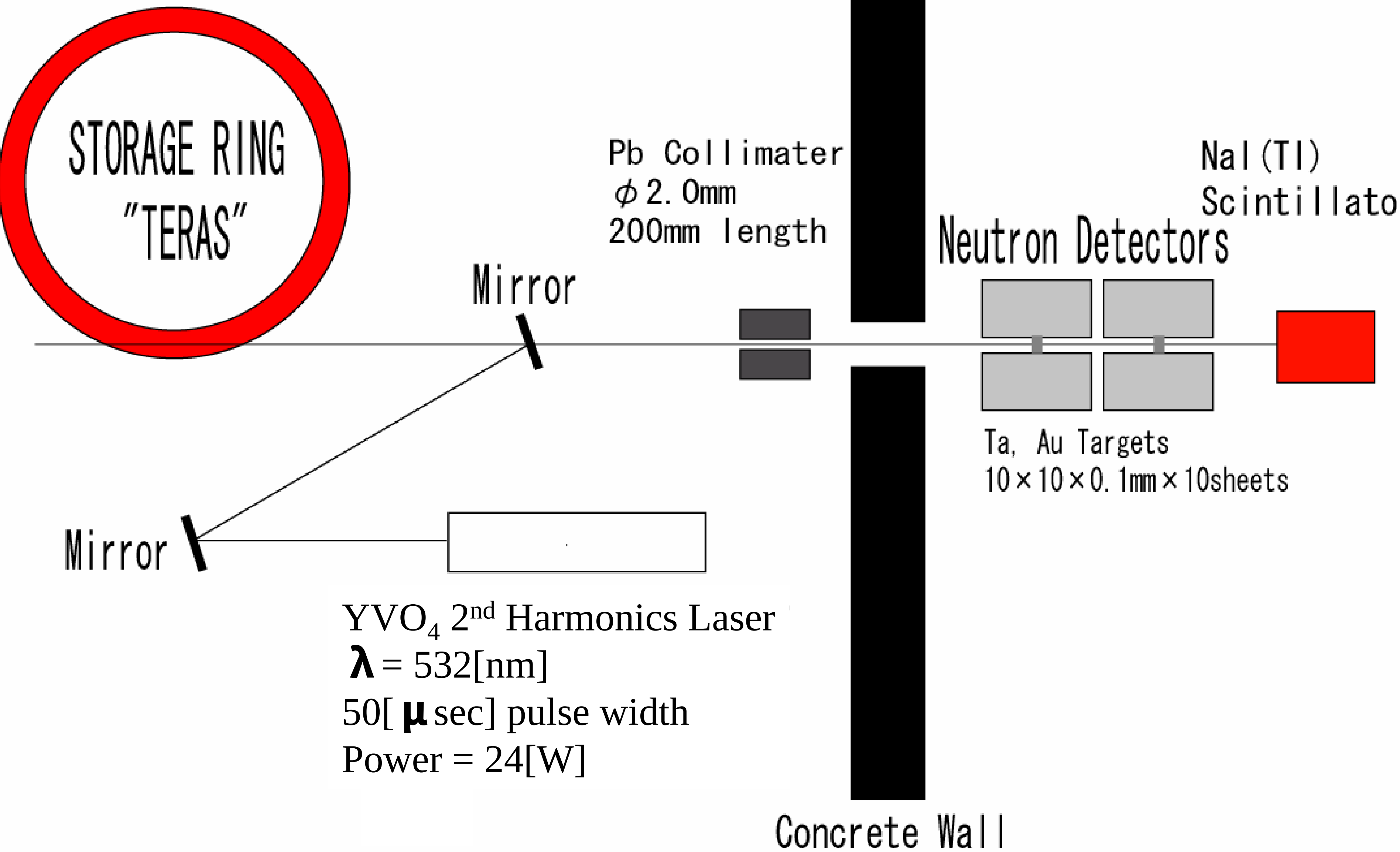
Laser Compton Scattering γ-ray (LCS)



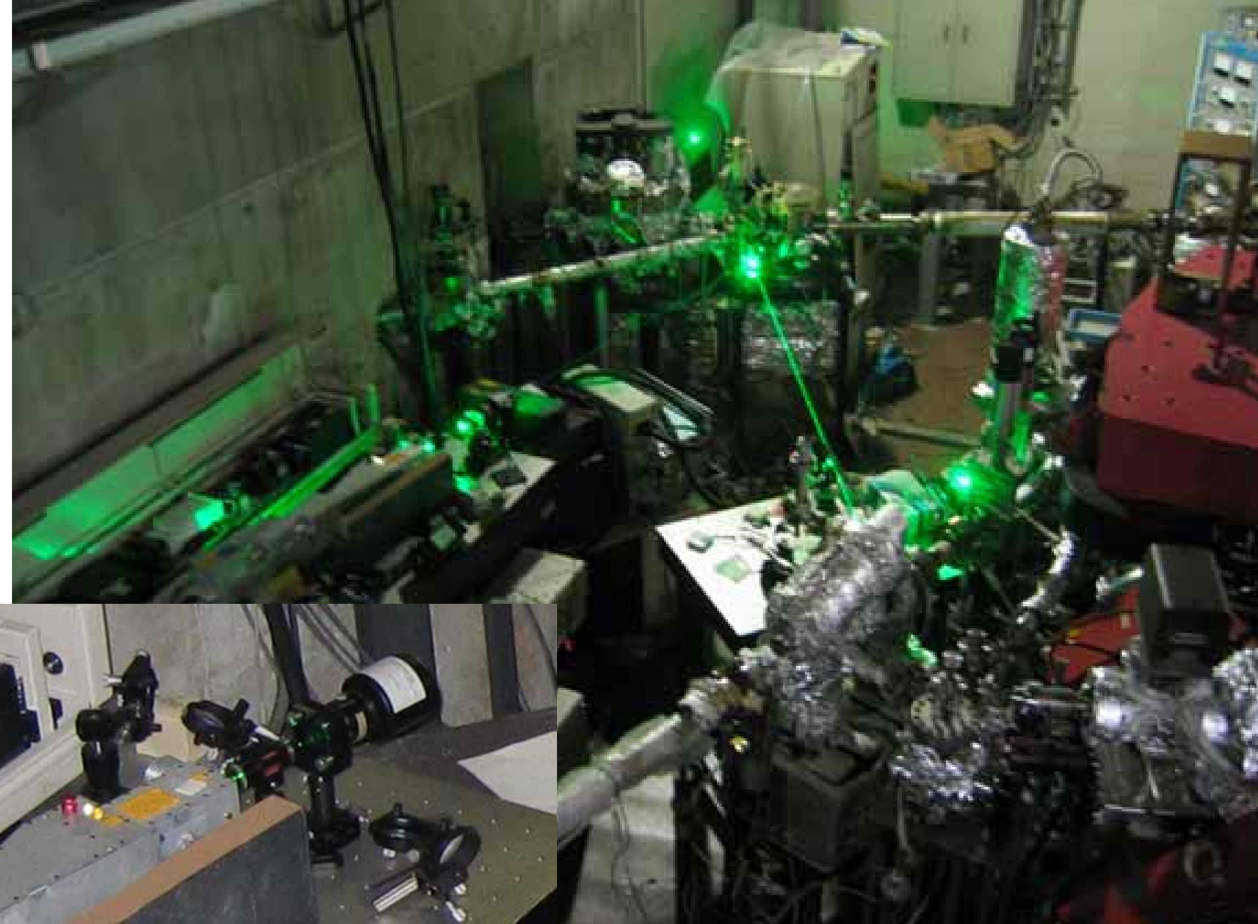
$$E_\gamma = \frac{\varepsilon_L (1 - \beta\cos\theta_L)}{1 - \beta\cos\theta + \frac{\varepsilon_L\{1 - \cos(\theta_L - \theta)\}}{Ee}}$$

β ：Velocity of Electron／c
θ ：Scattered Angle of Laser Photon
θ_L ：Incident Angle of Laser Photon

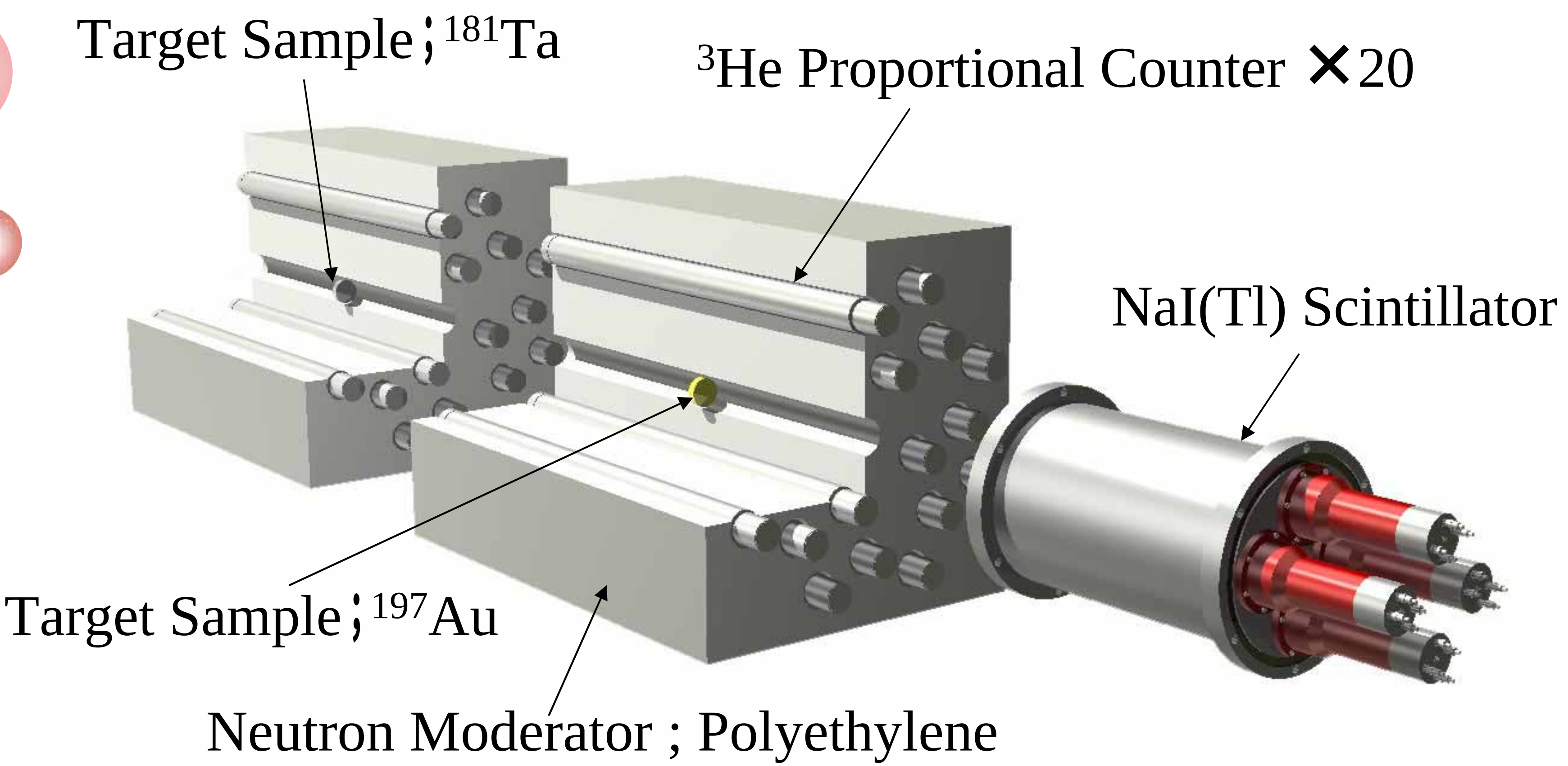
Experimental Set-up



$Nd:YVO_4$ Q-Switch Laser "INAZUMA"



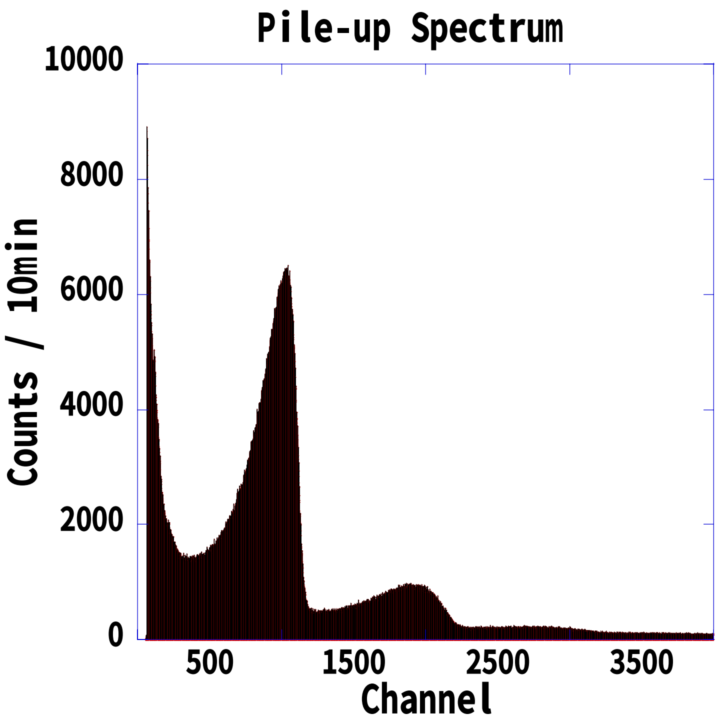
Neutron Detectors

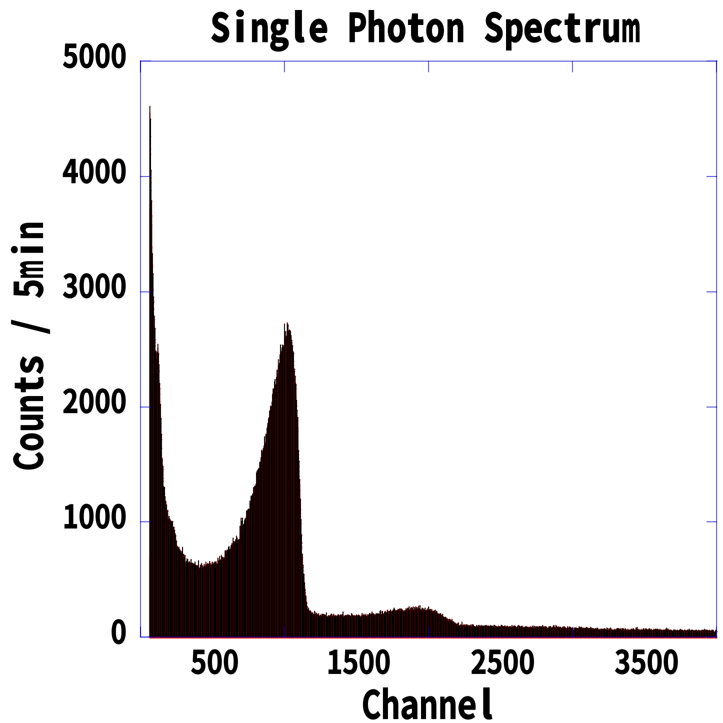


The measurements of total photoneutron cross sections with the direct neutron counting

- $^{181}Ta(\gamma,n)^{180}Ta$反応において、入射γ線数、散乱中性子数を測定
- Ge検出器にて入射γ線Energy分布を測定
- γ線Energy広がりを考慮に入れ、測定Dataを元にLorentz関数型の励起関数を決定する

NaI(Tl) Scintillator Spectra

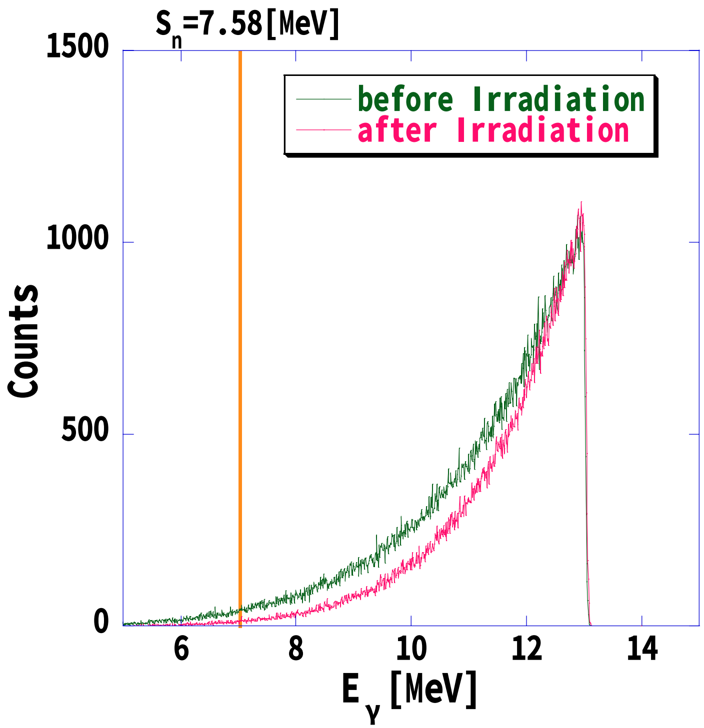




The number of incident **γ** -ray

$$n_{\gamma} = \frac{Average\ channel\ \ for\ Pile-up\ Spectrum}{Average\ channel\ \ for\ Single\ Photon\ Spectrum} \times Total\ counts\ \ for\ Pile-up\ Spectrum$$

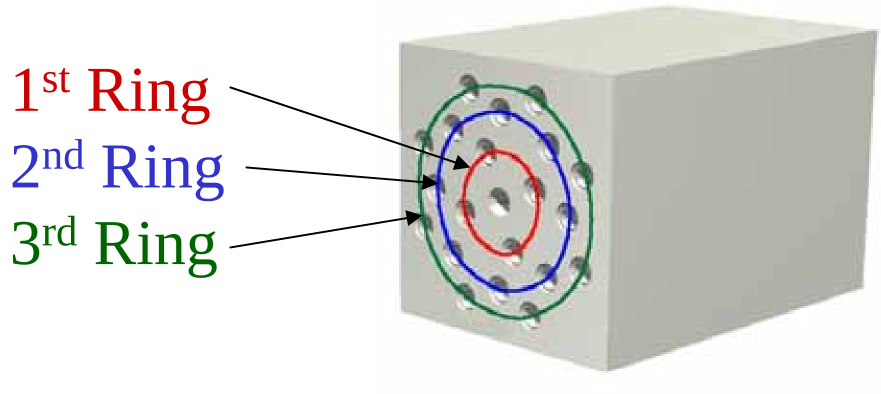
LCS-γ Energy Distribution

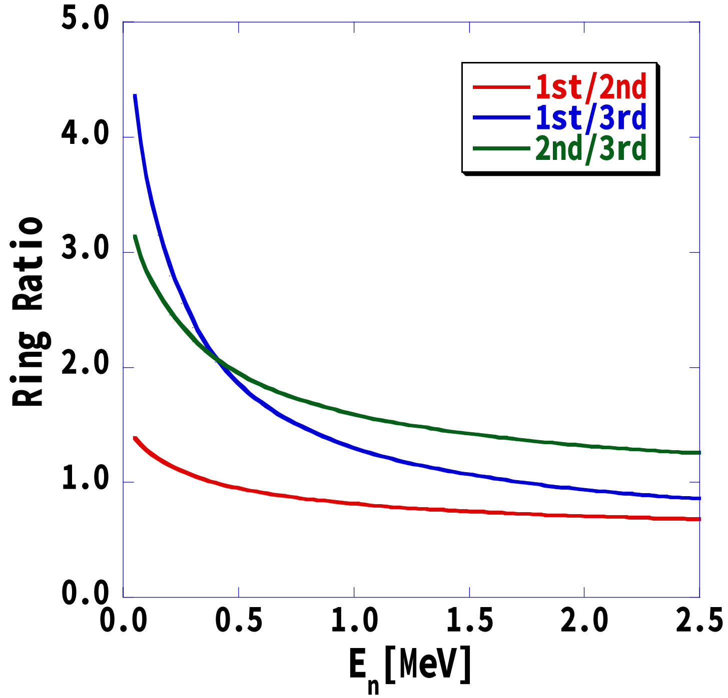


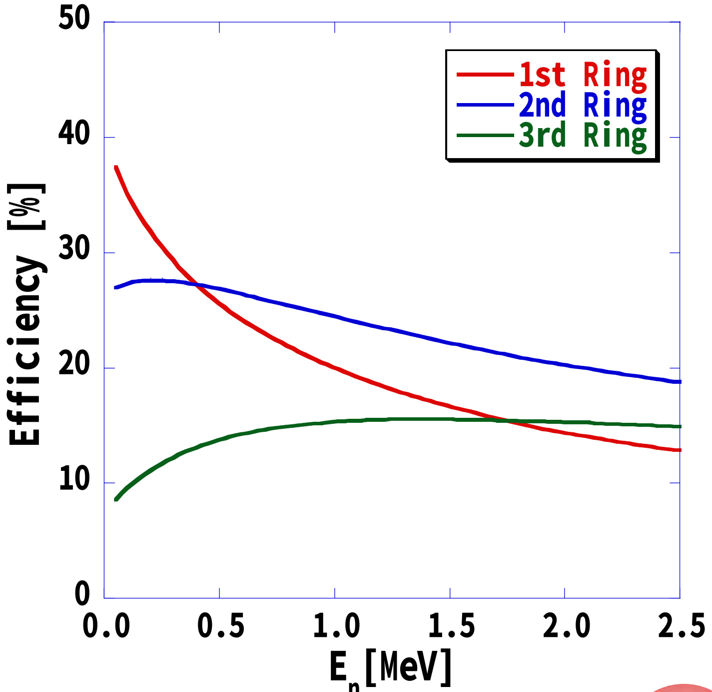
Irradiation time ; 5.67[hour]

	Fraction	Avg.E_γ[MeV]
before	0.950	10.77
after	0.986	10.98

Neutron Detector Efficiency







Total Cross Sections

Fitting to Lorentz function

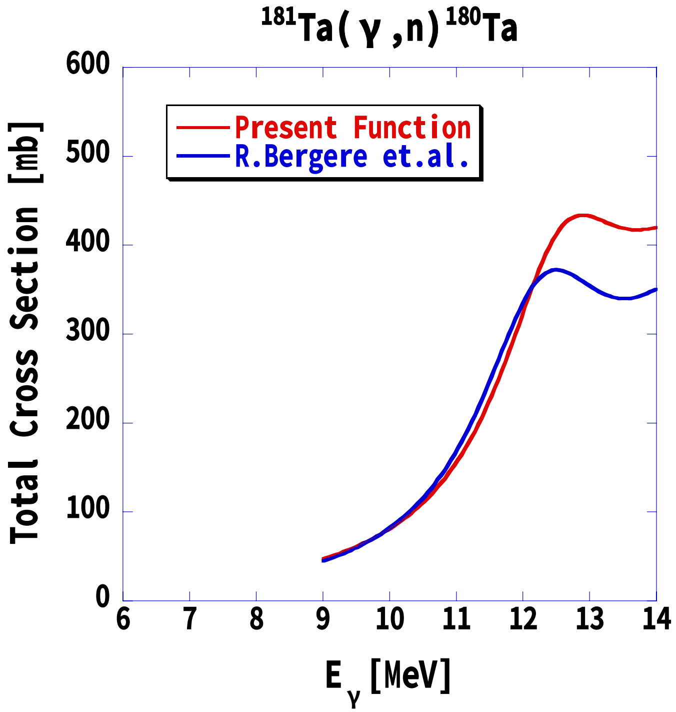
(13 data points ; 7.58<E_γ[MeV]<14.2)

$$\sigma^{tot}(E) = \sum_{k=1}^{2} \frac{\sigma_k}{1 + \frac{(E^2 - E_k^2)^2}{E^2 \Gamma_k^2}}$$

E_k : Resonance energy

σ_k : Peak Cross Section at E_k

Γ_k : FWHM



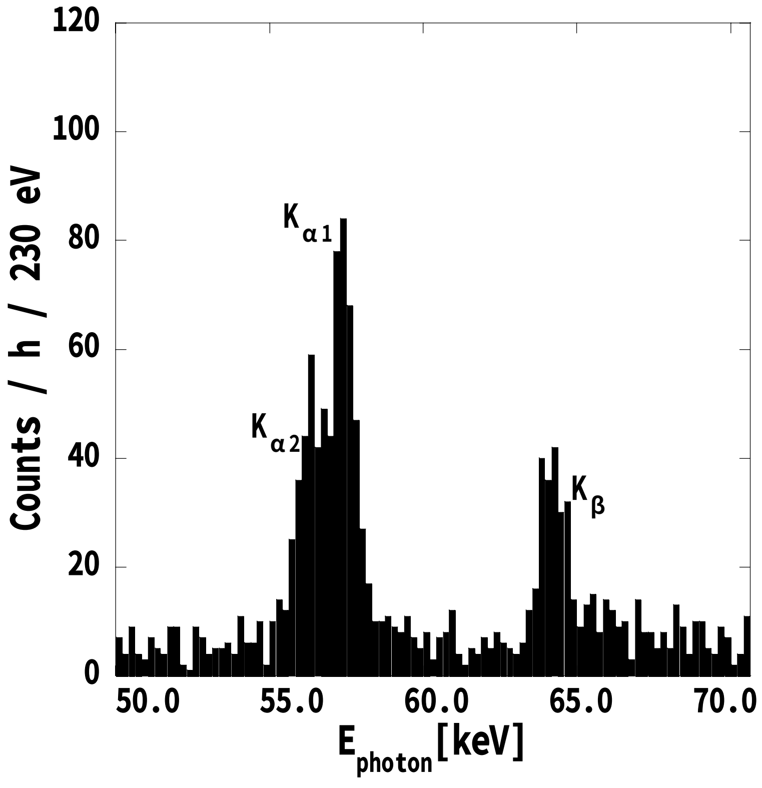
The measurements of partial photoneutron cross sections with the photoactivation

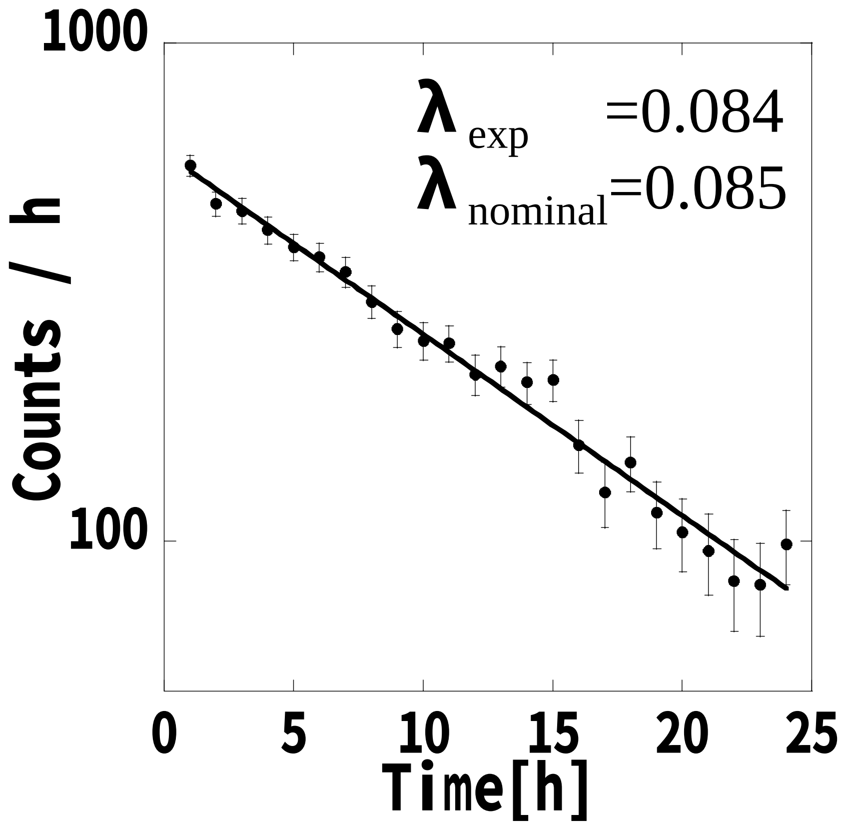
- $^{181}Ta(\gamma,n)^{180}Ta$反応において、入射γ線数の時間変化を追いながら、数時間照射を続ける
- 照射終了後にGe Detectorにて、放射化したTarget sampleの崩壊を測定する
- 得られたデータより、Total Cross Section、Partial Cross Sectionそれぞれの$\int_{Sn} n_\gamma(E)\,\sigma(E)dE$の値を求める
- 上記のEnergy積分値の比と、先に求めたLorentz型Fitting FunctionからPartial Cross Sectionの絶対値を求める

Ge Detector Set-up

Activated Ta foils on the acrylic cap

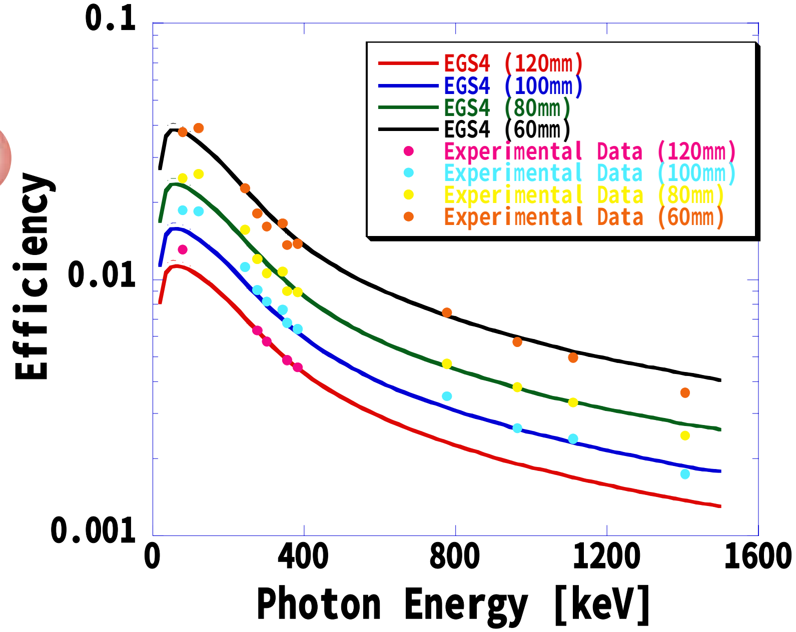
$^{180}Ta^{gs} \rightarrow {}^{180}Hf$; Electron Capture

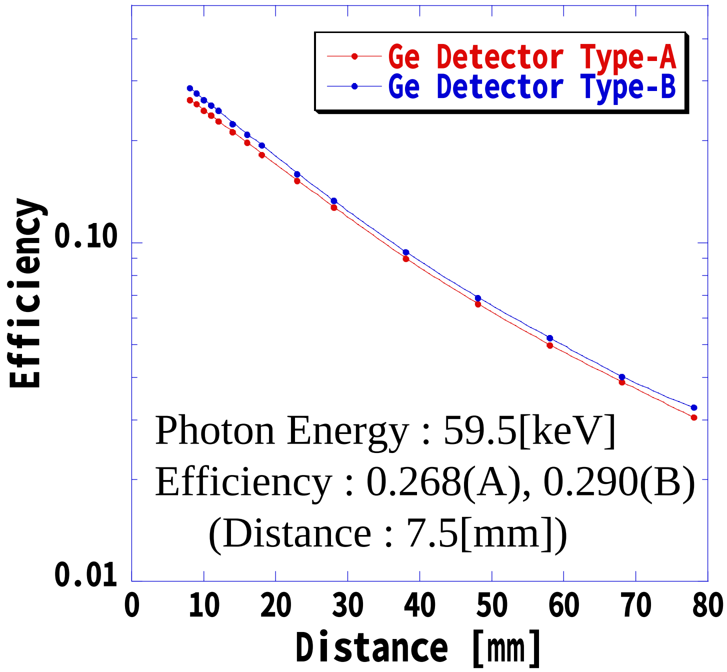




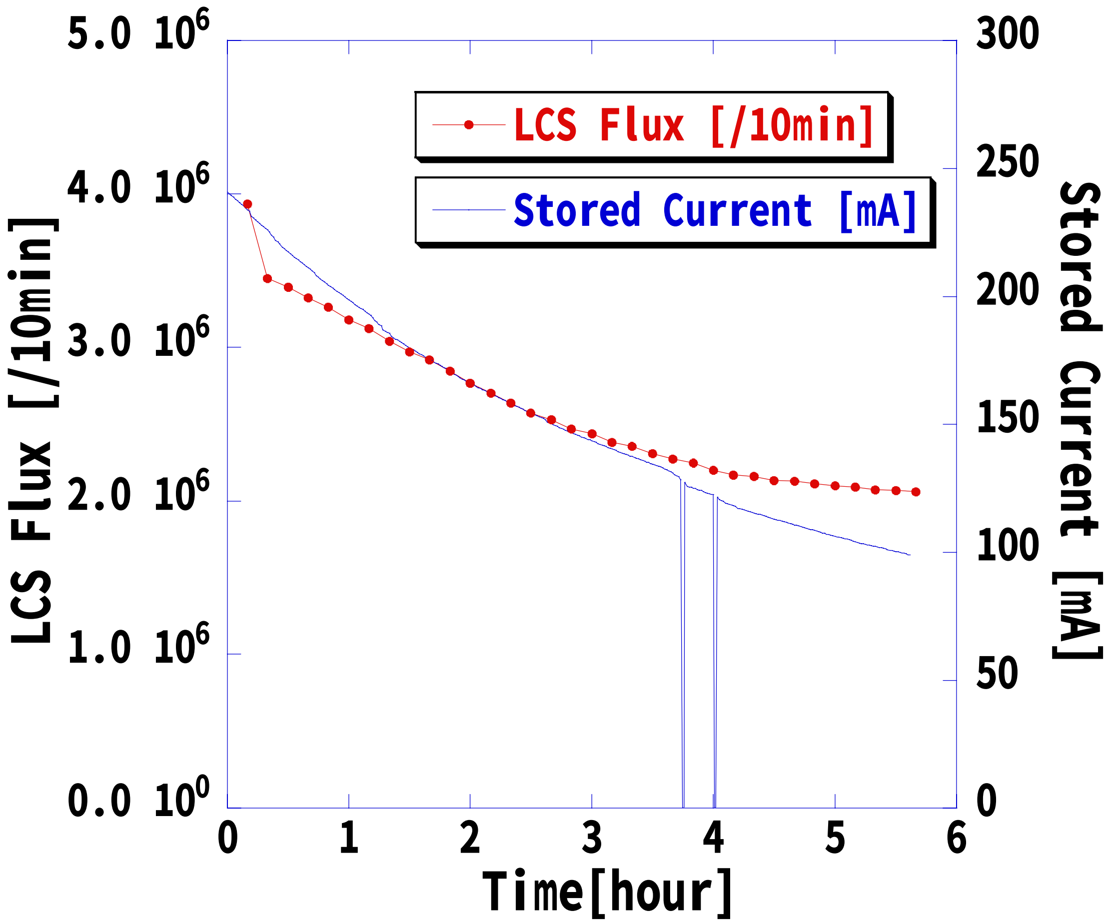
Ge Detector Efficiency

We obtained detection efficiency from Monte Carlo Simulation Code "EGS4" and Experimental Data with ^{241}Am and ^{109}Cd source.





LCS-γ Flux



LCS Flux [/10min]
Stored Current [mA]
5.0 10^6
4.0 10^6
3.0 10^6
2.0 10^6
1.0 10^6
0.0 10^0
300
250
200
150
100
50
0
0
1
2
3
4
5
6
Time[hour]
LCS Flux [/10min]
Stored Current [mA]

Data Analysis for Direct Neutron Counting

$$\int_{S_n} n_\gamma(E)\sigma^{tot}(E)dE = \frac{n_n}{N_t \cdot f \cdot \varepsilon_n(E_n)}$$

$n_\gamma(E)$：The number of incident γ-ray

$\sigma^{tot}(E)$：Total photoneutron cross section

n_n：The number of scattered neutrons

N_t：Area density of the target

S_n：Tneutron separation energy

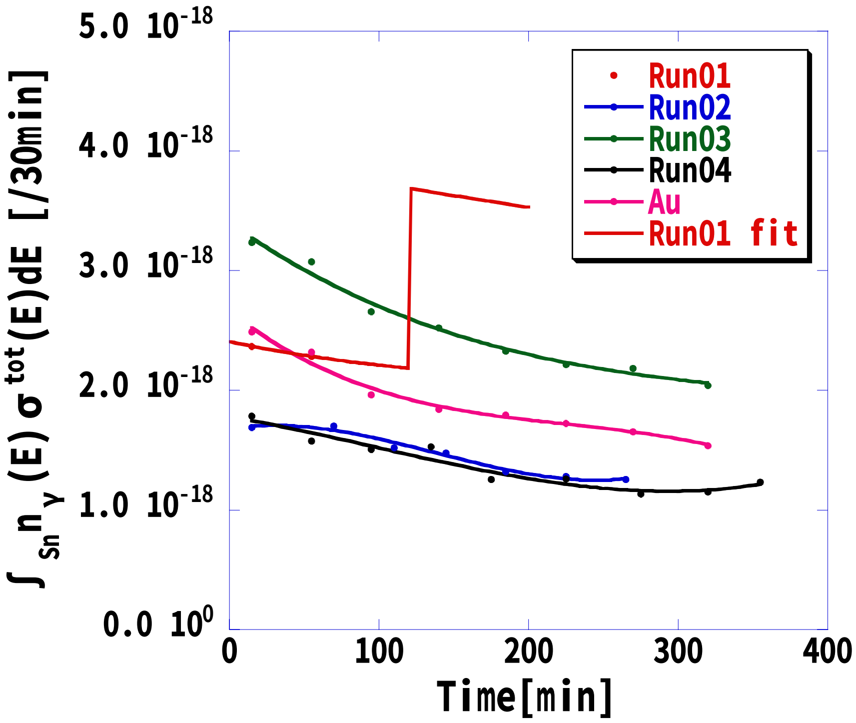
$\varepsilon_n(E_n)$：Neutron detection efficiency

f：Correction factor for γ attenuation in thick-target measurements

$$f = \frac{1-e^{-\mu t}}{\mu t}$$

μ：Linear attenuation coefficient

t：Thickness of the target material



Data Analysis for Activation Method

Activation Phase

$$\frac{dN(t)}{dt} = N_t \int_{S_n} \sigma^{gs}(E) I(t,E) dE - \lambda N(t)$$

N(t)：The number of daughter nuclei
N_t：Area density of the target
S_n：Neutron threshold
$\sigma^{gs}(E)$：Partial photoneutron cross section
I(t,E)：γ-ray Flux
λ：Decay constant of daughter nuclei

Decay Phase

$$\int_{t_{start}}^{t_{stop}} \lambda \cdot N(t_{ir}) \cdot e^{-\lambda t} \cdot h \cdot i \cdot \varepsilon_X(E_X) dt = Yield$$

t_{start}：Start time of the measurement
t_{stop}：Stop time of the measurement
h：Emission Intensity of X-ray
i：Self absorption of the targets
$\varepsilon_X(E_X)$：Efficiency of the Ge Detector
t_{ir}：Stop time of the irradiation

$$\int_{S_n} n_\gamma(E) \sigma^{gs}(E) dE = \frac{Yield \cdot e^{\lambda t_{ir}}}{N_t \cdot h \cdot i \cdot \varepsilon_X(E_X) \cdot (e^{-\lambda t_{start}} - e^{-\lambda t_{stop}})} \cdot \frac{\int_0^{t_{ir}} K(t) dt}{\int_0^{t_{ir}} K(t) \cdot e^{\lambda t} dt}$$

$$n_\gamma(E) = \int_0^{t_{ir}} I(t,E) = \int_0^{t_{ir}} J(E) K(t) dt$$

Partial Cross Sections $\boldsymbol{\sigma}^m$

$$\sigma^m = \sigma^{tot} - \frac{\int_{S_n} n_\gamma(E)\sigma^{gs}(E)dE}{\int_{S_n} n_\gamma(E)\sigma^{tot}(E)dE} \times \sigma^{tot}$$

$$\int_{S_n} n_\gamma(E)\sigma^{gs}(E)dE = \frac{Yield \cdot e^{\lambda t_{ir}}}{N_t \cdot h \cdot i \cdot \varepsilon_X(E_X) \cdot (e^{-\lambda t_{start}} - e^{-\lambda t_{stop}})} \cdot \frac{\int_0^{t_{ir}} K(t)dt}{\int_0^{t_{ir}} K(t) \cdot e^{\lambda t} dt}$$

$$\int_{S_n} n_\gamma(E)\sigma^{tot}(E)dE = \frac{n_n}{N_t \cdot f \cdot \varepsilon_n(E_n)}$$

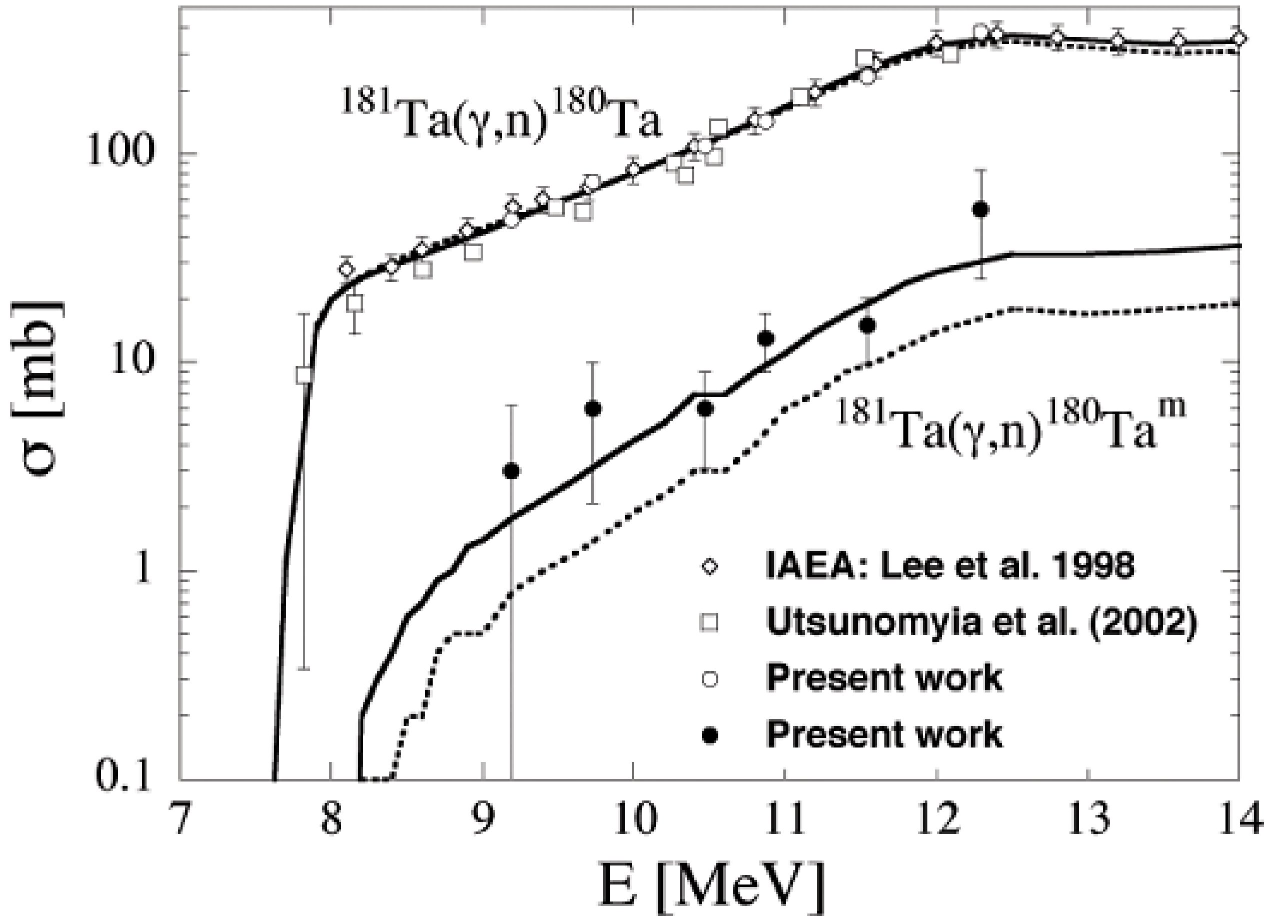
$$\sigma^{tot}(E) = \sum_{k=1}^{2} \frac{\sigma_k}{1 + \frac{(E^2 - E_k^2)^2}{E^2\Gamma_k^2}}$$

The case of ^{197}Au

$\boldsymbol{\sigma}^{photoactivation} = (0.99 \pm 0.015)\ \boldsymbol{\sigma}^{neutron\ counting}$

Systematic error for $\boldsymbol{\sigma}^{tot}$: 4.4% ($n_{\boldsymbol{\gamma}}$:3.0%, $\boldsymbol{\varepsilon}_n$:3.2%)

Experimental results, and comparison with theoretical models



The Solid Line ; Combinatorial NLD model

The Dashed Line ; Statistical NLD model

Consideration for the nucleosynthesis of ^{180}Ta

- p-processは比較的高いエネルギー（$1.8 \leqq T[10^9 K] \leqq 3.0$; typically 300[keV])で起こる為、^{180}Taの基底状態と9^-励起状態が熱平衡状態となり、σ^mが生成率決定因子となり得ない。
- p-processによって生成された^{180}Taは、再度光核分解を起こし^{179}Taへ崩壊する事が考えられ、その反応断面積の実験情報が必要となる。

Summary

- 産総研のLCS-γ線を用いて$^{181}Ta(\gamma,n)^{180}Ta^{m}$部分光核反応断面積の測定を行い、6点の$E_{\gamma}$において結果を得た。
- ^{180}Taの熱平衡や、光核分解の効果により、本実験結果だけからp-processによる^{180}Taの生成率を決定する事は出来ない。
- Spring-8にSCWを設置する事で発生する放射光を使えば$^{180}Ta^{m}(\gamma,n)^{179}Ta$消滅断面積の測定が可能となる。
- 上記の放射光のエネルギー分布はp-process光子のそれと酷似しており、本研究にとって最適の光源として期待できる。