

大強度放射光を使った 最稀少同位元素 ^{180}Ta 消滅断面積測定

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産業技術総合研究所 光技術研究部門
後神進史

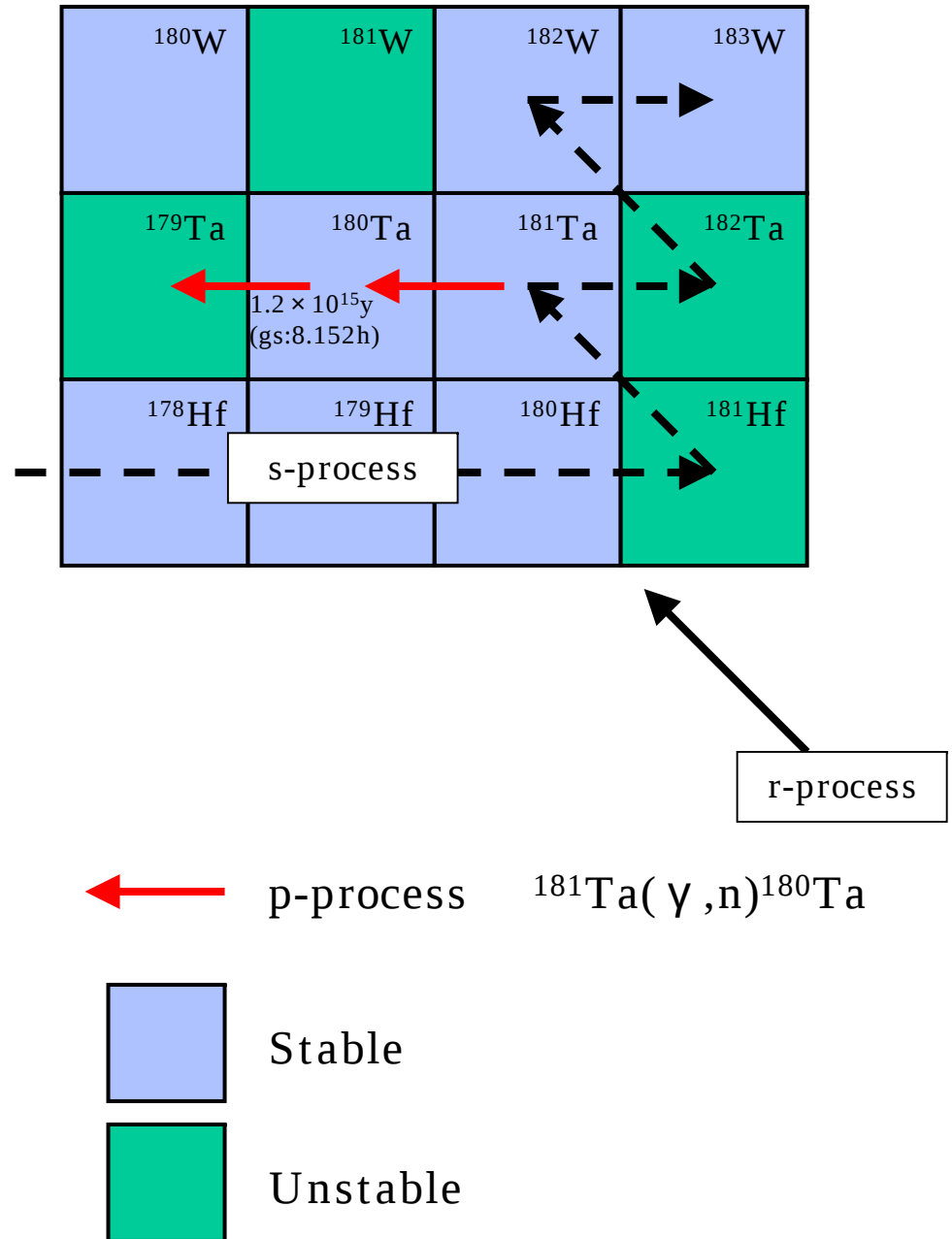
1. 実験目的
2. 実験手順、収量の見積もり
3. 産総研での実験例

24. Dec. 2003

実験目

$^{180}\text{Ta}(9^-)$ Nature's rarest isotope
 odd-odd nucleus
 abundance 0.012%
 halflife $>1.2 \times 10^{15}\text{y}$
 $E_x = 75\text{keV}$

$^{180}\text{Ta}(\text{gs})$
 halflife 8.152h



p-process nuclei

Type Supernova Scenario

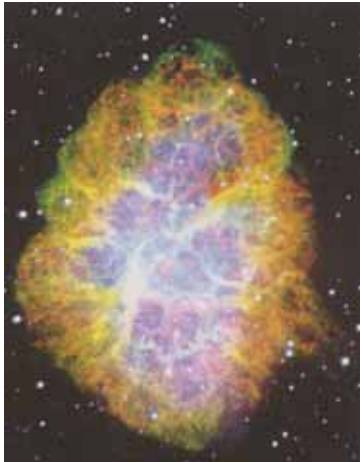
Pranzos(1989), Rayet(1987,1990),

Woosley & Haward(1987)

Explosive burning of O/Ne rich
layers by shock wave heating

$T_9=2-3$, $\rho=10^6[\text{g/cm}^3]$,

$\tau_{\text{ex}} < 1[\text{sec}]$



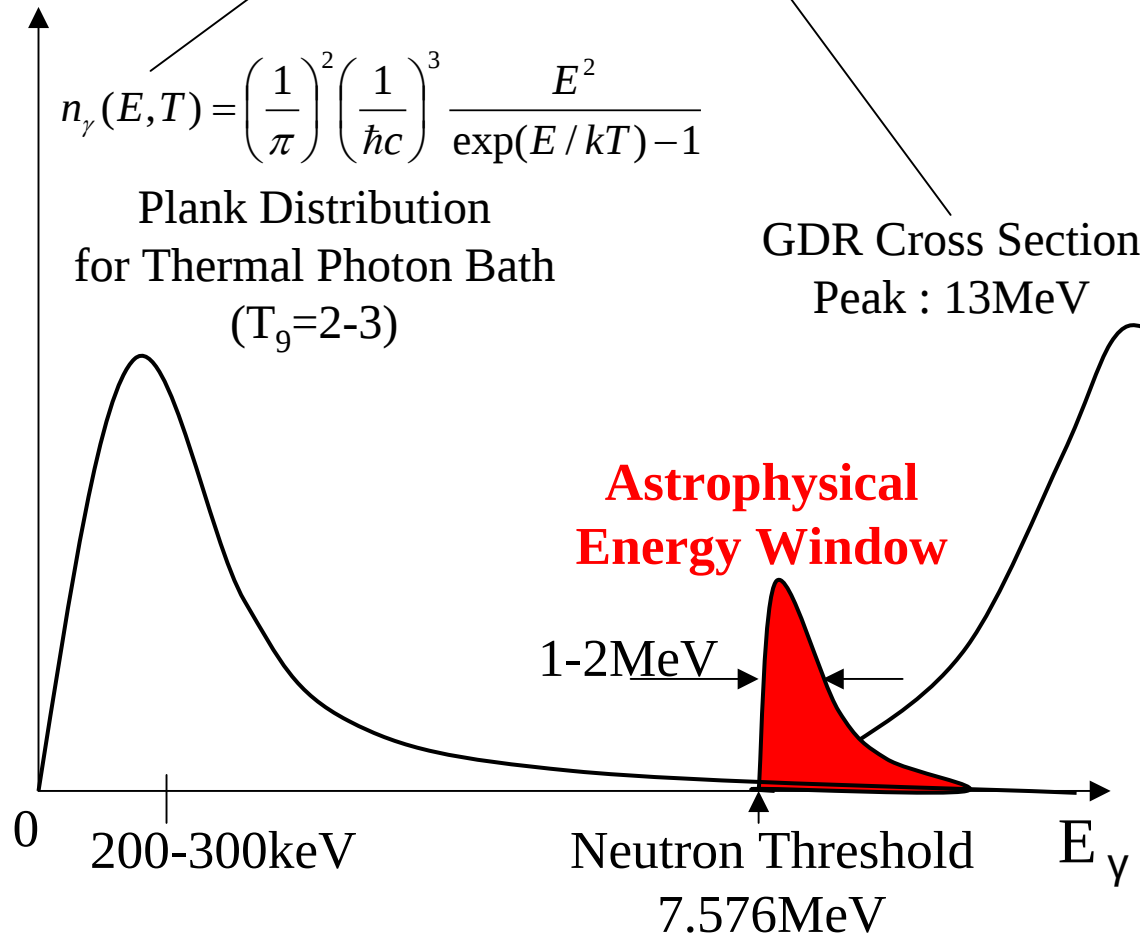
Reaction Rate

$$\lambda(T) = \int_0^\infty \underbrace{cn_\gamma(E,T)}_{\text{Plank Distribution for Thermal Photon Bath (T}_9=2-3)} \underbrace{\sigma_\gamma(E)}_{\text{GDR Cross Section Peak : 13MeV}} dE$$

$$n_\gamma(E,T) = \left(\frac{1}{\pi}\right)^2 \left(\frac{1}{\hbar c}\right)^3 \frac{E^2}{\exp(E/kT) - 1}$$

Plank Distribution
for Thermal Photon Bath
($T_9=2-3$)

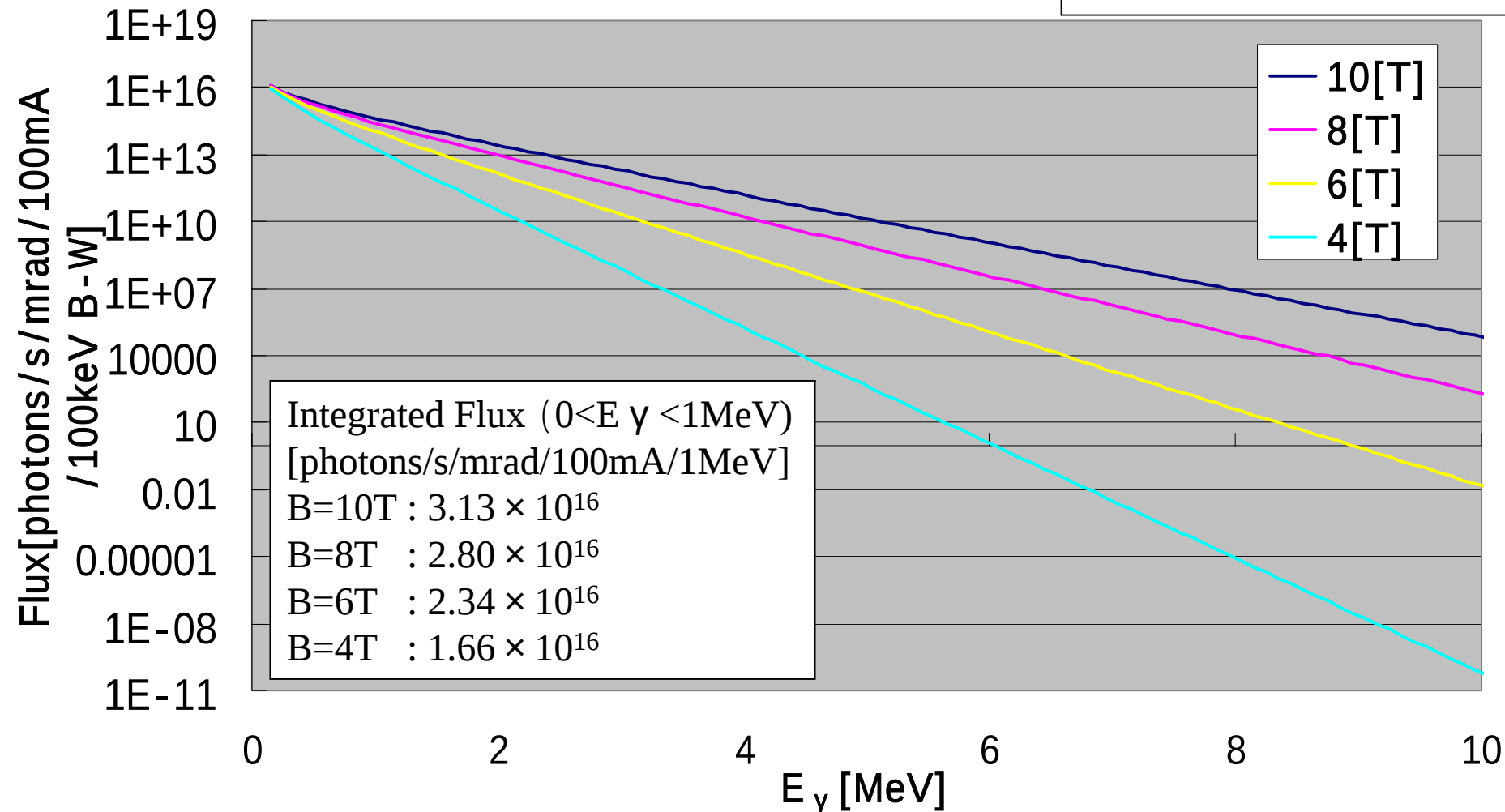
GDR Cross Section
Peak : 13MeV



超伝導ウィグラーからの γ 線Flux

Photon Flux

Integrated Flux
($7.5\text{MeV} < E_\gamma < 8.5\text{MeV}$)
[photons/s/mrad/100mA/1MeV]
B=10T : 1.11×10^8
B=8T : 1.26×10^6
B=6T : 7.12×10^2
B=4T : 2.77×10^{-4}



Target Material Tantalum

^{181}Ta

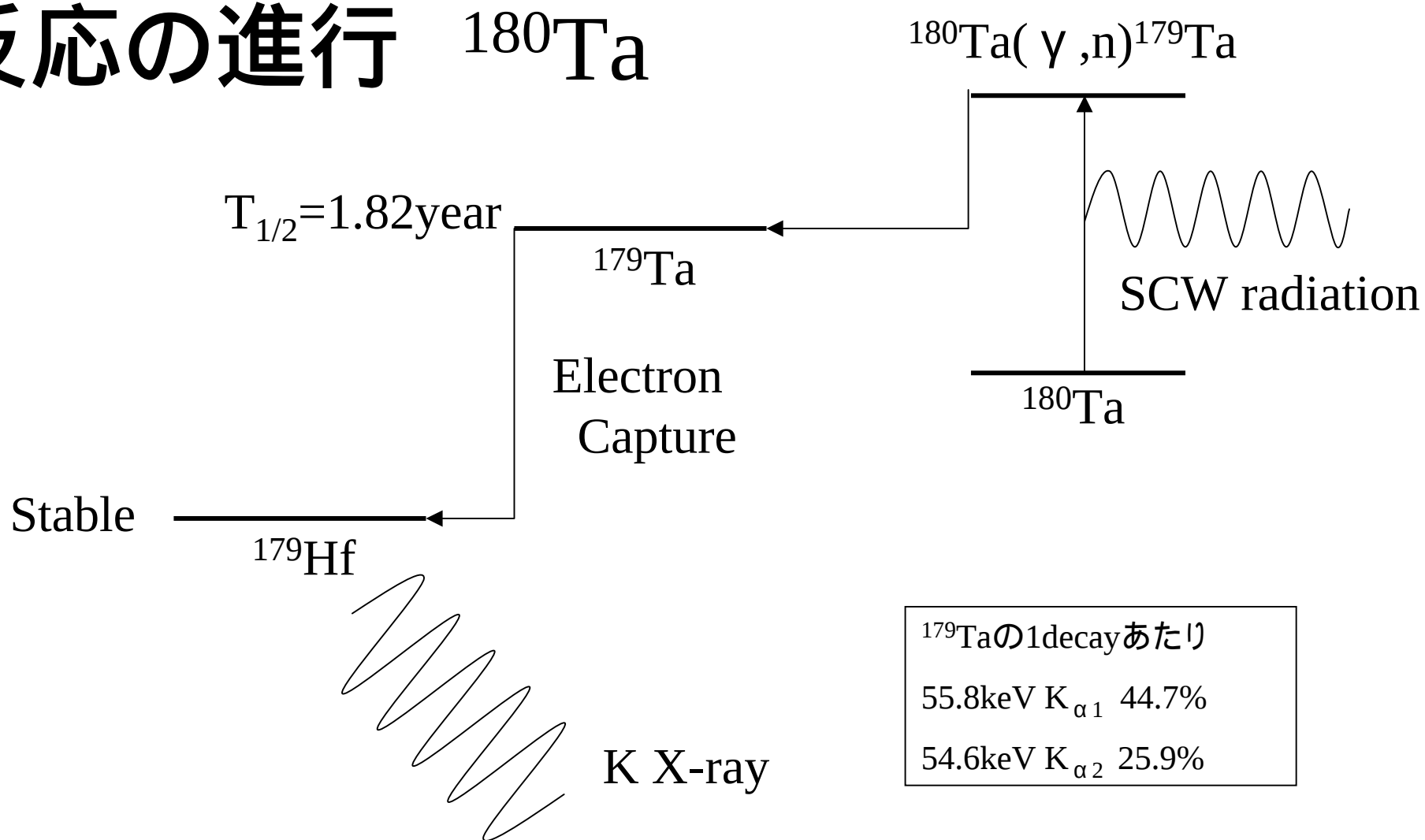
- Abundance : 99.988%
- Threshold : 7.578MeV
- Half Life : Stable

^{180}Ta

- Abundance : 0.012%
- Threshold : 6.645MeV
- Half Life :
ground state : 8.152h
9⁻ state : $>1.2 \times 10^{15}\text{y}$

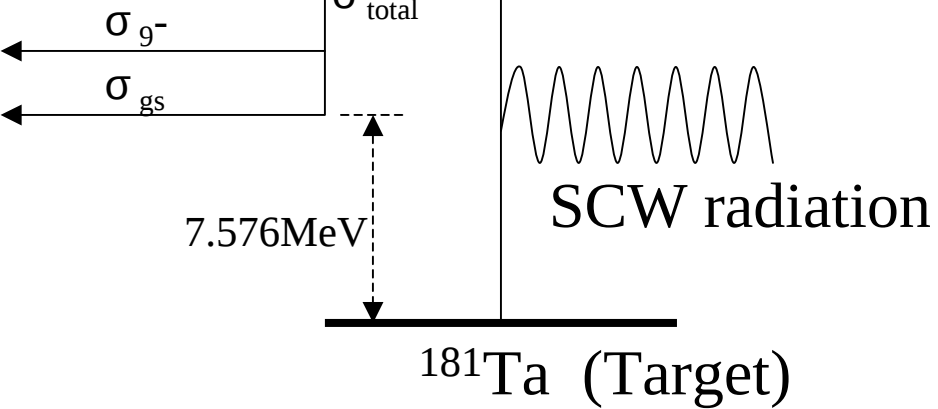
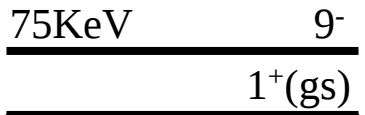
実験手順

反応の進行



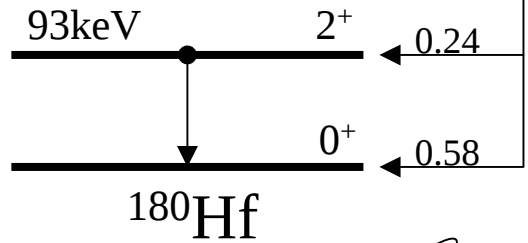
反応の進行 ^{181}Ta

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

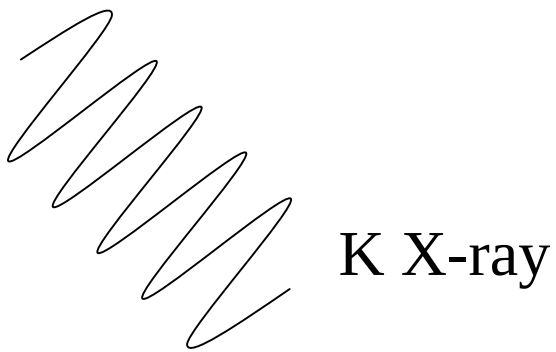
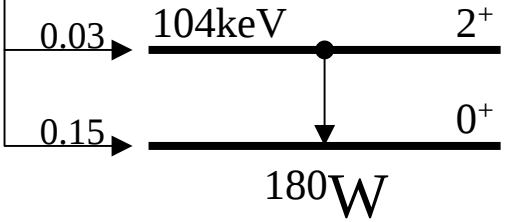


^{180}Ta

Electron
Capture



β^- - decay



収量の見積もり

$_{73}\text{Ta}$ ターゲット(purity:99.985%) に含まれる不純物

- $_1\text{H}$ <0.0005%
- $_6\text{C}$ <0.001%
- $_7\text{N}$ 0.001%
- $_8\text{O}$ 0.004%
- $_{14}\text{Si}$ 0.001%
- $_{22}\text{Ti}$ <0.001%
- $_{26}\text{Fe}$ <0.001%
- $_{28}\text{Ni}$ <0.001%
- $_{41}\text{Nb}$ 0.001%
- $_{74}\text{W}$ <0.01%

^{181}Ta

- $^{181}\text{Ta}(\gamma, n)^{180}\text{Ta}^{\text{gs}} \rightarrow ^{180}\text{Hf}(86\%)$
 $^{180}\text{W}(14\%)$
- Content : 99.973%
- Threshold : 7.577MeV
- Decay Mode : Electron Capture, β^- decay
- Half Life : 8.152hour
- X-ray : 55.790keV($K_{\alpha 1}$), 54.611kev($K_{\alpha 2}$)

^{180}Ta

- $^{180}\text{Ta}(\gamma, n)^{179}\text{Ta} \rightarrow ^{179}\text{Hf}$
- Content : 0.012%
- Threshold : 6.645MeV
- Decay Mode : Electron Capture
- Half Life : 1.82year
- X-ray : 55.790keV($K_{\alpha 1}$), 54.611kev($K_{\alpha 2}$)



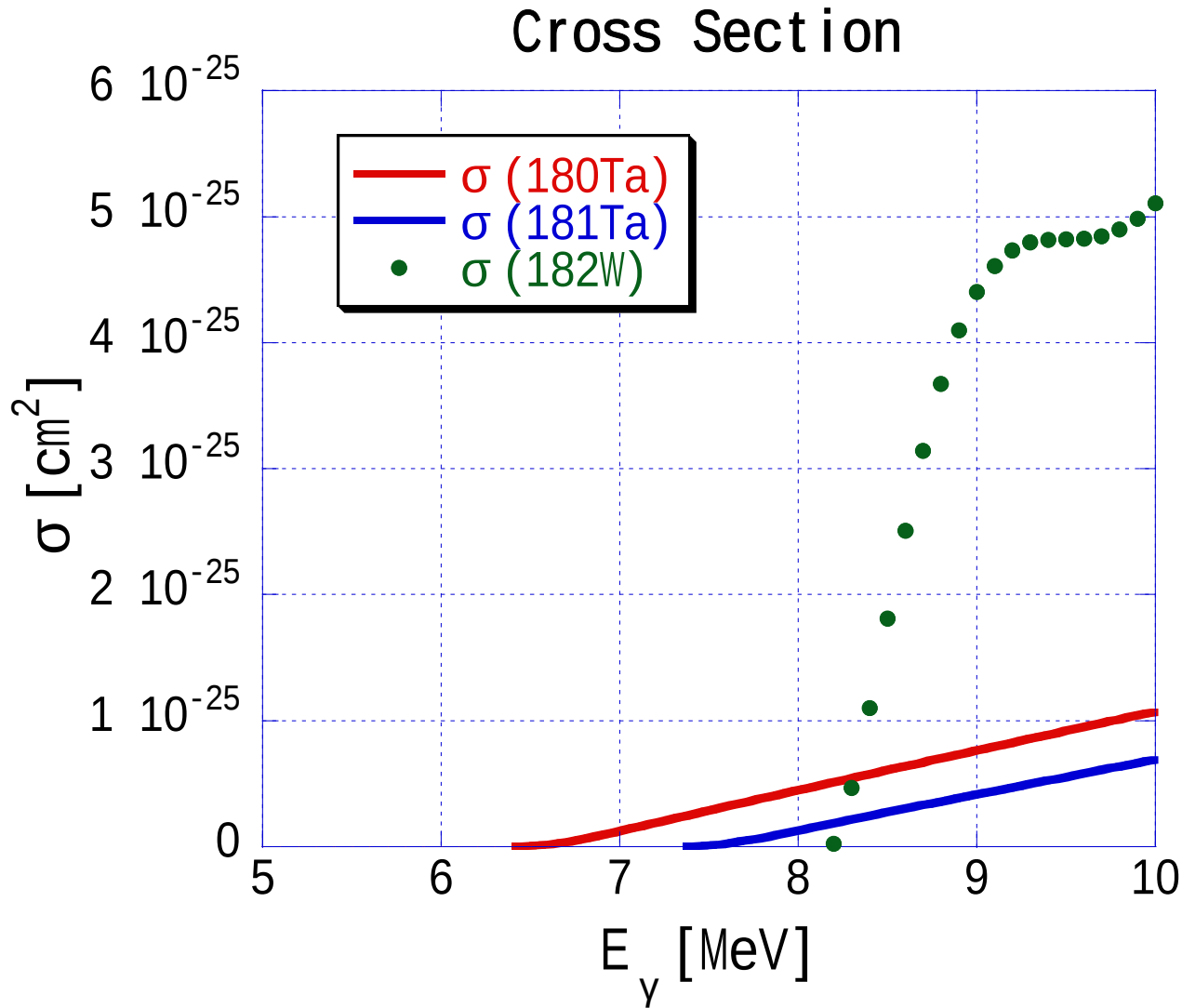
- $^{182}\text{W}(\gamma, n)^{181}\text{W} \rightarrow ^{181}\text{Ta}$
- Content : 0.00265%
- Threshold : 8.064MeV
- Decay Mode : Electron Capture
- Half Life : 121.2day
- X-ray : 57.535keV($K_{\alpha 1}$), 56.280keV($K_{\alpha 2}$)

$$\sigma = \sigma_0 \left(\frac{E_\gamma - S_n}{S_n} \right)^p$$

Threshold

^{181}Ta : 7.577MeV

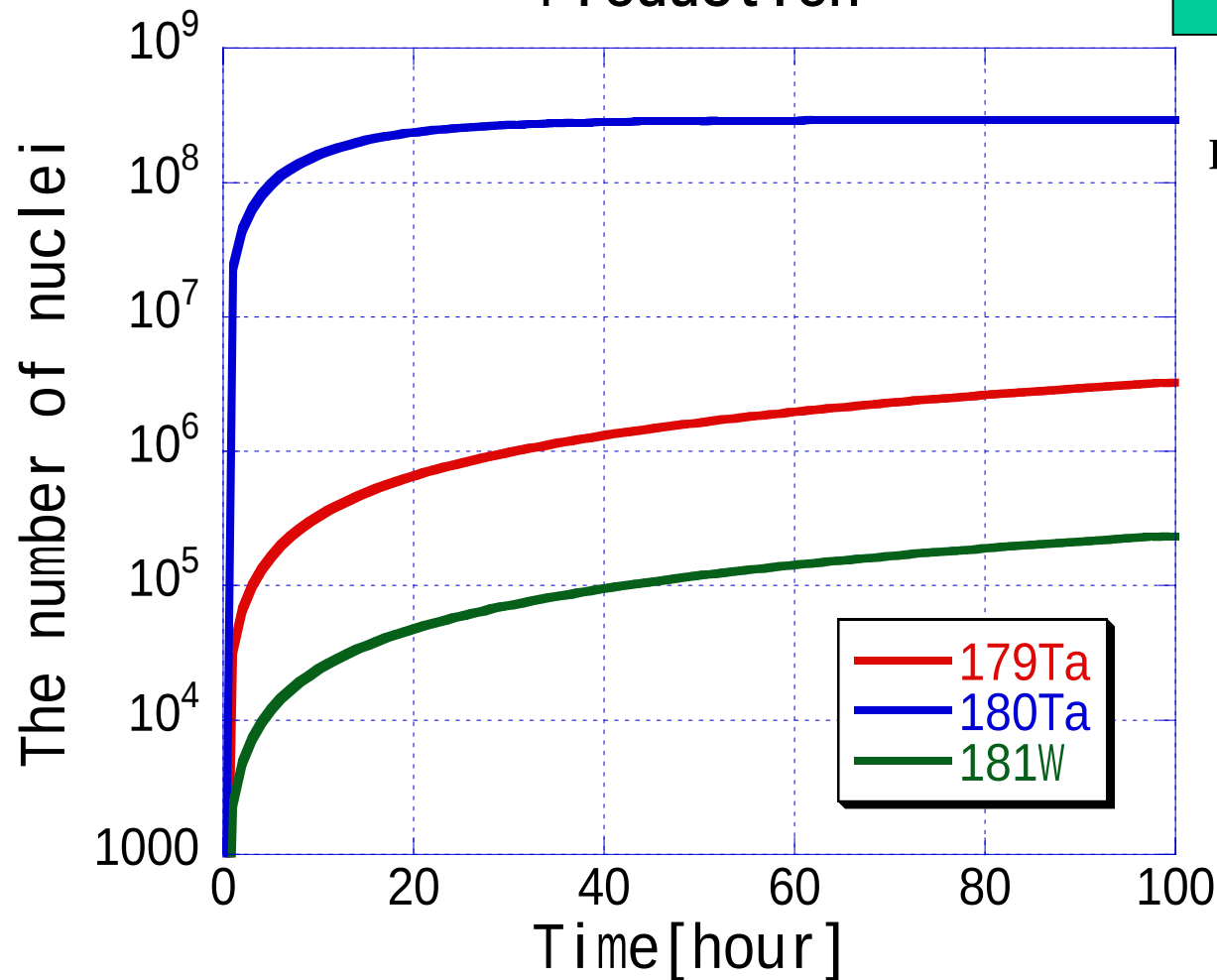
^{180}Ta : 6.645MeV



ターゲットの100時間照射

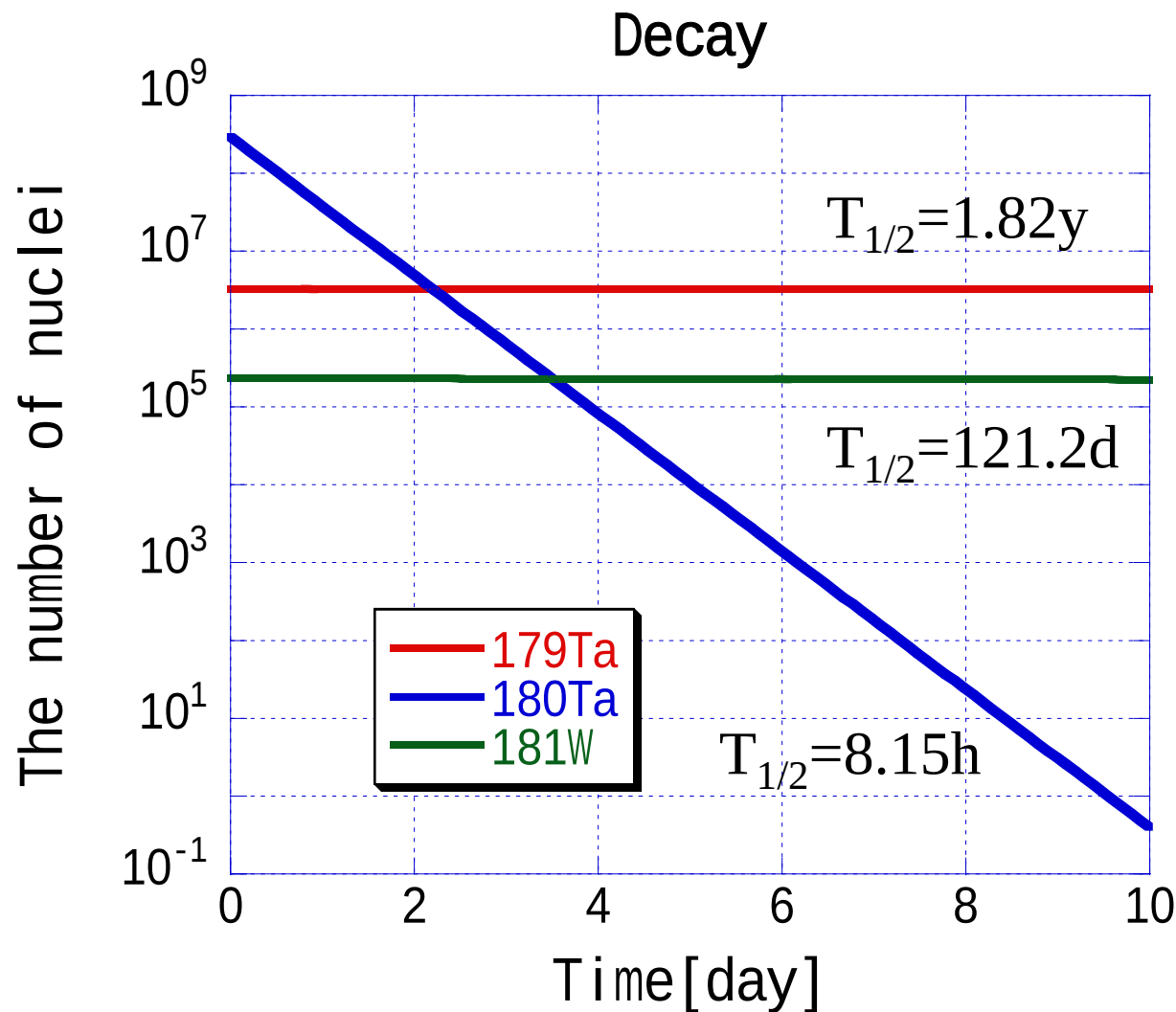
$$N = \frac{n\sigma I}{\lambda} \left(1 - \frac{1}{e^{\lambda t}} \right)$$

Production

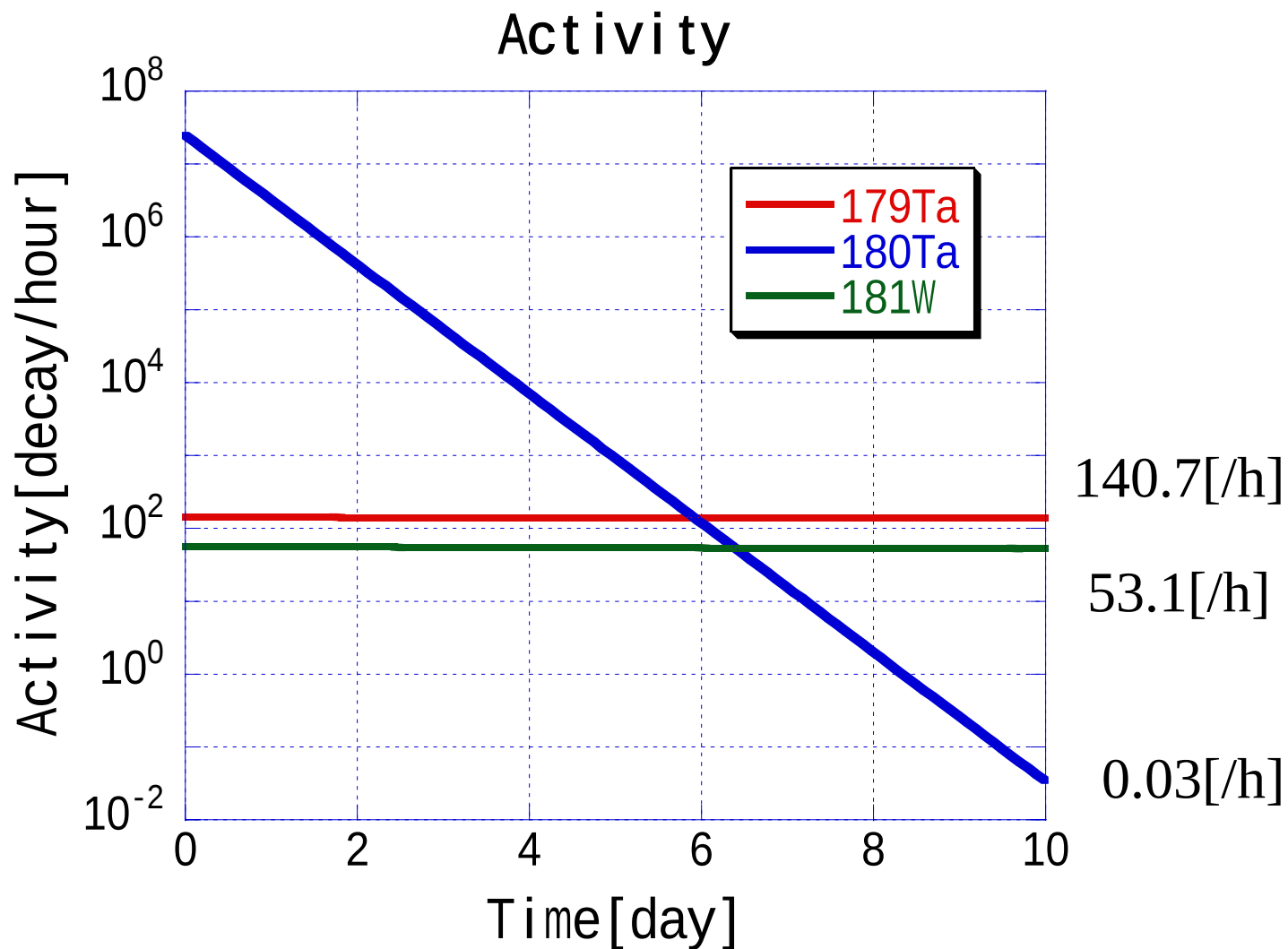


$$n_t : 5.54 \times 10^{21} [\text{/cm}^2]$$

100時間照射後の娘核崩壊



100時間照射後の娘核放射能



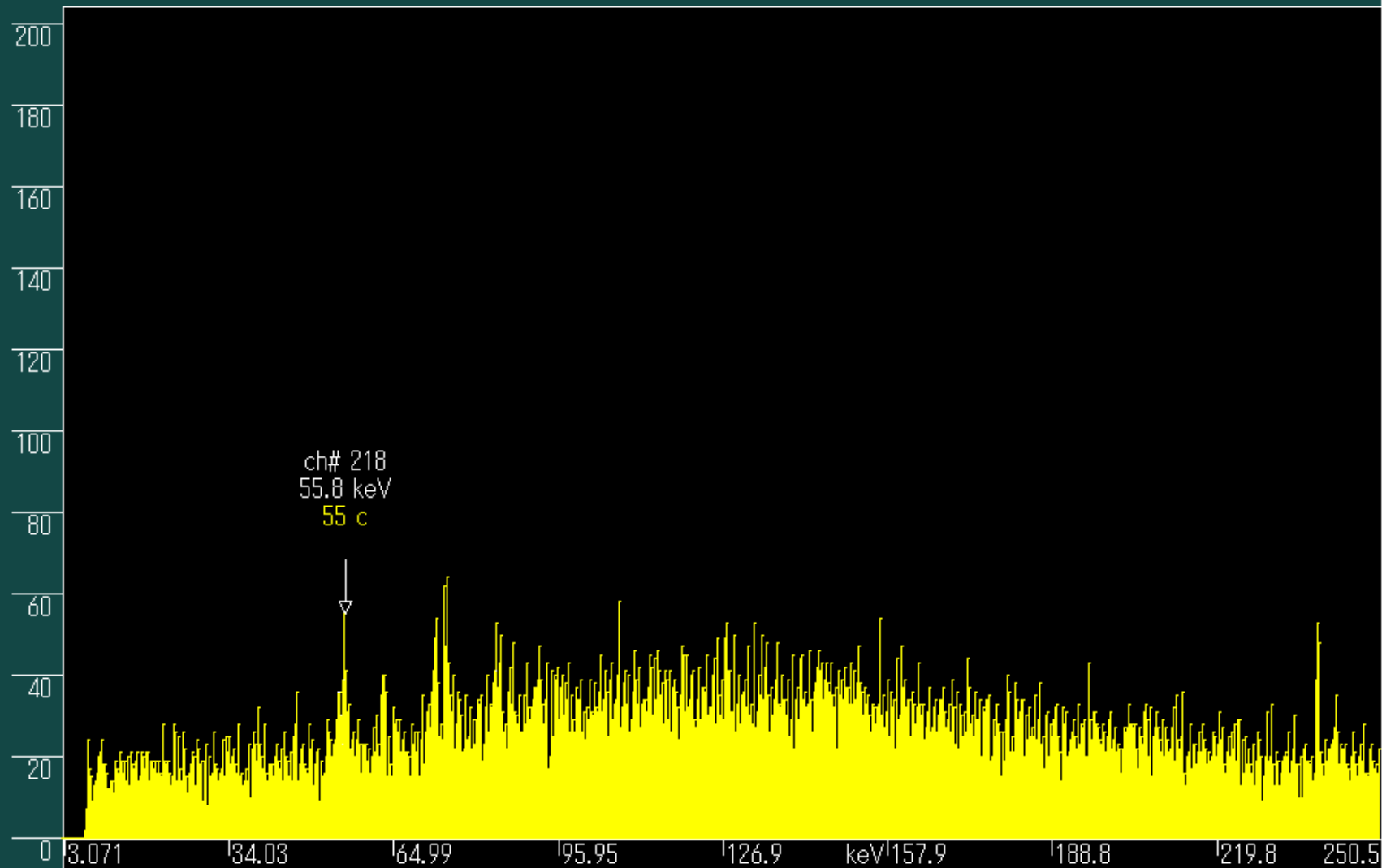
KX-ray Measurement

- Activity 140.7[decay/hour]
- X線放射確率 $K_{\alpha 1}$ 44.7%
 $K_{\alpha 2}$ 25.9%
- Ge Detector Efficiency 34.4% $\times 2$
- Self Absorption (0.1[mm]thick) 27%

Count Rate 49.8[counts/hour]

Photon Spectrum measured at AIST

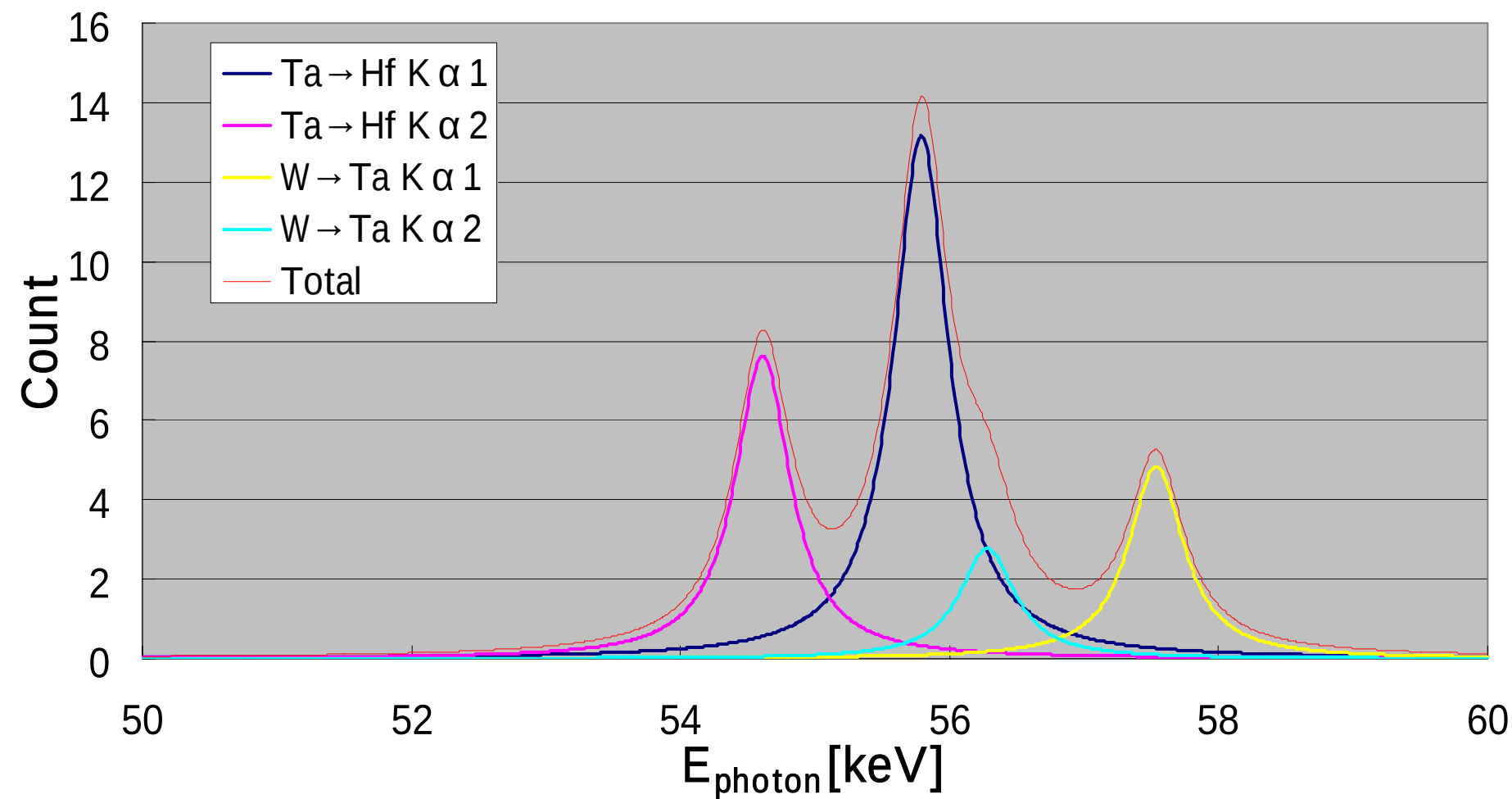
Linear



Preset-T	3600.000
Stopped	
True Time	3600.000
Live Time	3597.431
% Dead	0.07
Gross Count	49911
LTC	1
Counts/sec	13.8741
Pole Zero	0
Collect Start	2003/Jul/11 18:57:06
Collect Stop	2003/Jul/11 19:57:06
User ID	

予想されるスペクトル

X-ray Spectra



産総研での実験例

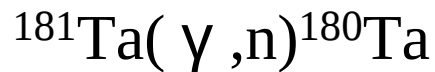
レーザー逆コンプトン γ 線を使った

$^{181}\text{Ta}(\gamma, n)^{180\text{m}}\text{Ta}$ 部分断面積測定

(July 2001 ~ Sep. 2003)

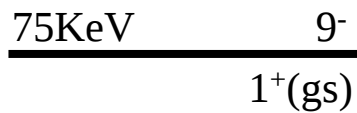
1. 中性子の直接計数による全断面積測定
2. 放射化法による $^{181}\text{Ta}(\gamma, n)^{180}\text{Ta}(\text{gs})$ 部分断面積測定

$$\sigma_{9^-} = \sigma_{\text{total}} - \sigma_{\text{gs}}$$



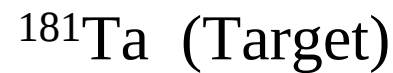
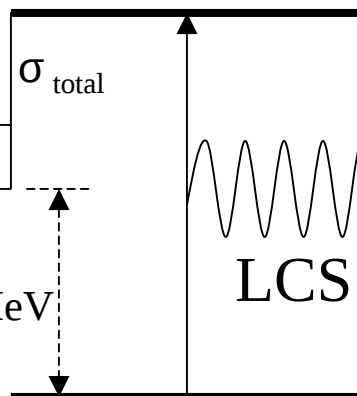
$$T_{1/2} > 1.2 \times 10^{15} \text{y}$$

$$T_{1/2} = 8.152 \text{h}$$

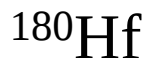
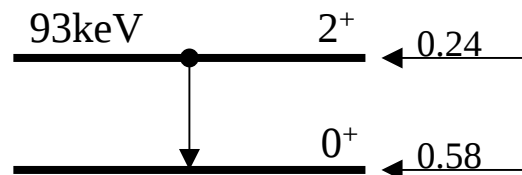


$$\sigma_{9^-}$$

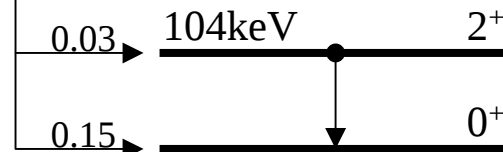
$$\sigma_{\text{gs}}$$



Electron
Capture



β^- - decay

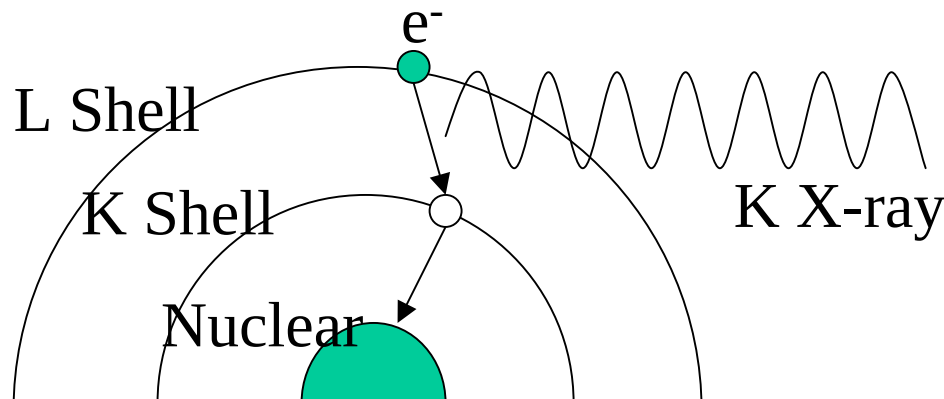


$^{180}\text{Ta}(\text{gs})$ の1decayあたり

93keV γ -ray 4.665%

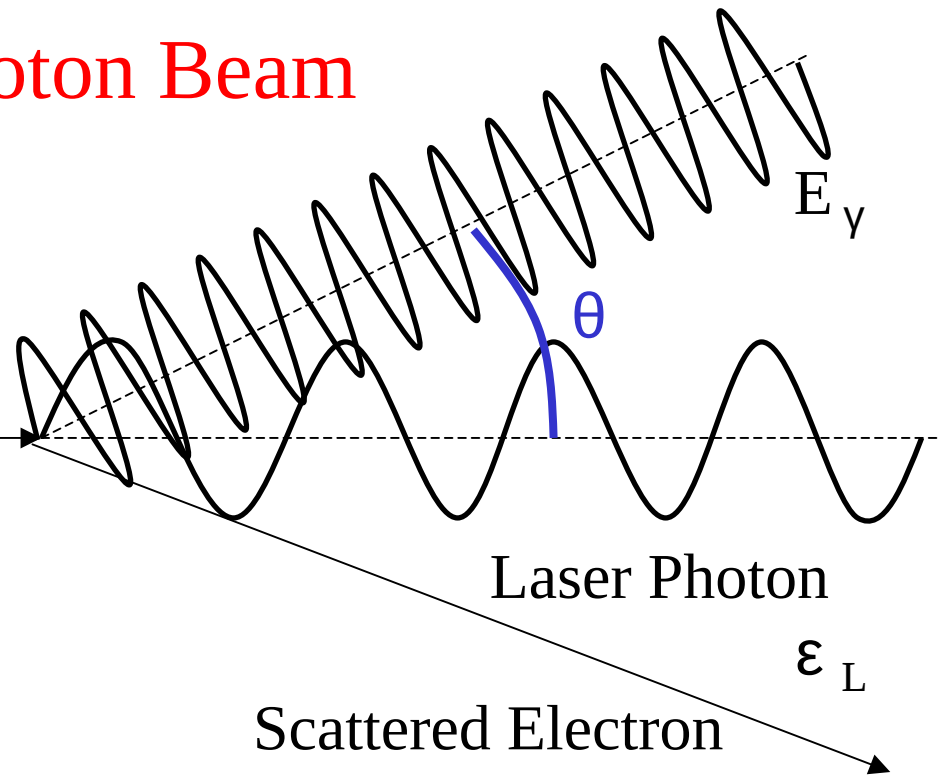
55.8keV $K_{\alpha 1}$ 40.3%

54.6keV $K_{\alpha 2}$ 23.4%



Laser Electron Photon Beam

Incident Electron
 E_e



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

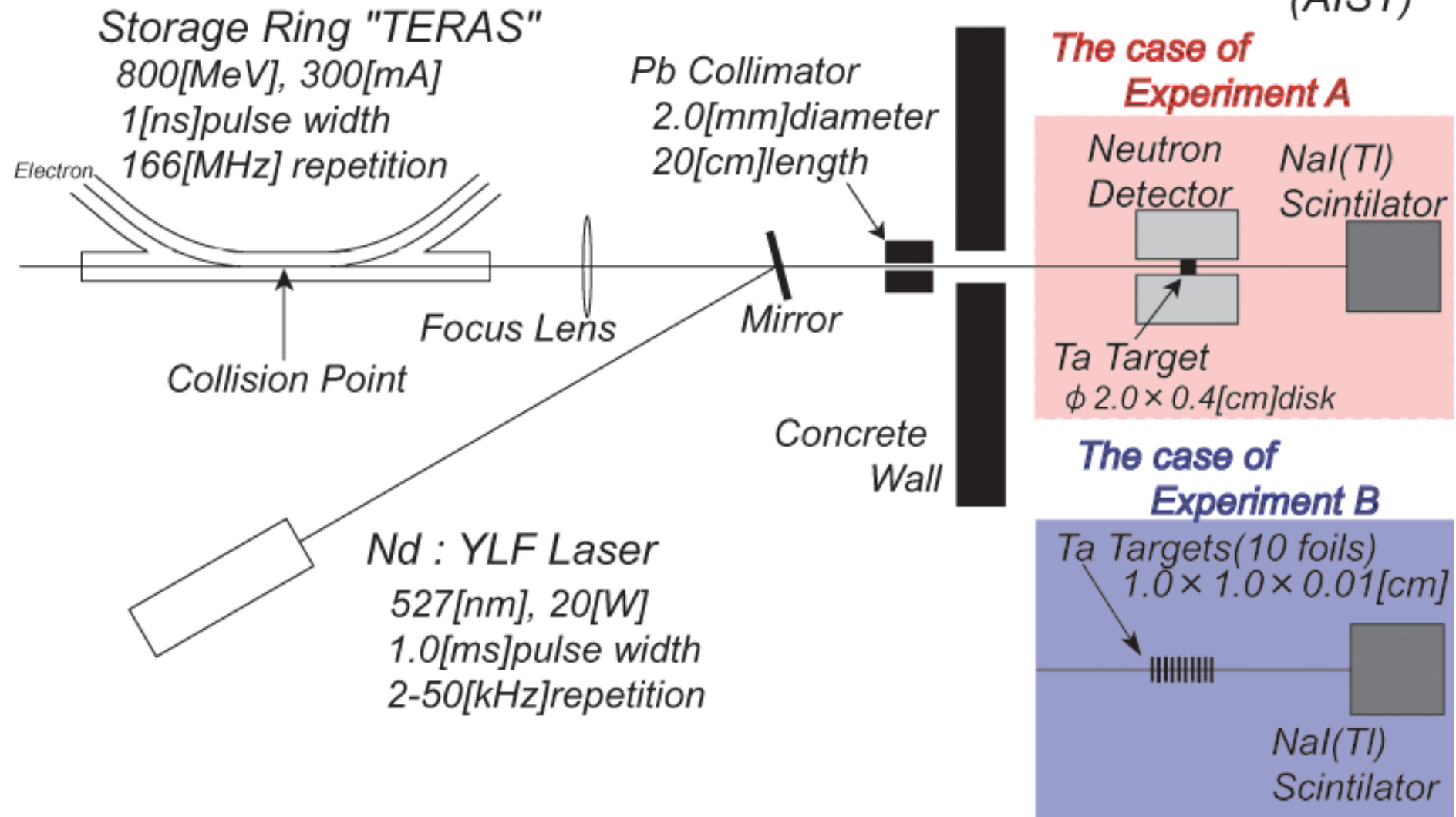
β : Velocity of Electron / c

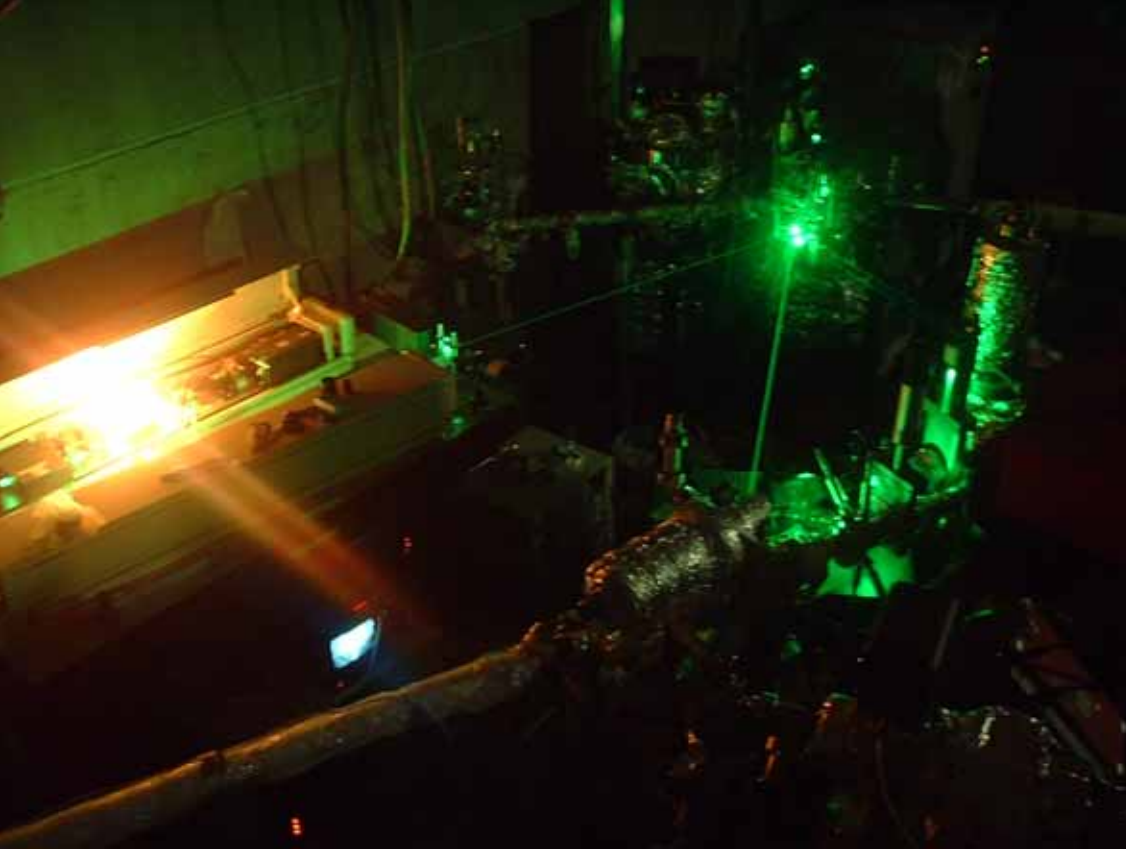
θ : Scattered Angle of Laser Photon

θ_L : Incident Angle of Laser Photon

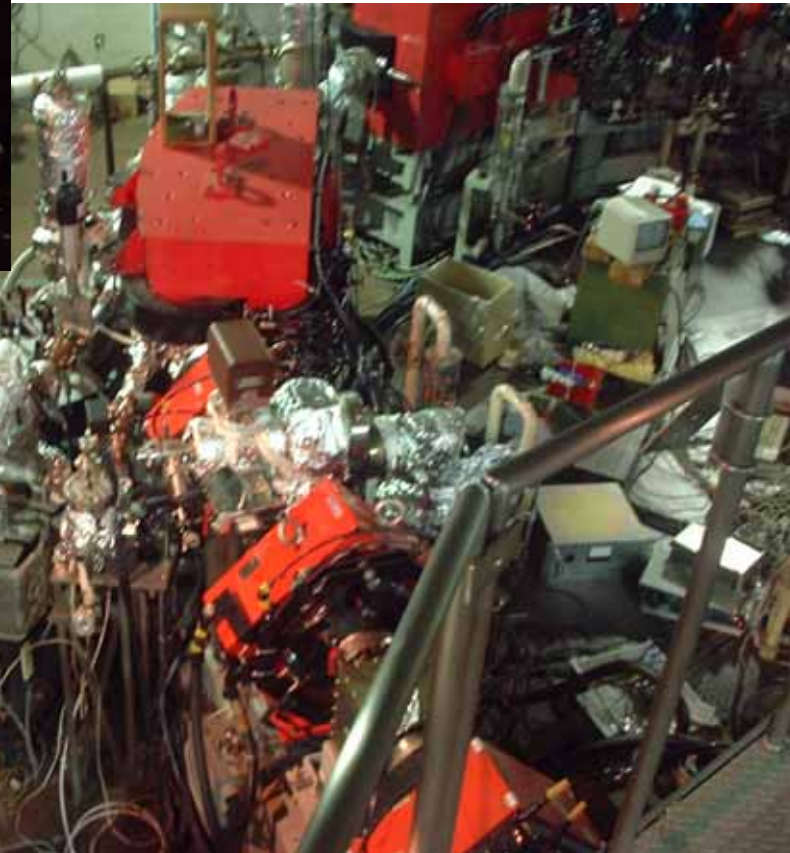
Experimental Set-up

at National Institute of Advanced Industrial Science and Technology
(AIST)





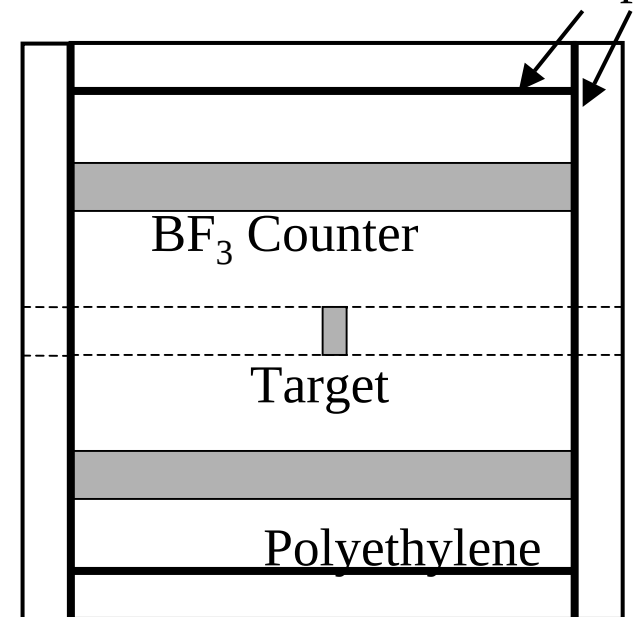
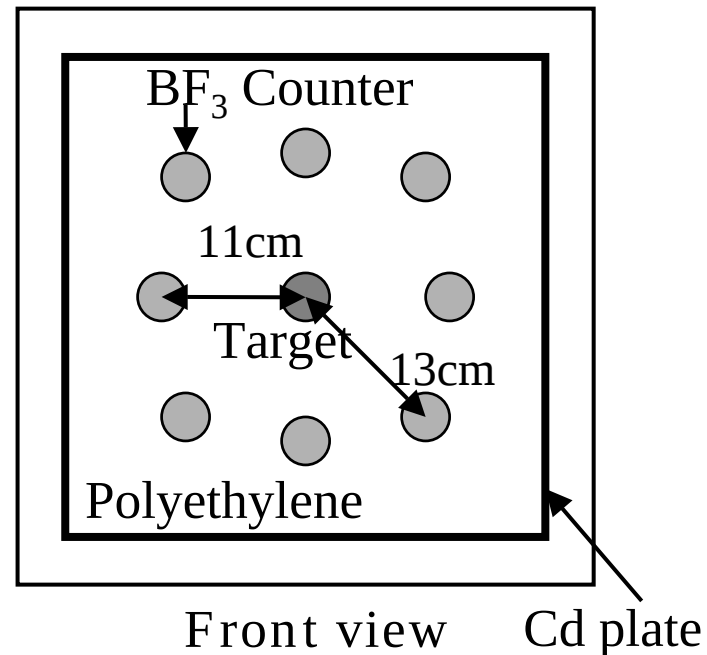
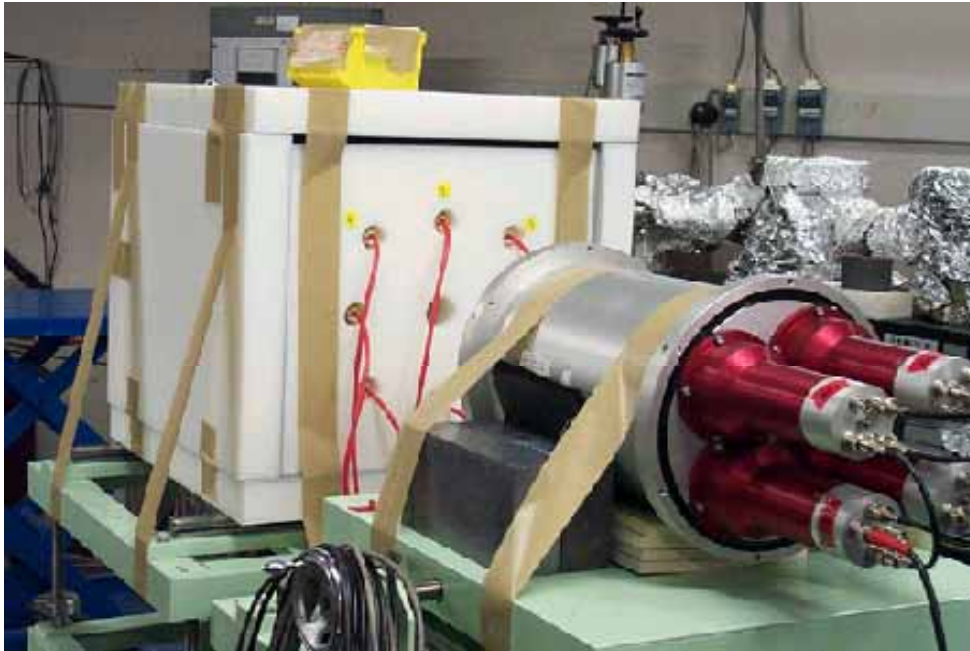
Laser Electron
Photon Beam



Electron Storage Ring
“TERAS”

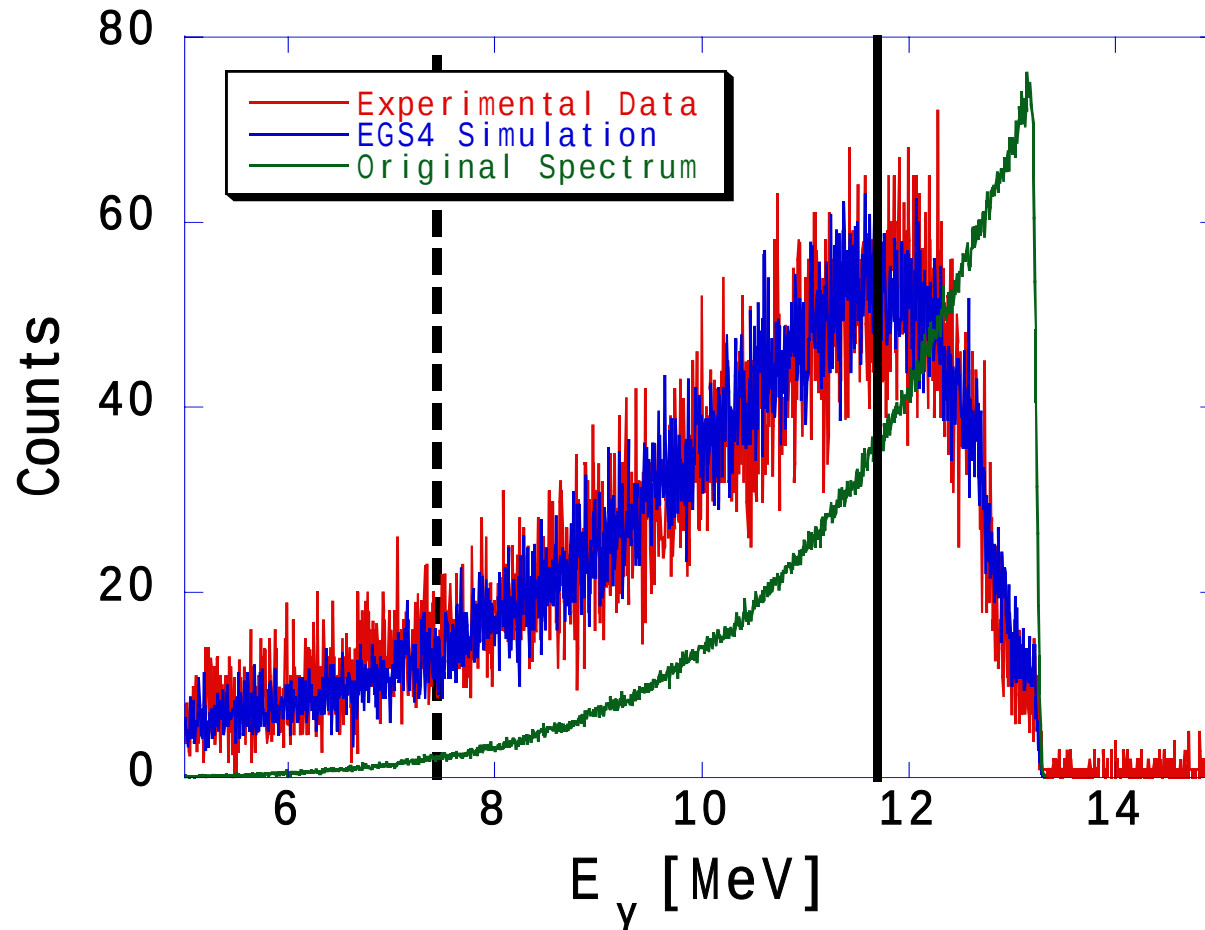


Neutron Detector and NaI(Tl) Scintillator



The cross sectional view
From the side

Laser-Electron Photon Beam Energy Distribution



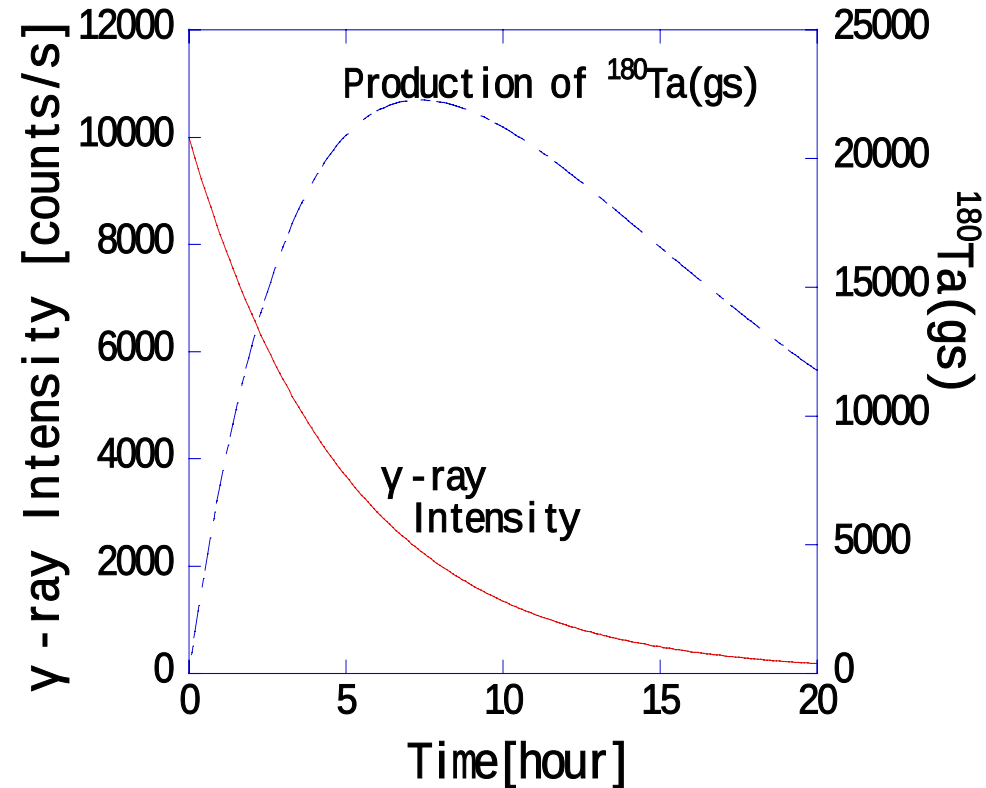
- Reaction Threshold 7.576[MeV]
- Fraction Factor 0.983
- Average Energy 11.70[MeV]

Measurements of Partial Cross Sections σ_{gs}

The first step

The number of $^{180}\text{Ta}(\text{gs})$ produced

$$N(T) = \frac{n_t \sigma \int_0^T e^{\lambda t} I(t) dt}{e^{\lambda T}}$$



σ : Cross Section [cm^2]

n_t : The number of target nuclei [$/\text{cm}^2$]

$I(t)$: γ -ray intensity [$/\text{hour}$]

λ : Decay constant of $^{180}\text{Ta}(\text{gs})$ [$/\text{hour}$]

Parameters

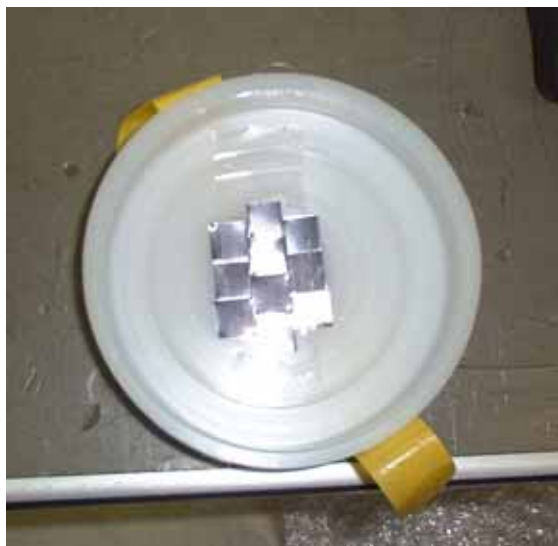
$\sigma = 4.50 \times 10^{-25} [\text{cm}^2]$

$n_t = 5.52 \times 10^{20} [/cm^2]$

$I(t) = 3.6 \times 10^7 \times e^{-0.2t} [\text{counts/h}]$

$\lambda = 0.087 [/h]$

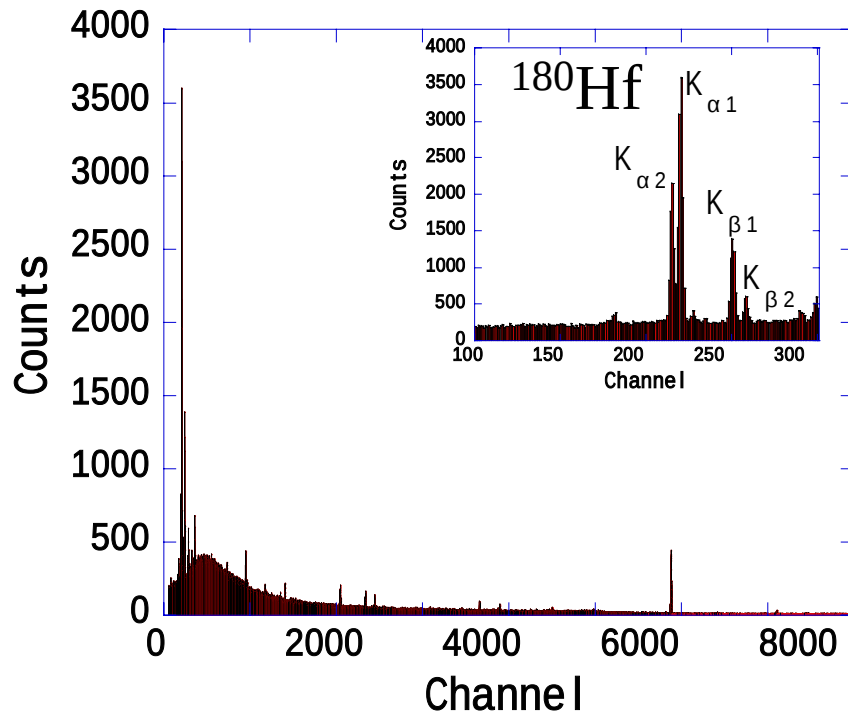
Ge Detector Set-up



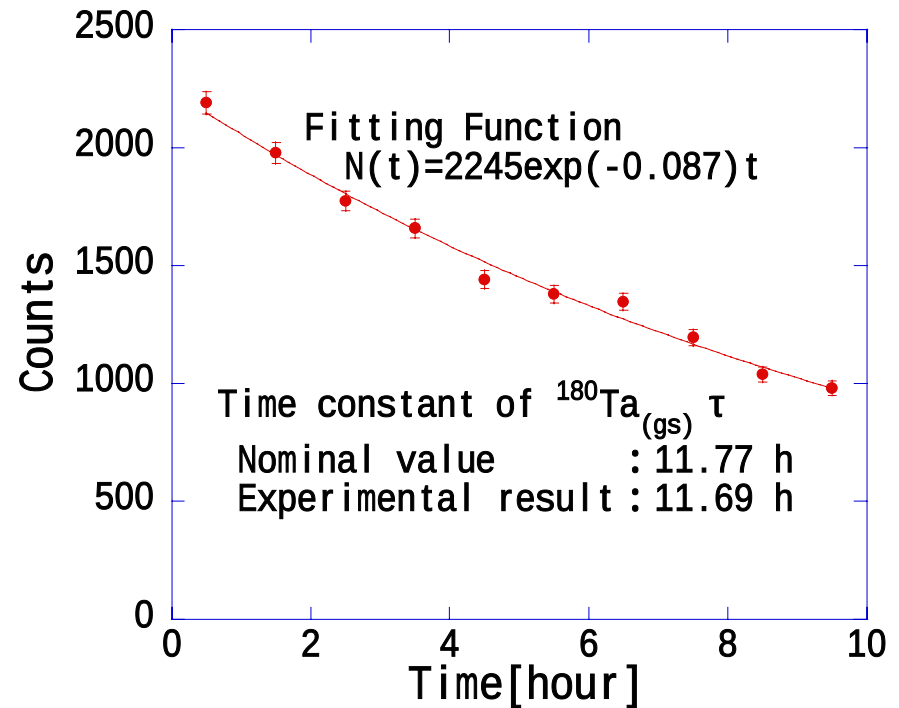
Activated Ta Foils
on Polyethylene Cap



$^{180}\text{Ta}(\text{gs})$ Decay measured by Ge Detector



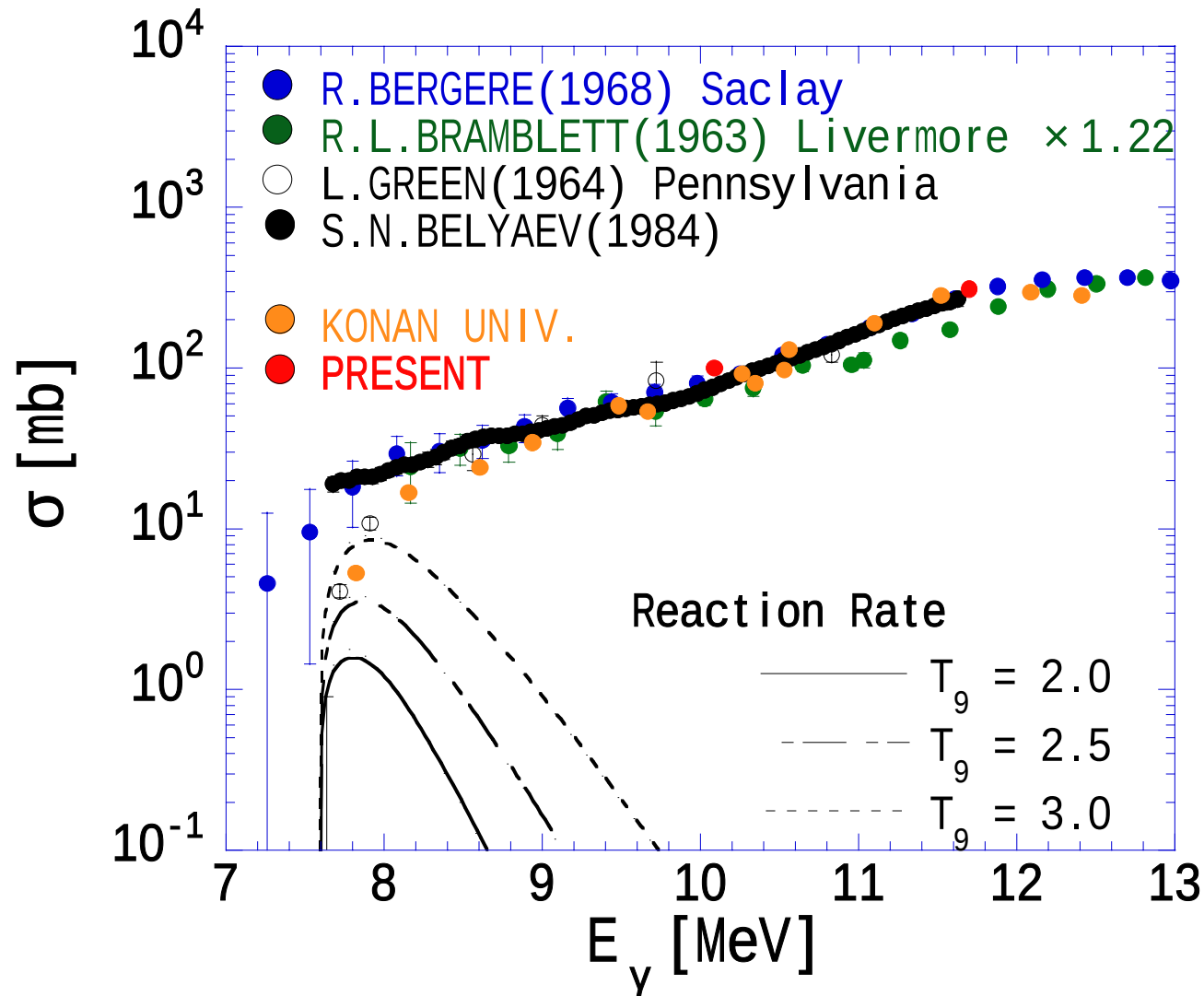
Photon Spectrum
with Ge Detector



The Sum Total Counts of
 $K_{\alpha 1}$ and $K_{\alpha 2}$ per 1 hour

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

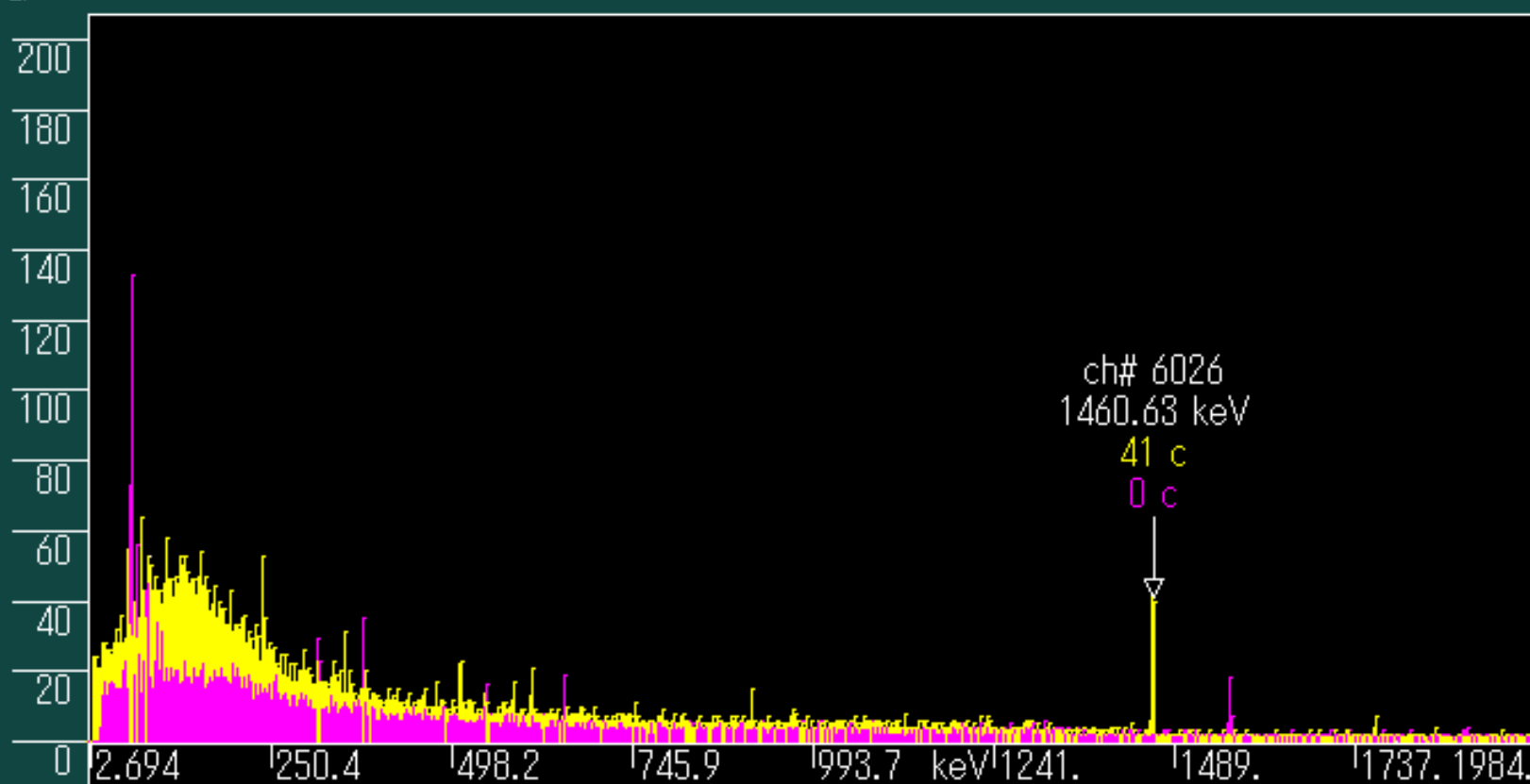
Total Cross Sections





Photon Spectrum

Linear



Preset-T
3600.000
Stopped

True Time
3600.000

Live Time
3597.431

% Dead
0.07

Gross Count
49911

LTC
1

Counts/sec
13.8741

Pole Zero
0

Collect Start
2003/Jul/11
18:57:06