清華大學 Tsinghua University

Radiation Physics and Detection Technology

Department of Engineering Physics

# The study of $^{181}Ta$ $\sigma_{(e,e'xn)}$ with 100MeV electrons


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# outline

1. Research motivation
2. The measurement of (e,e'xn) reaction
3. Summary

# 1. Research motivation

Reactions of producing neutrons:

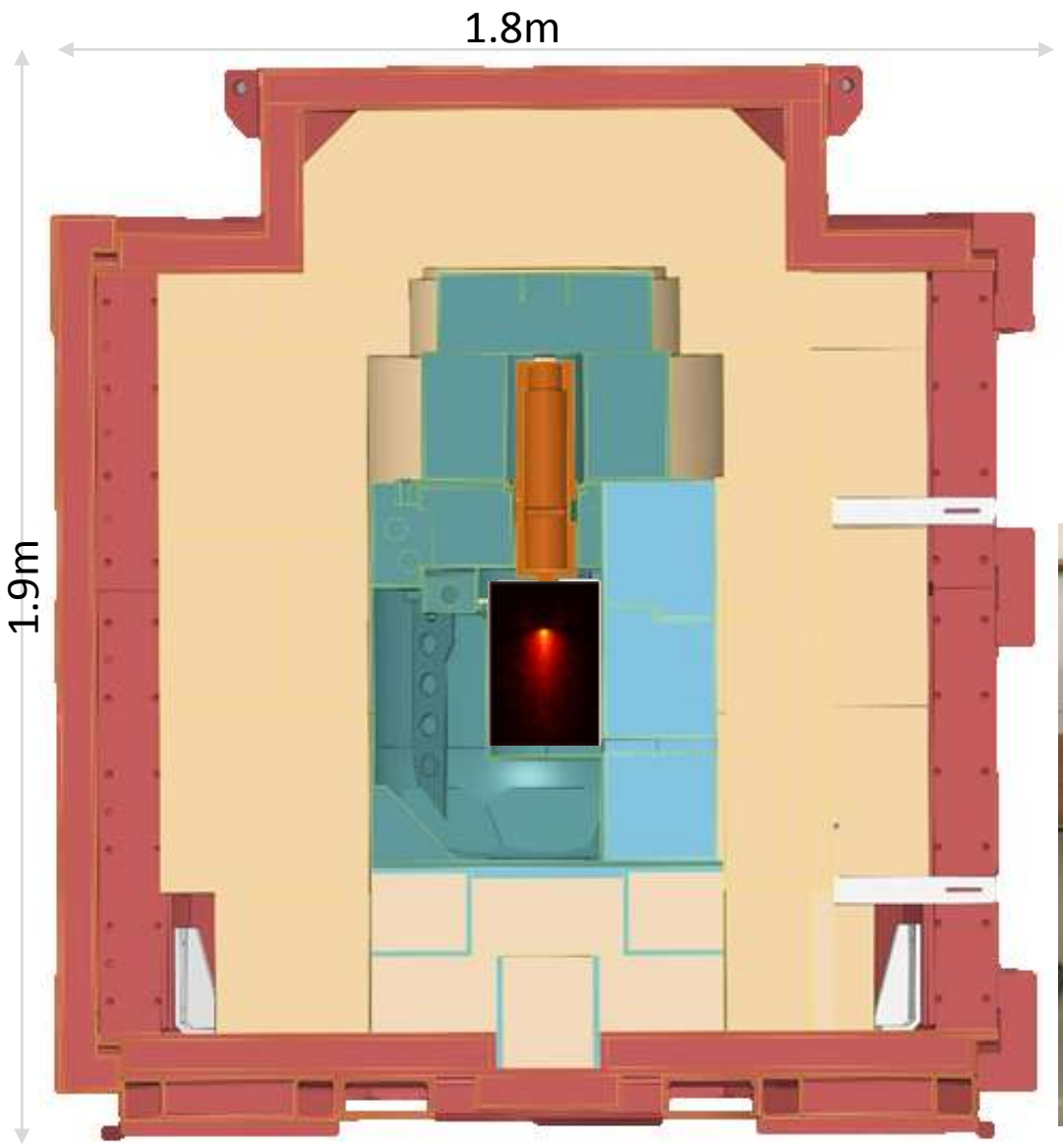
$$ {}^{A_2}_{Z_2}C + {}^{A_1}_{Z_1}X \rightarrow {}^{A_1+A_2-1}_{Z_1+Z_2}Y + n $$

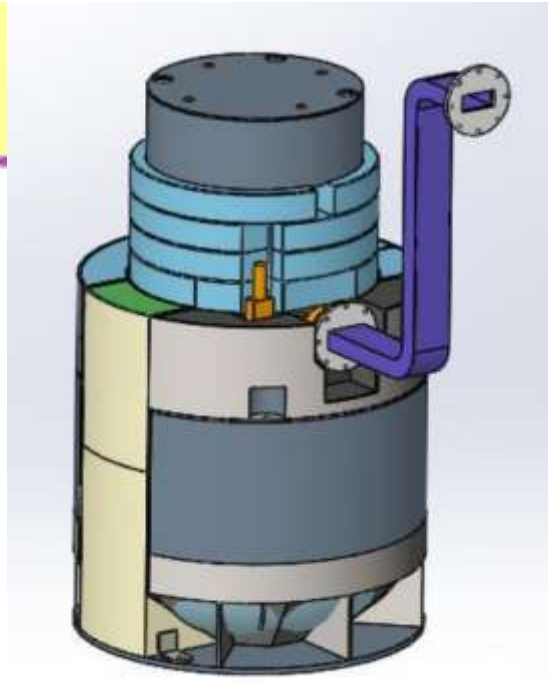
- Incident particles:
  - Proton, deuteron, alpha particle…
- Force:
  - Nuclear force, electromagnetic force
- Energy for emitting neutrons
  - Binding energy, relative kinetic energy
- Deposition on the target
  - Heat
  - New elements

$$ \gamma + {}^{A_1}_{Z_1}X \rightarrow {}^{A_1-1}_{Z_1}X + n $$

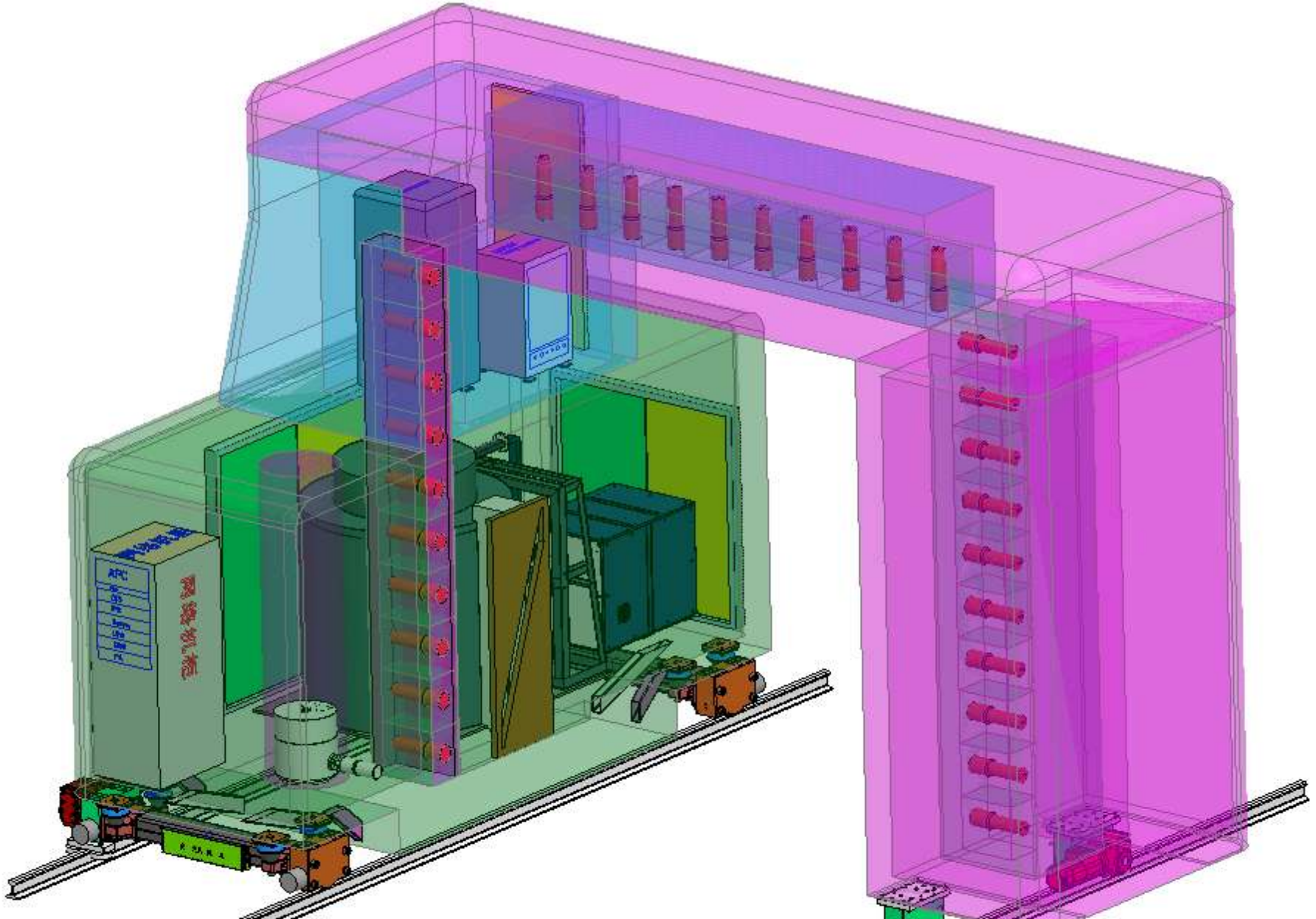
- Incident particles:
  - Photon
- Force:
  - Electromagnetic force
- Energy for emitting neutrons:
  - Relative kinetic energy
- Deposition on the target:
  - Heat

# 5 $\mu s$ 7MeV $e^- + {}^2H_2O \rightarrow 10^{10}$n/s ($\gamma$,n)source

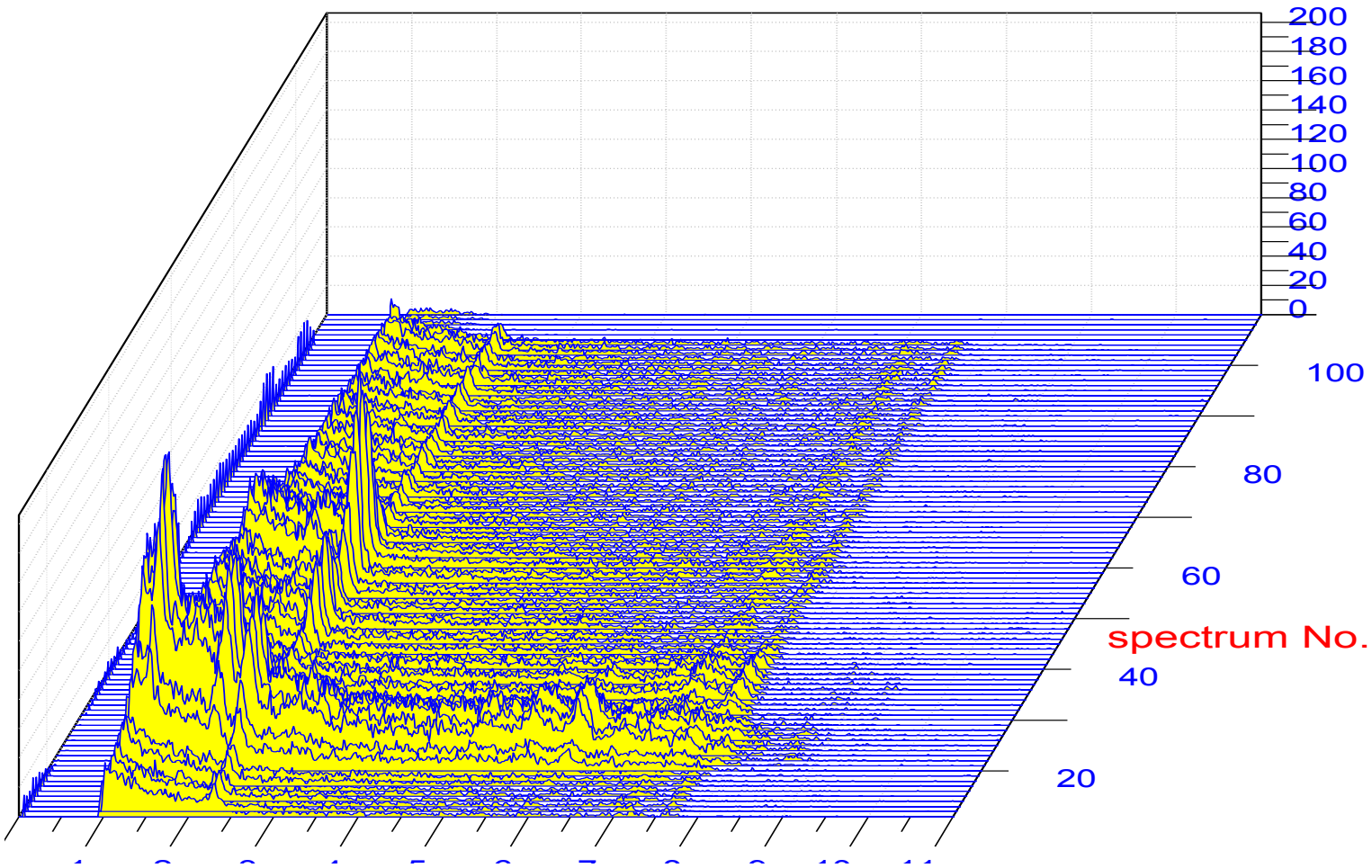


# A (γ,n) source for the in-situ applications

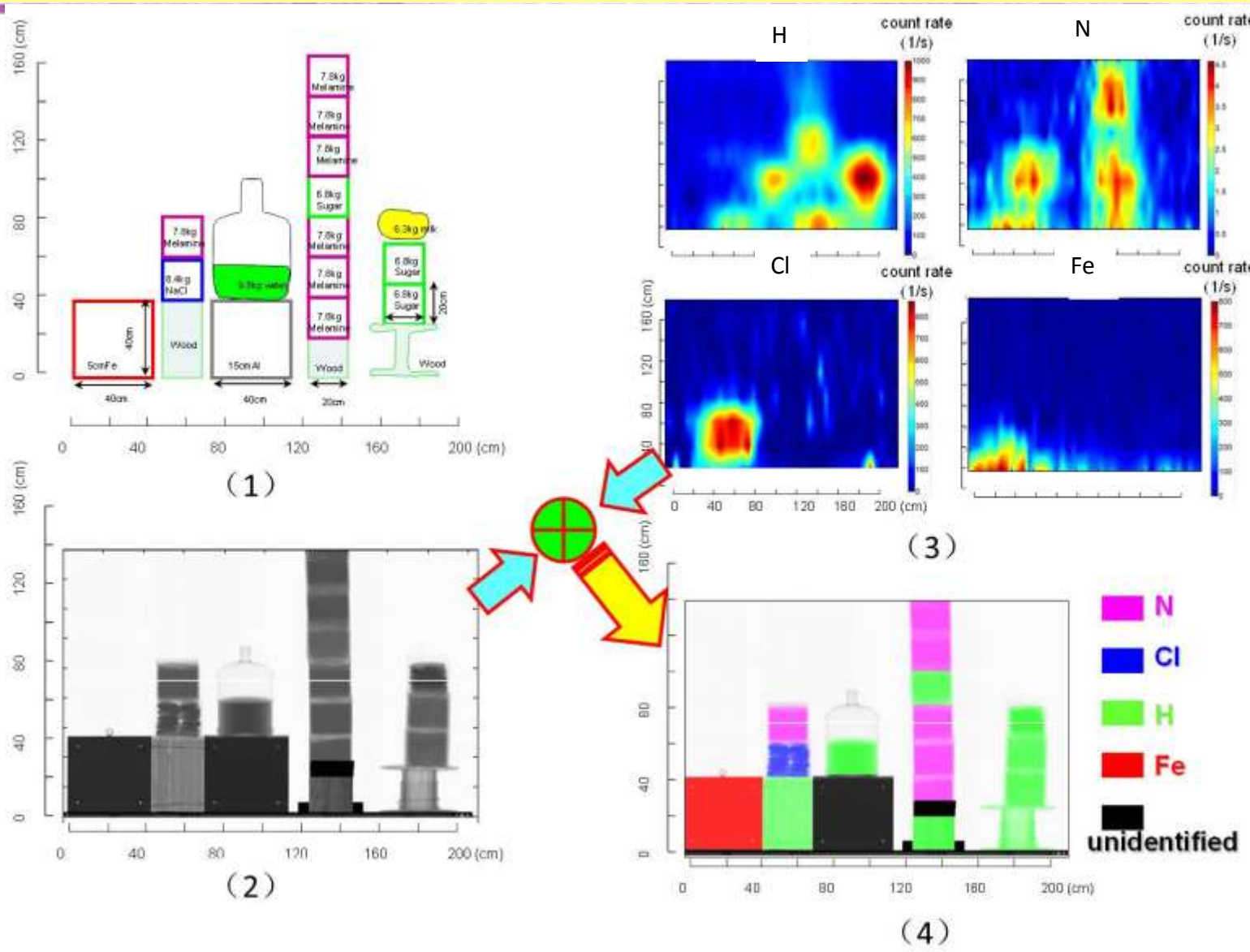


# Elemental analysis




**Y. Yigang***, L. Yuanjing, W. Haidong, L. Tiezhu, and W. Bin, "*Explosives detection using photoneutrons produced by X-rays*," ***Nuclear Inst. and Methods in Physics Research, A,*** vol. 579 (2007), pp. 400-403

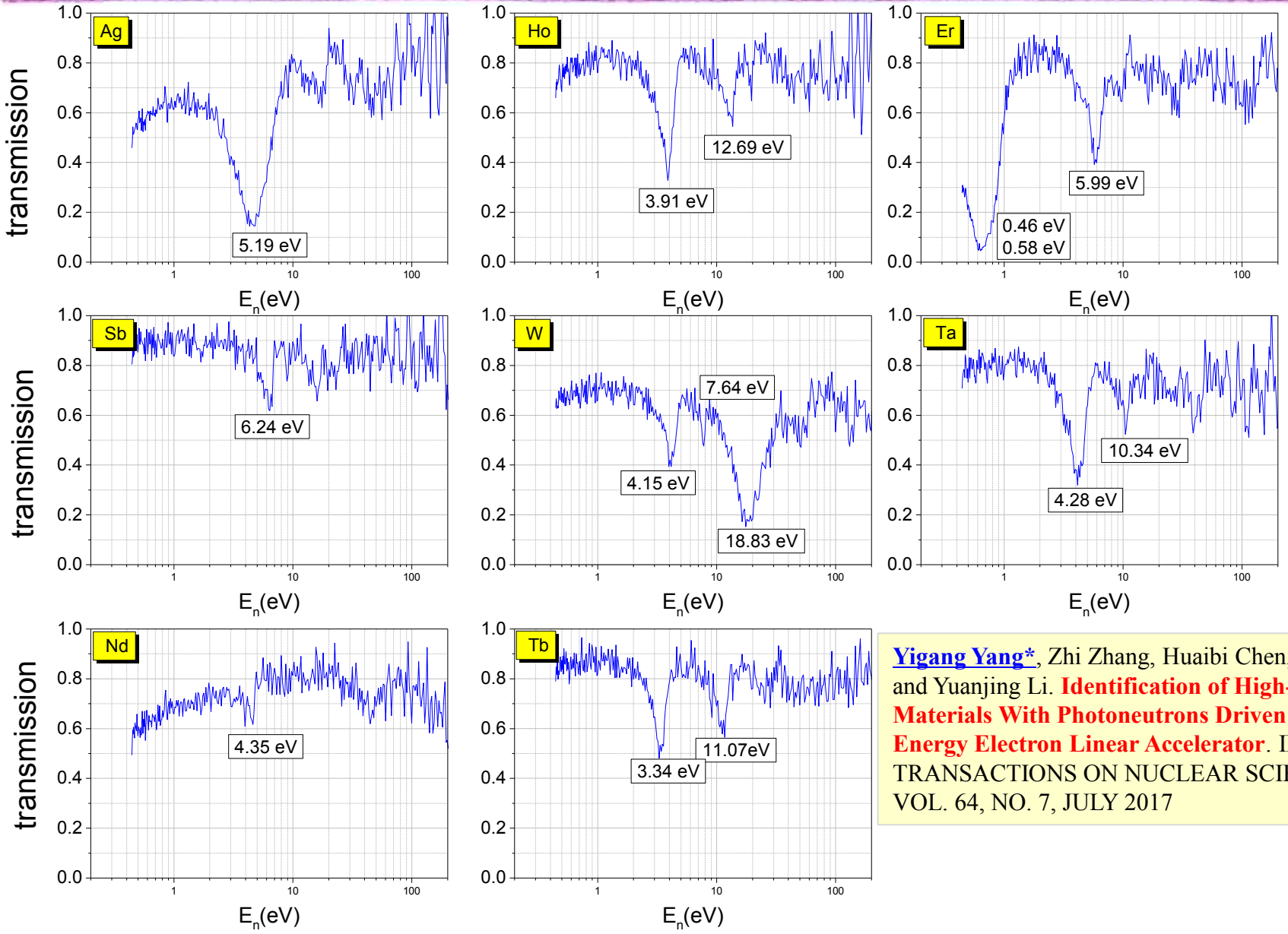
# Fusion of elemental distributions and X-ray imaging





**Yigang Yang***, Jianbo Yang and Yuanjing Li, "*Fusion of X-ray Imaging and Photoneutron Induced Gamma Analysis for Contrabands Detection*," ***IEEE TRANSACTIONS ON NUCLEAR SCIENCE***, vol. 60, p. 6, 2013.

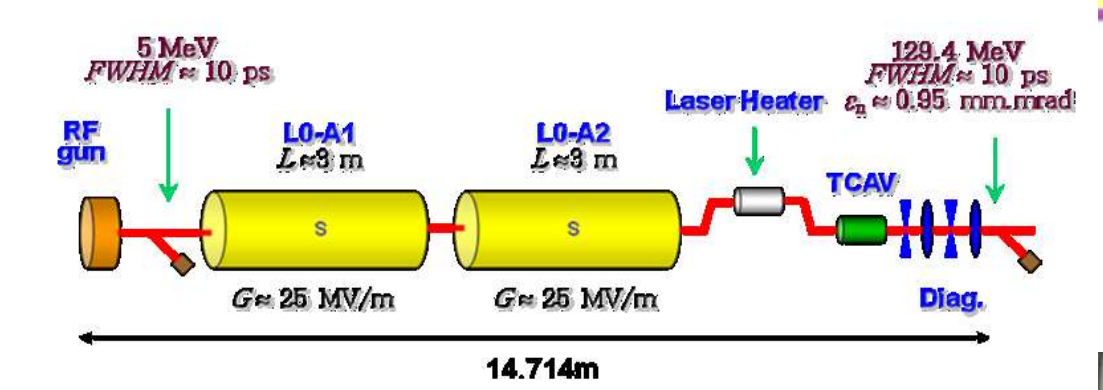
# Energy resolving measurement for the epithermal neutrons

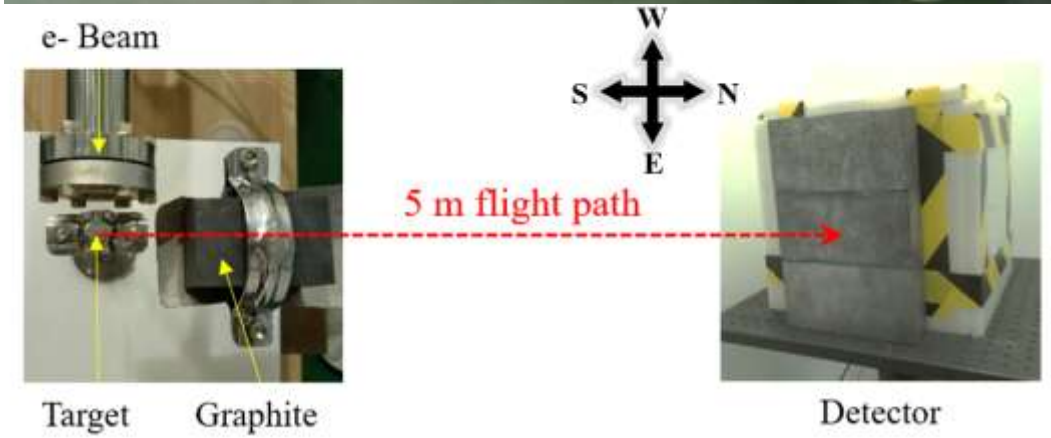


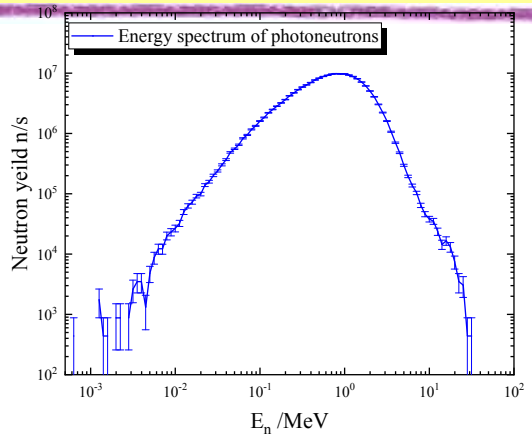


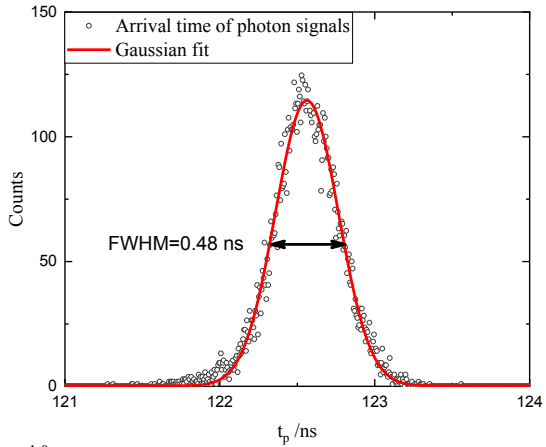
Yigang Yang*, Zhi Zhang, Huaibi Chen, Yulan Li, and Yuanjing Li. **Identification of High-Z Materials With Photoneutrons Driven by a Low-Energy Electron Linear Accelerator**. IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 64, NO. 7, JULY 2017

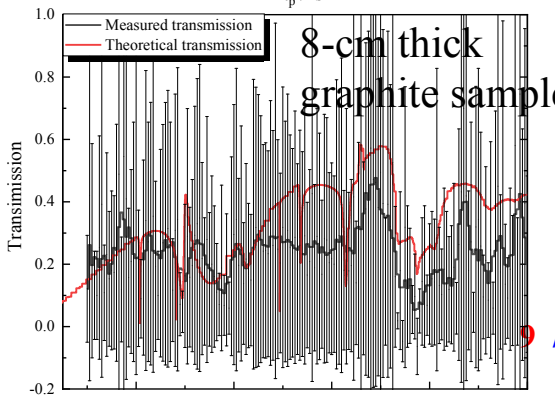
# 10 *ps* 100MeV e$^-$+$^{181}$Ta→MeV neutron resonant analysis




8-cm thick graphite sample

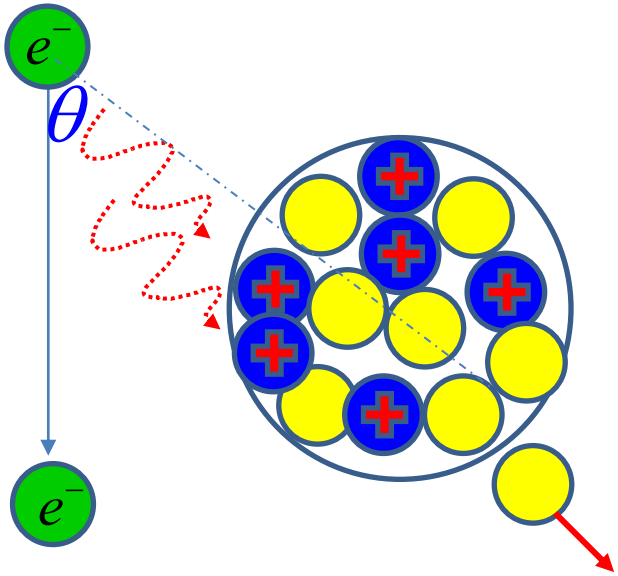
Q.Wang;X.Weng,Y.Yu; C.Deng, Z.Zhang;X.Tuo;Y.Yang*.**Investigation of Fast Neutron Resonance Transmission Analysis based on the Ultrashort Pulsed Electron Beam-driven Photoneutron Source**. https://doi.org/10.1088/1748-0221/14/05/P05004

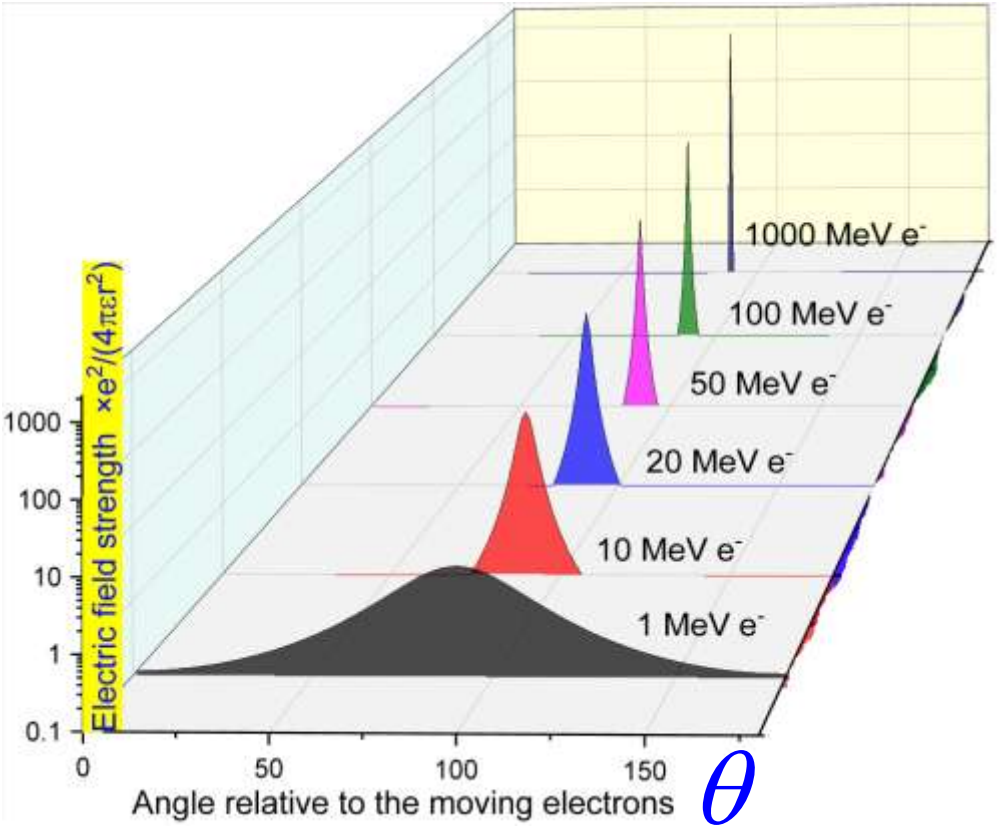
# Two steps for the photoneutron production

$$e \rightarrow n = e \rightarrow \gamma \otimes \gamma \rightarrow n$$

γ →n Photonuclear reaction

e→γ Bremsstrahlung



# outline

1. Research motivation
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# Real photons *vs* Virtual photons

(1) Real photons

e-LINAC

100 ms 8 ps

100 MeV electron pulses

Distance for producing neutrons via the (γ,n) reaction, ~cm or even larger

$D \sim \frac{1}{N\sigma_{\gamma,n}}$

incident electron

Bremsstrahlung photons

(γ,n) reaction

Emitted neutron

(2) Virtual photons

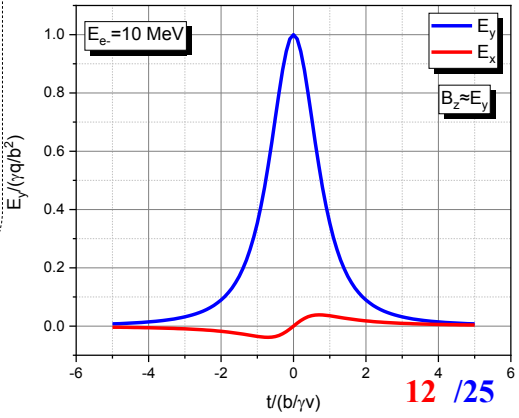
Virtual photons of "plane wave"

(γ,n) reaction

Emitted neutron

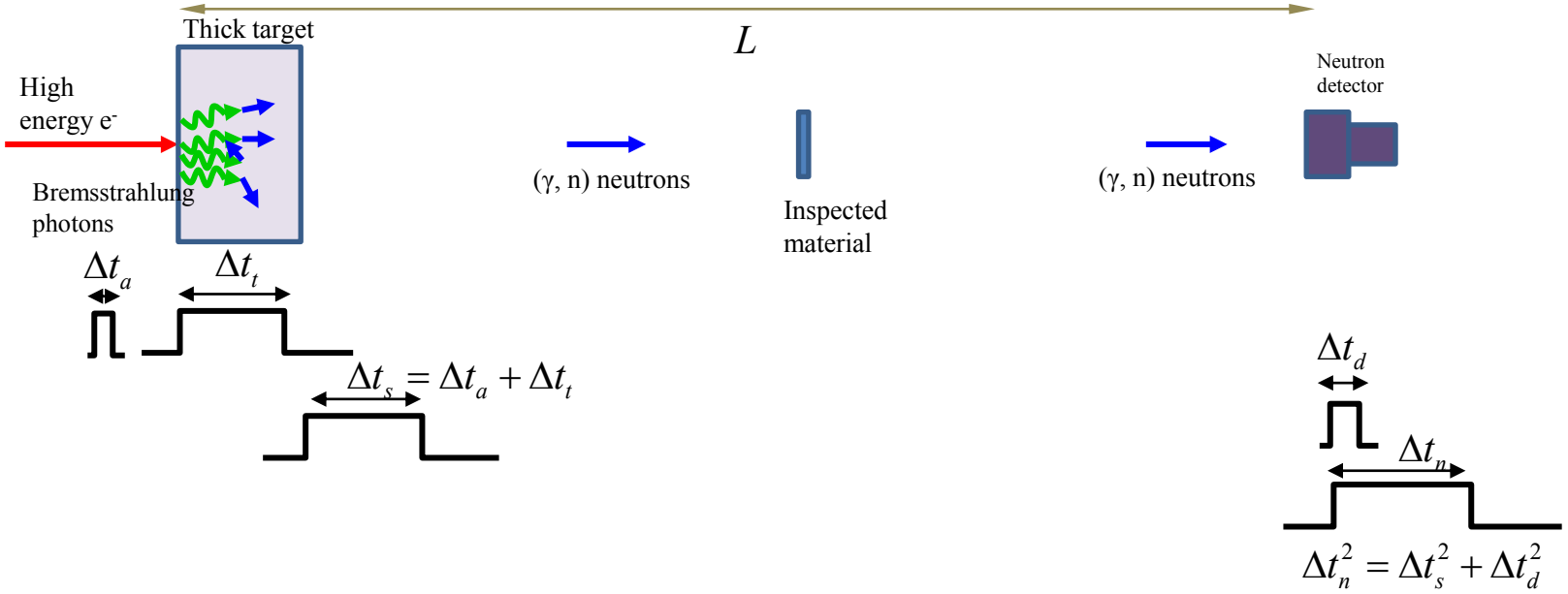
deflected electron

incident electron

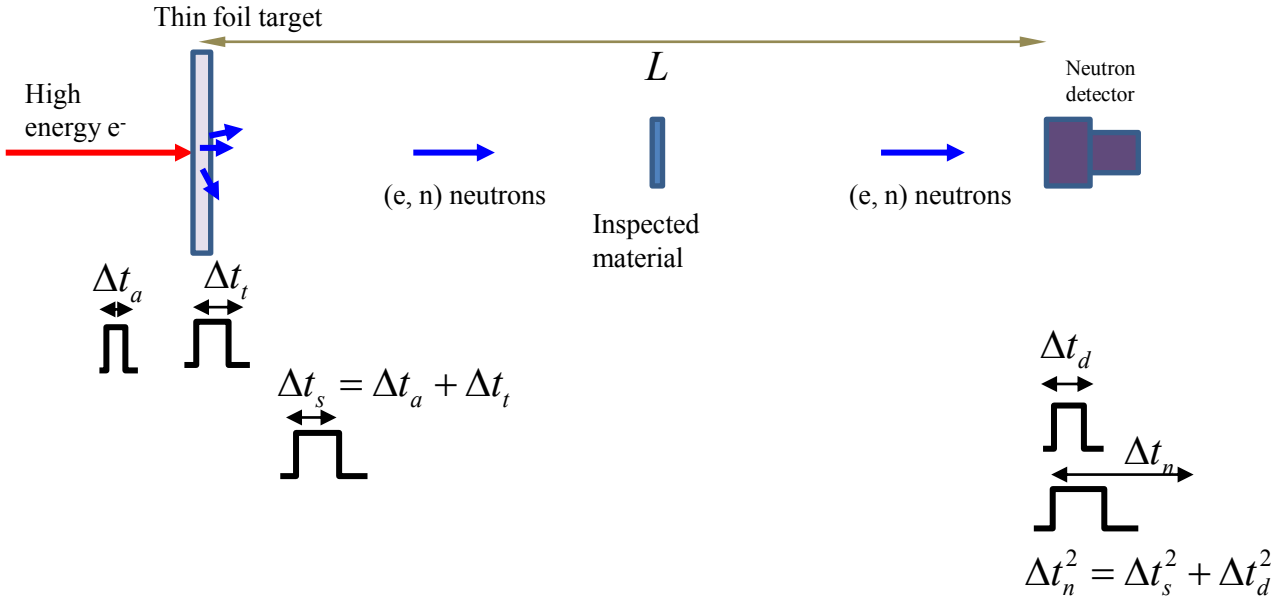


# Short pulse-width of neutrons → short flight distance

(1)



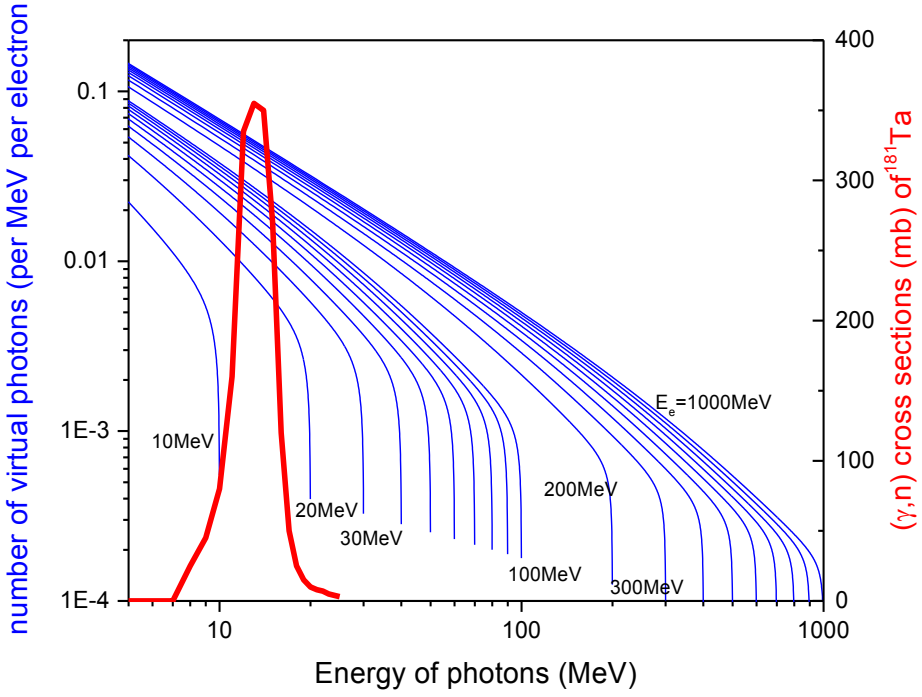

(2)

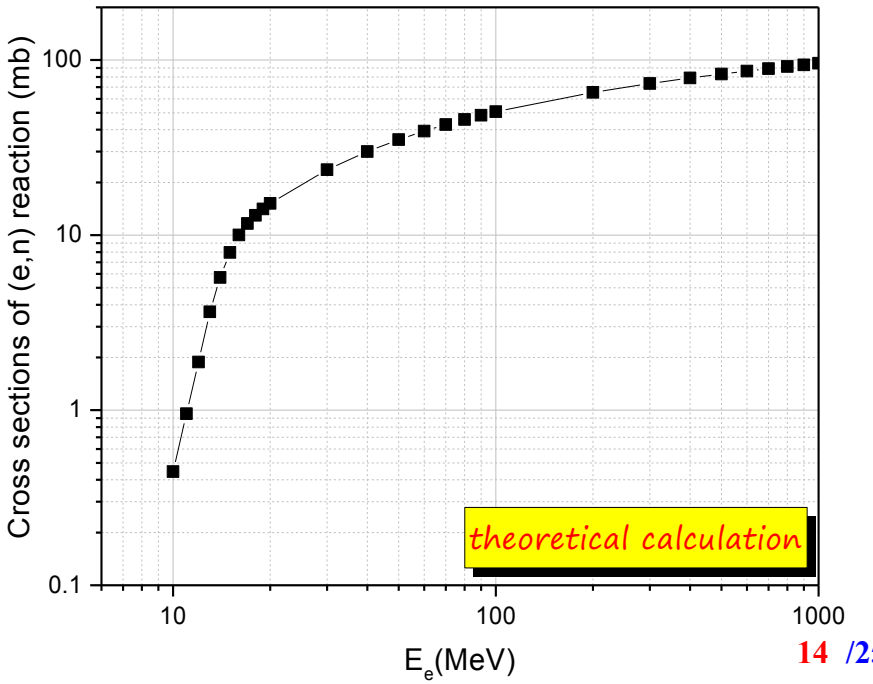


# 2. The measurement of (e,e' n) reactions

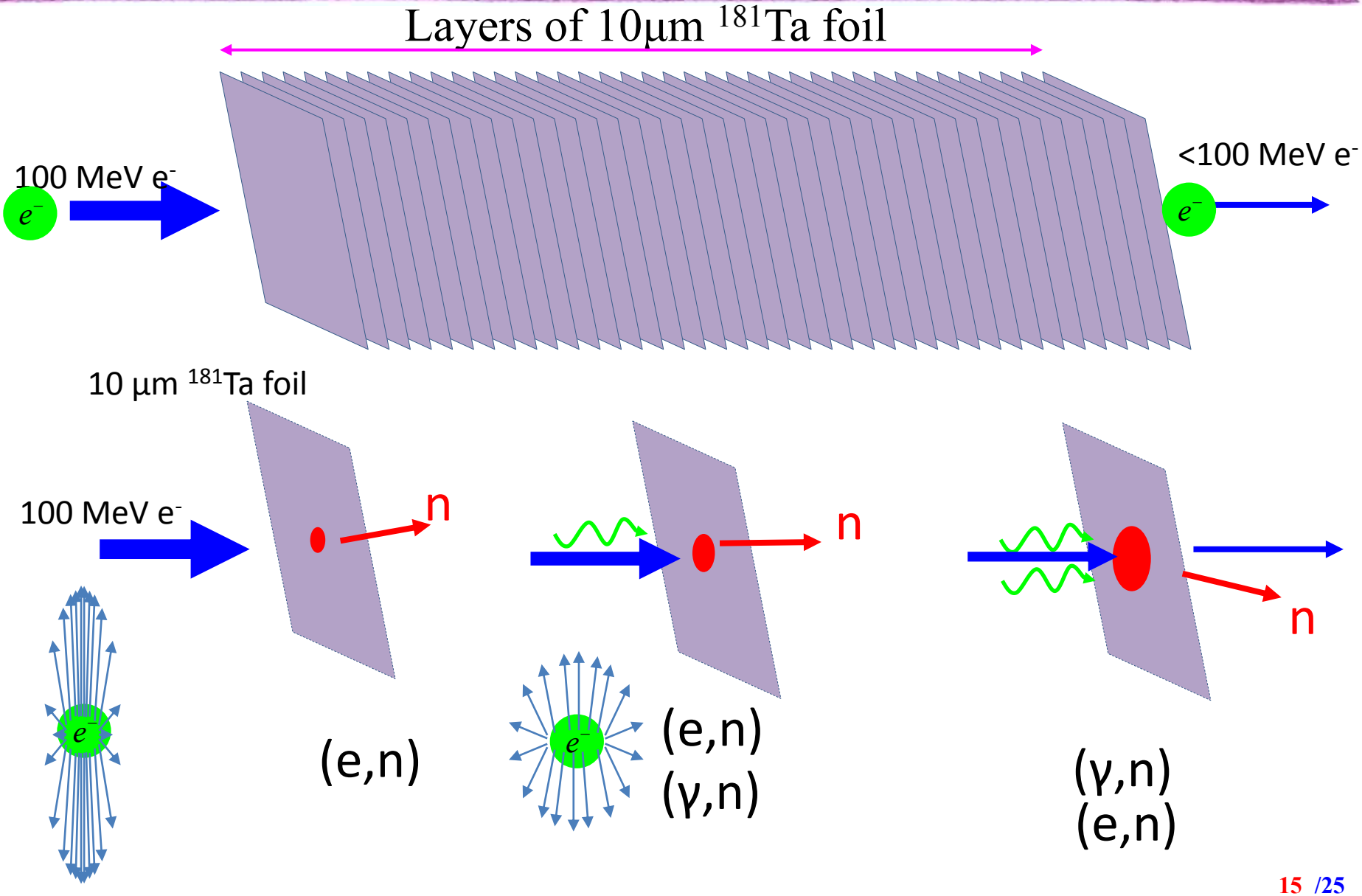
$$e + {}^{A}_{Z}X \rightarrow {}^{A-1}_{Z}X + n + e' \qquad \sigma_{E_i} = \int_{E_{th}}^{E_i} \sigma(h\nu)\cdot N_e(E_i, h\nu)\cdot d(h\nu)$$

$$N_e(E_i, h\nu) = \frac{4e^2}{hc\cdot h\nu}\times\left\{\frac{\left(E_i + m_0c^2\right)^2 + \left(E_i - h\nu + m_0c^2\right)^2}{2E_i\left(E_i + 2m_0c^2\right)}\times \ln\left[\frac{E_i(E_i - h\nu) + m_0c^2(2E_i - h\nu) + \sqrt{E_i(E_i - h\nu)\left(E_i + 2m_0c^2\right)\left(E_i - h\nu + 2m_0c^2\right)}}{m_0c^2 h\nu}\right] - \sqrt{1 - \frac{h\nu}{E_i}\left(1 + \frac{E_i - h\nu}{E_i + 2m_0c^2}\right)}\right\}$$



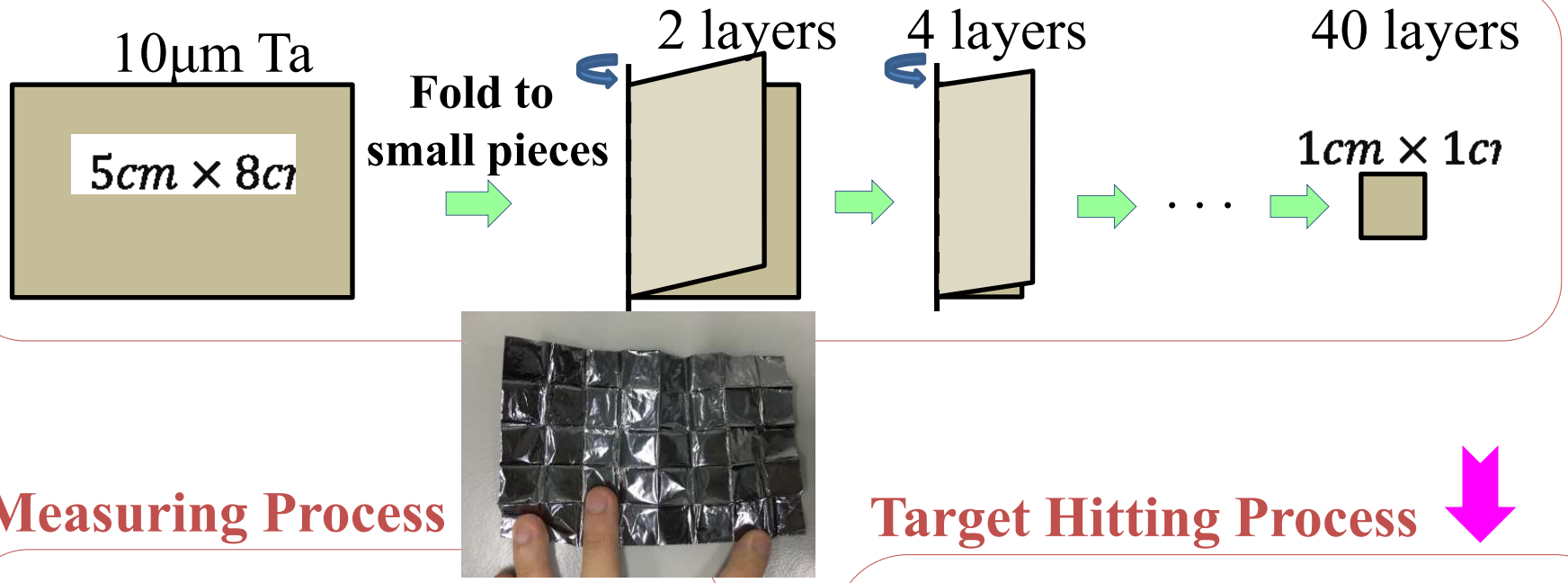



# (e,e'n) and (γ,n) reactions, both exist



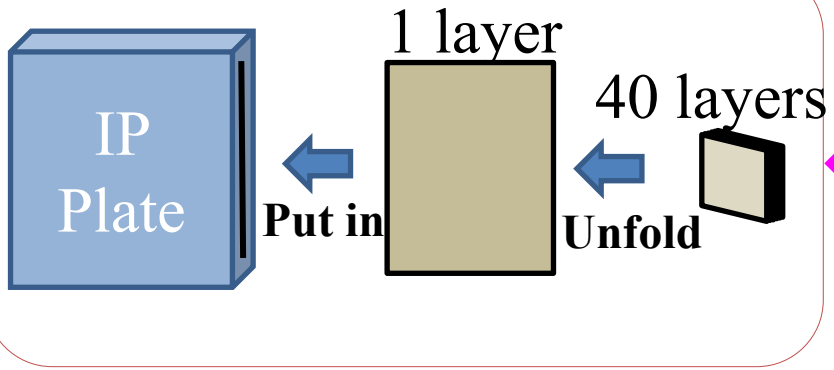
# Irradiation → IP detector measurement

## Target Preparing Process

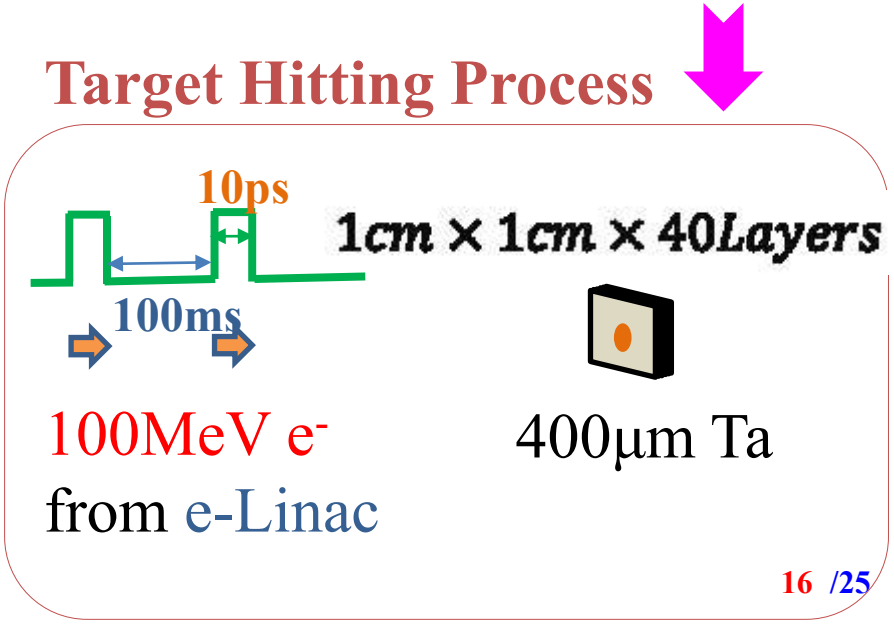




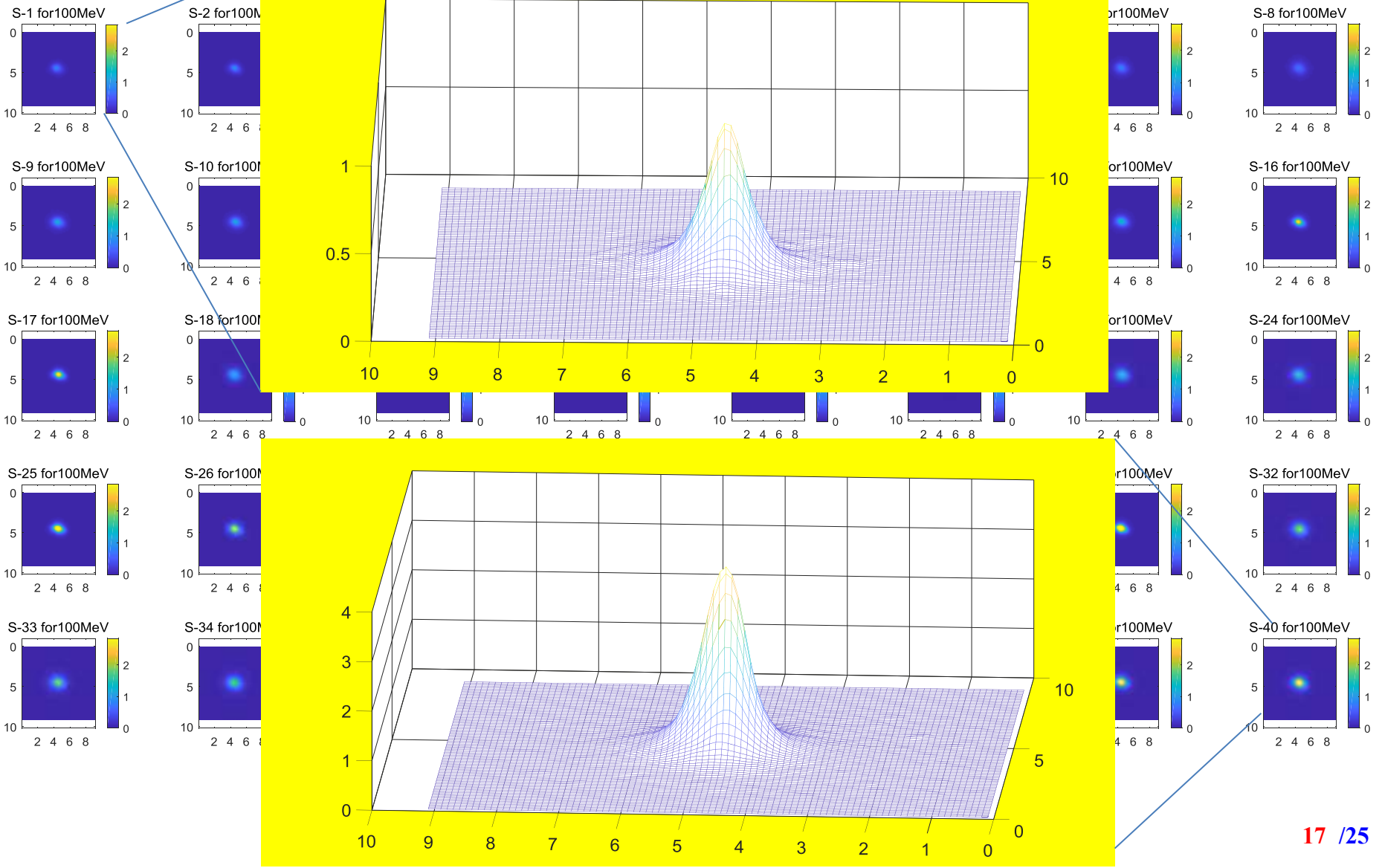

## Measuring Process



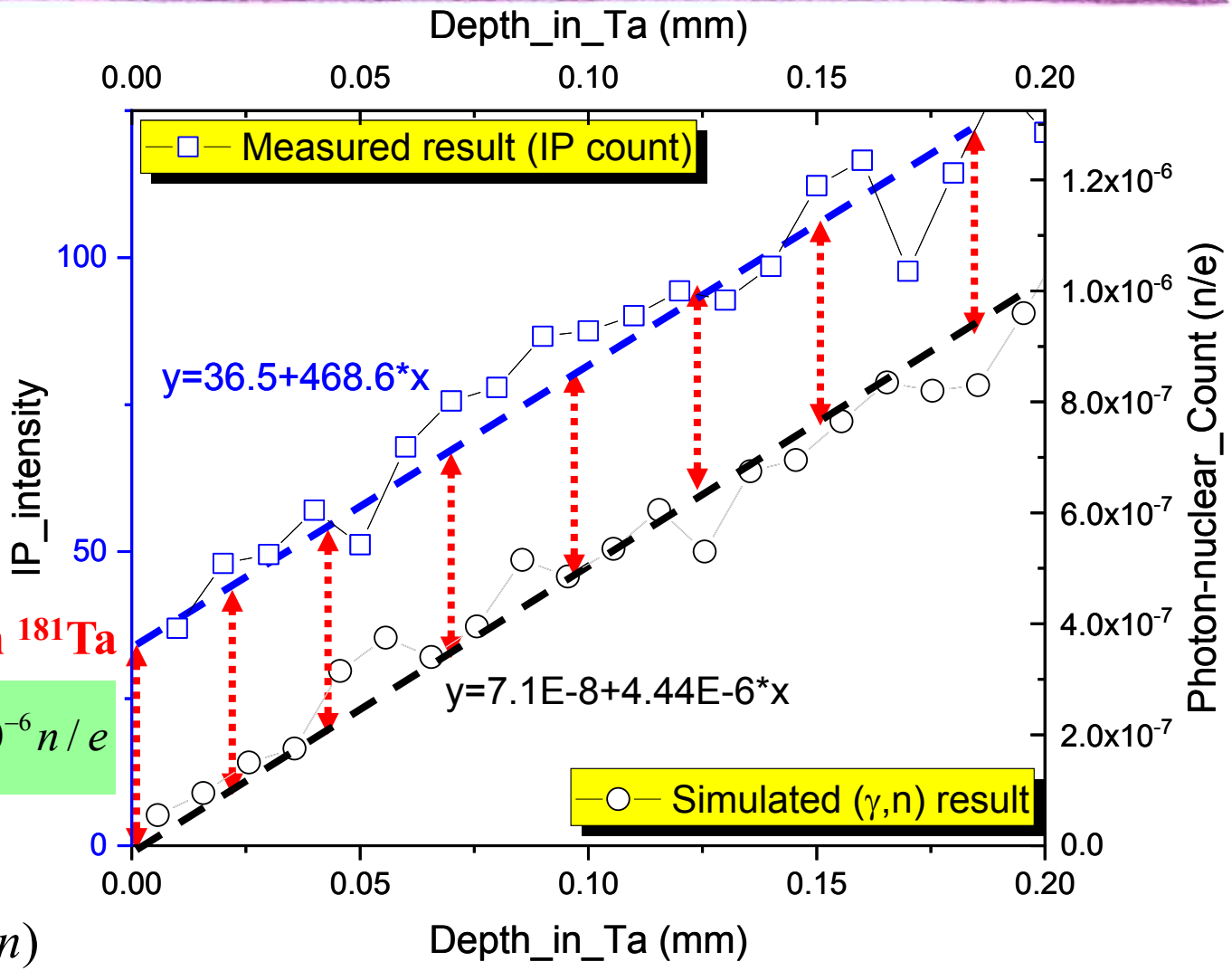

## Target Hitting Process



# Measured activities of each layer



# Activities @ different depths

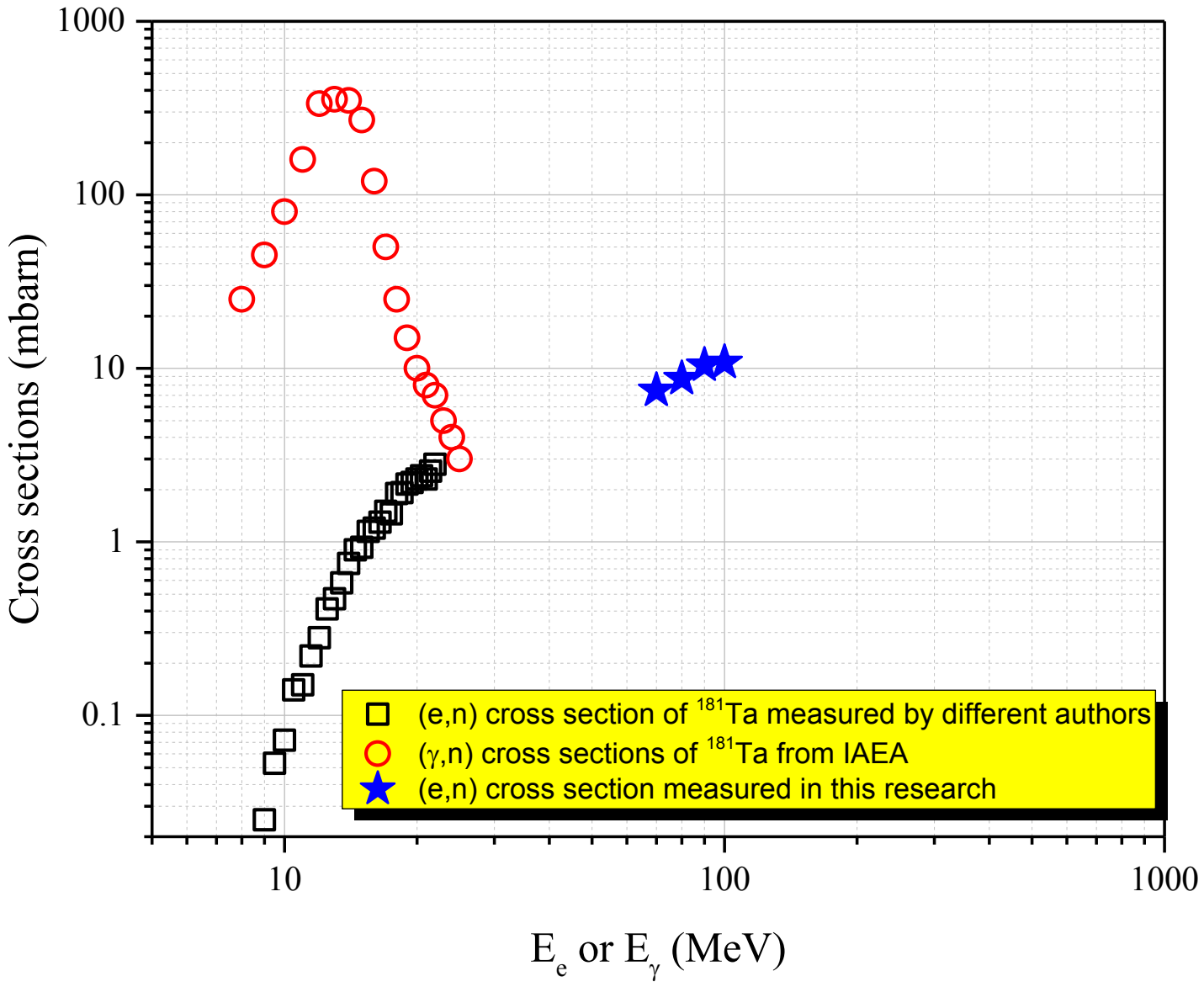



**(e,e'n) neutron of 10 μm $^{181}$Ta**

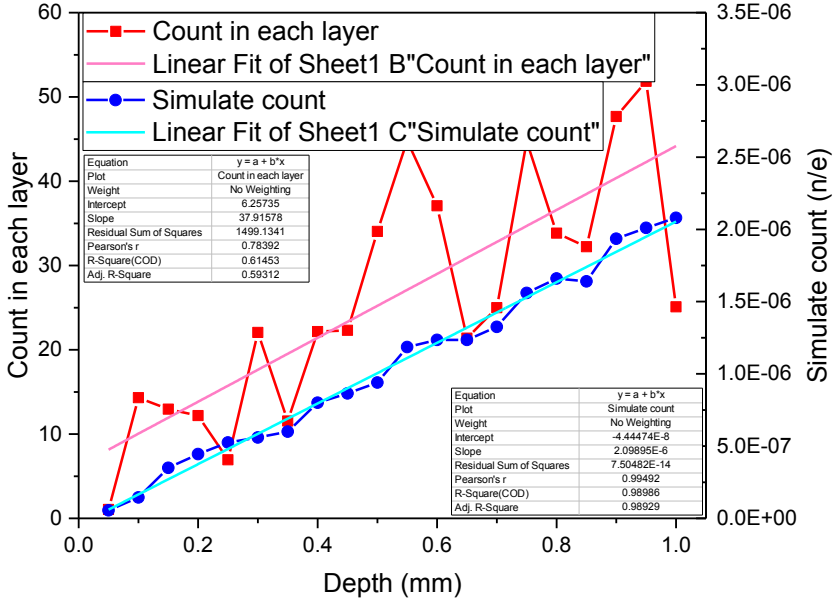
$$N(e,e'n) = \frac{36.5}{468.6} \times 4.44 \times 10^{-6}\, n/e$$

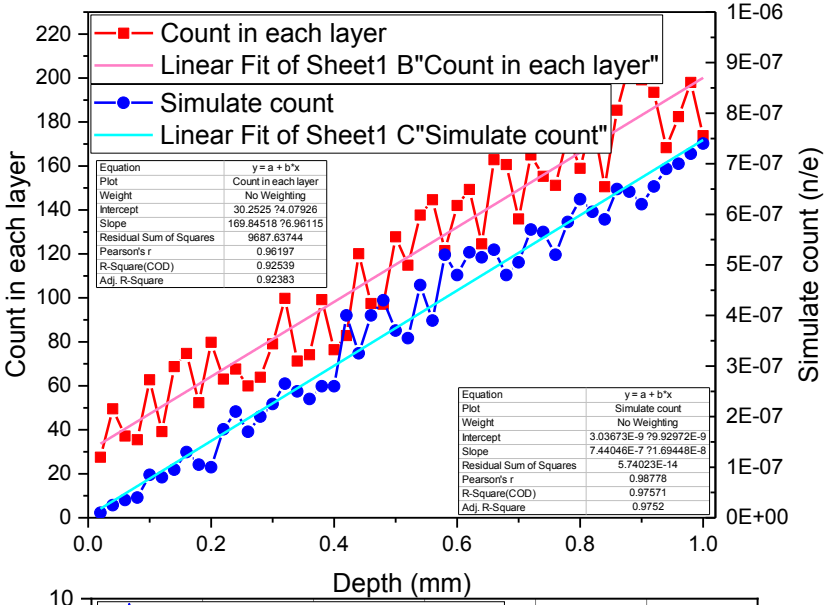
$$\sigma(e,e'n) = \frac{N(e,e'n)}{\frac{\rho}{A} \times N_A \times 10^{-3}\, cm}$$

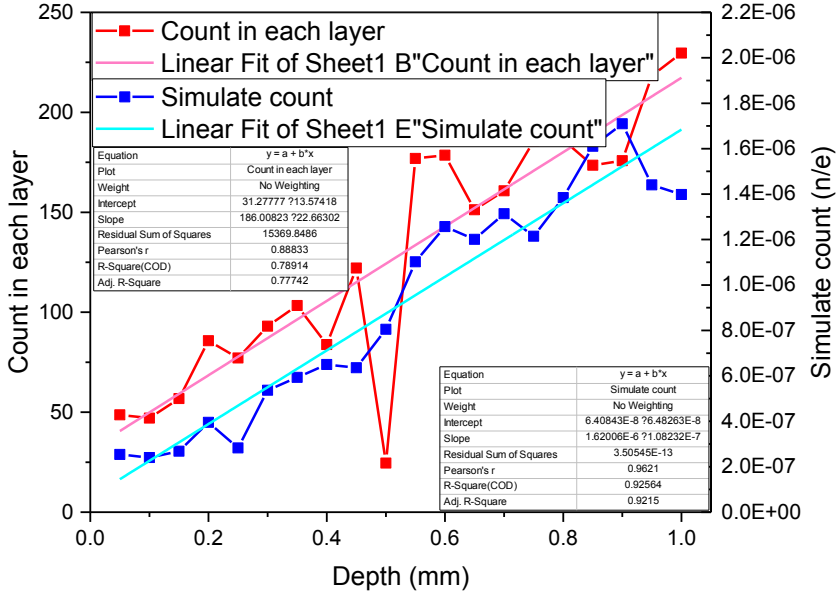
# (e,e'n) cross sections @ different energy

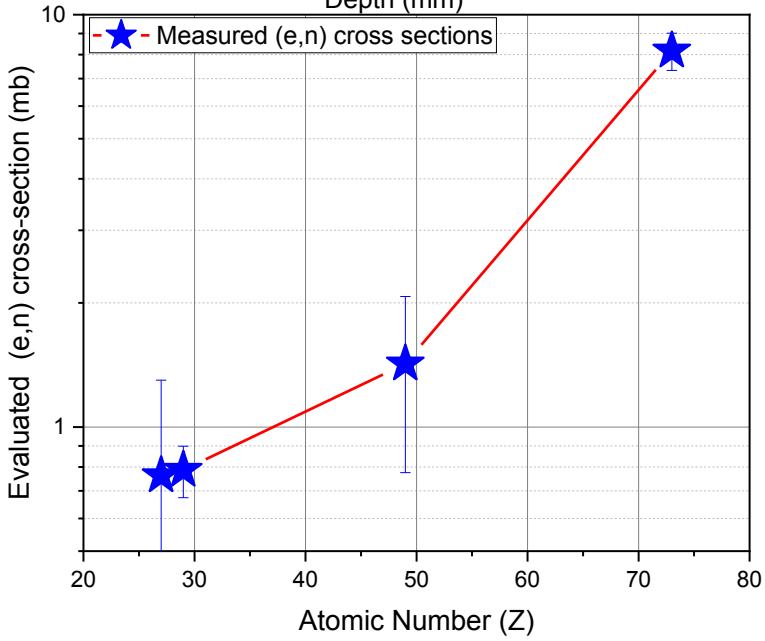


# Z=27,29,49,73

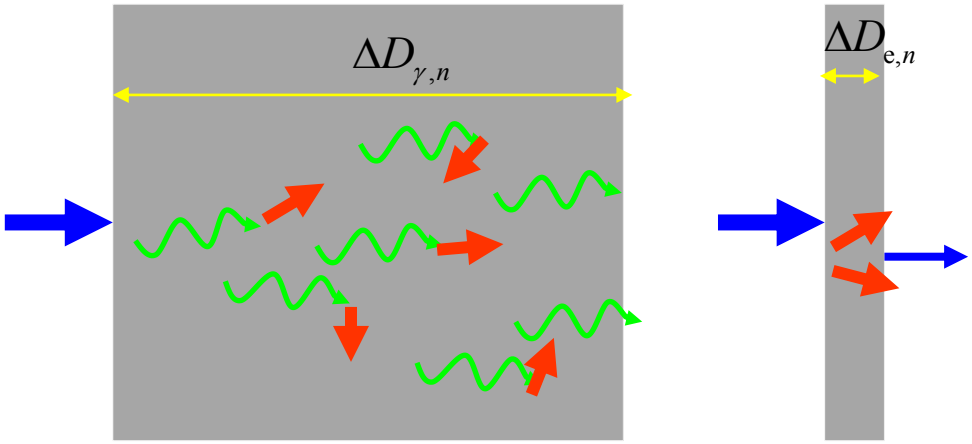

Count in each layer
Linear Fit of Sheet1 B"Count in each layer"
Simulate count
Linear Fit of Sheet1 C"Simulate count"
Equation y = a + b*x
Plot Count in each layer
Weight No Weighting
Intercept 6.25735
Slope 37.91578
Residual Sum of Squares 1499.1341
Pearson's r 0.78392
R-Square(COD) 0.61453
Adj. R-Square 0.59312
Equation y = a + b*x
Plot Simulate count
Weight No Weighting
Intercept -4.44474E-8
Slope 2.09895E-6
Residual Sum of Squares 7.50482E-14
Pearson's r 0.99492
R-Square(COD) 0.98986
Adj. R-Square 0.98929
Count in each layer
Simulate count (n/e)
Depth (mm)


Count in each layer
Linear Fit of Sheet1 B"Count in each layer"
Simulate count
Linear Fit of Sheet1 C"Simulate count"
Equation y = a + b*x
Plot Count in each layer
Weight No Weighting
Intercept 30.2525 ?4.07926
Slope 169.84518 ?6.96115
Residual Sum of Squares 9687.63744
Pearson's r 0.96197
R-Square(COD) 0.92539
Adj. R-Square 0.92383
Equation y = a + b*x
Plot Simulate count
Weight No Weighting
Intercept 3.03673E-9 ?9.92972E-9
Slope 7.44046E-7 ?1.69448E-8
Residual Sum of Squares 5.74023E-14
Pearson's r 0.98778
R-Square(COD) 0.97571
Adj. R-Square 0.9752
Count in each layer
Simulate count (n/e)
Depth (mm)


Count in each layer
Linear Fit of Sheet1 B"Count in each layer"
Simulate count
Linear Fit of Sheet1 E"Simulate count"
Equation y = a + b*x
Plot Count in each layer
Weight No Weighting
Intercept 31.27777 ?13.57418
Slope 186.00823 ?22.66302
Residual Sum of Squares 15369.8486
Pearson's r 0.88833
R-Square(COD) 0.78914
Adj. R-Square 0.77742
Equation y = a + b*x
Plot Simulate count
Weight No Weighting
Intercept 6.40843E-8 ?6.48263E-8
Slope 1.62006E-6 ?1.08232E-7
Residual Sum of Squares 3.50545E-13
Pearson's r 0.9621
R-Square(COD) 0.92564
Adj. R-Square 0.9215
Count in each layer
Simulate count (n/e)
Depth (mm)


Measured (e,n) cross sections
Evaluated (e,n) cross-section (mb)
Atomic Number (Z)

# (e,e'n) source for MeV neutron TOF



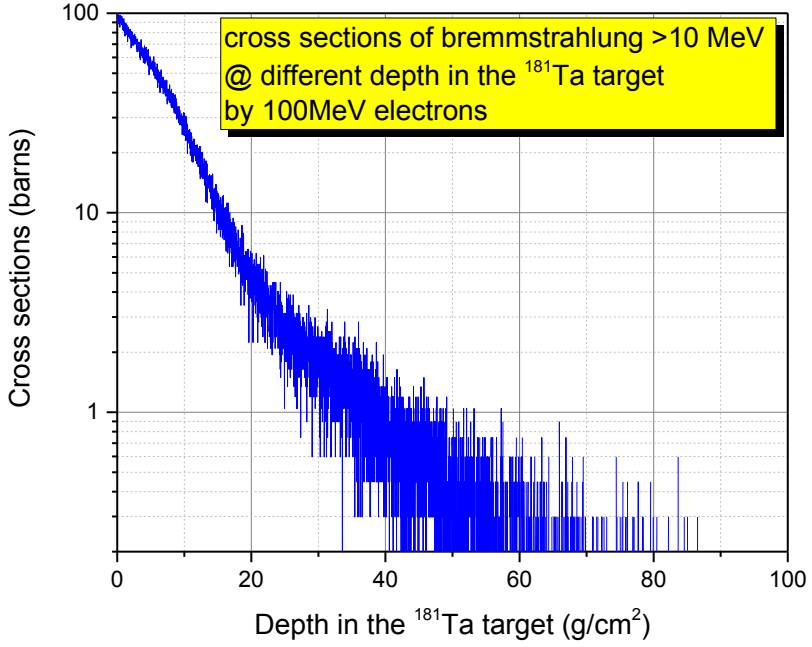

$$FOM = \frac{1}{T} \propto \frac{\nu_n^2 \cdot Y_n}{L^2}$$

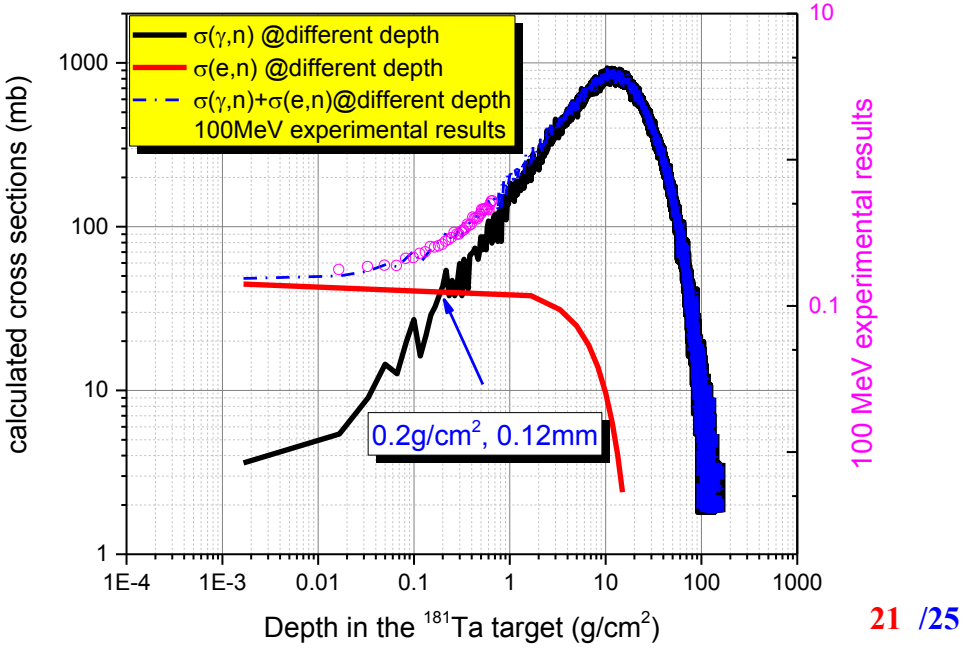
$$\propto \frac{\nu_n^2 \cdot Y_n}{\left(\frac{\Delta t_n}{\eta}\right)^2} = \frac{\nu_n^2 \cdot Y_n}{\frac{\Delta t_d^2 + \Delta t_s^2}{\eta^2}}$$

$$\approx \frac{\nu_n^2 \cdot Y_n \cdot \eta^2}{\Delta t_s^2} \propto \frac{\nu_n^2 \cdot Y_n \cdot \eta^2}{\Delta D_n^2} \propto \frac{Y_n}{\Delta D_n^2}$$

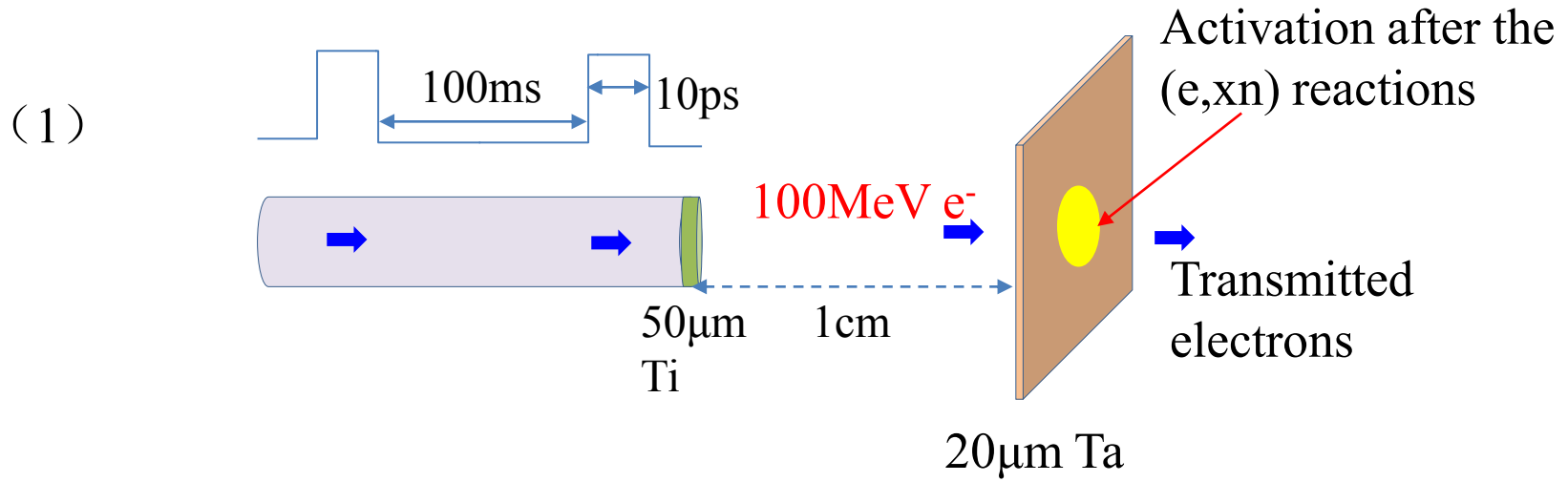
Neutron yield

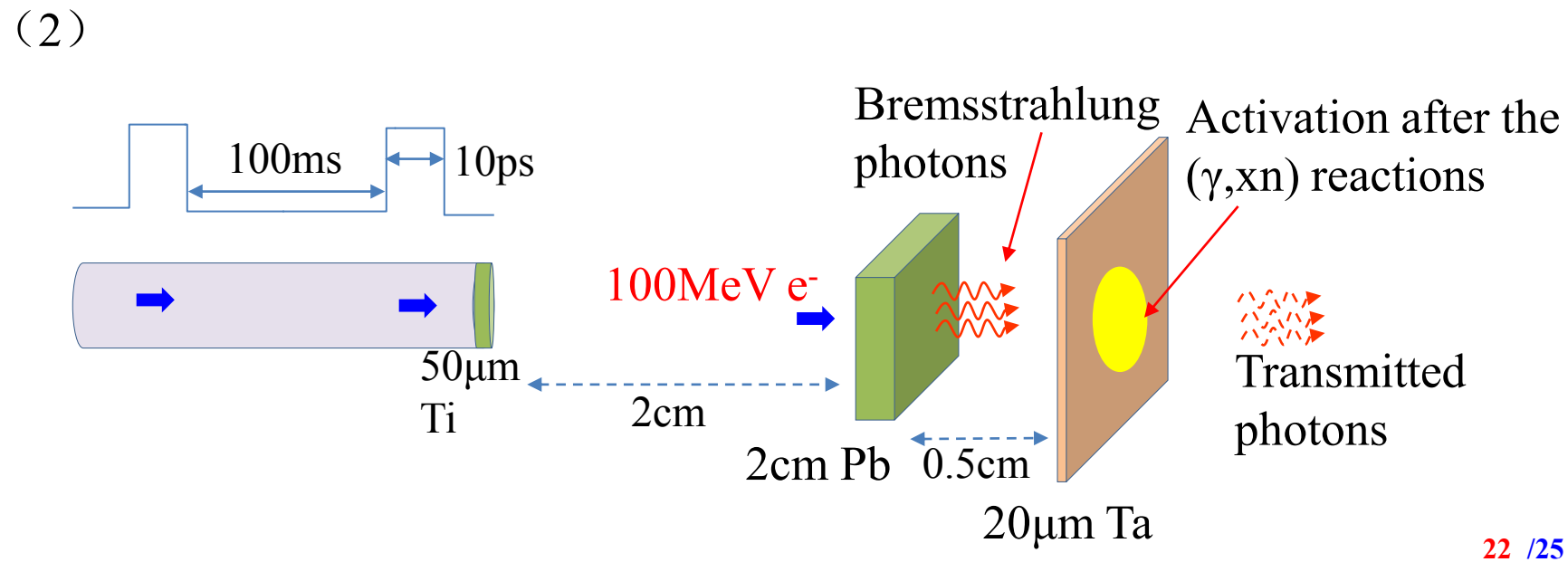
Target thickness



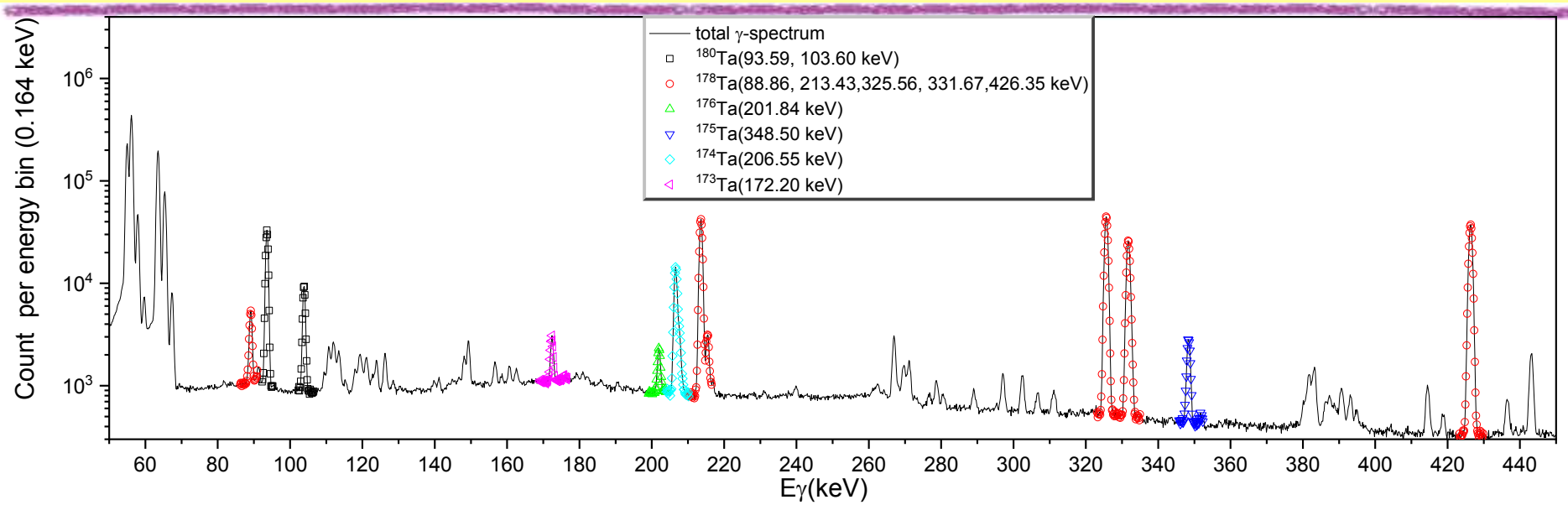



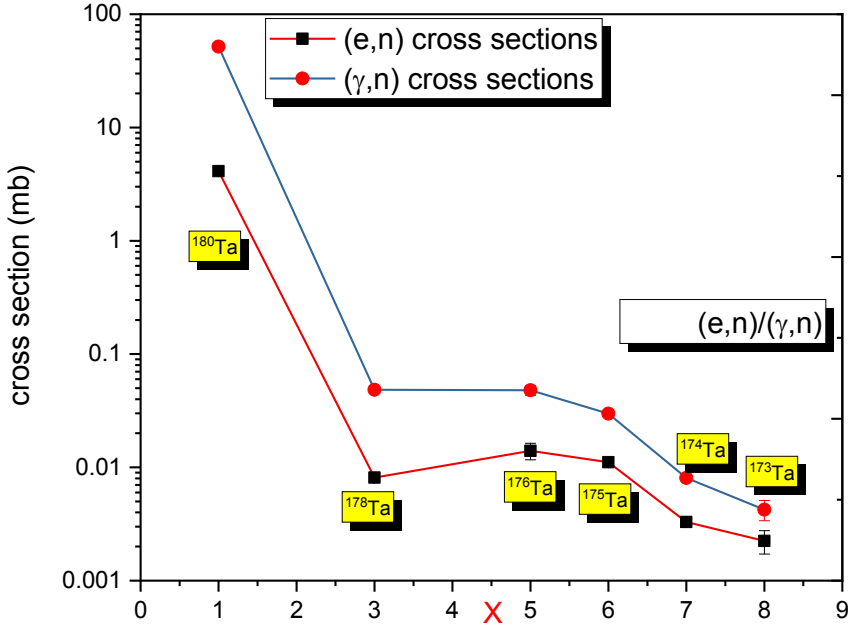
# (e,e'xn) *vs* (γ,xn)

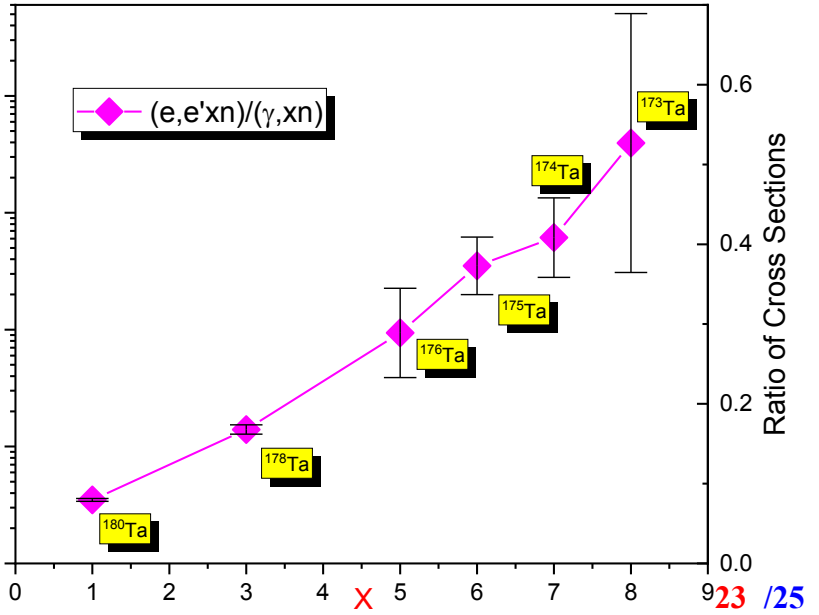

(1)
100ms
10ps
100MeV e-
Activation after the
(e,xn) reactions
Transmitted
electrons
50μm
Ti
1cm
20μm Ta


(2)
100ms
10ps
Bremsstrahlung
photons
Activation after the
(γ,xn) reactions
100MeV e-
Transmitted
photons
50μm
Ti
2cm
2cm Pb
0.5cm
20μm Ta

# Cross sections of (e,e'xn) & (γ,xn)

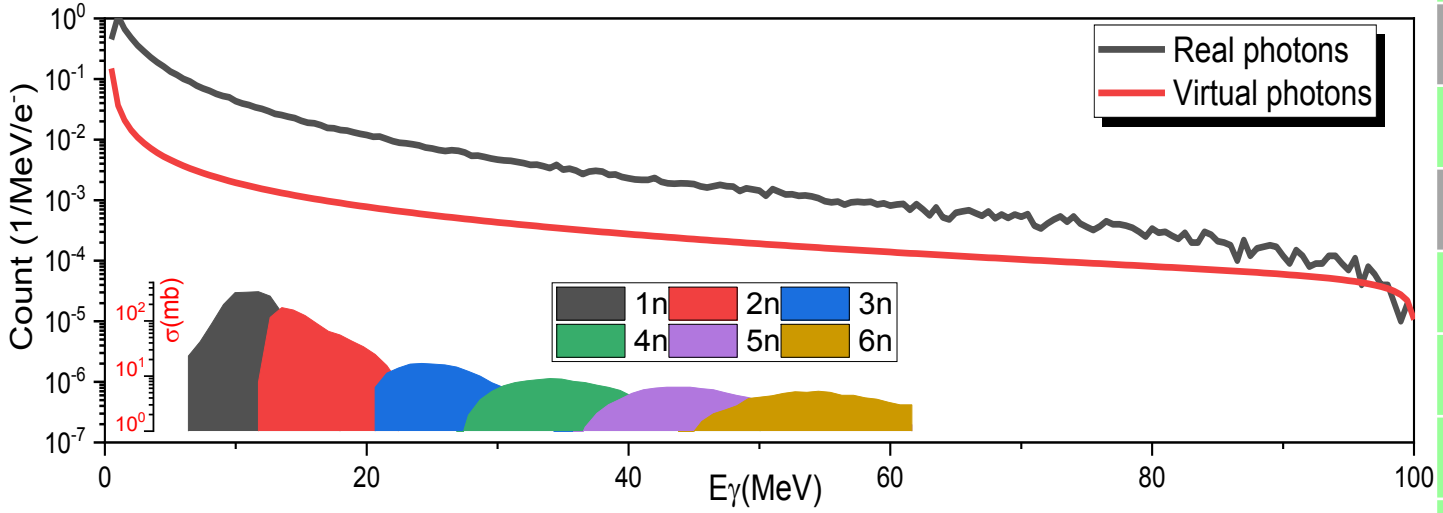


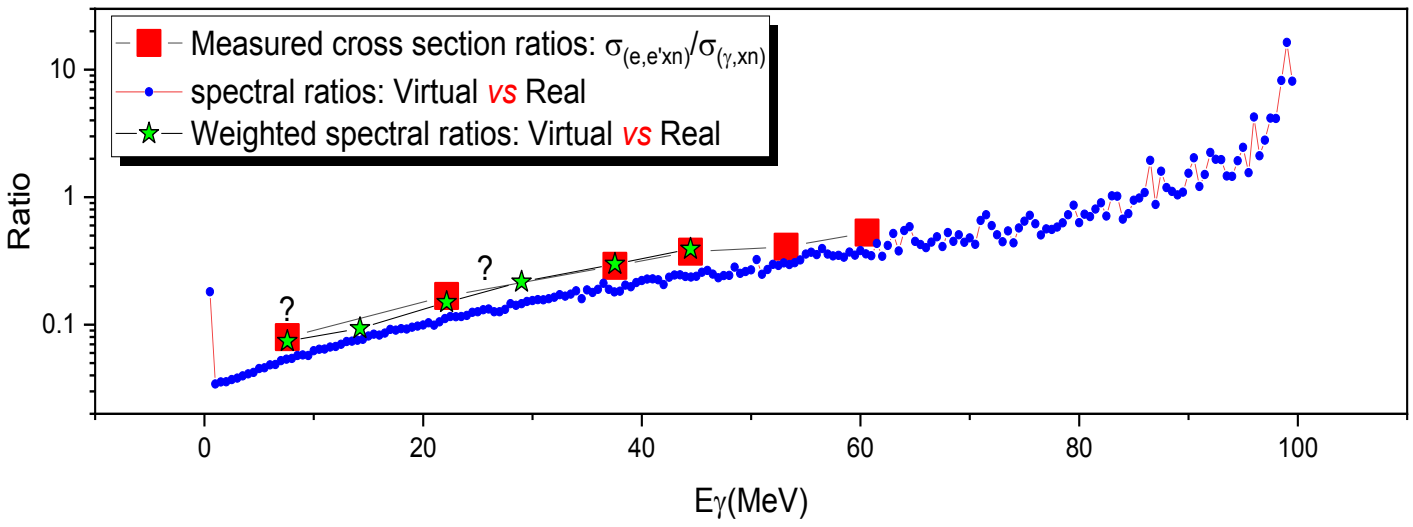



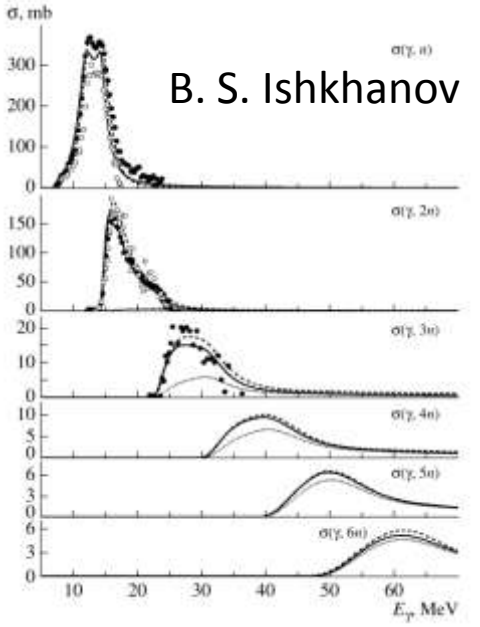



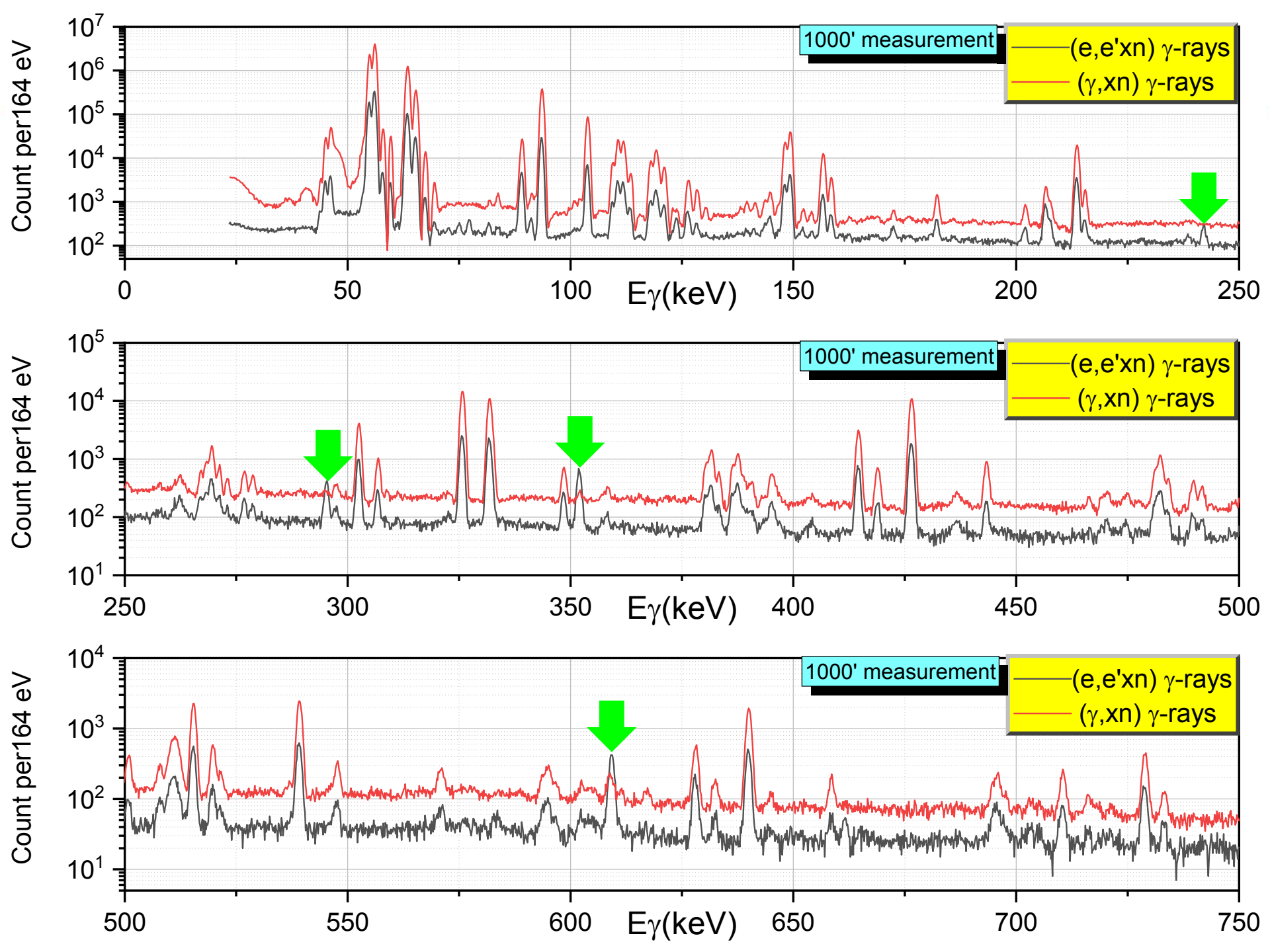
# x ↑ → $\sigma_{(e,e'xn)}/\sigma_{(\gamma, xn)}$ ↑

| $E_{th}$ of (e,e'xn) reactions (MeV): $^{181}$Ta | |
|---|---|
| x=1 | 7.58 |
| x=2 | 14. 22 |
| x=3 | 22.15 |
| x=4 | 29. 01 |
| x=5 | 37.54 |
| x=6 | 44.46 |
| x=7 | 53.2 |
| x=8 | 60.61 |




1000' measurement
(e,e'xn) γ-rays
(γ,xn) γ-rays
Count per164 eV
Eγ(keV)
1000' measurement
(e,e'xn) γ-rays
(γ,xn) γ-rays
Count per164 eV
Eγ(keV)
1000' measurement
(e,e'xn) γ-rays
(γ,xn) γ-rays
Count per164 eV
Eγ(keV)

# 3. Summary

- The **exchange of virtual photons** between the relativistic electrons and target nucleus can lead to the excitation of target nucleus and emission of neutrons.

- $\sigma_{(e,e'n)}$ for 70~100 MeV electrons is measured. It might **grow rapidly with Z**.

- $\sigma_{(e,e'xn)}$ with **x=1,3,5,6,7,8**, are firstly measured for 100 MeV electrons.

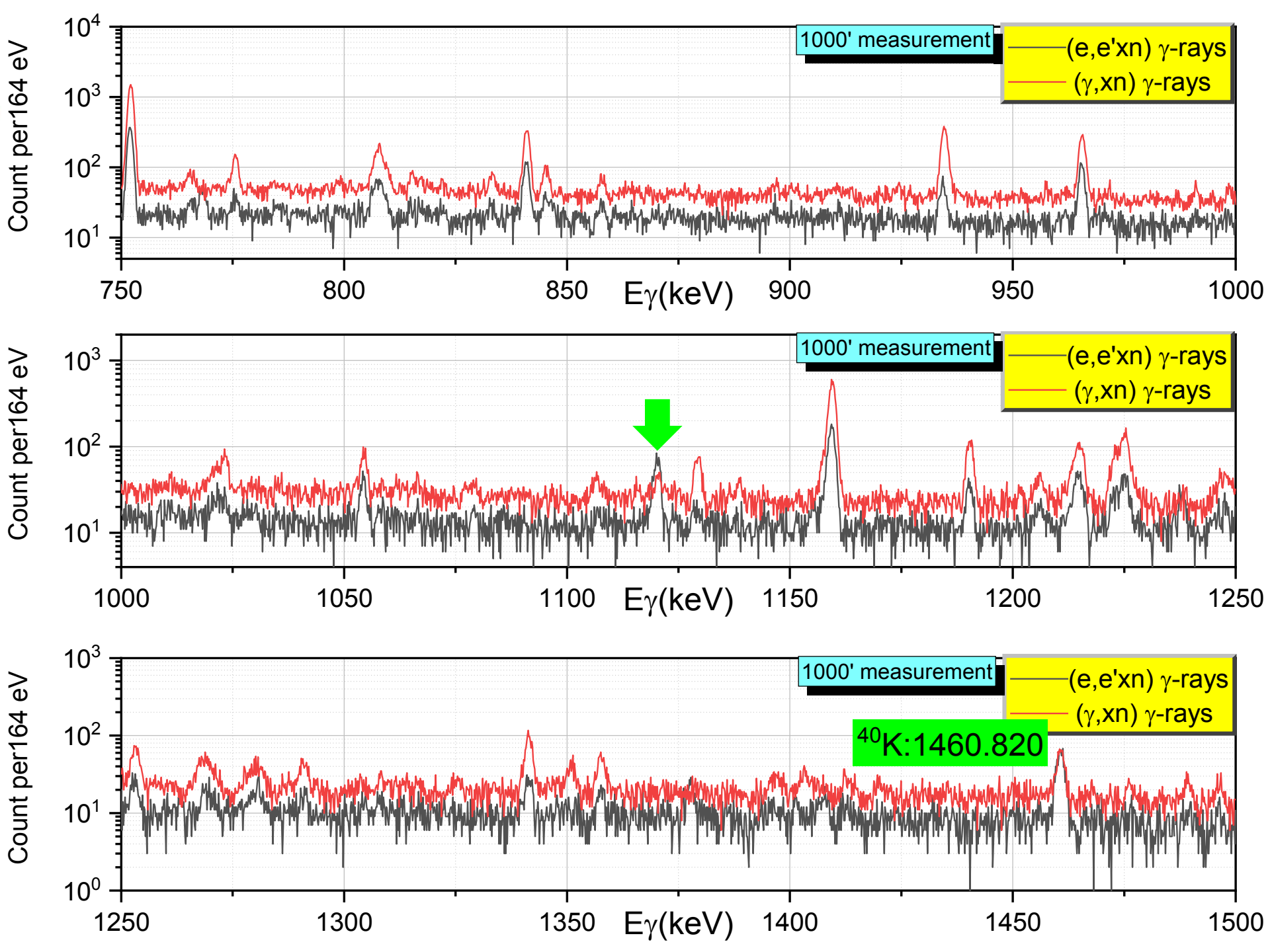
- The ratio of $\sigma_{(e,e'xn)}/\sigma_{(\gamma, xn)}$ **increases with the increasing x**, which might be explained by that the virtual photons' spectrum has a larger portion in the high energy region than that of the real photons.

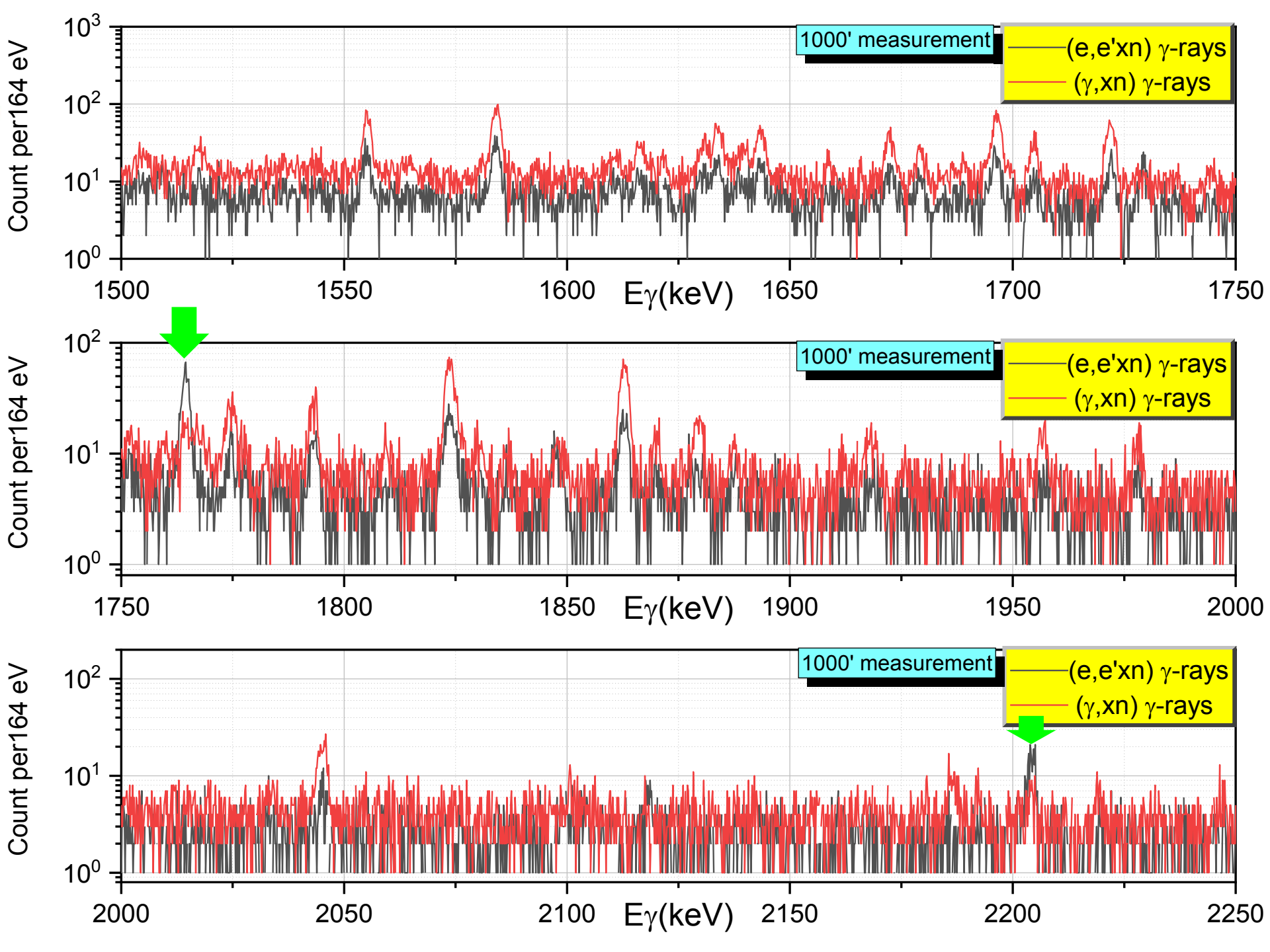
- (e,n) reaction may produce **ultra-short pulse-width fast neutron source**, which may play a role for MeV-neutron-resonance based light-nuclei analysis.

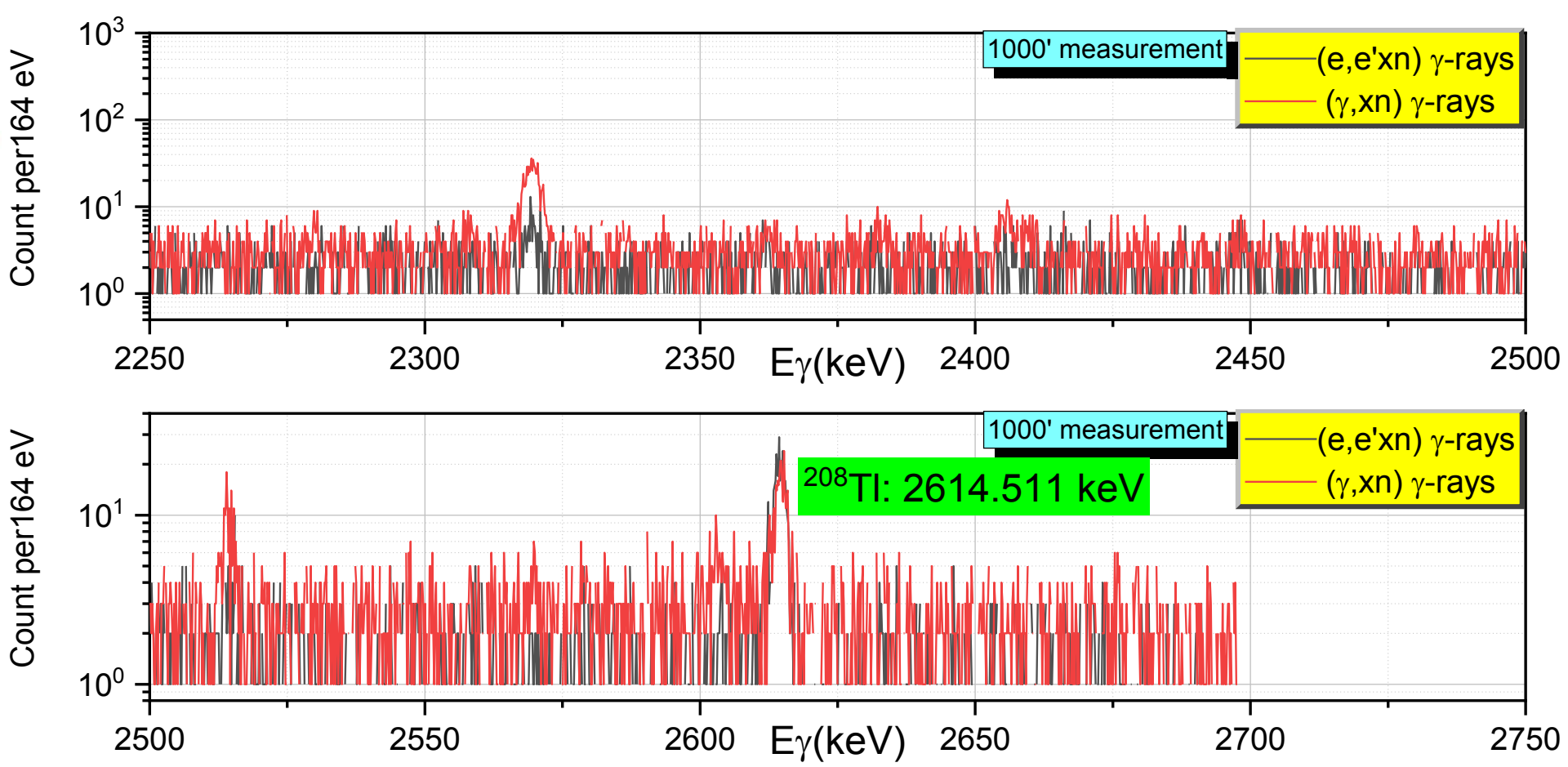
**Thank you for your attention**

**&**

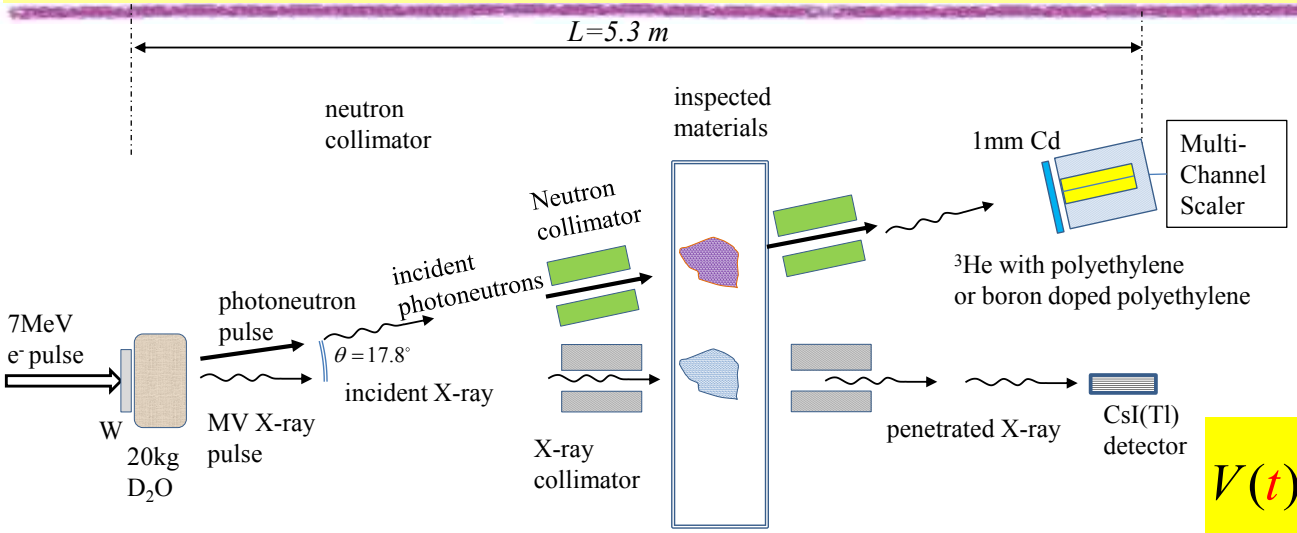
**Questions please.**


1000' measurement
(e,e'xn) γ-rays
(γ,xn) γ-rays
Count per164 eV
Eγ(keV)
1000' measurement
(e,e'xn) γ-rays
(γ,xn) γ-rays
Count per164 eV
Eγ(keV)
1000' measurement
(e,e'xn) γ-rays
(γ,xn) γ-rays
40K:1460.820
Count per164 eV
Eγ(keV)

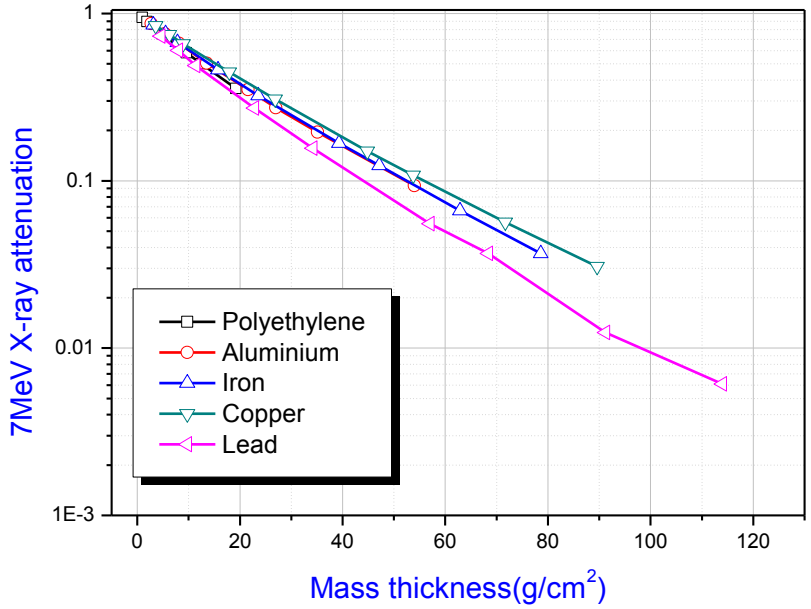

1000' measurement
(e,e'xn) γ-rays
(γ,xn) γ-rays
Count per164 eV
Eγ(keV)
1500
1550
1600
1650
1700
1750
1800
1850
1900
1950
2000
2050
2100
2150
2200
2250

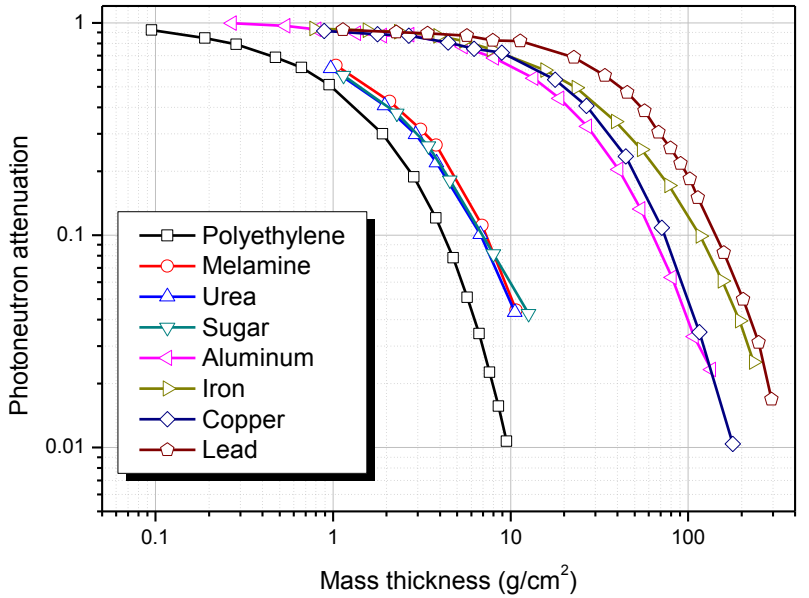

1000' measurement
(e,e'xn) γ-rays
(γ,xn) γ-rays
Count per164 eV
Eγ(keV)
1000' measurement
(e,e'xn) γ-rays
(γ,xn) γ-rays
208Tl: 2614.511 keV
Count per164 eV
Eγ(keV)

# Material identification using dual particle interrogation

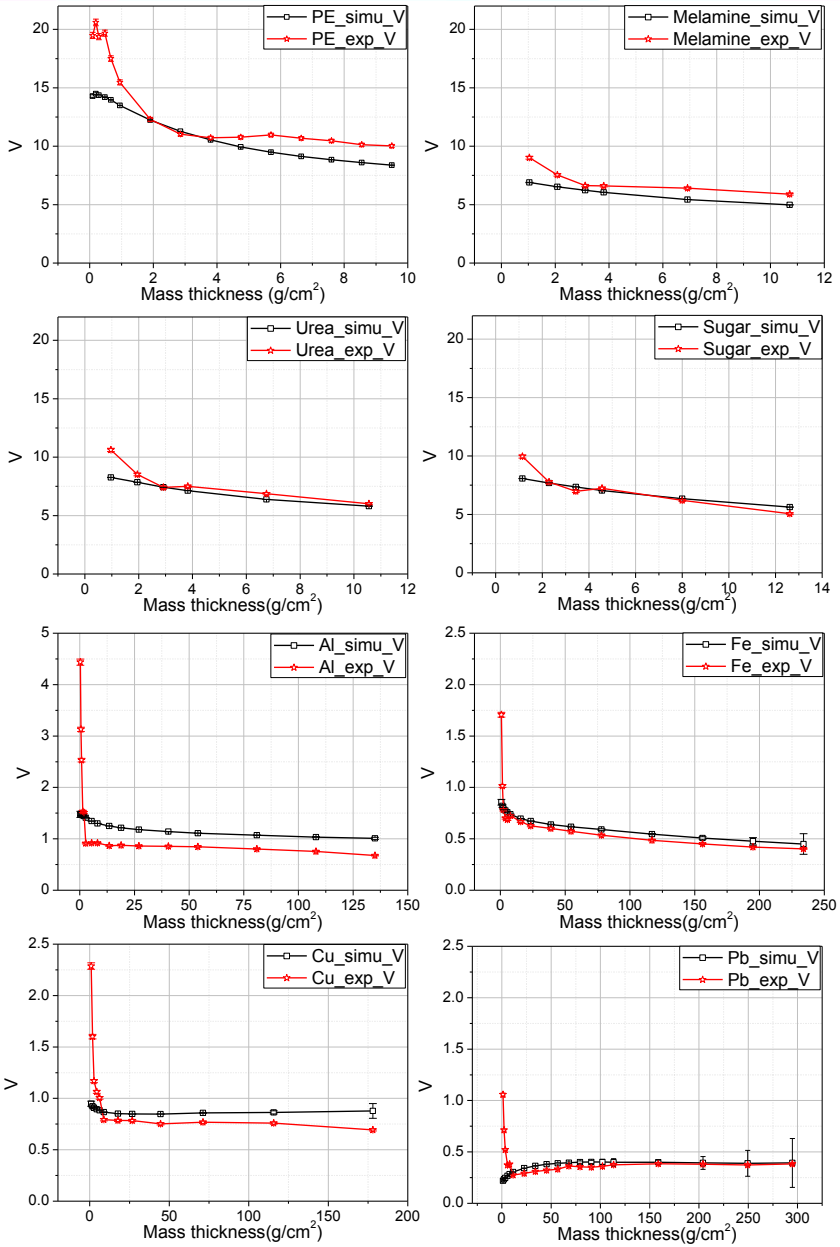


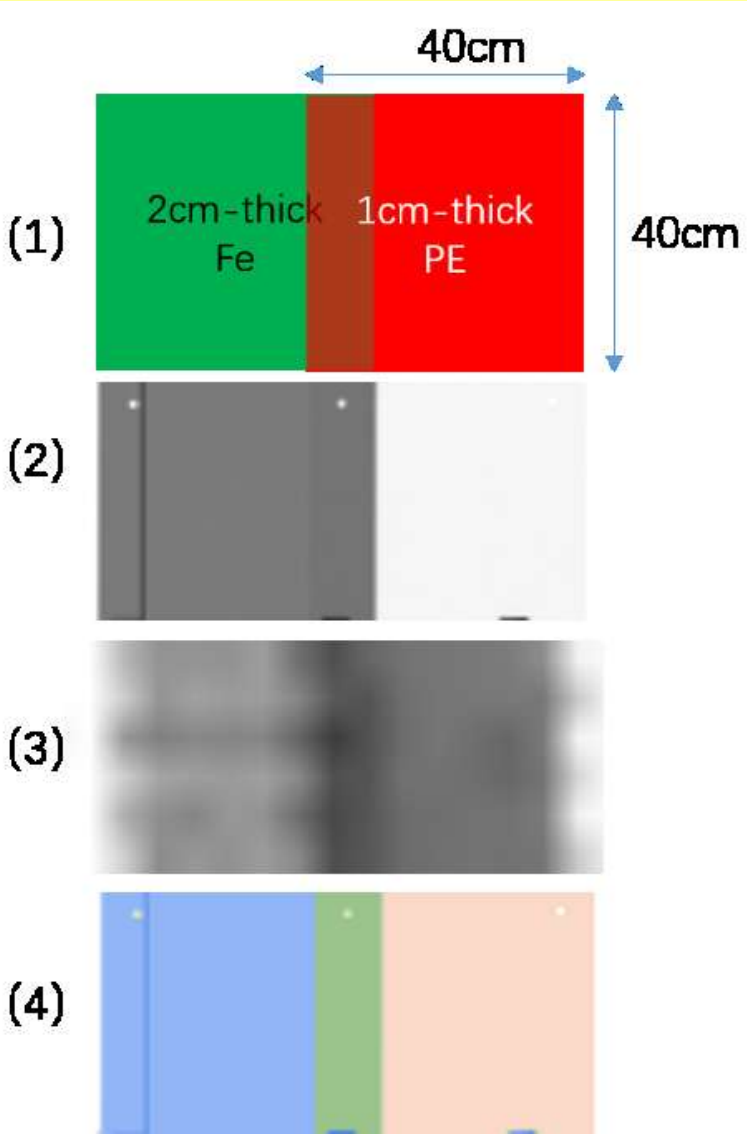

$$V(t) = \frac{\mu_n(t)\times t}{\mu_X(t)\times t} = \frac{\ln\left(I_n(t)/I_n(0)\right)}{\ln\left(I_X(t)/I_X(0)\right)}$$



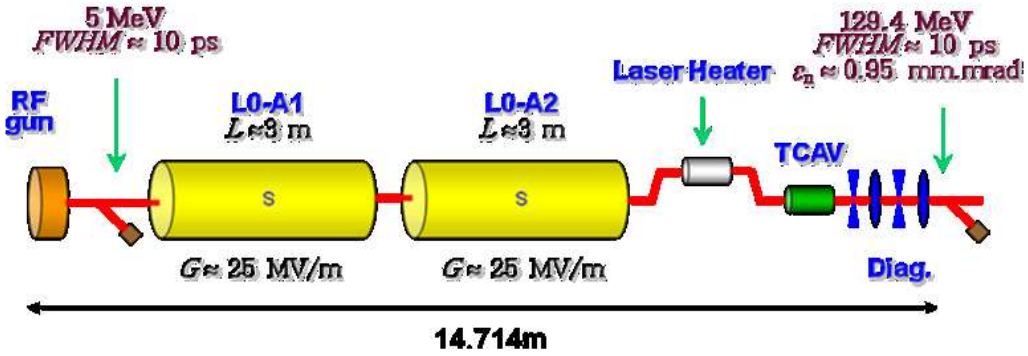
# Bi-modal imaging: MeV neutrons + MV X-rays

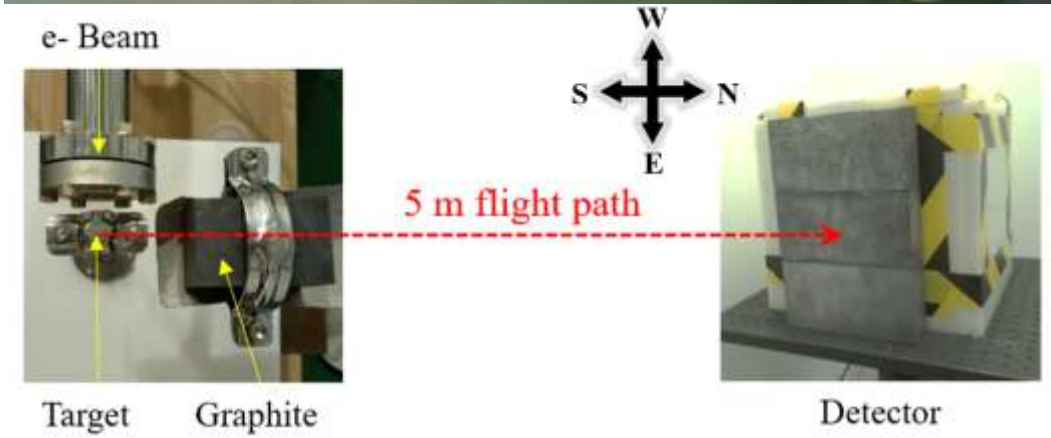


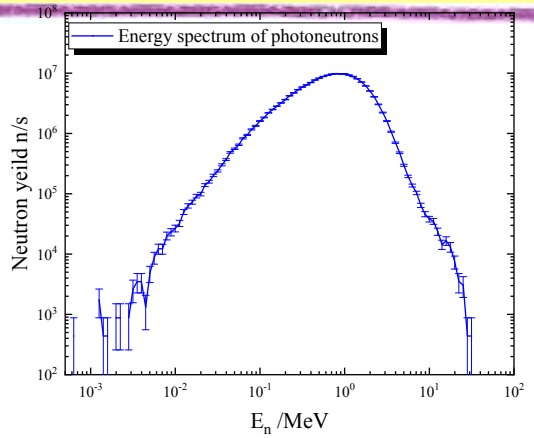



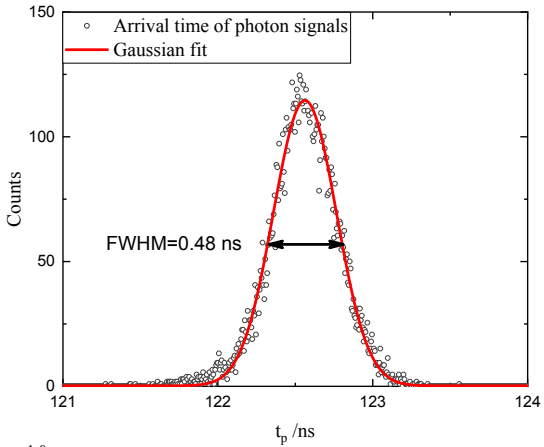

Tongyuan Cui, Yangyi Yu, Yigang Yang*, Zhi Zhang, Xuewu Wang. **Material identification using dual particle interrogation**. https://doi.org/10.1016/j.nima.2019.01.053

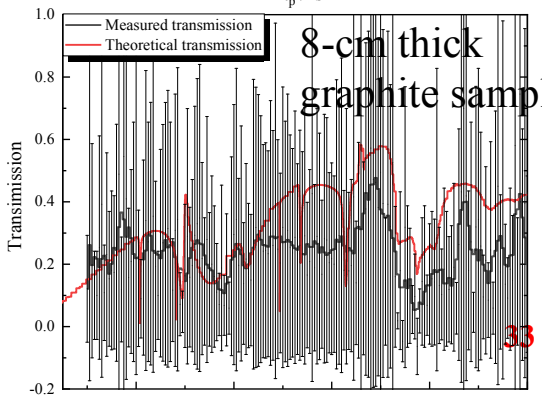
# 10 *ps* 100MeV e$^-$+$^{181}$Ta→MeV neutron resonant analysis



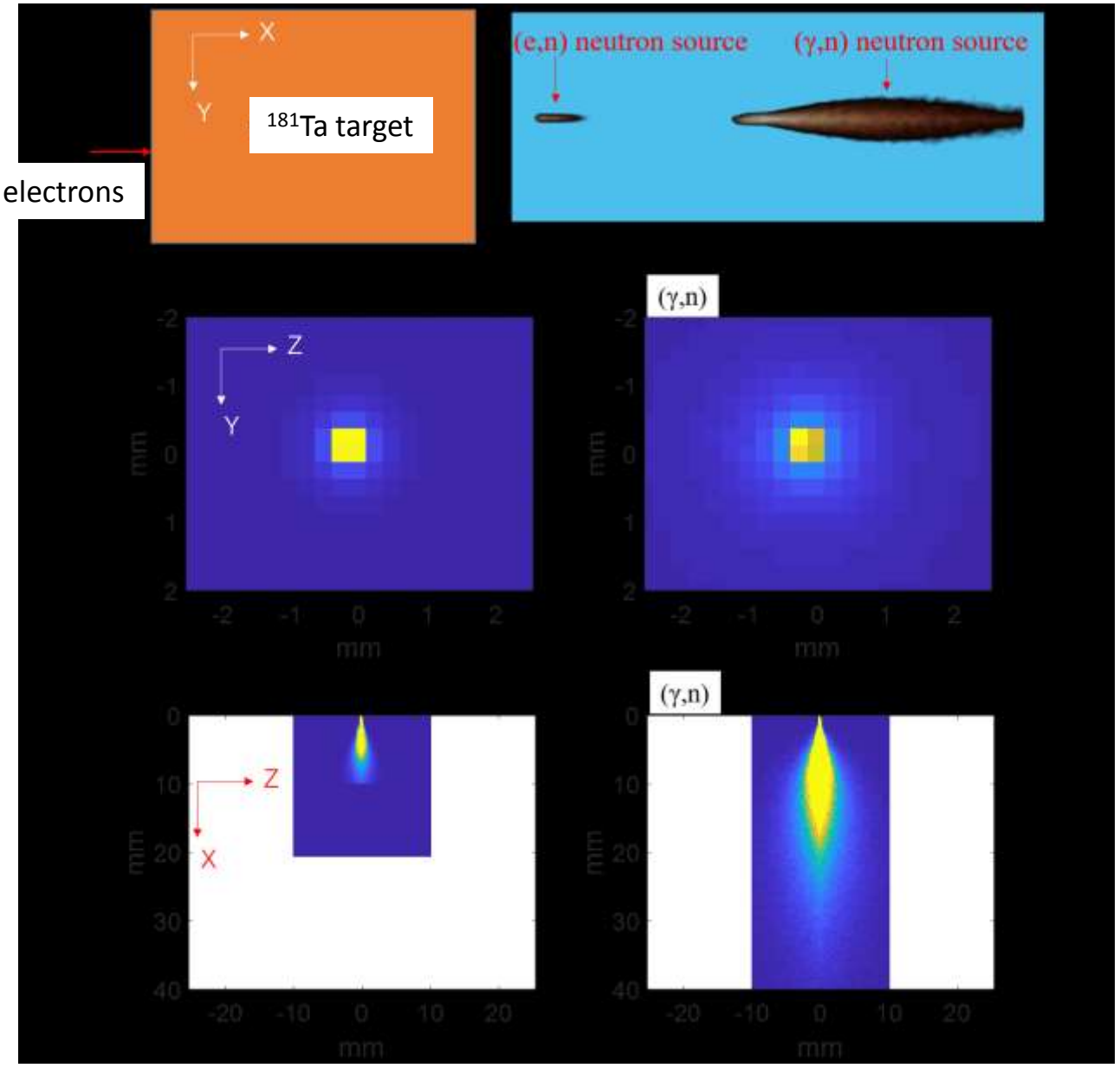




8-cm thick graphite sample

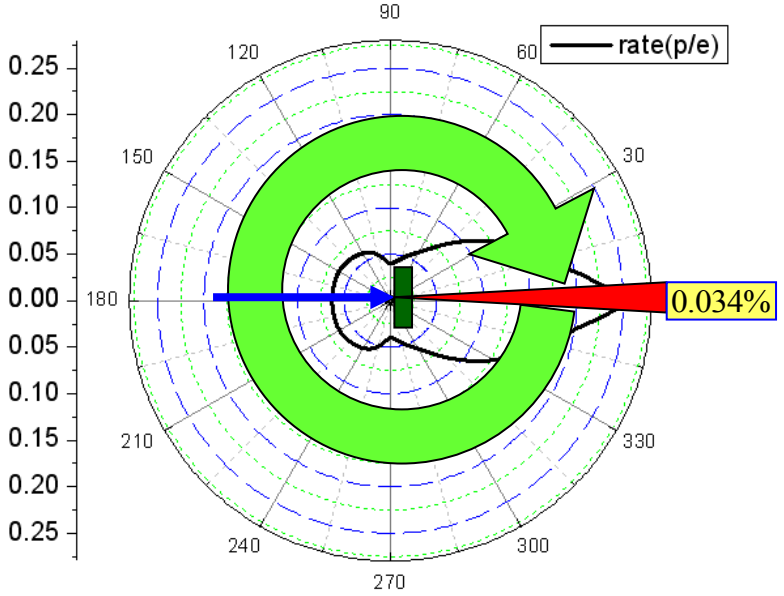
Q.Wang;X.Weng,Y.Yu; C.Deng, Z.Zhang;X.Tuo;Y.Yang*.**Investigation of Fast Neutron Resonance Transmission Analysis based on the Ultrashort Pulsed Electron Beam-driven Photoneutron Source**. https://doi.org/10.1088/1748-0221/14/05/P05004

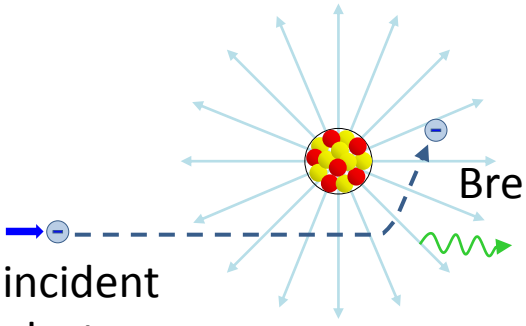
# a “point” fast neutron source



# photoneutron source

Angular distribution of X-ray

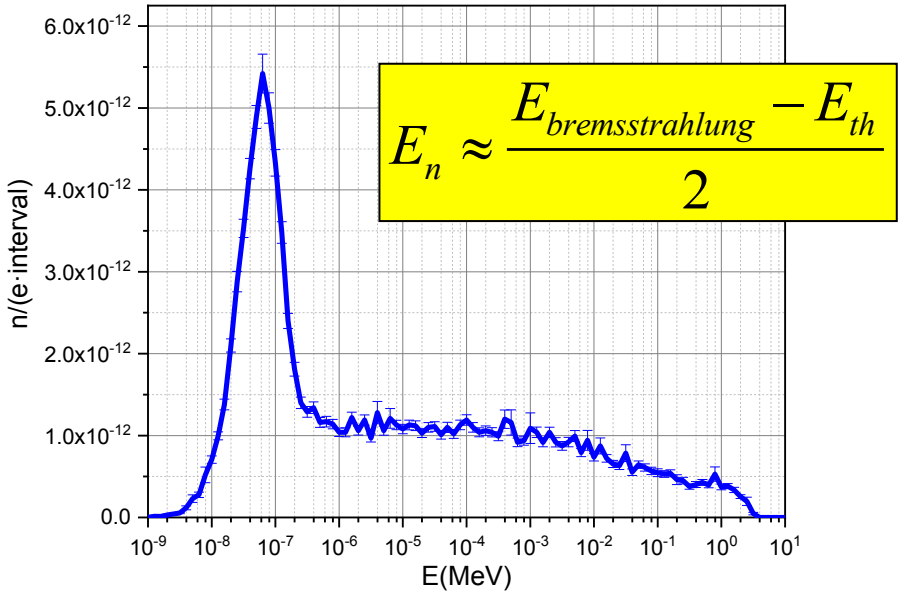


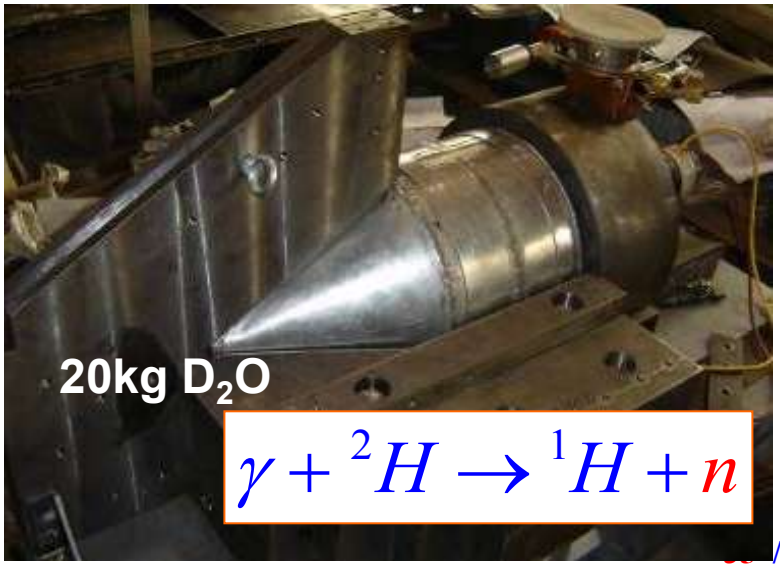

(γ,n) reaction

*GDR or QD*

Emitted neutron

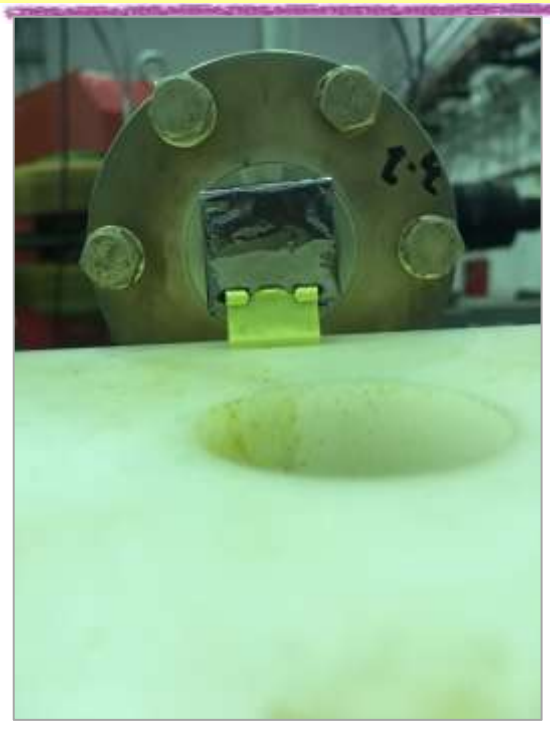


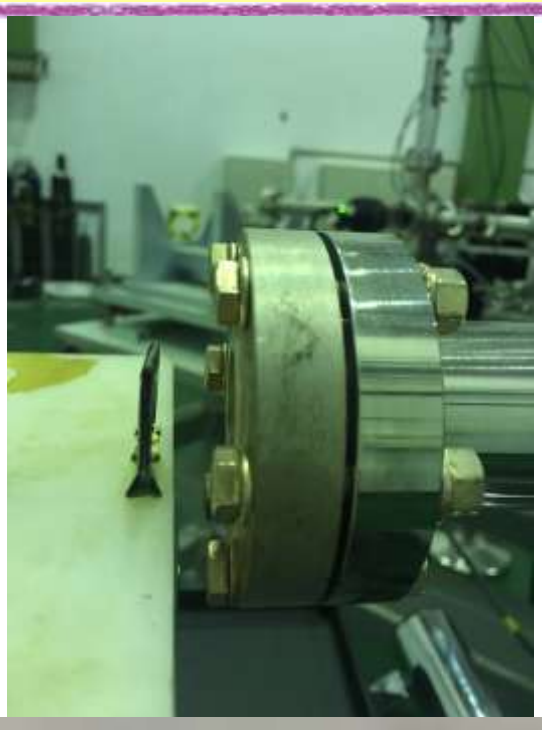

$$E_n \approx \frac{E_{bremsstrahlung} - E_{th}}{2}$$

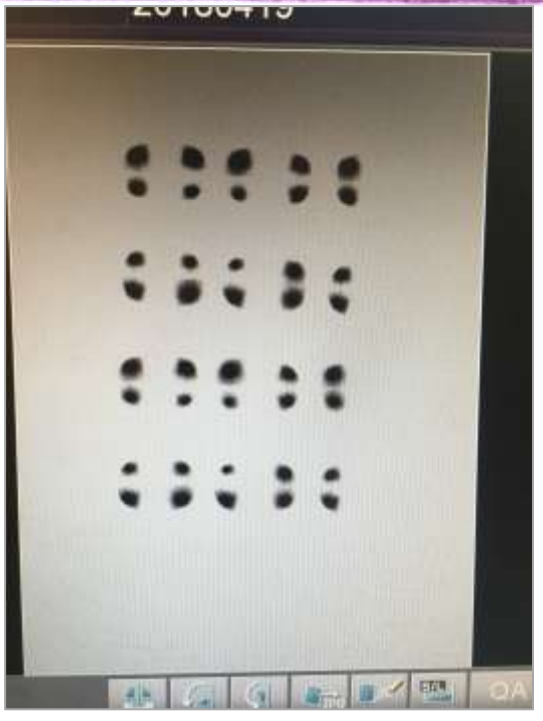



$$\gamma + {}^{2}H \rightarrow {}^{1}H + n$$

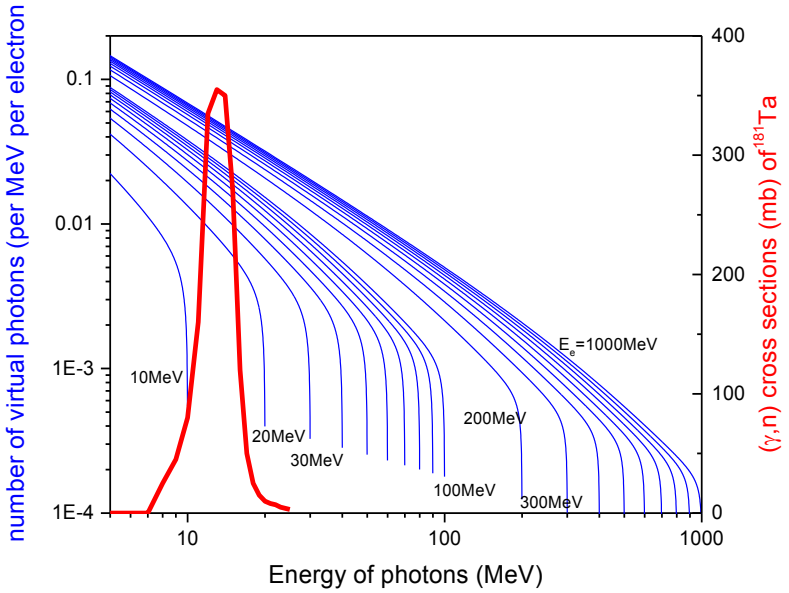
# The measurement of (e,n) cross sections

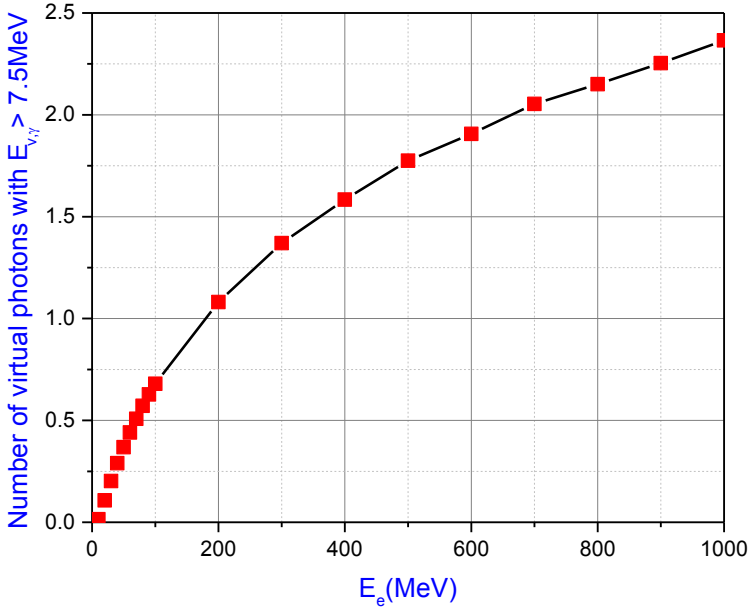


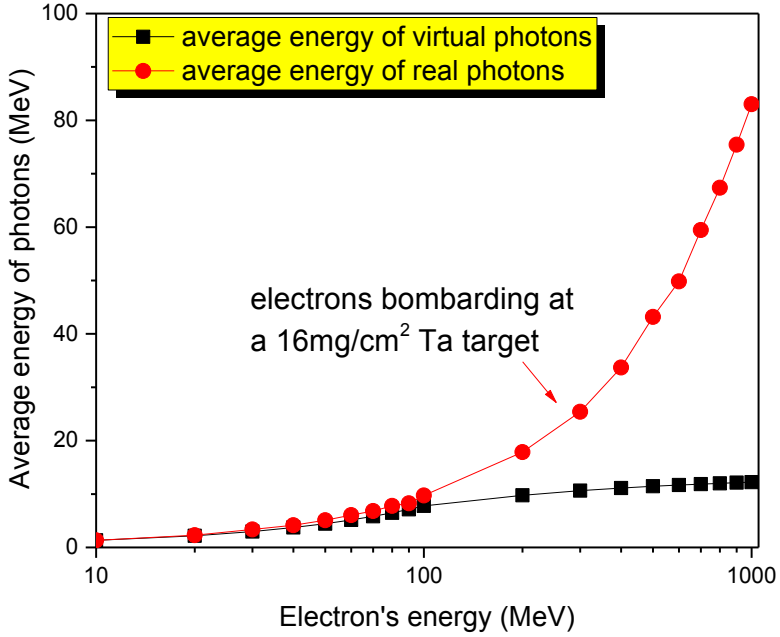


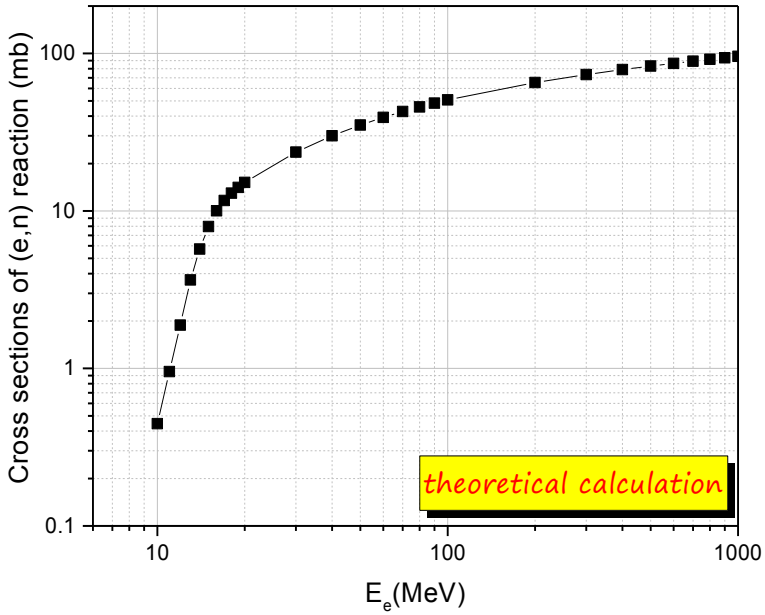


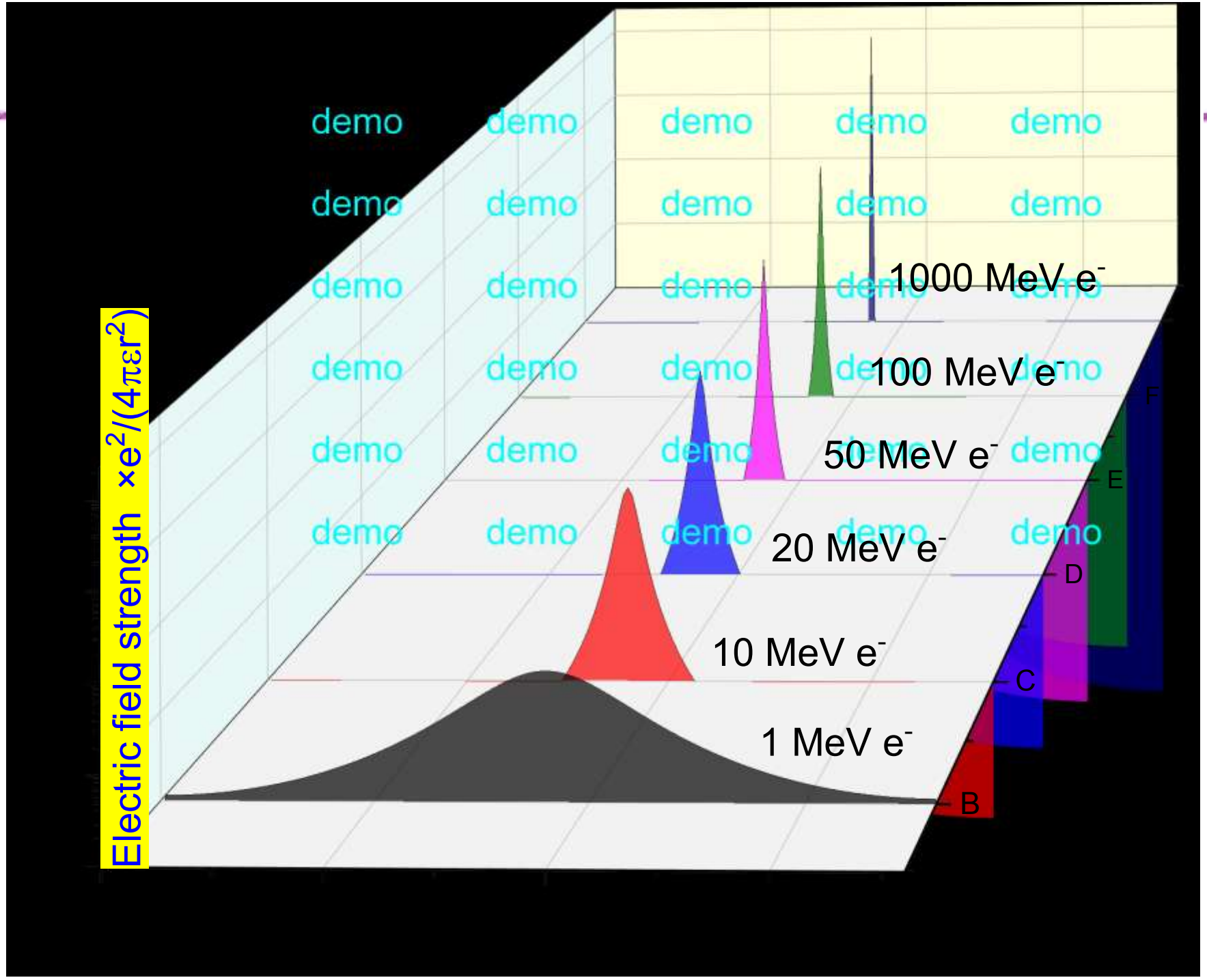
# The (e,e'n) cross sections



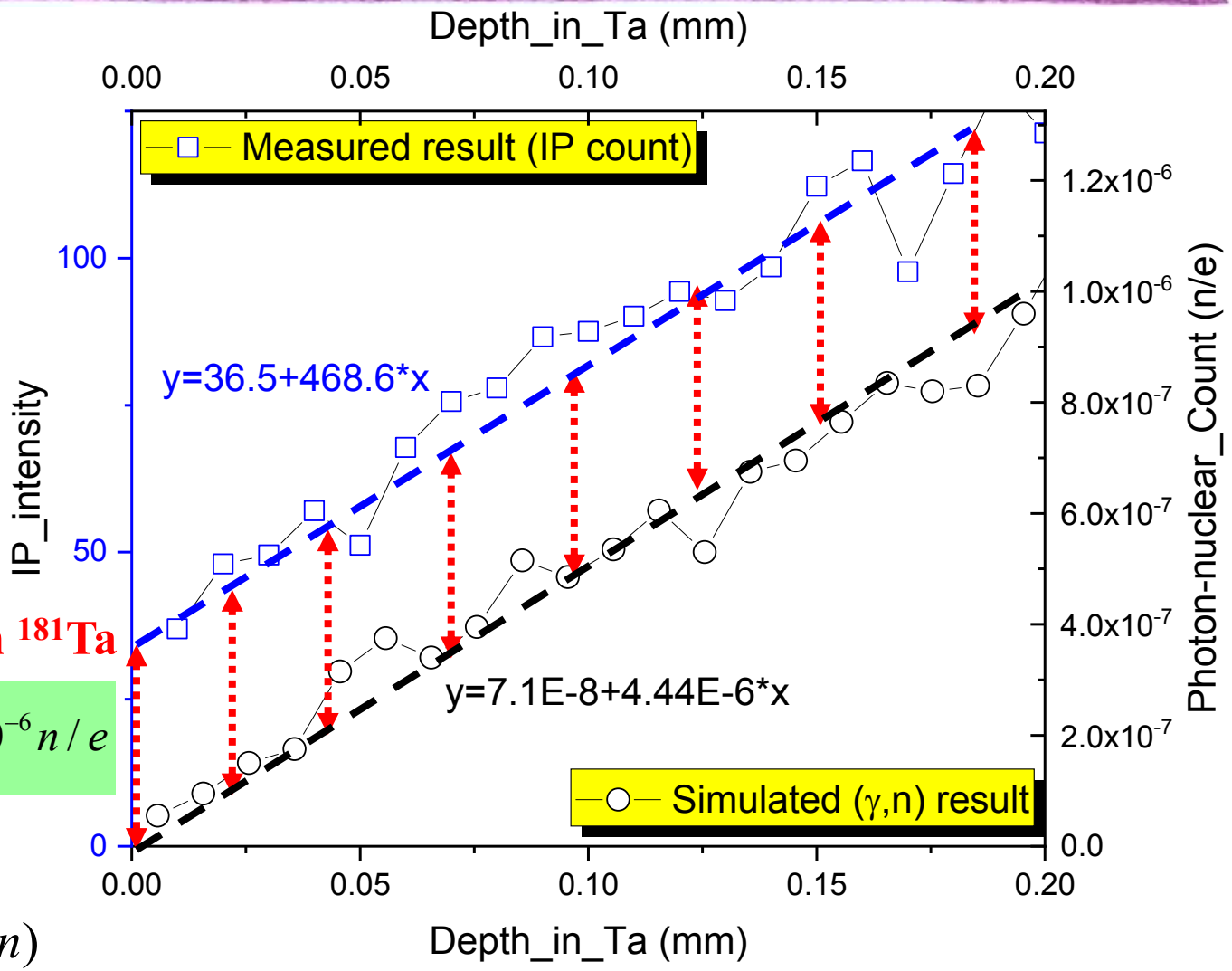




demo
Electric field strength ×e²/(4πεr²)
1000 MeV e⁻
100 MeV e⁻
50 MeV e⁻
20 MeV e⁻
10 MeV e⁻
1 MeV e⁻
F
E
D
C
B

# Activities @ different depths




**(e,e'n) neutron of 10 μm $^{181}$Ta**

$$N(e,e'n) = \frac{36.5}{468.6} \times 4.44 \times 10^{-6}\, n/e$$

$$\sigma(e,e'n) = \frac{N(e,e'n)}{\frac{\rho}{A} \times N_A \times 10^{-3}\, cm}$$