Measurement of High-Energy Prompt γ-rays from Neutron-Induced Fission of ^{235}U

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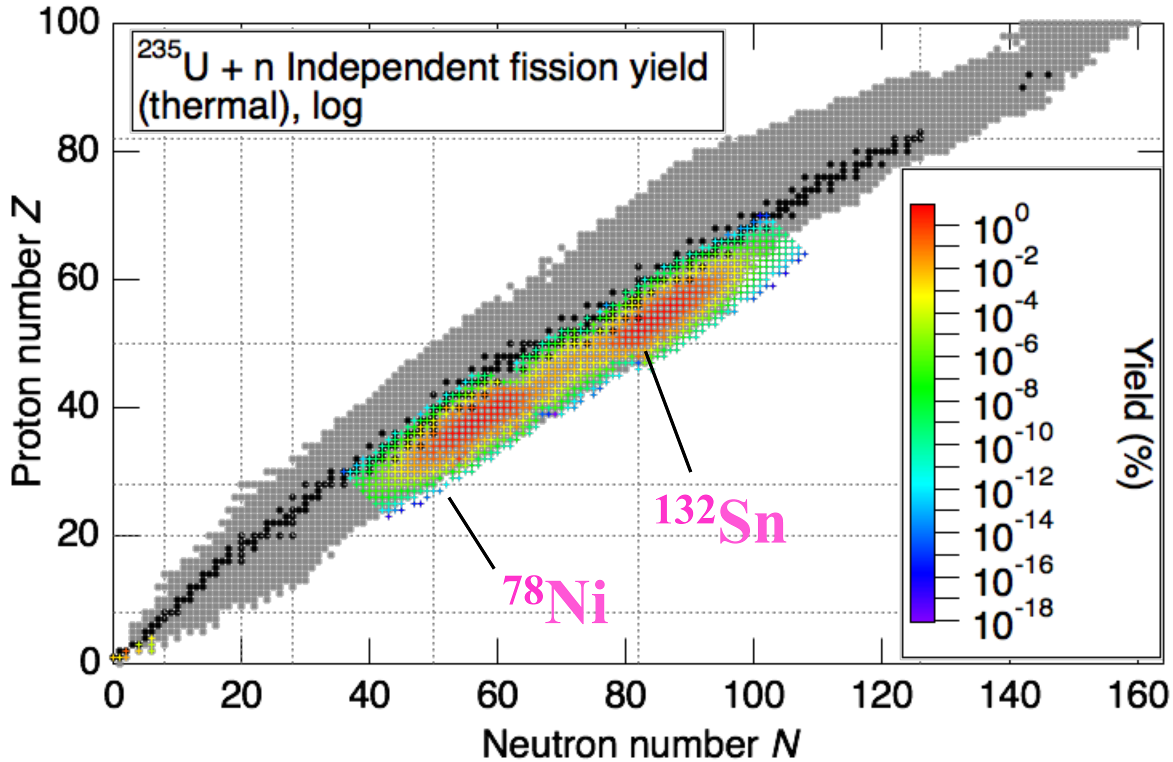
1. Introduction

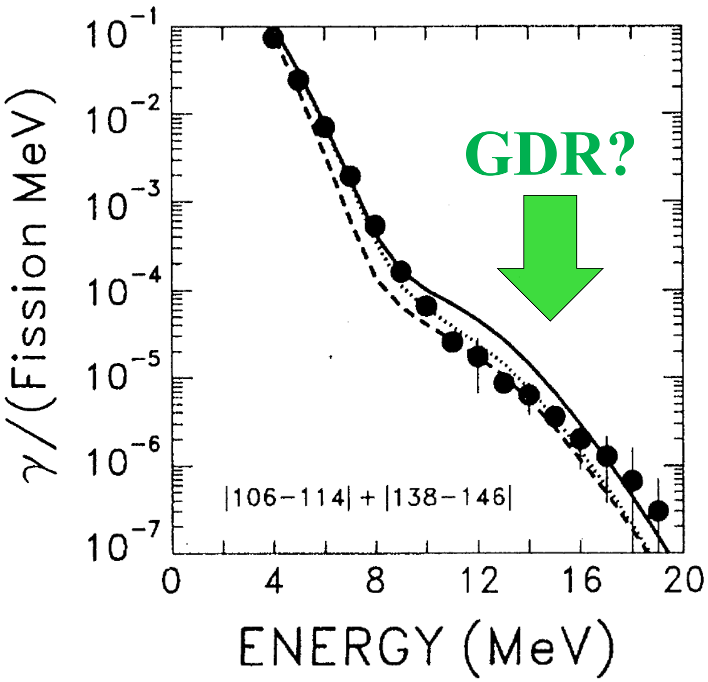
Prompt fission γ-ray spectra (PFGS)

- Include valuable information
  - ➢ Sharing the total excitation energy between two FFs
  - ➢ Spin distributions, level densities, γ-ray strength functions, etc...
- Important for atomic energy applications.

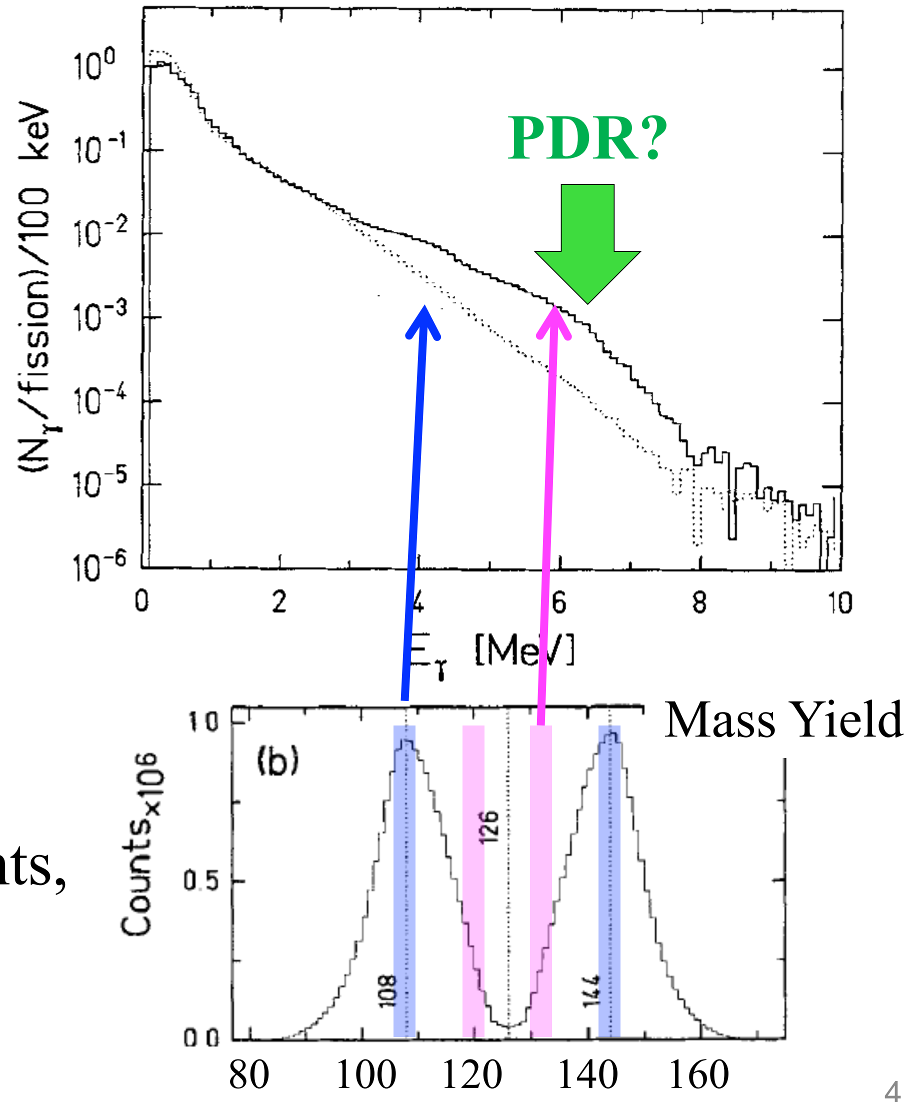


PFGS measured for ^{252}Cf(sf)

H. van der Ploeg *et al.*,
Phys. Rev. C, **52**, 1915 (1995).

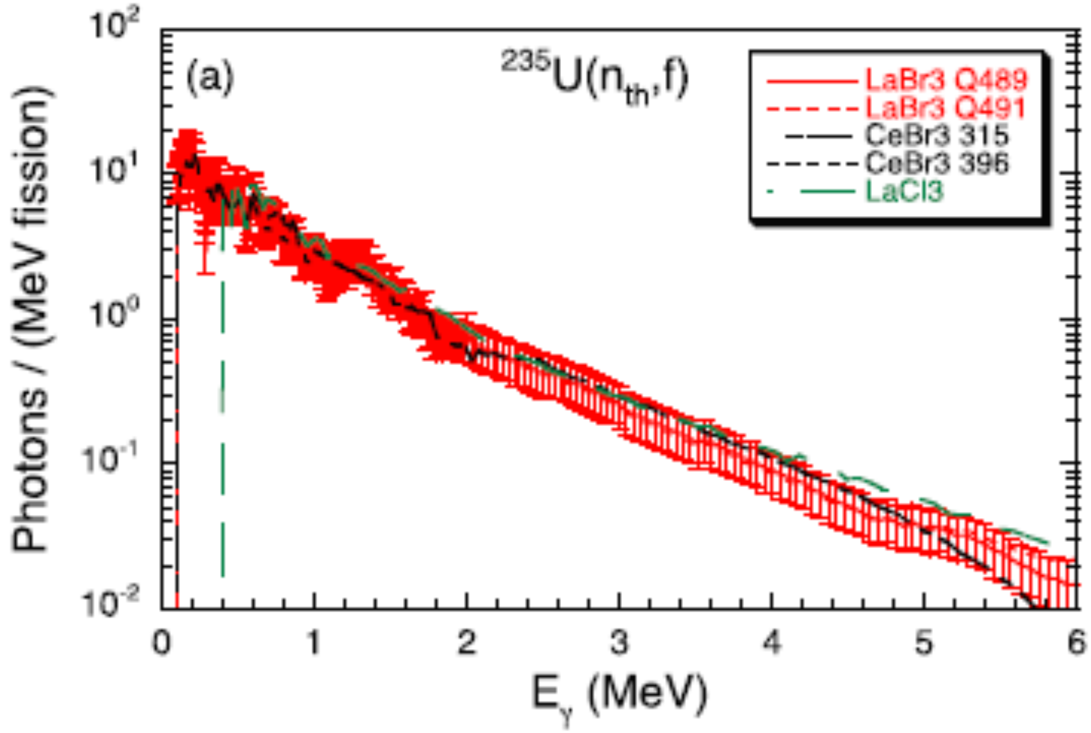


A. Hotzel et al., Z. Phys. A336 (1996) 299.



To understand origins of enhancements, one need data for fission of other isotopes with different mass yield.

PFGS measured for (n_{th},f)



A. Oberstedt et al., PRC 87 (2013) 051602.

- Measurements are limited up to about 6 MeV
- Fragment mass dependence was not obtained

We proposed to measure the PFGS in ^{235}U(n,f) up to ~ 20 MeV

2. Measurement

Developed a new setup consists of detectors for FFs and γ-rays to measure the PFGS **down to ~10^{-7} γ/fis./MeV @ 20 MeV**

- 10^5 times larger sensitivity compared with previous measurements
- Simple setup to measure the PFGS at any beam-line facility

→ Large solid angle FF detector and large volume γ-ray detector

- Capability being withstood against high counting rates
- Ability being able to separate prompt γ-rays from neutrons

→ Fast timing properties for both FF and γ-ray detectors

Our decision was to use

- two position-sensitive multi-wire proportional counters (MWPCs)
- two large volume $LaBr_3(Ce)$ scintillators

Detectors for FFs and γ-rays

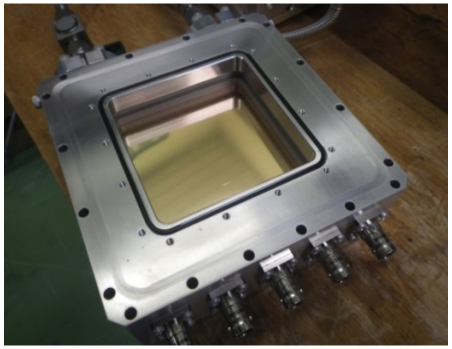
MWPC for FFs

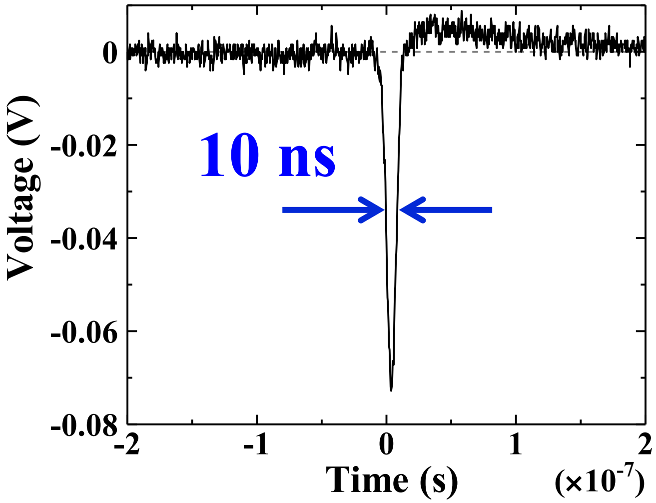
Large area (80 × 80 mm^2)

Position sensitive

No radiation damage

Fast timing



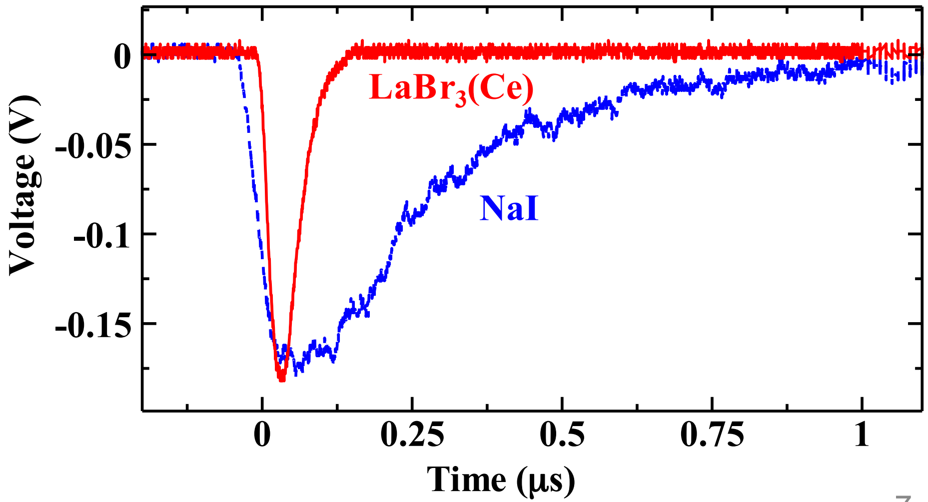


LaBr$_3$(Ce) scintillators for γ-rays

Large Volume (4inϕ ×5in)

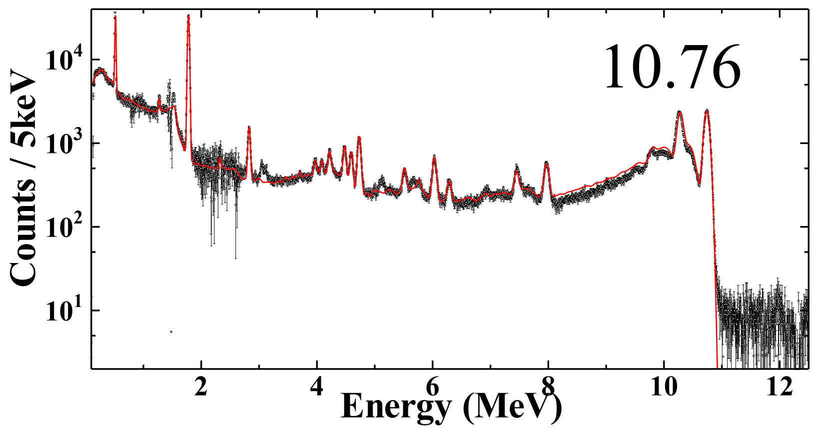
High-energy resolution

Fast timing



Response functions of $LaBr_3(Ce)$ scintillator

Need to obtain PFGS from measured spectrum



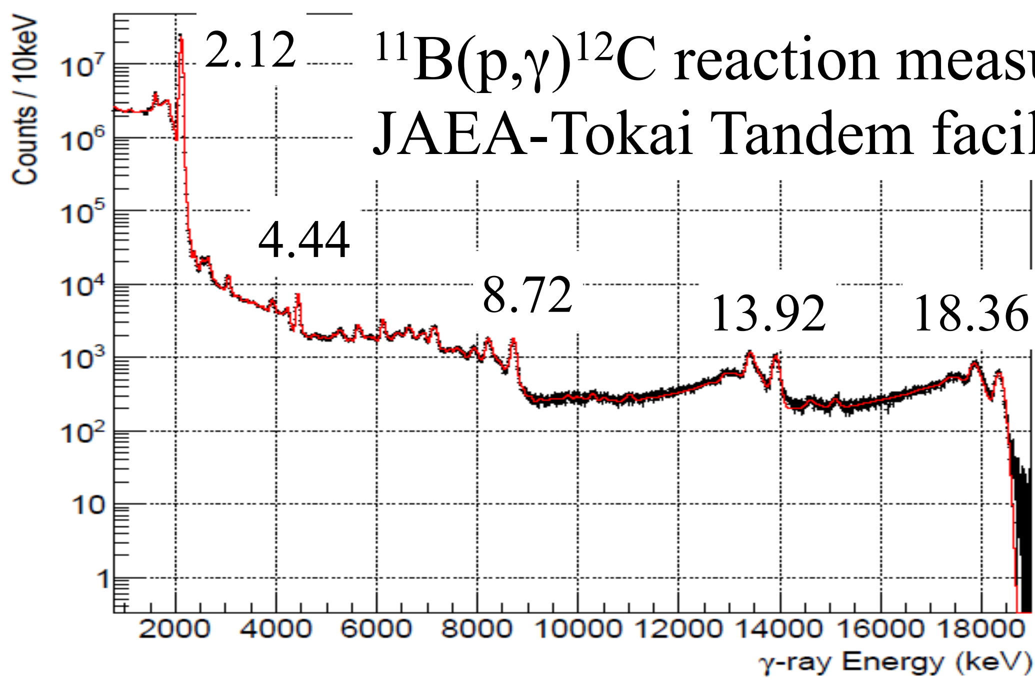
γ-rays from $^{27}Al(p,\gamma)^{28}Si$ reaction (up to 10.76 MeV)

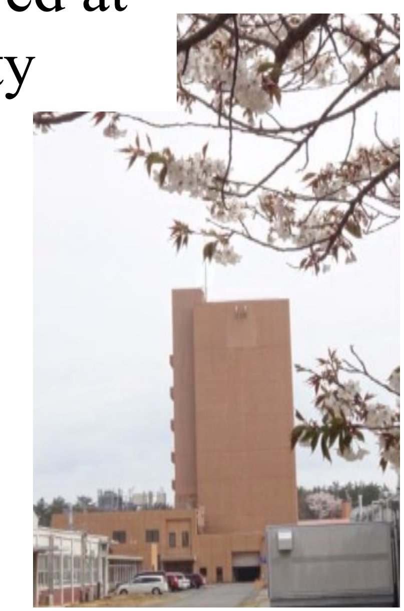
■ : Exp. Data

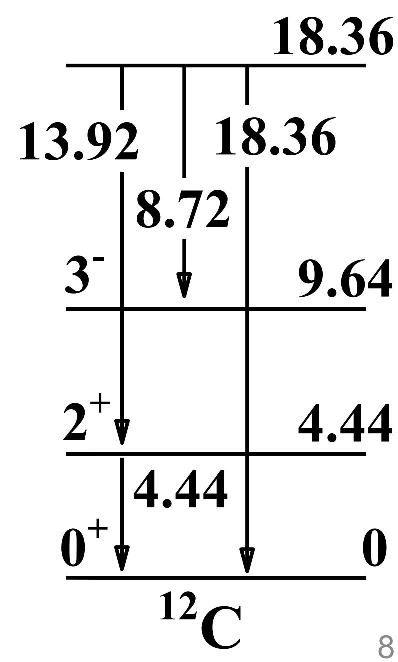
— : GEANT4

H. Makii et al. NIMA 797 (2015) 83.

$^{11}B(p,\gamma)^{12}C$ reaction measured at JAEA-Tokai Tandem facility

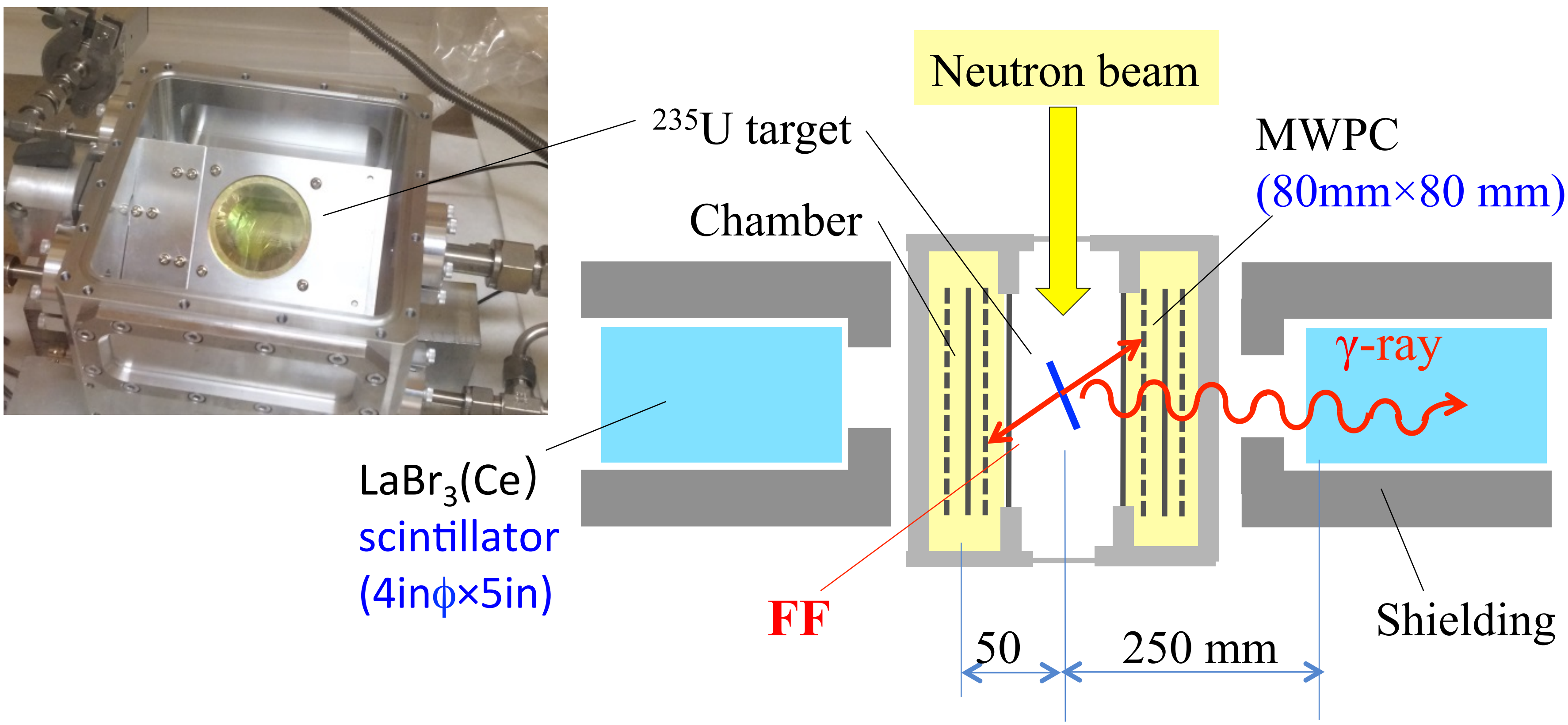


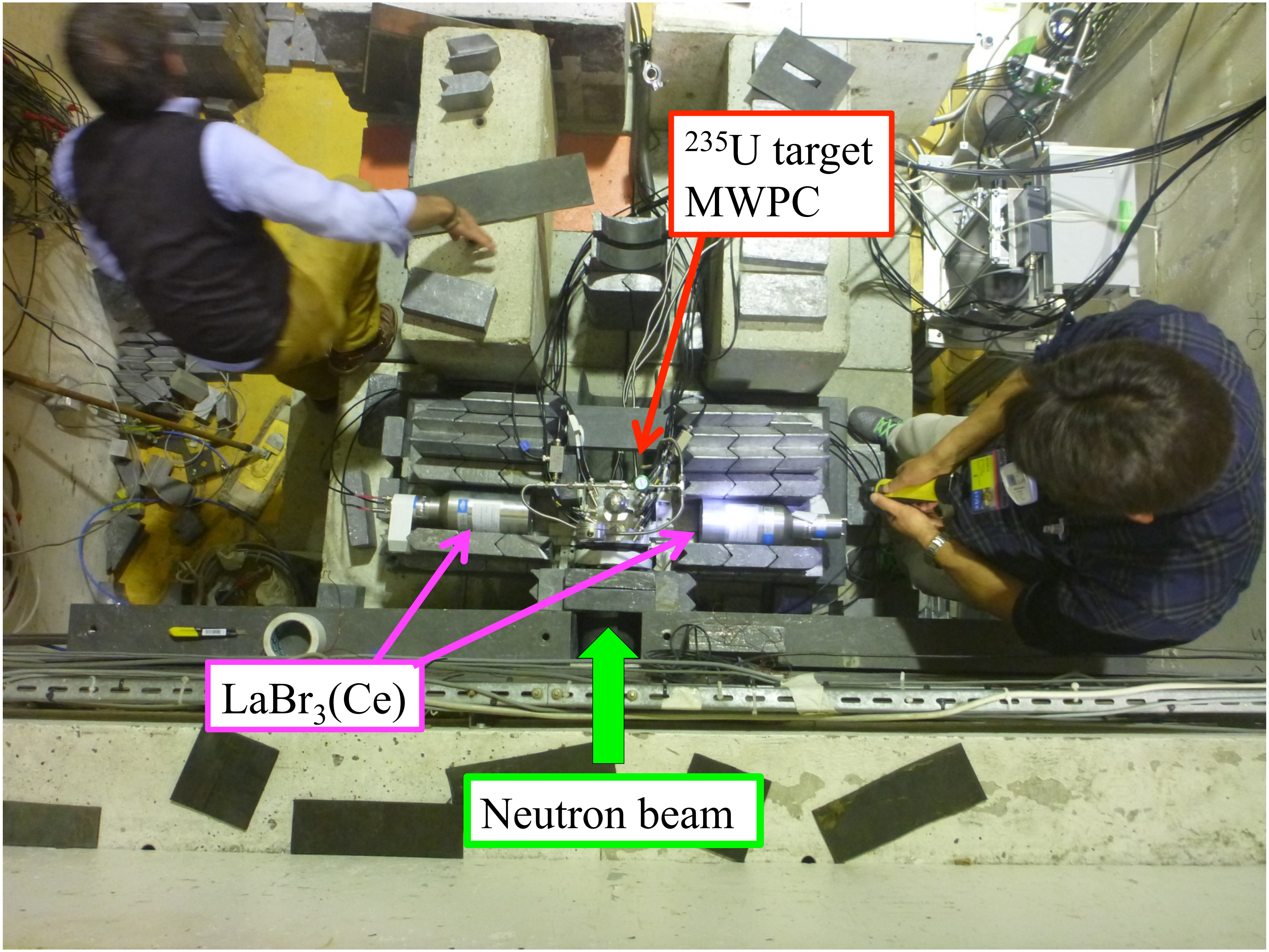




2. Measurement

Observe γ-rays coincidence with FFs at the PF1b cold-neutron facility
at Insitute Laue-Langevin (ILL), Grenoble, France



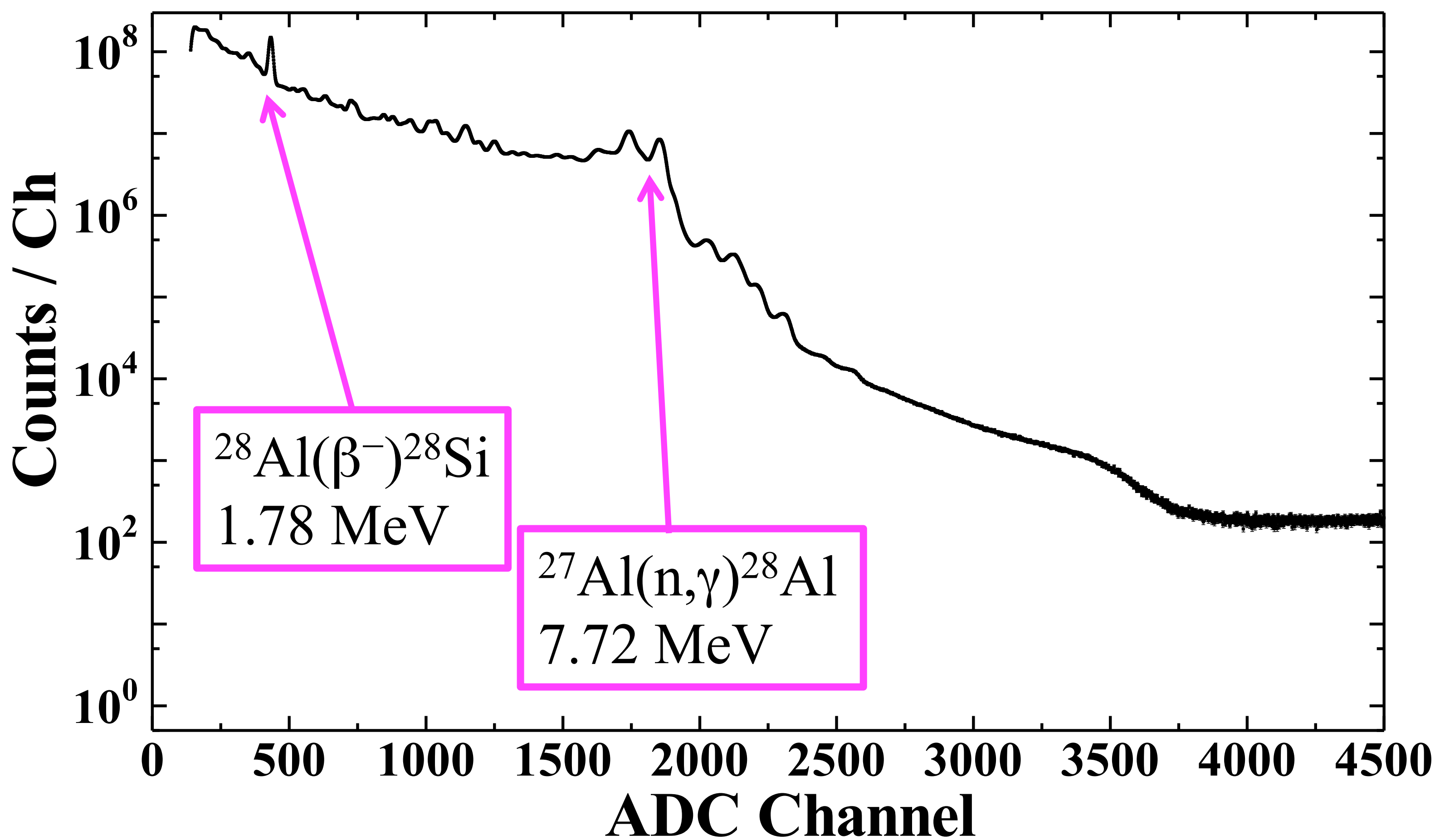

^{235}U target
MWPC
$LaBr_3(Ce)$
Neutron beam

Measurement condition and statistics

- Neutron flux : **~10^8 n / cm^2 / s, ϕ20mm**
- Target : $^{235}UF_4$ (**> 99.9 %, ϕ30mm, 117 μg/cm^2, 0.85 mg**)
  - From EU-JRC (IRMM), Belgium
- Measurement time : **436.7 h**
- Counting Rates for each detector
  - MWPC (FFs) : **~56 kHz**
  - $LaBr_3$(Ce) scintillator (γ-rays) : **~30 kHz** (Threshold: 0.8 MeV)
- High throughput digital waveform processing system
  Output energy, timing, and pile-up events
  - Dead time : **1 ~ 2 %** for each MWPC and $LaBr_3$(Ce) scintillator
  - Fraction of pile-up events : **~ 0.03 %** of total events
- Registered events
  - Two FFs in coincidence : **5.1×10^{10}**
  - γ-rays in coincidence with FFs : **1.7×10^9**

3. Results and Analysis

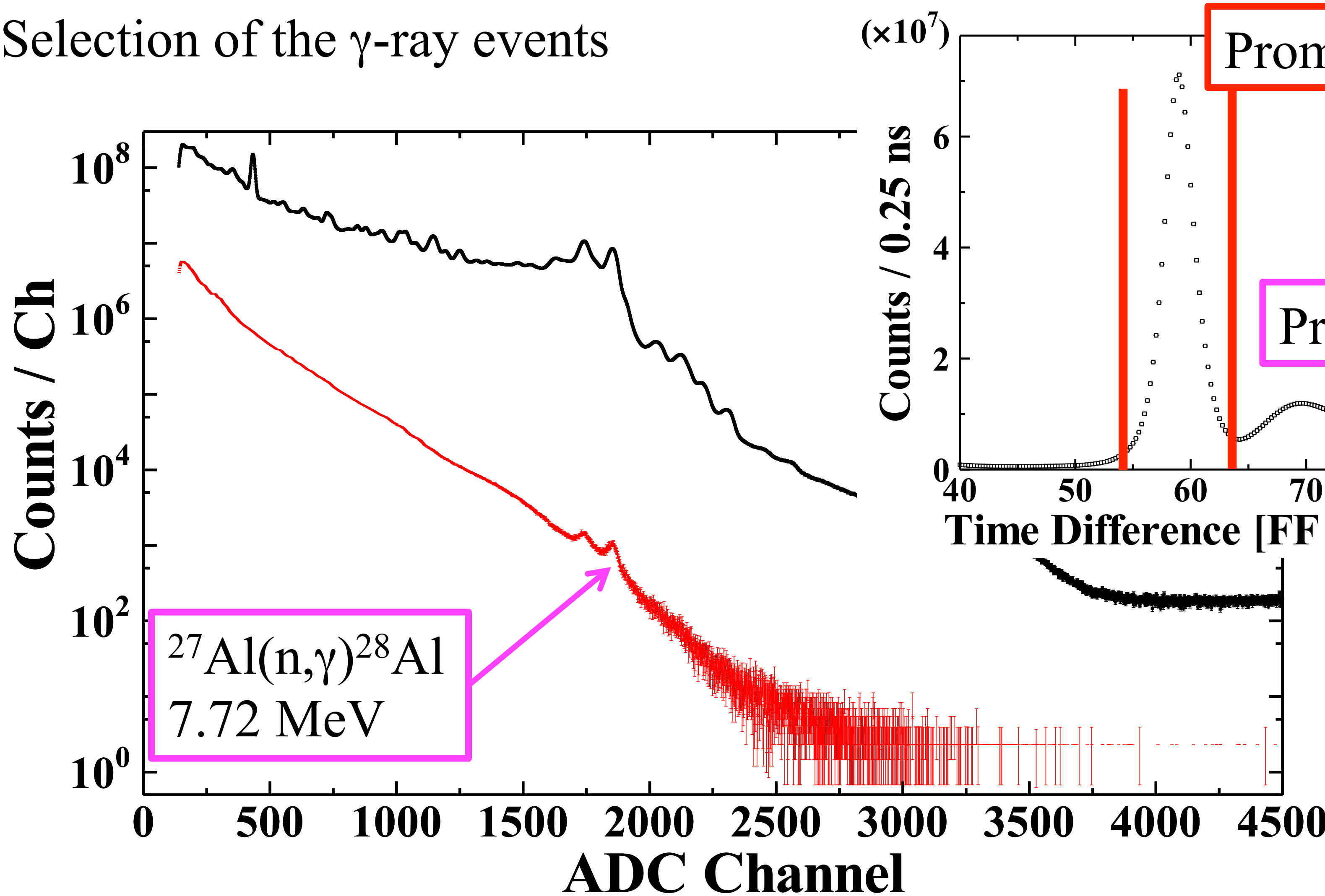
Total γ-ray events observed by one $LaBr_3(Ce)$ scintillator



Almost all events are background due to scattered neutrons

3. Results and Analysis

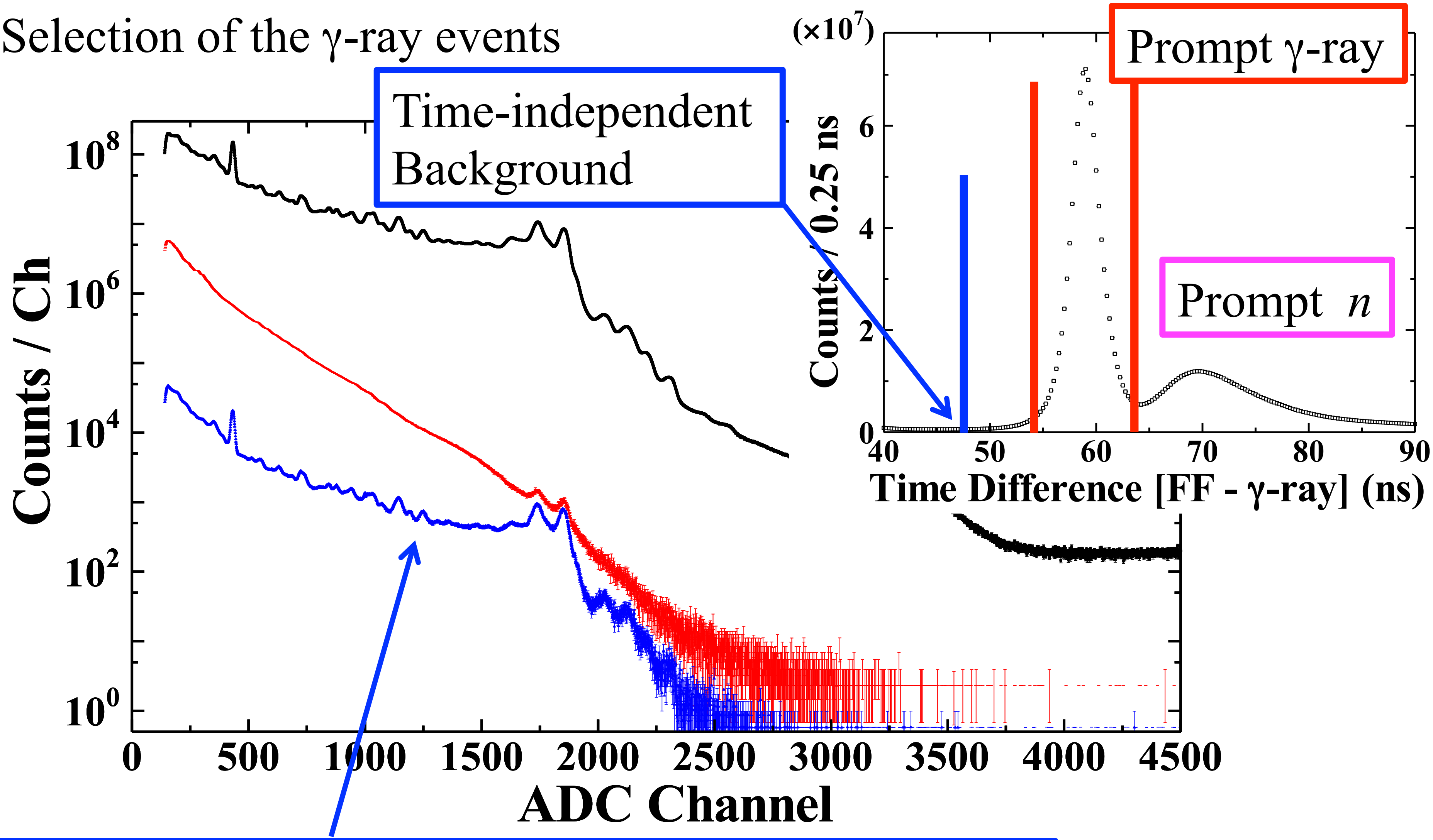
Selection of the γ-ray events



Non-negligible amounts of time-independent background are seen

3. Results and Analysis

Selection of the γ-ray events

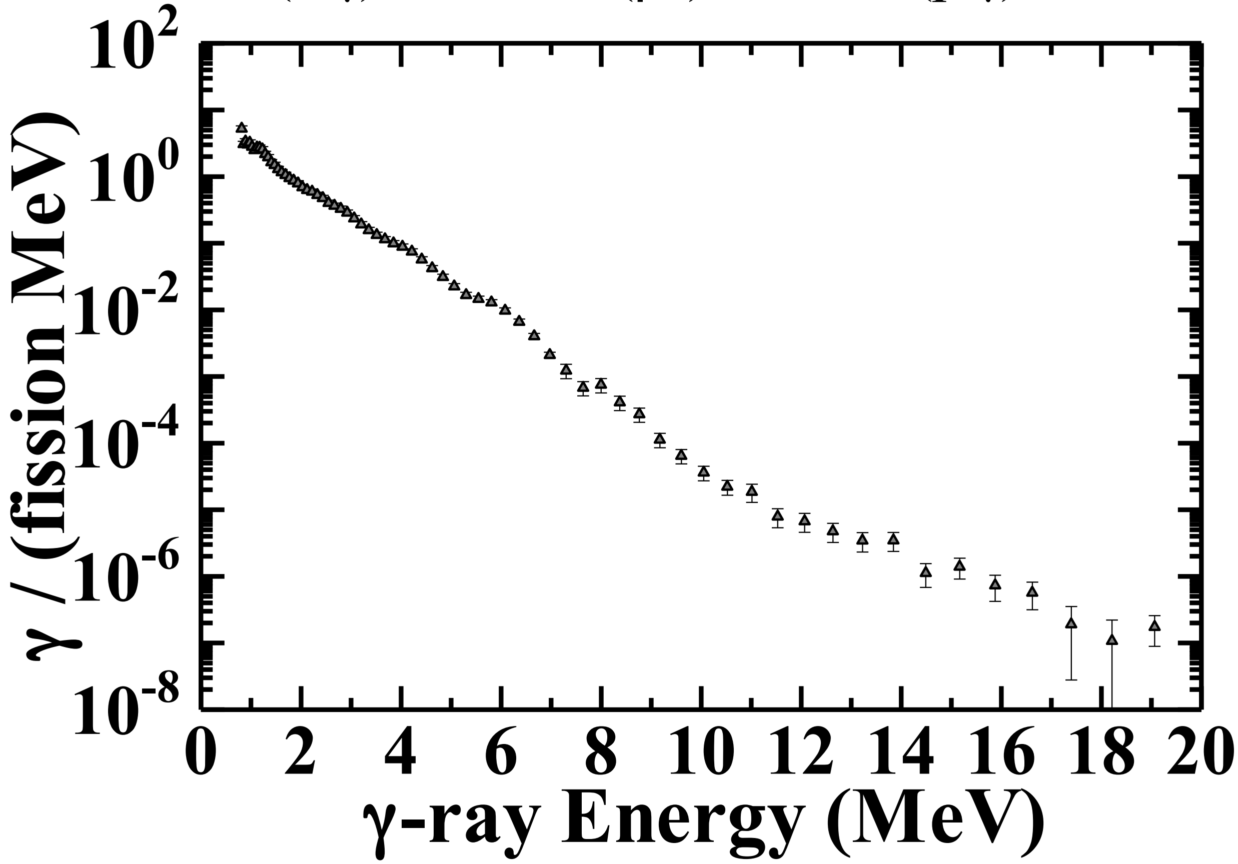


Estimated time-independent background component

PFGS for $^{235}U(n_{th}, f)$

Unfolded net spectrum with response of $LaBr_3(Ce)$ scintillators

Energy calibration: $^{27}Al(n,\gamma)\,^{28}Al$, $^{28}Al(\beta^-)$, and $^{11}B(p,\gamma)^{12}C$



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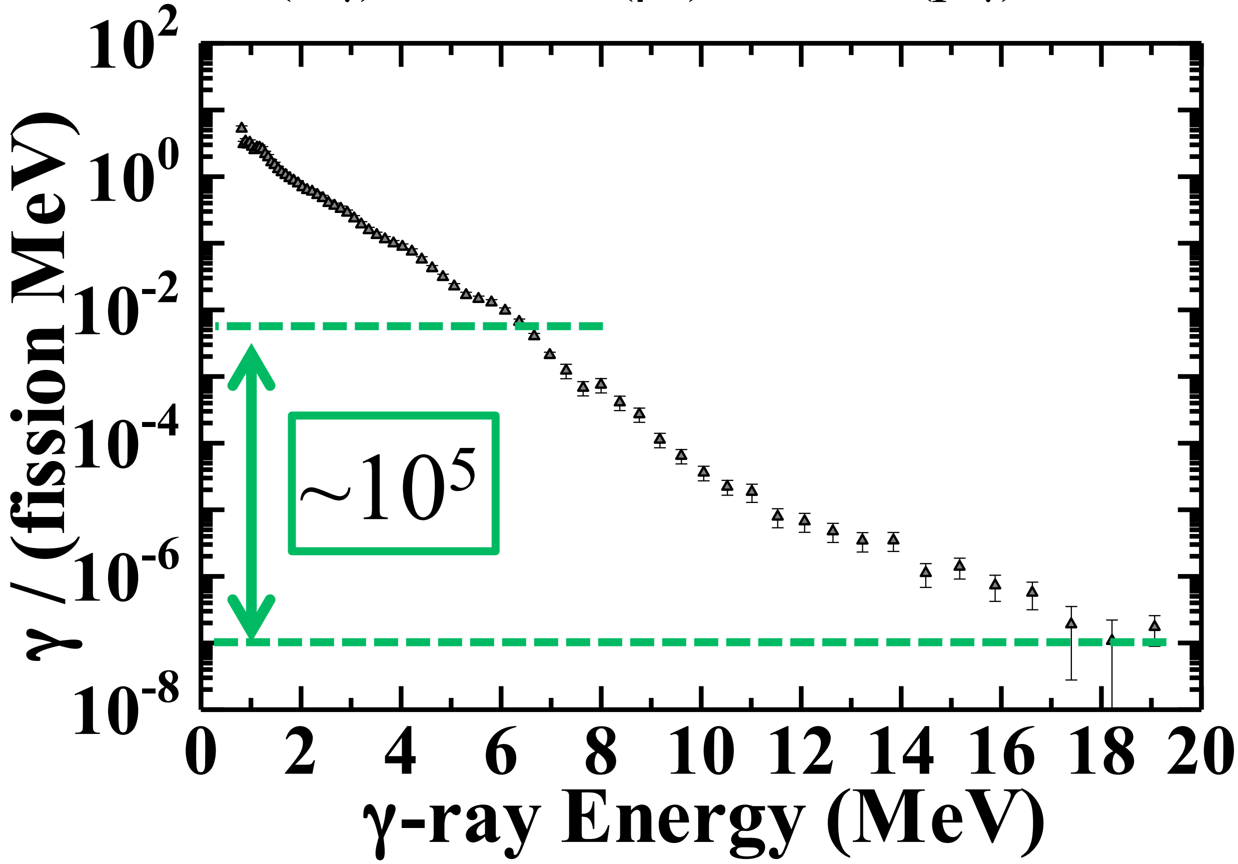

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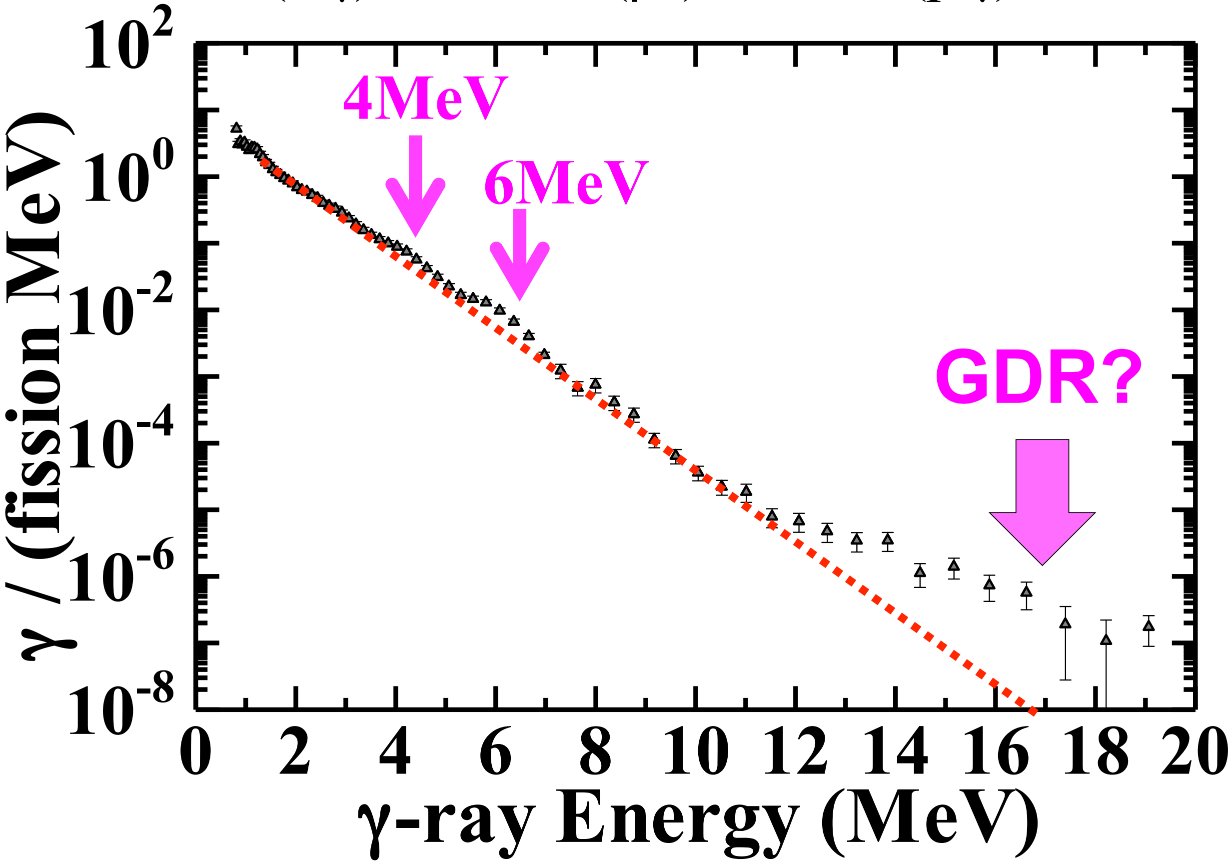
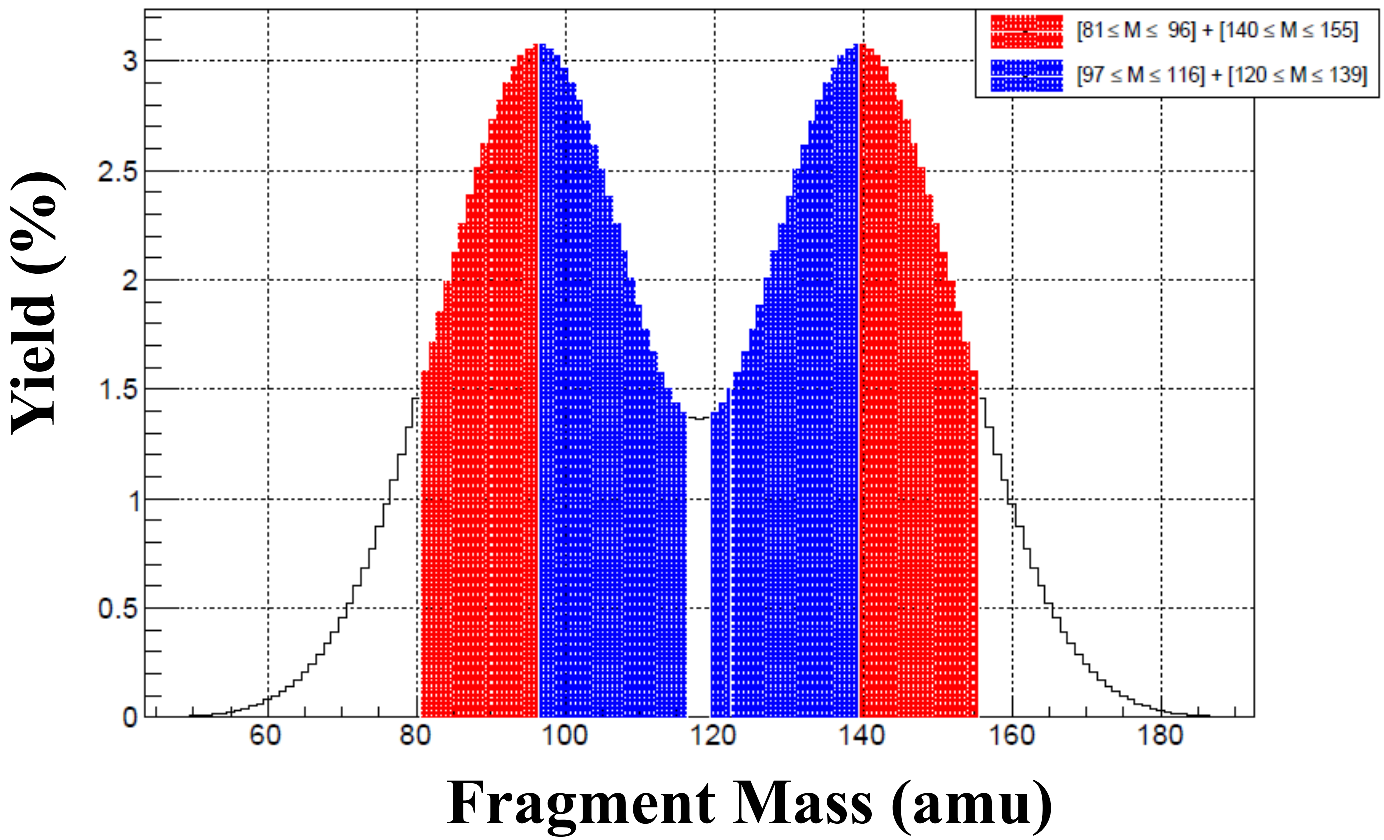


Hump structures are observed at E ~4, ~6 MeV and > 10 MeV

Fission Fragment Mass Distribution for $^{235}U(n_{th}, f)$

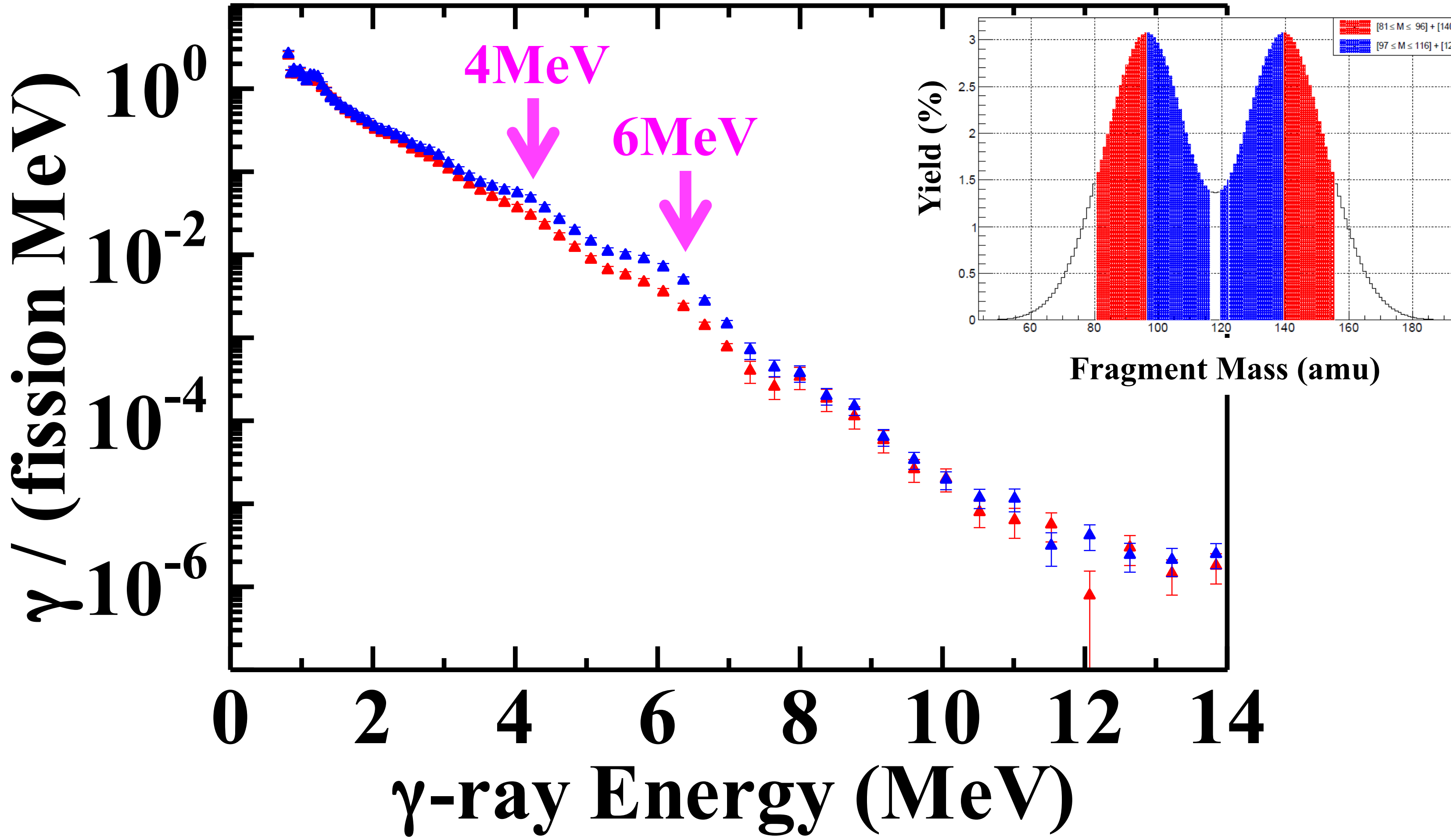
Derived from time difference between two FFs (flight pass : 50 mm)



[81 ≤ M ≤ 96]+[140 ≤ M ≤ 155] and **[97 ≤ M ≤ 116]+[120 ≤ M ≤ 139]**

Fragment-Mass Gated PFGS for $^{235}U(n_{th}, f)$

[81 ≤ M ≤ 96]+[140 ≤ M ≤ 155] and **[97 ≤ M ≤ 116]+[120 ≤ M ≤ 139]**



Humps correlated with **[97 ≤ M ≤ 116]+[120 ≤ M ≤ 139]** are seen

4. Discussions

Compare the present PFGS with a theoretical model

Hauser-Feshbach model [K. Kawano et al., Nucl. Phys., A 913 (2013) 51.]

- Experimental TKE and Mass distribution → TXE distribution
- Initial spin (*J*) distribution

(assumed same as the level density spin distribution)

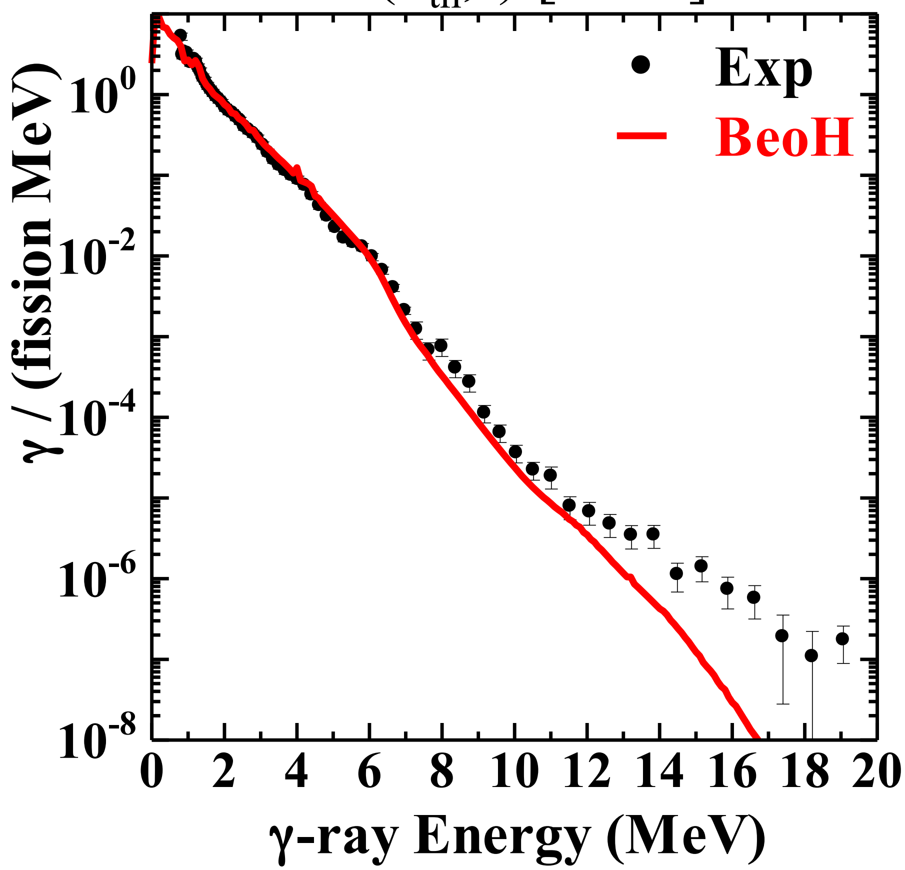
$$R(J,\pi)=\frac{J+1/2}{2\sigma^2}\exp\left\{-\frac{(J+1/2)^2}{2(f\sigma)^2}\right\}$$

  - σ : spin cut-off parameter
  - *f* : scaling factor to reproduce some observable quantities

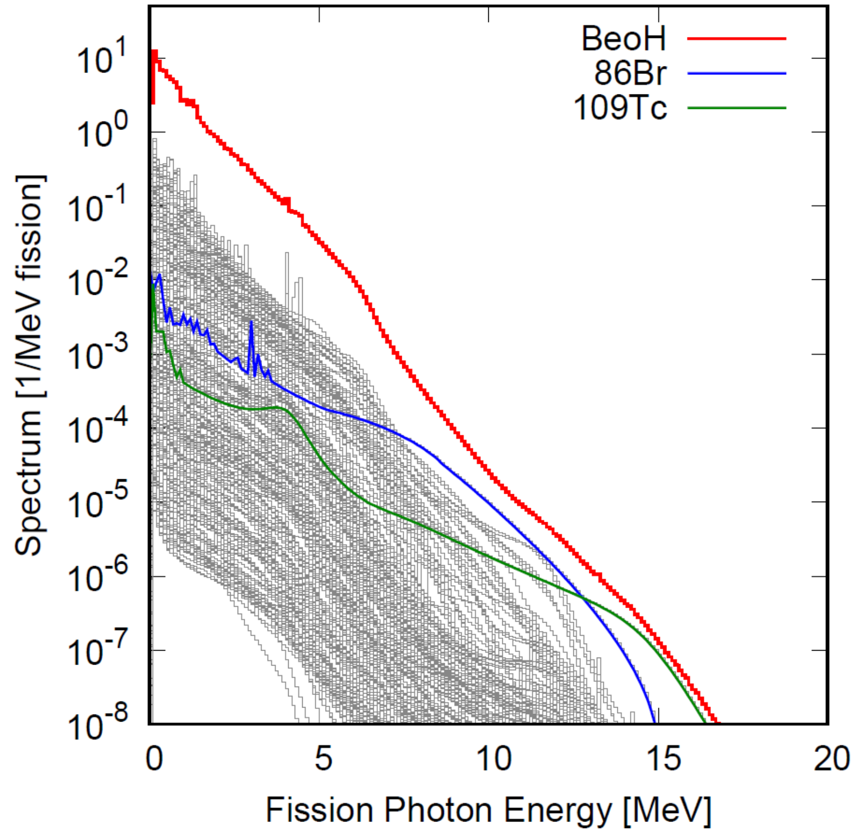
- Competition between prompt neutrons and γ-rays
- Discrete level data : taken from RIPL-3
- Fully deterministic calculation (instead of MC technique)

Comparison with theoretical model

PFGS for $^{235}U(n_{th},f)$ [Total]



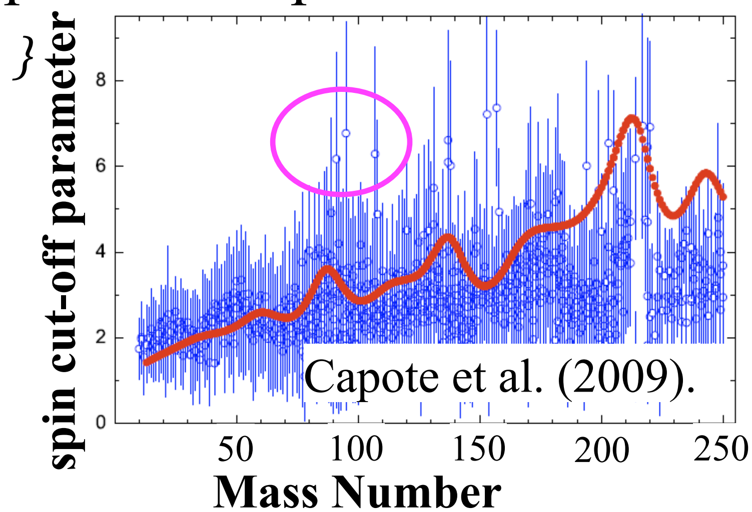
Contributions from each isotope



A fairly good agreement was obtained at E < 12 MeV.
A few isotopes contribute to the enhancement at E > 10 MeV.
(^{86}Br, ^{109}Tc … etc)

Initial spin distributions of FFs depend on spin cut-off parameter σ

R(J,π)=J+1/2/2σ↑2 exp{−(J+1/2)↑2 /2(fσ)↑2 }

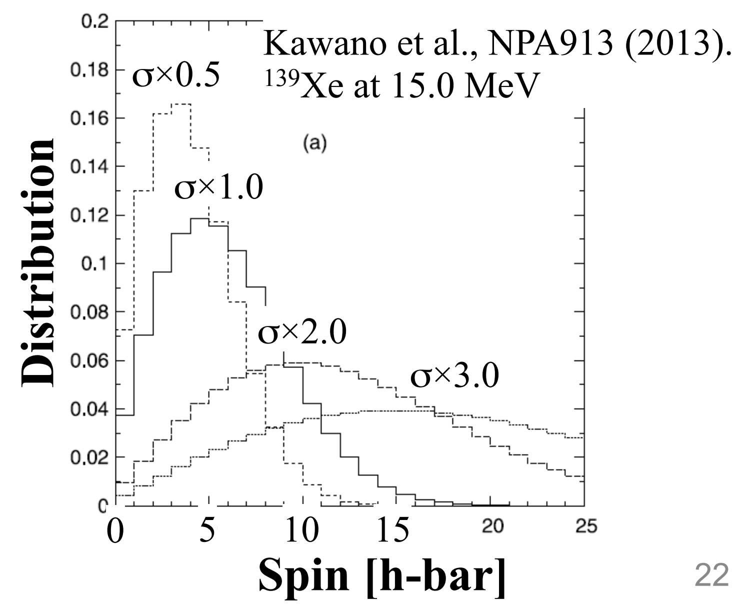


Large σ causes the increases of

- Average *J* in initial spin distribution, and
- Probability of finding a high spin state in low-lying levels of decaying FFs,

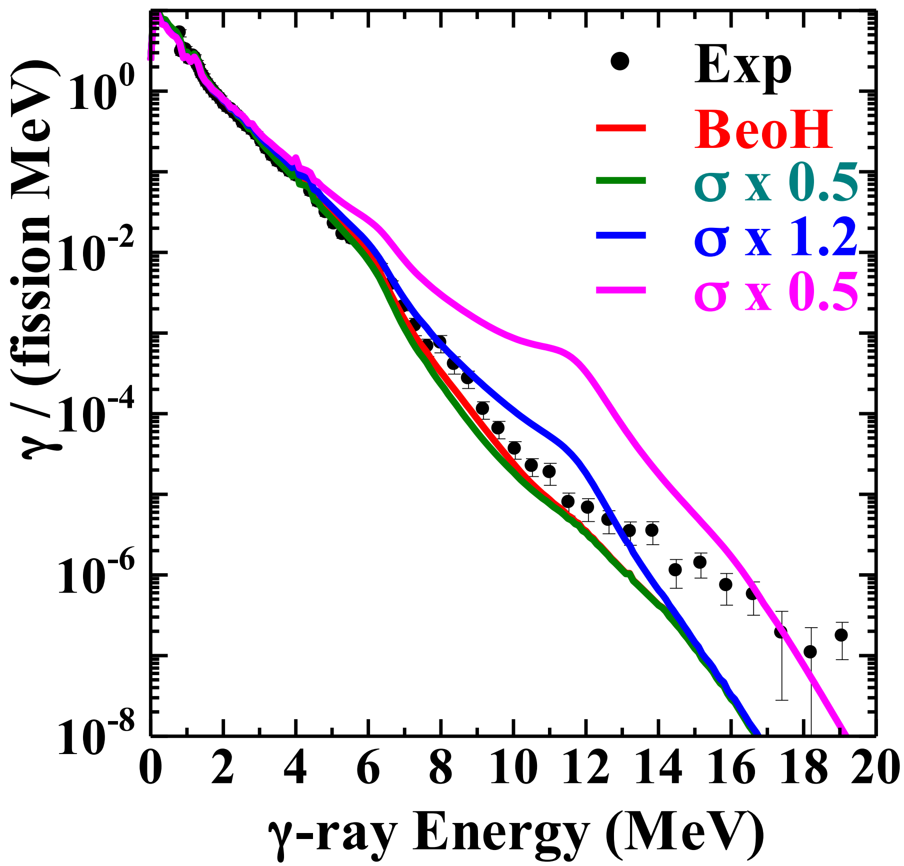
But hinders neutron emission to the residual nucleus with small σ.

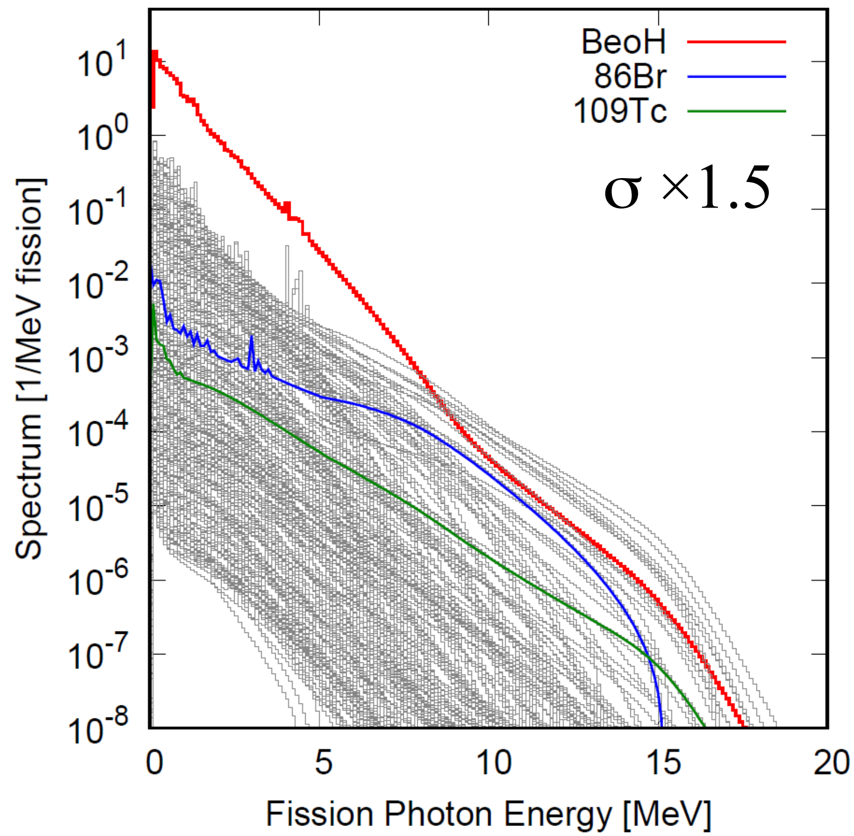
→ **High energy γ-rays might be emitted from the isotopes with large σ value**



Comparison with theoretical model

σ (spin cut-off parameter) dependence of the PFGS

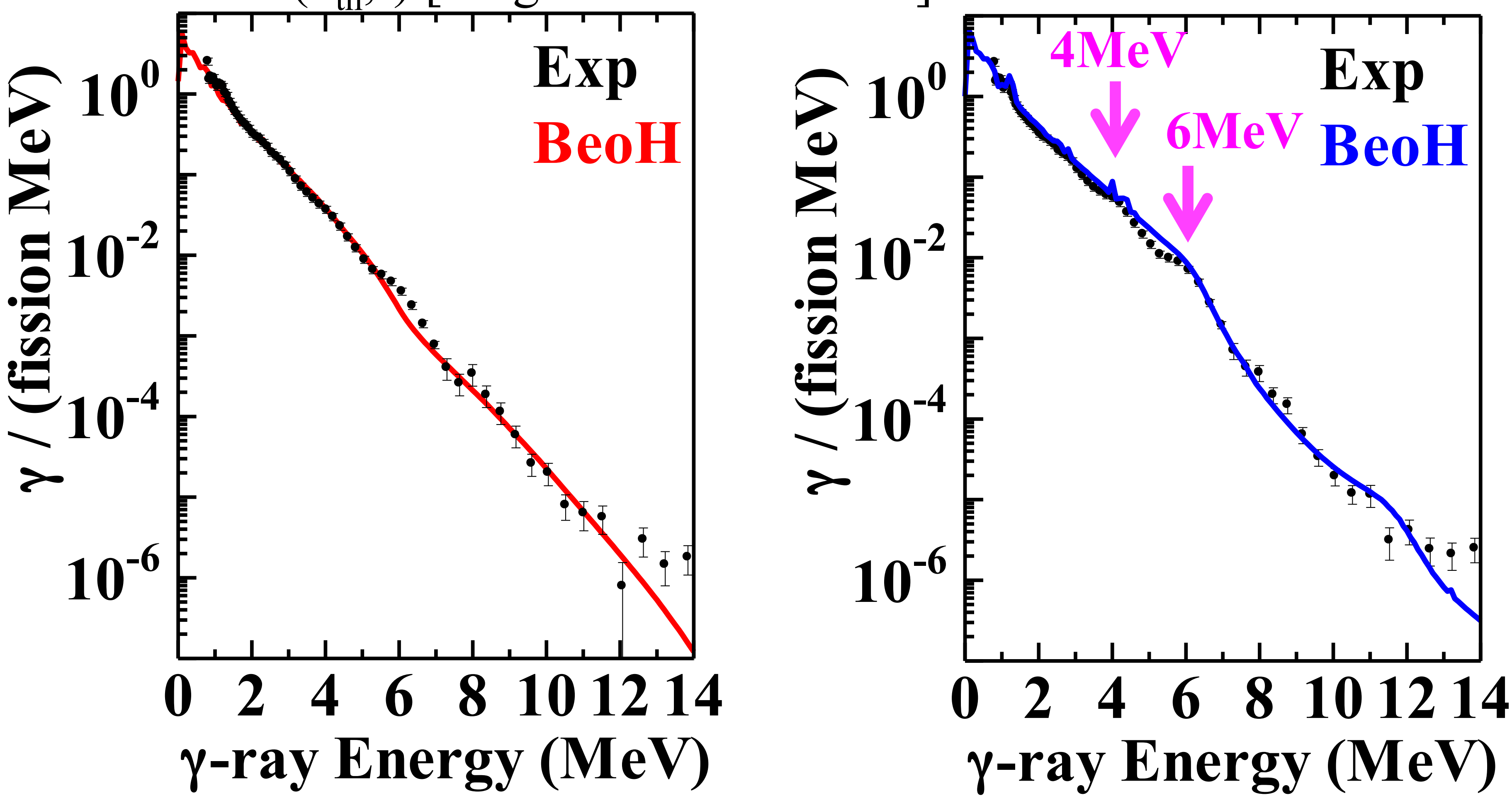




As σ increases, fraction of the high energy γ-rays increases, and Many isotopes contribute to the enhancement at E > 10 MeV.

Comparison with theoretical model

PFGS for $^{235}U(n_{th},f)$ [Fragment-Mass Gated]

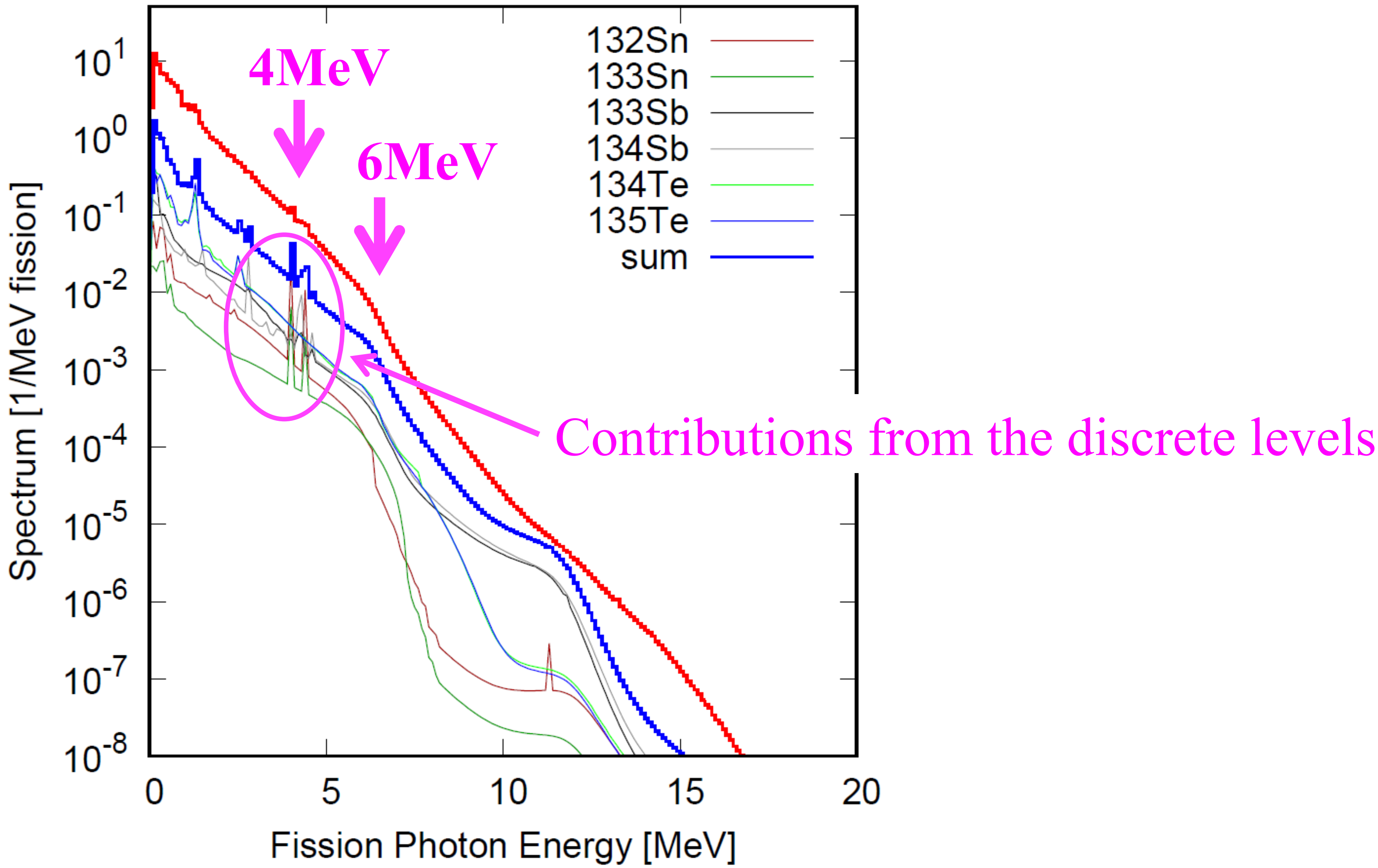


Reproduce the difference between spectra obtained by the gates at

[81 ≤ M ≤ 96]+[140 ≤ M ≤ 155] and **[97 ≤ M ≤ 116]+[120 ≤ M ≤ 139]**

Comparison with theoretical model

Contributions from selected isotopes

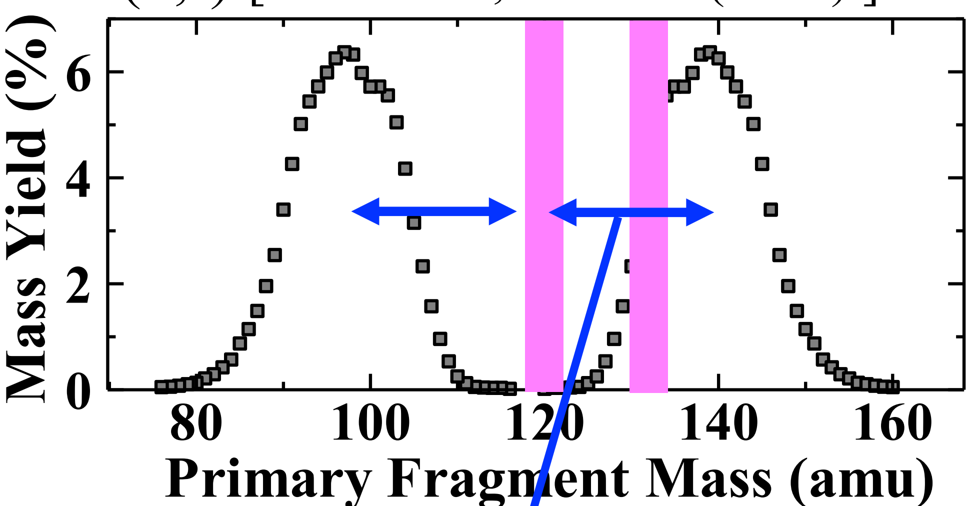


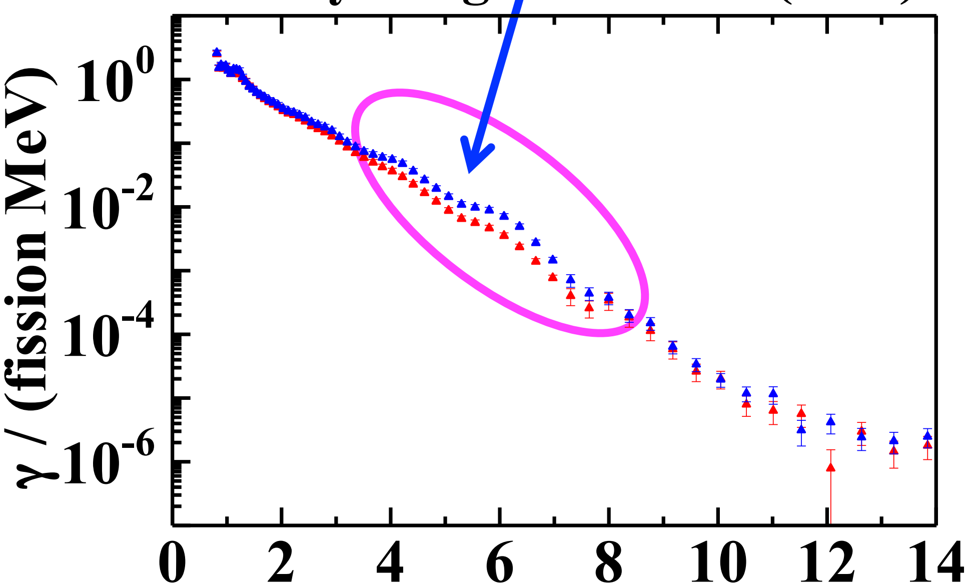
Isotopes around N=82 contribute to 4 and 6 MeV hump structures

Comparison with ^{252}Cf(sf)

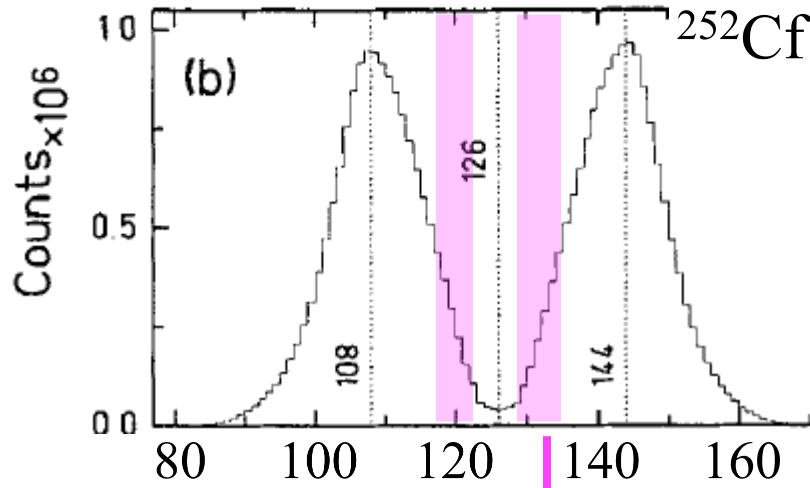
$[97 \le M \le 116]+[120 \le M \le 139]$

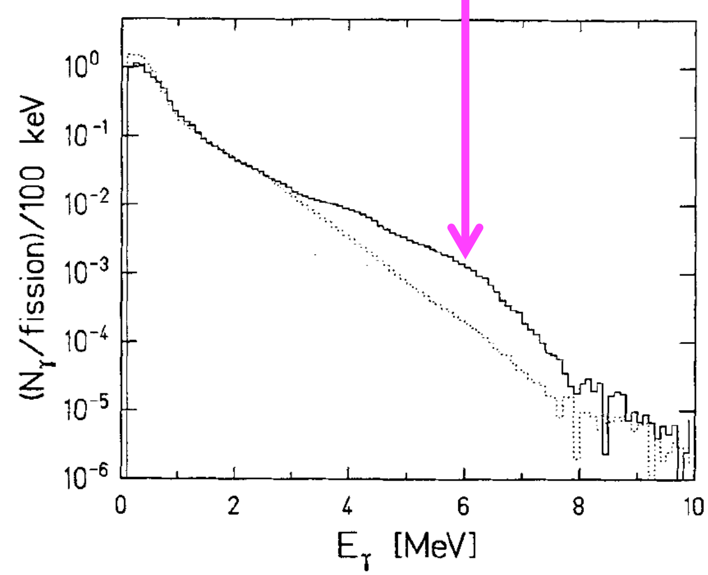
^{235}U(n,f) [Baba et al., JNST34 (1997).]





$[118 \le M \le 122]+[130 \le M \le 134]$

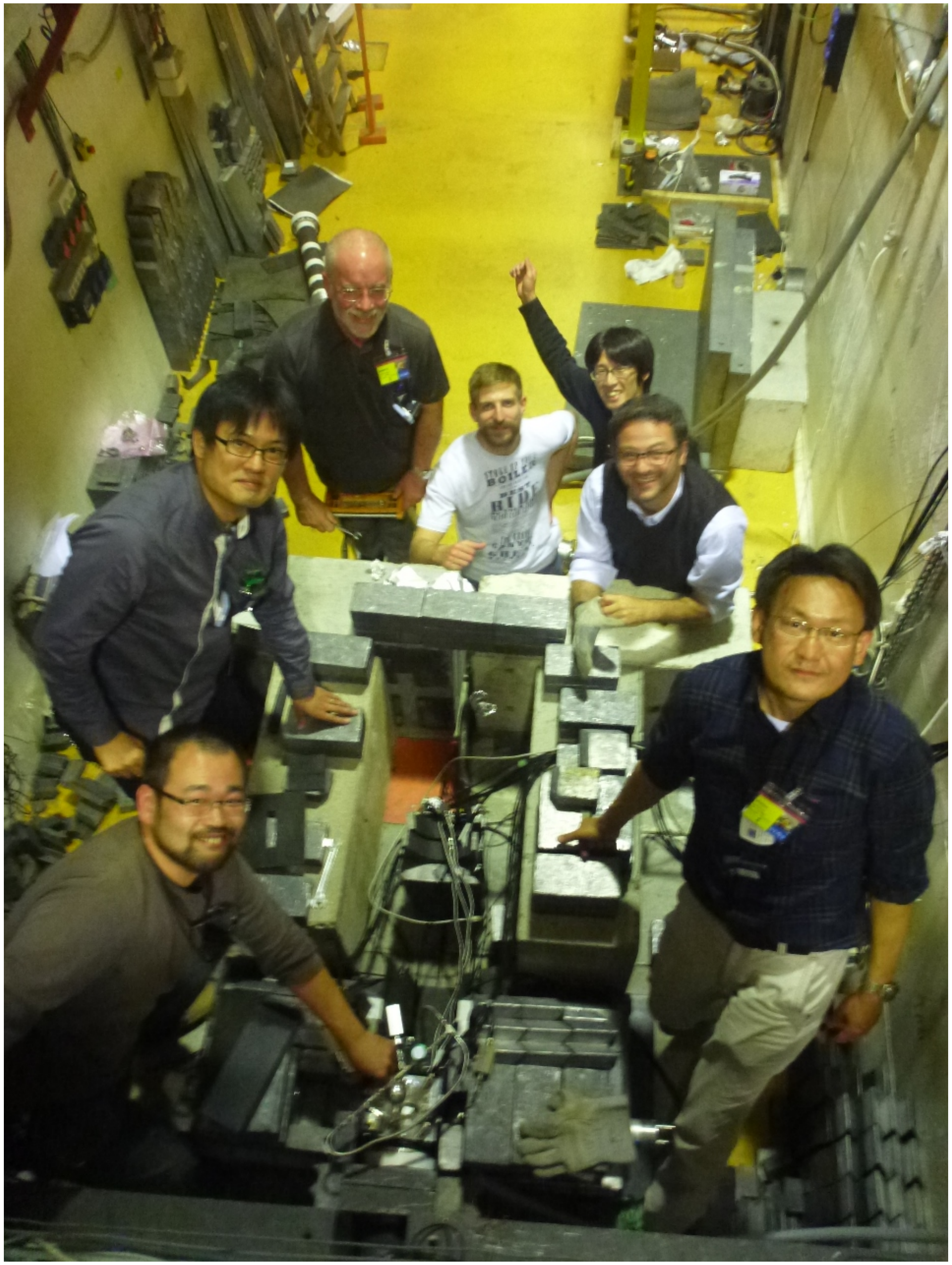




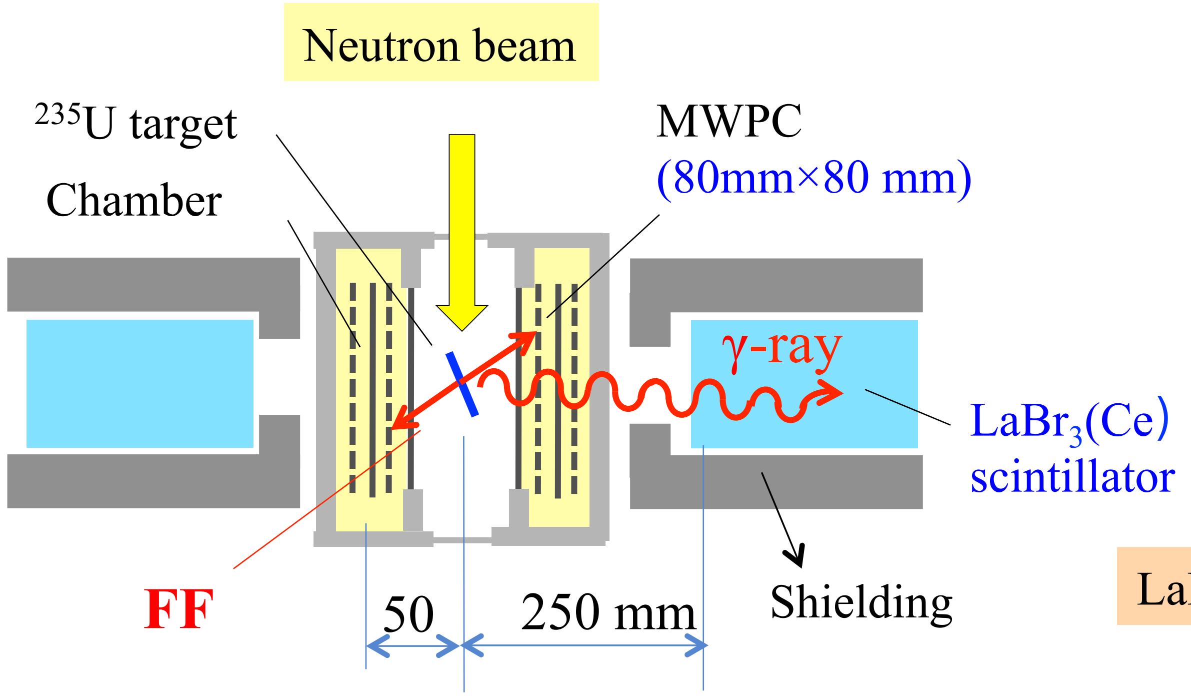
A. Hotzel et al., Z. Phys. A336 (1996) .

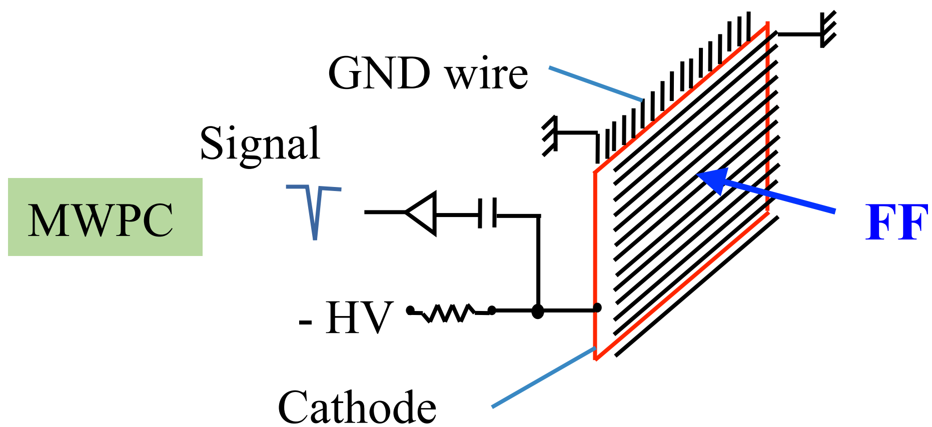
5. Summary

- High efficiency set up for measurement of PFGS was developed.
- PFGS for $^{235}U(n_{th},f)$ were measured **up to 20 MeV**.
- PFGS do not decrease linearly with energy on logarithmic scale, but reveal a broad hump at E > 10 MeV.
- Hump structures were also observed around 4 MeV and 6 MeV.
- Calculation using Hauser-Feshbach model was compared to the present PFGS
  - Hump at E > 10 MeV originates from a few isotopes with the large spin cut-off parameter (^{86}Br, ^{109}Tc, and …).
  - Fraction of high-E γ-rays (E > 10 MeV) strongly depends on the spin cut-off parameter (initial spin distribution of FFs)
  - Isotopes in the vicinity of ^{132}Sn contribute humps around 4 and 6 MeV.

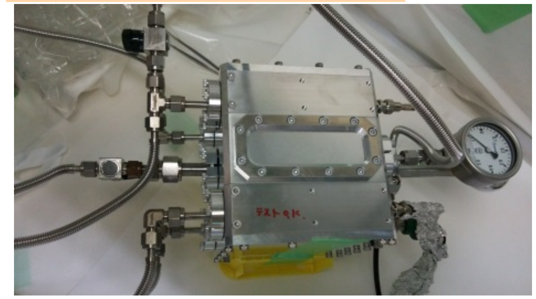


Measurement - setup



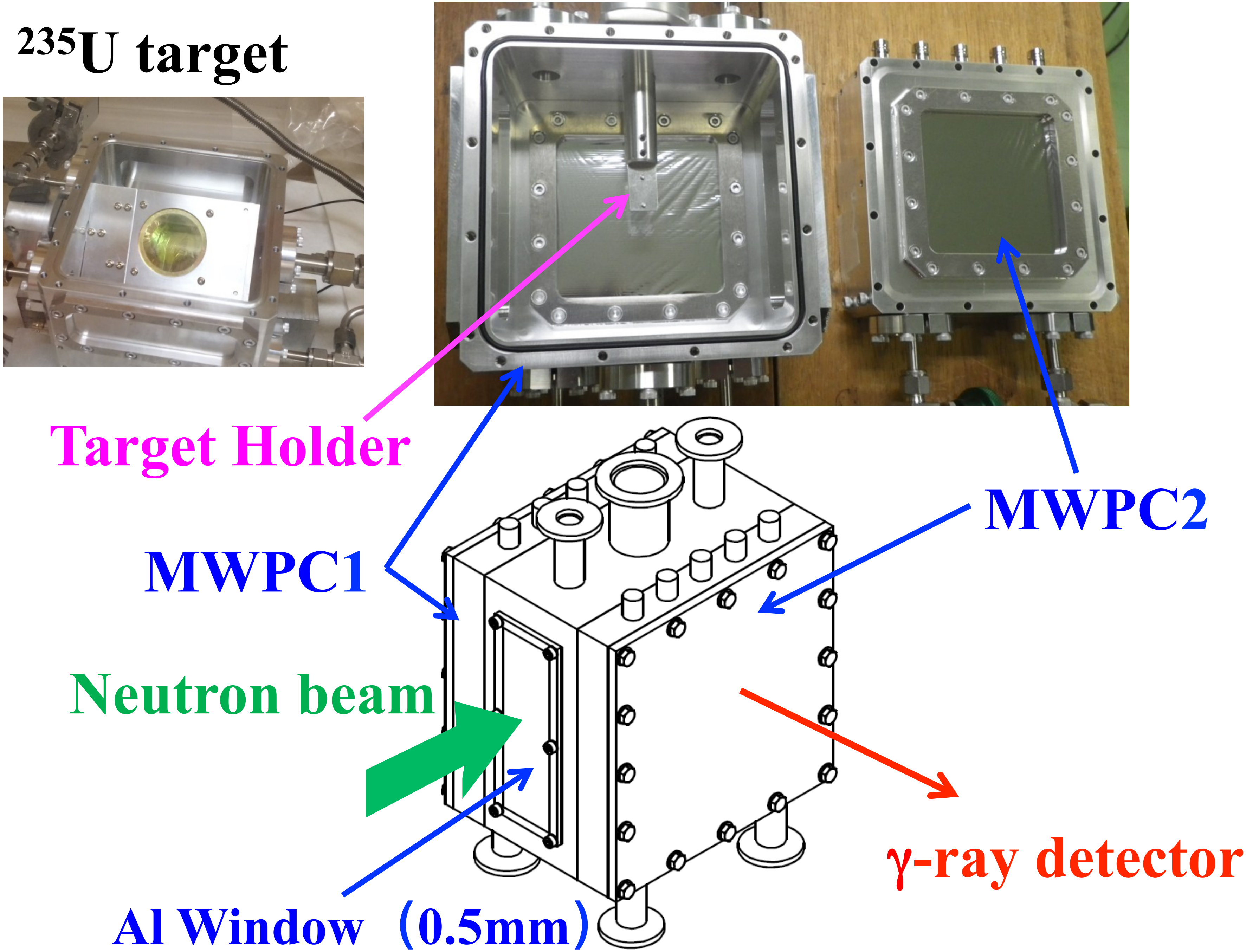


Fission Chamber



$LaBr_3(Ce)$ scintillators

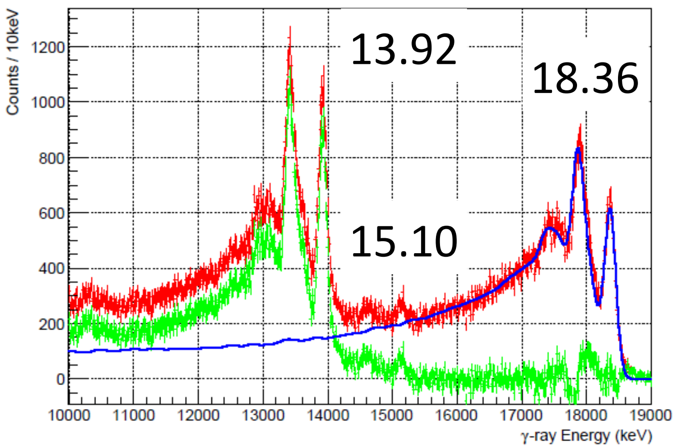
DAQ system



^{235}U target
Target Holder
MWPC1
MWPC2
Neutron beam
γ-ray detector
Al Window（0.5mm）

Determination of g-ray spectrum for $^{11}B(p,\gamma)^{12}C$

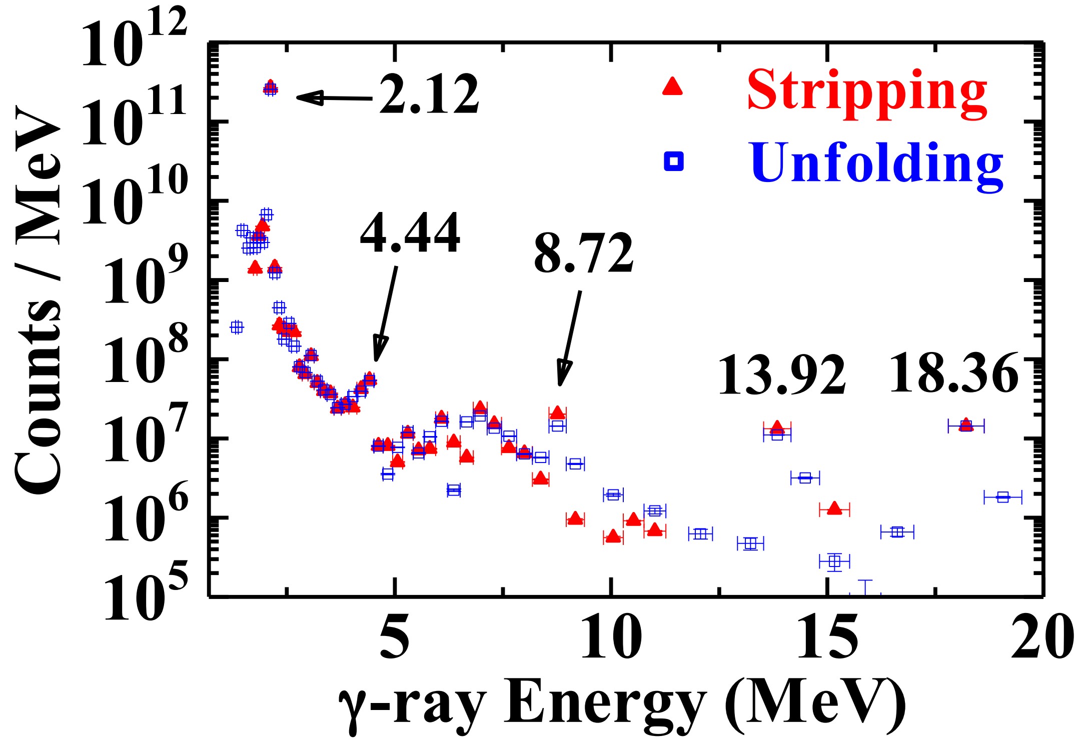
- Stripping method



- Unfolding Method

$$\upsilon(E) = \mathbf{R}^{-1}\ S(I)$$

$\upsilon(E)$: γ-ray spectrum
R : Response matrix
S(*I*) : observed yield at ch *I*
Unfolding was performed with a program "TUnfold" [S. Schmit, JINST 7 (2012).]



Unfolding method was used to obtain the PFGS for $^{235}U(n_{th},f)$

Coincidence between FFs and γ-rays

Correlation between TOF of γ-ray events and pulse height of $LaBr_3(Ce)$