Measurement of the $^{235,\,238}$U(n, f) cross-section relative to n-p scattering from 10 to 70 MeV at CSNS Back-n

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30th International Seminar on Interaction of Neutrons with Nuclei,
Sharm El-Sheikh, Egypt, April 14-18, 2024

Outline

1. **Motivations**
2. Experimental setup
3. Analysis and preliminary results
4. Summary

Motivations

^{235}U and ^{238}U are very important isotopes in the nuclear energy system

- ^{235}U is the fissile material in the current thermal reactor
- ^{238}U is the fertile material in the future U-Pu cycle

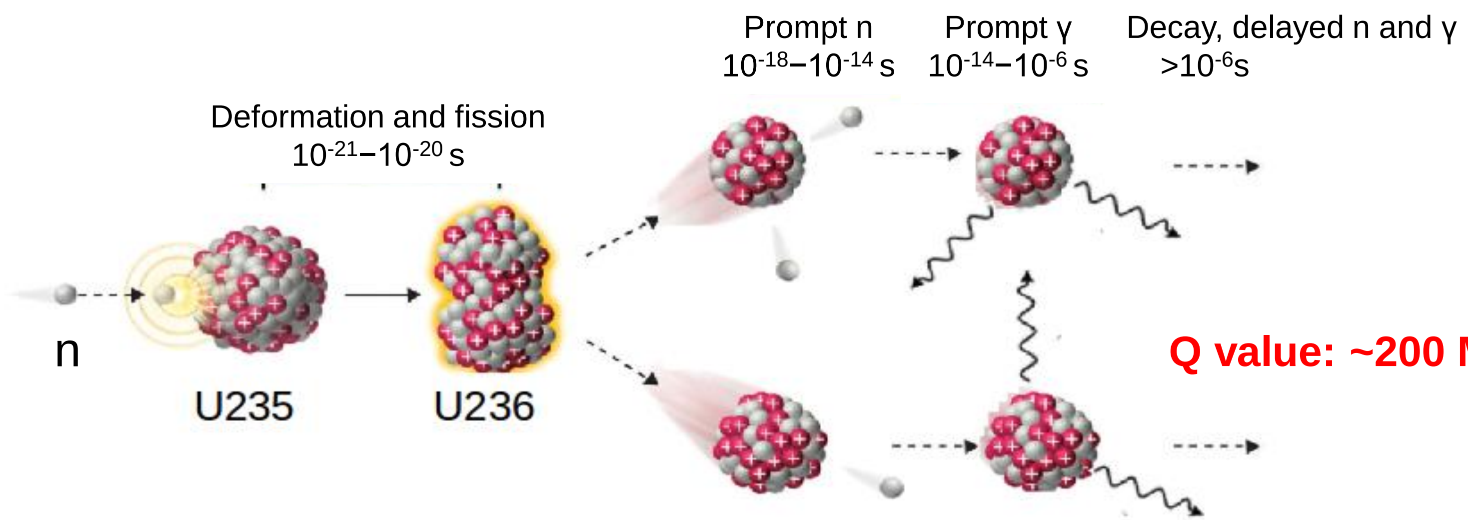
$^{235, 238}$U(n, f) cross-sections are evaluated as standard up to 200 MeV

- References for cross section measurement, neutron flux determination, etc

However, the experimental data in high energy region (above 20 MeV) are scarce

- There are only a few sets of measurements with significant discrepancies (EXFOR)

New dataset in high energy region at state-of-the-art facility is essential and indispensable!



Q value: ~200 MeV

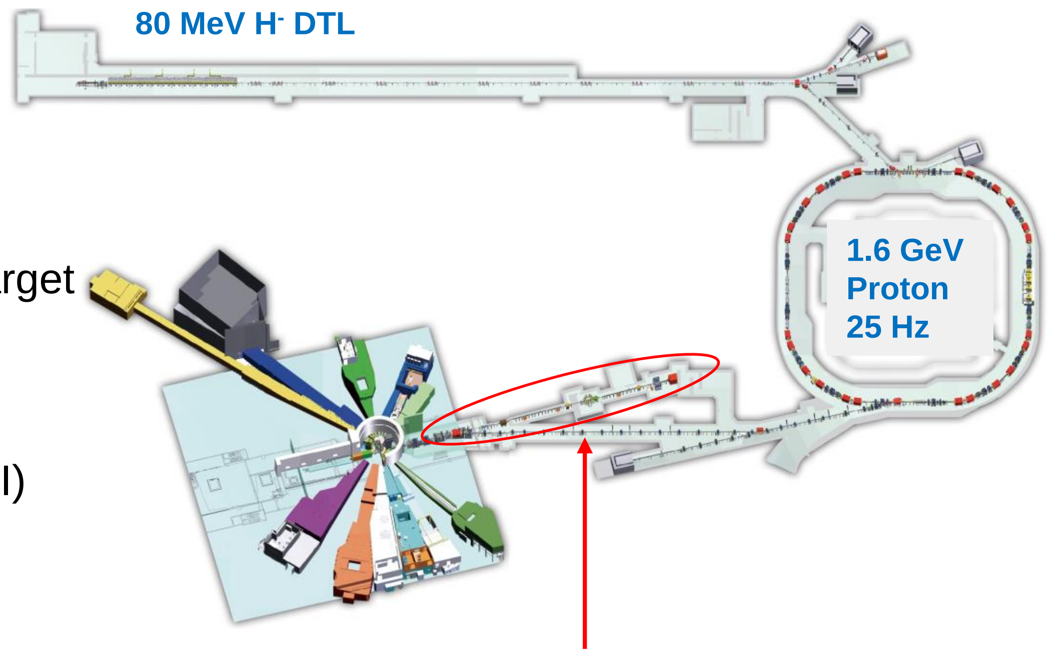
Outline

Experimental setup

(1) Back-n facility at CSNS

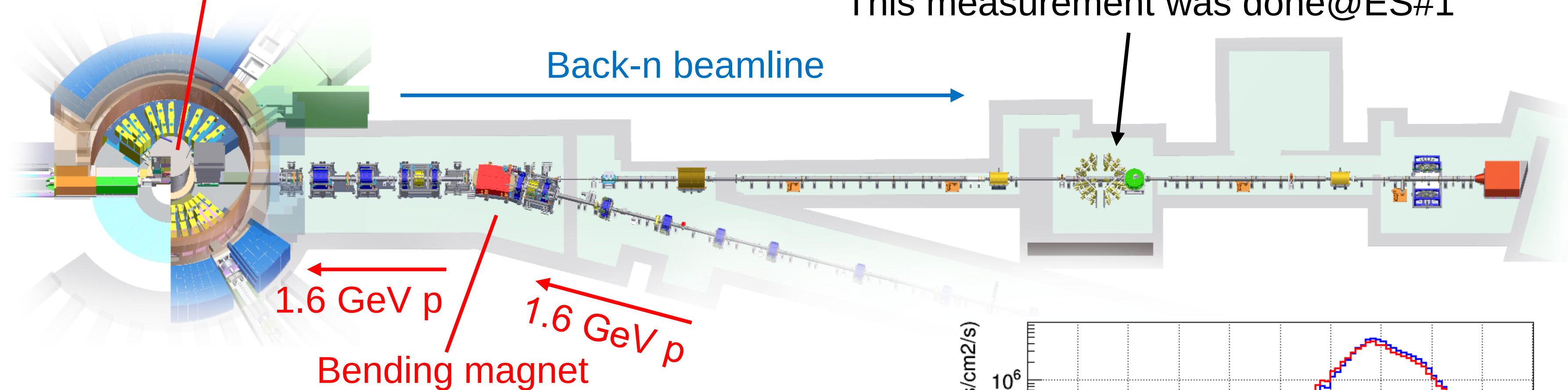
China Spallation Neutron Source (CSNS)

- Started running since 2018
- 1.6 GeV protons bombard tungsten target
- 25 Hz repetition frequency
- Current beam power: ~160 kW
- Upgraded to 500 kW in 2029 (CSNS-II)

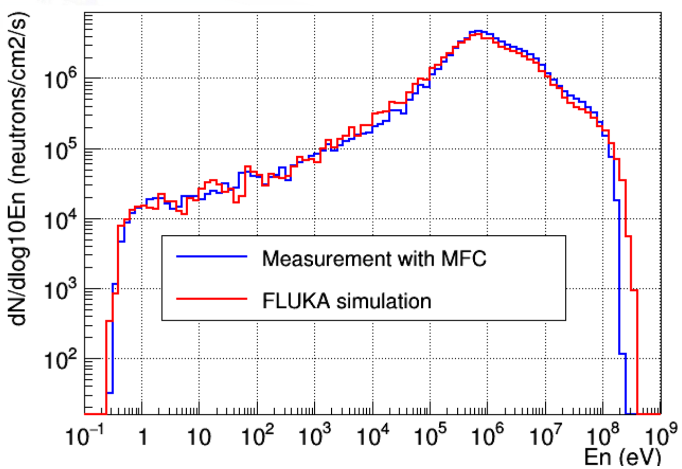


Experimental setup

(1) Back-n facility at CSNS



- Time-of-flight (TOF) facility
- Two end stations: ES#1 (~55 m) and ES#2 (~76 m)
- Wide neutron energy range (from 0.3 eV to ~300 MeV)
- Weak γ-flash due to back-streaming design

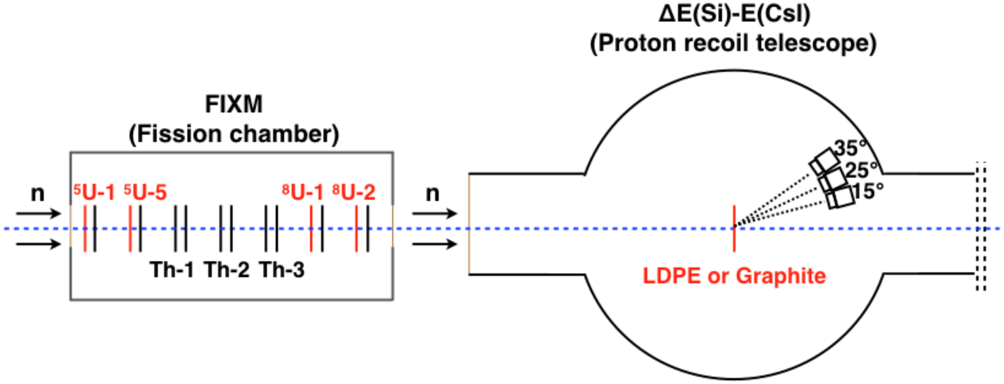


Yonghao Chen et al., *Eur. Phys. J. A* (2019) 55: 115
Yonghao Chen et al., *Eur. Phys. J. A* (2024) 60: 63

Experimental setup

(2) Detector setup

- Setup at Back-n ES#1 with small collimators (beam spot: ~φ18 mm)
- A fission chamber (FIXM) is used for measuring the fissions of U5 and U8
- Proton recoil telescope (PRT) is used for monitoring the neutron flux by measuring the n-p scattering



Neutron flux measurement by n-p scattering

$$\Phi(E_n) = \frac{R_p(E_n)}{\sigma_{np}\varepsilon_p(E_n)N_p}$$

Fission measurement

$$\sigma_f = \frac{R_f(E_n)}{\Phi(E_n)\varepsilon_f(E_n)N_f}$$

Sample quantity; n-p scattering XS

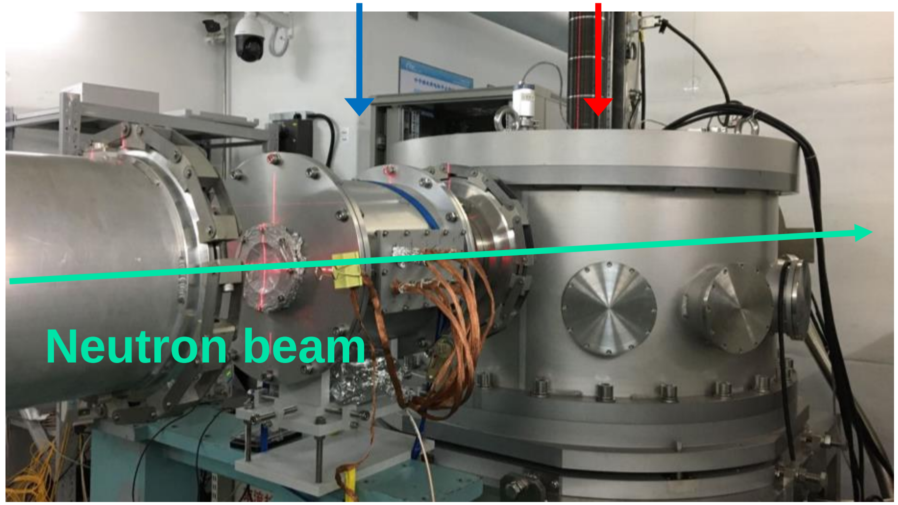
$$\sigma_f = \frac{R_f(E_n)}{R_p(E_n)} \times \frac{N_p}{N_f} \times \frac{\varepsilon_p(E_n)}{\varepsilon_f(E_n)} \times \sigma_{np}$$

Reaction rate; Efficiency

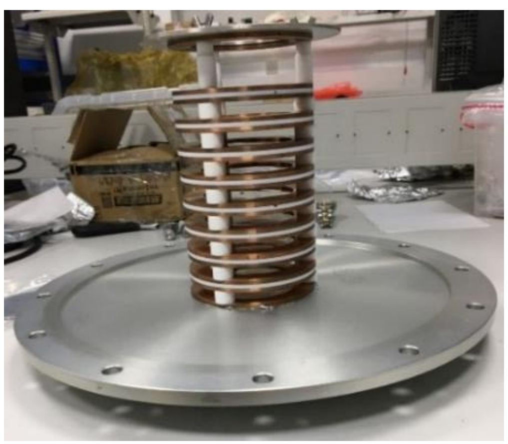
Experimental setup

(2) Detector setup

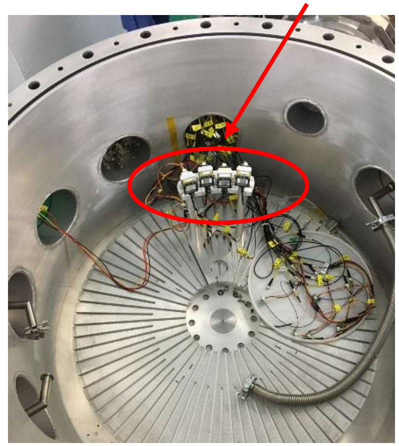
FIXM PRT



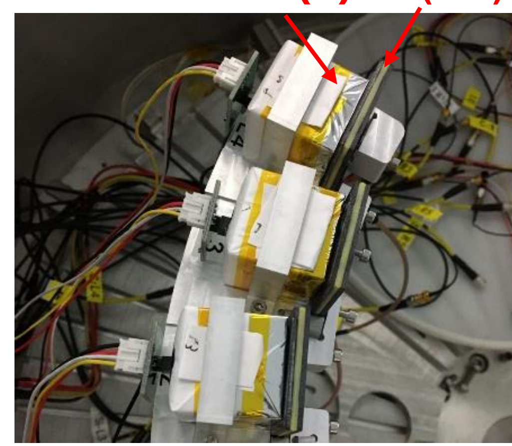
FIXM



PRT



CsI (E) Si (ΔE)

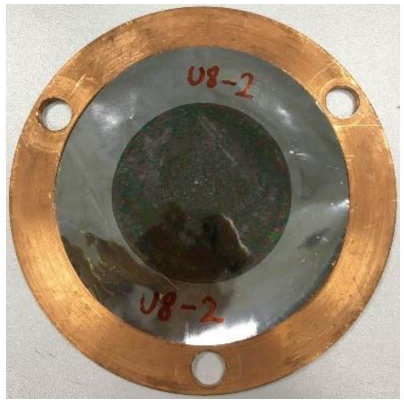


Experimental setup

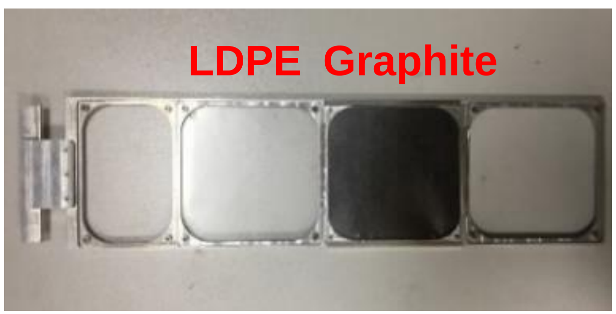
(3) Sample details

U5

U8



Sample	Mass (mg)	Size (mm)
U5-1	5.173	φ50
U5-5	6.319	φ50
U8-1	4.991	φ50
U8-2	4.987	φ50



Sample	Thickness (mg/cm^2)	Size (mm)
LDPE	9.989	77×77
Graphite	8.653	77×77

The masses of all the samples are accurately known, however, we do not know their homogeneities which are key parameters in this experiment configuration.

Outline

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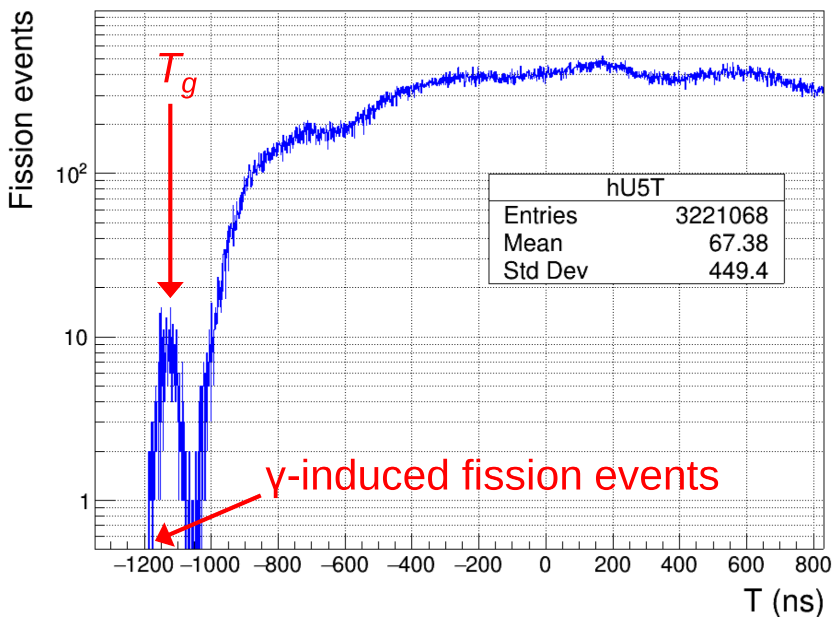
Analysis and preliminary results

(1) Analysis of the FIXM

- Time-of-flight (TOF) method for determining neutron energy

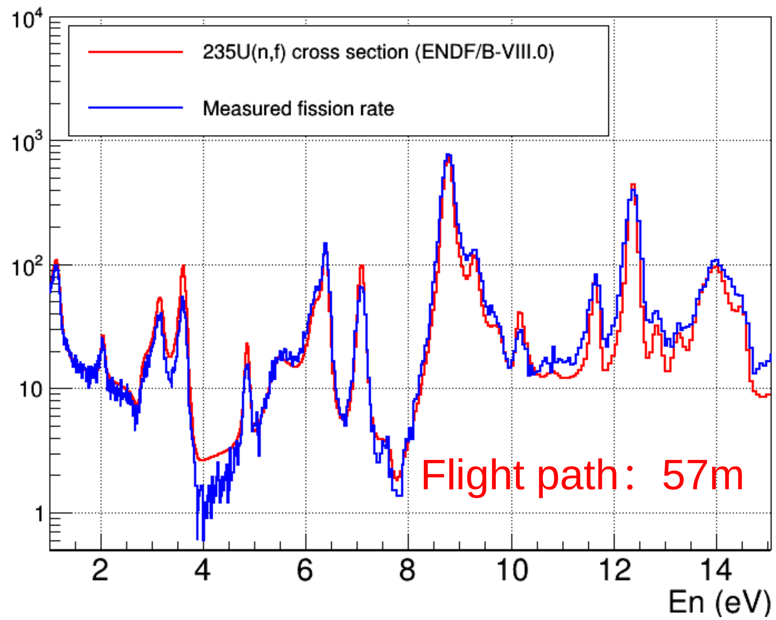
$$v = \frac{L}{TOF} = \frac{L}{T - T_0}$$

Time distribution of fission events



T_0 is determined by the γ-flash events

Comparison of fission rate and cross section



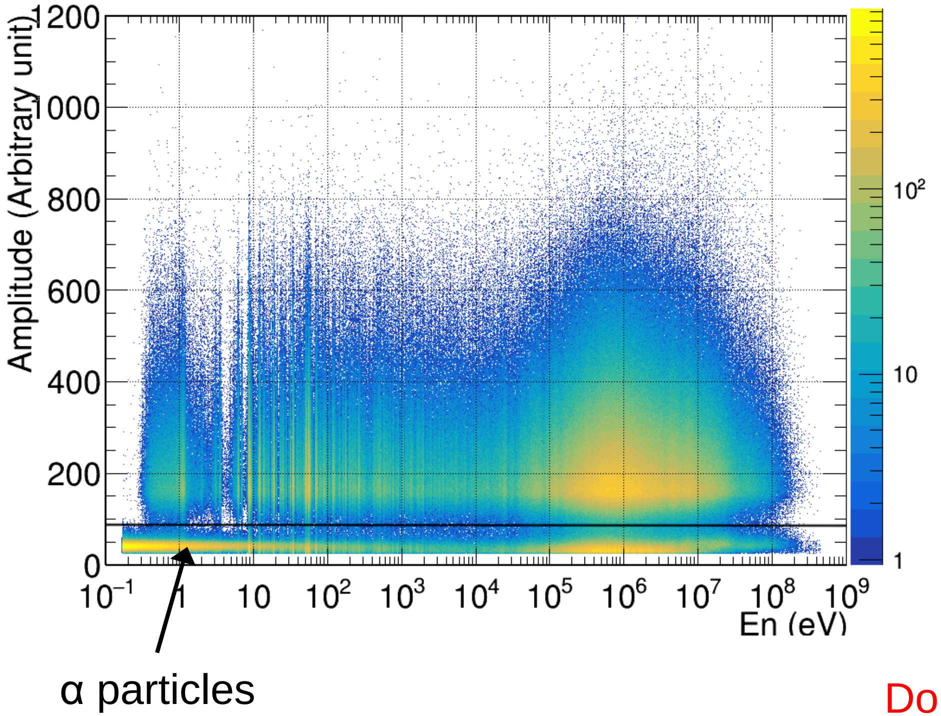
L is determined by ^{235}U resonance peaks

Analysis and preliminary results

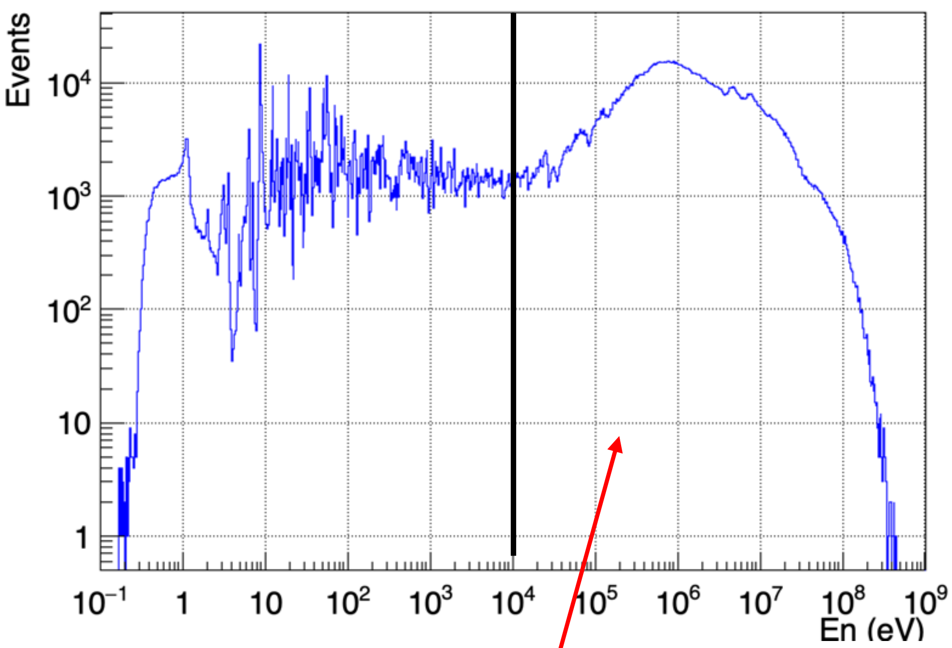
(1) Analysis of the FIXM

Measured in double-bunch mode: two identical proton bunches with well-defined interval (410 ns) in each proton pulse.

2D distribution of En *vs* amplitude



Fission rate as a function of En



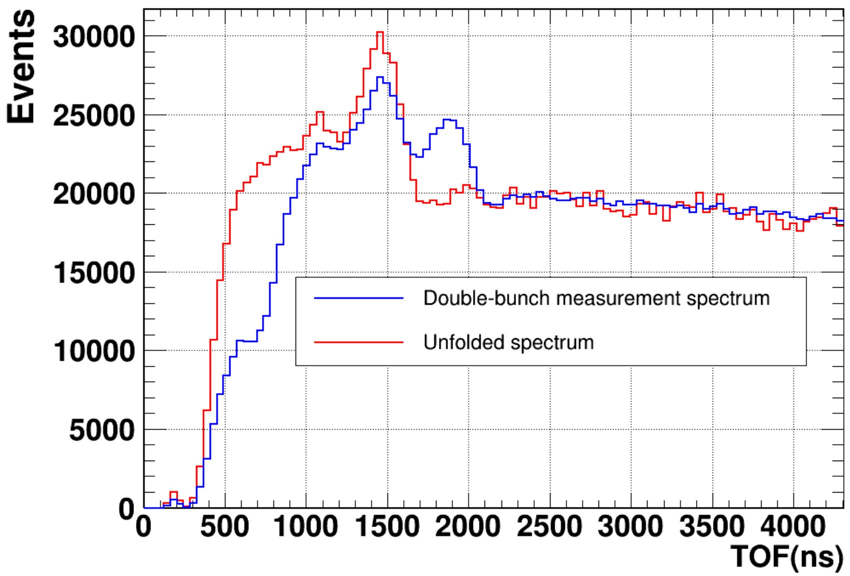
Double-bunch unfolding is necessary for En >10 keV

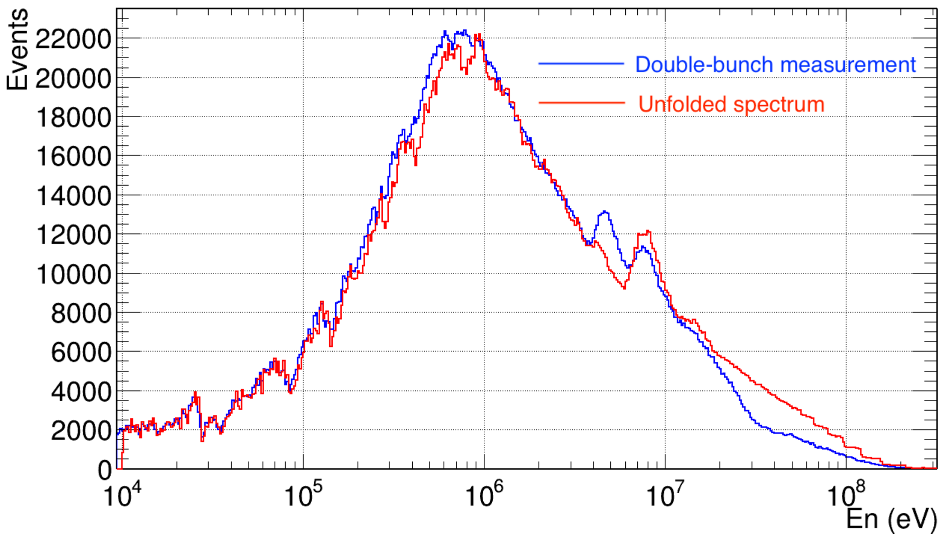
Analysis and preliminary results

(1) Analysis of the FIXM

- An iterative algorithm based on Bayes' theorem for unfolding the TOF spectrum is developed (*H. Yi et al, JINST 14 (2019): 02011*)

$$C_i^{(k+1)} = E_i \frac{C_i^{(k)}}{C_{i-\Delta}^{(k)} + C_i^{(k)}} + E_{i+\Delta} \frac{C_i^{(k)}}{C_i^{(k)} + C_{i+\Delta}^{(k)}}$$

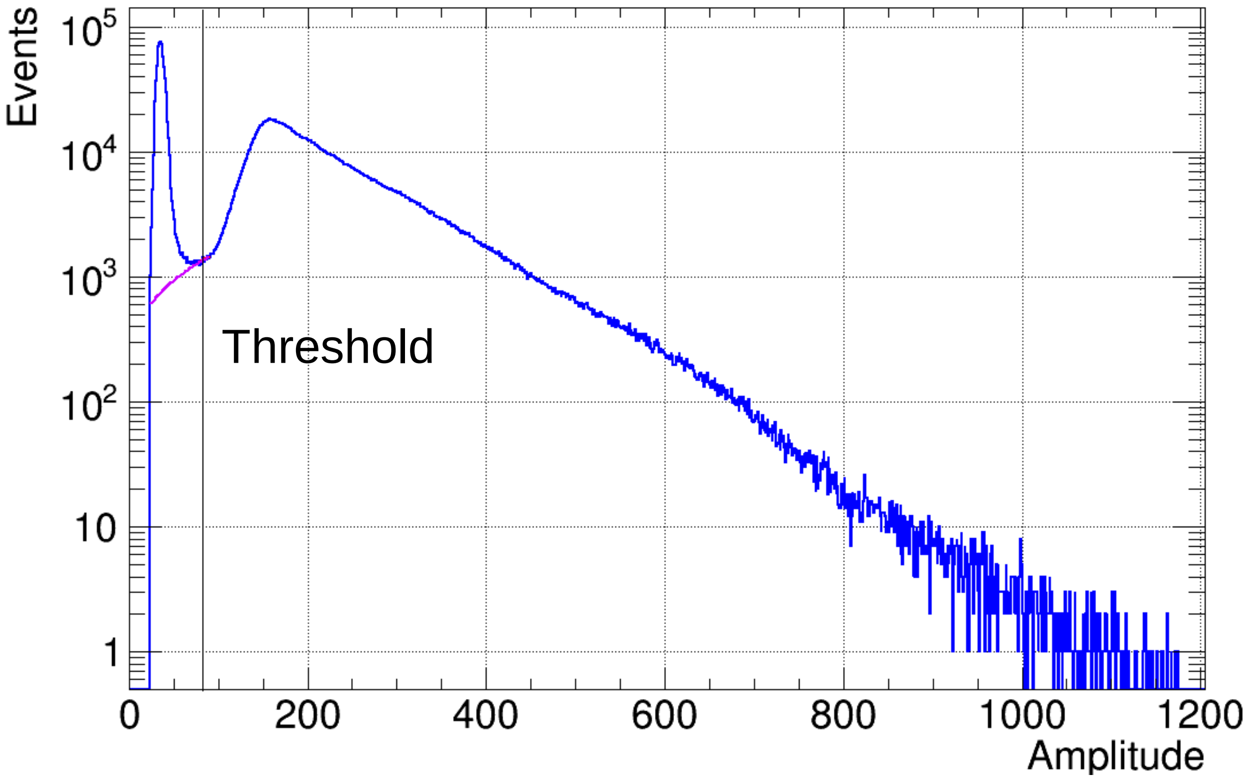




Analysis and preliminary results

(1) Analysis of the FIXM

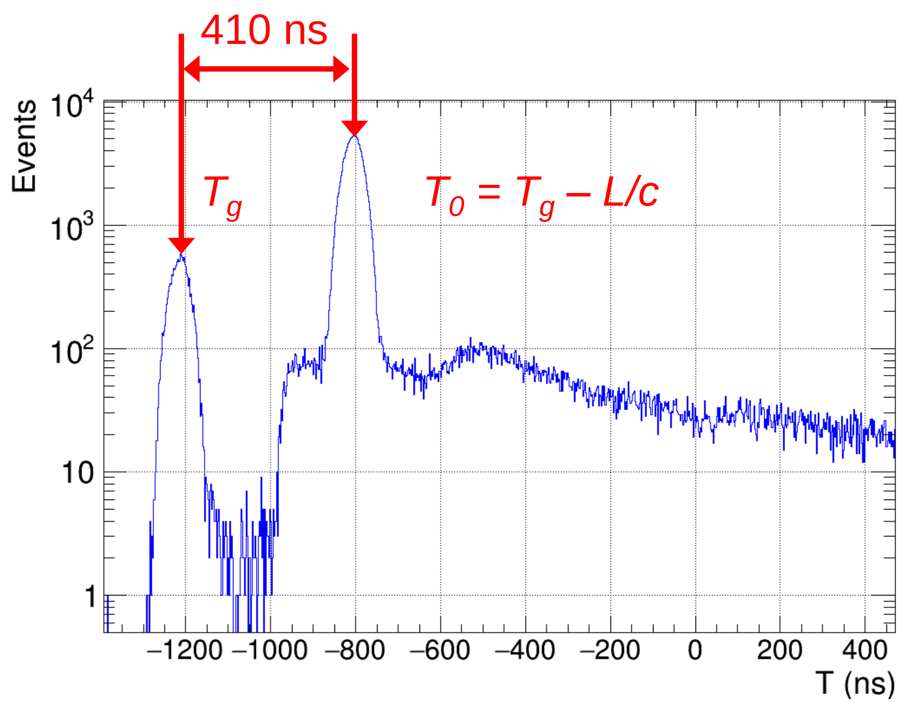
- Detection efficiency of the fission events: ~95%
- The efficiency of a fission chamber is not varying with the neutron energy



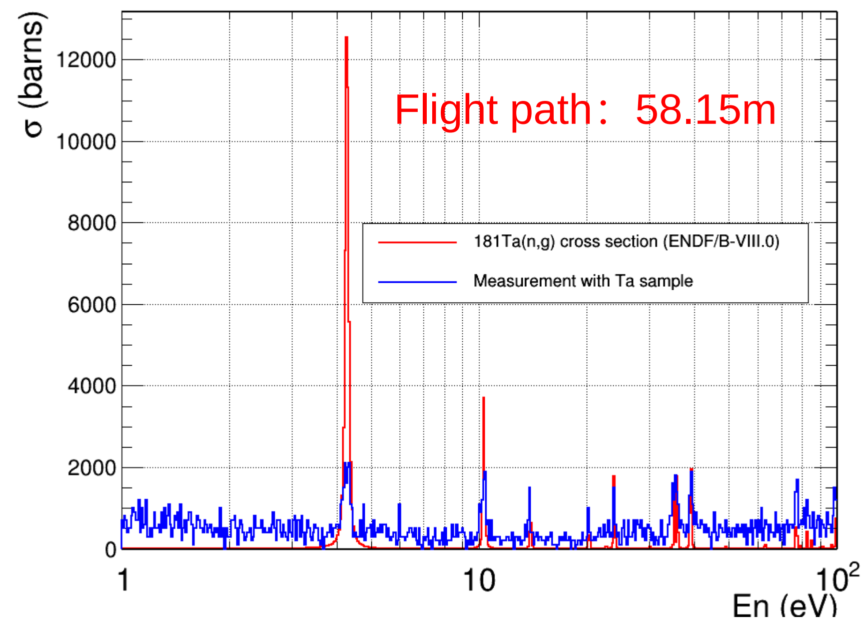
Analysis and preliminary results

(2) Analysis of the PRT

- TOF technique for determining neutron energy



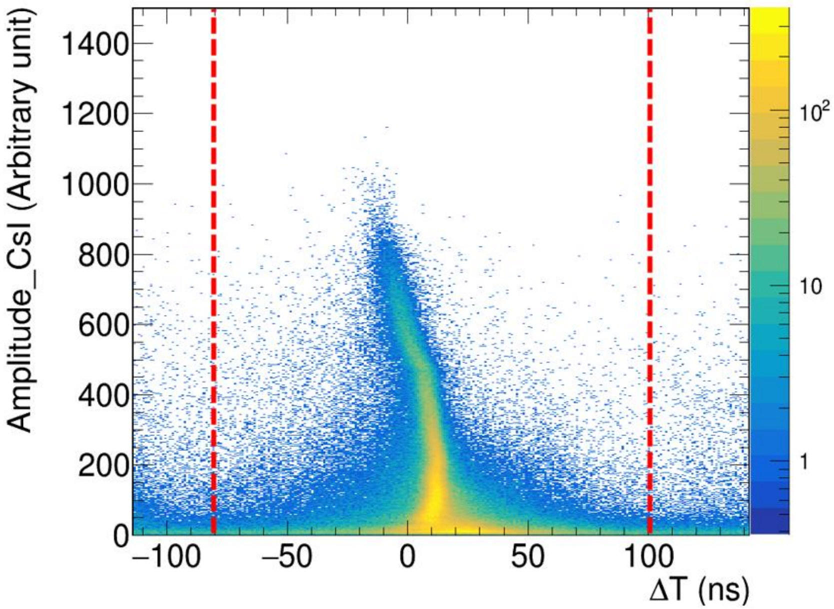
T_0 is determined by the γ-flash events



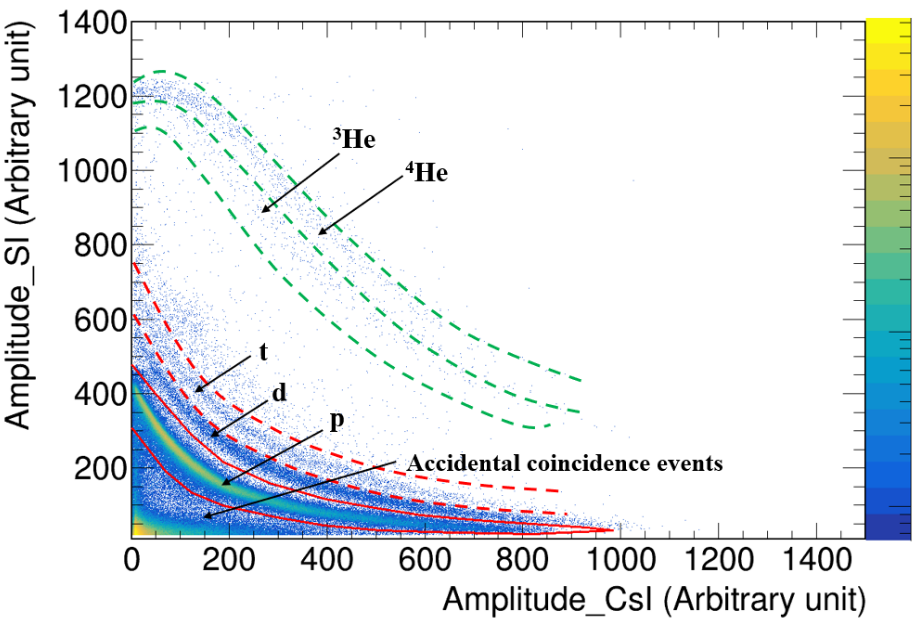
L is determined by ^{181}Ta (n, γ) resonance peaks

Analysis and preliminary results

(2) Analysis of the PRT



Coincidence selection of Si and CsI detector

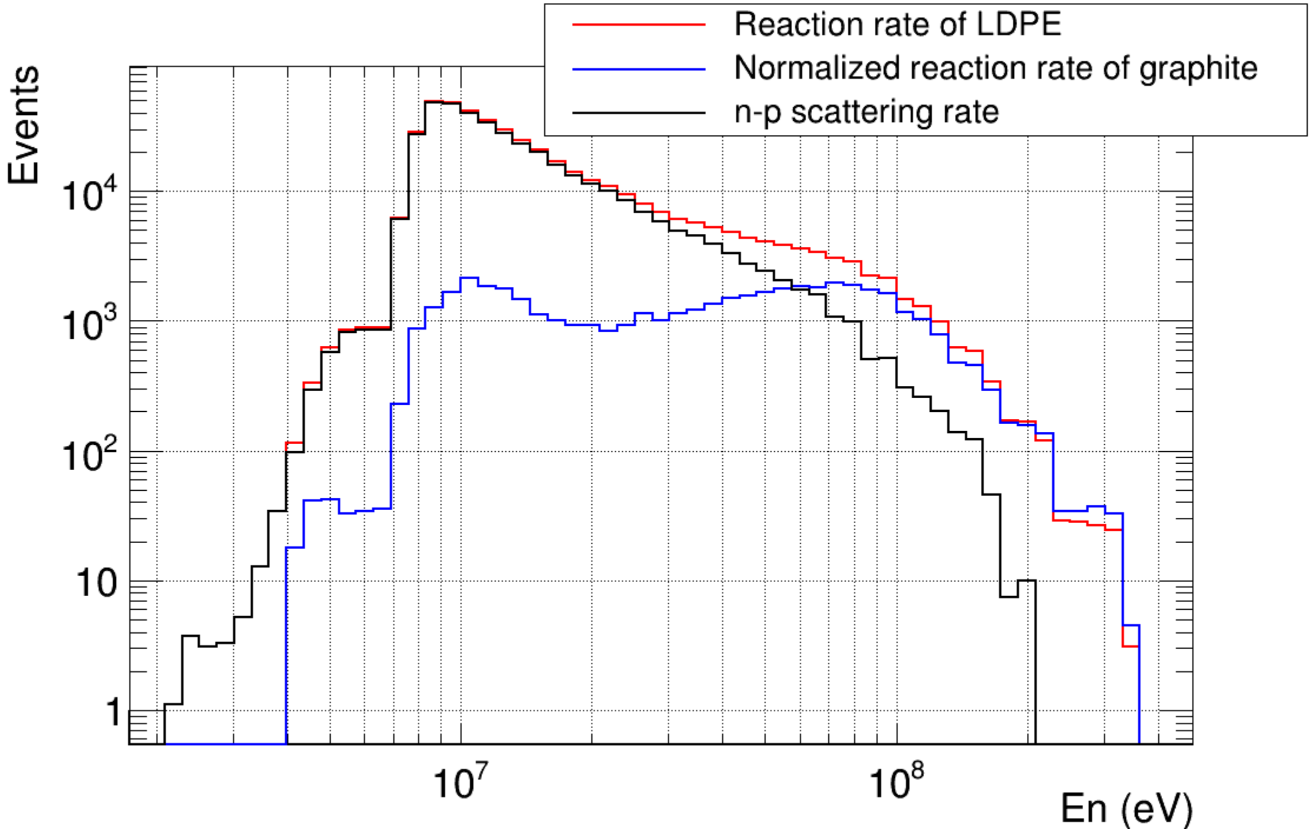


ΔE-E distribution for particle identification

Analysis and preliminary results

(2) Analysis of the PRT

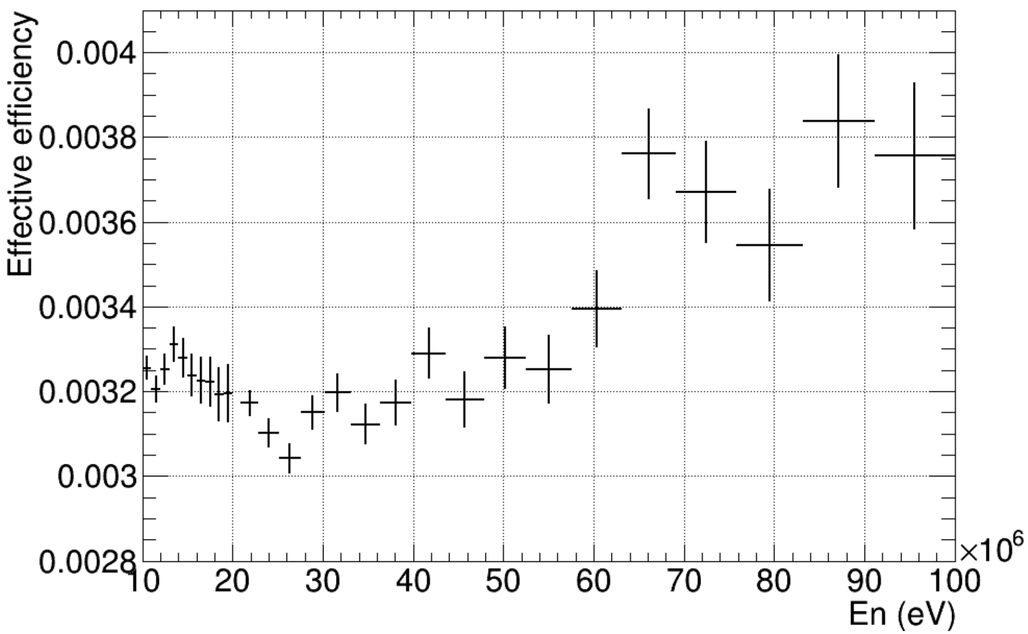
- A graphite sample with equivalent thickness as LDPE was measured to subtract the contribution from the carbon nuclei



Analysis and preliminary results

(2) Analysis of the PRT

- Geant4 Simulation for effective efficiency
- Physics list: FTFP_BERT_HP
- Neutron data: ENDF/B-VIII.0 (<20 MeV) and G4 model (> 20 MeV)



Effective efficiency: ratio of elastic scattering protons detected by PRT over all the n-p scattering events occurred in LDPE sample

Analysis and preliminary results

(3) Preliminary results

- The n-p elastic scattering cross section data used as references

Reaction	Library	Energy range
H(n, n)H	IAEA standards (2017)	En < 20 MeV
	JEFF-3.1.2	En > 20 MeV

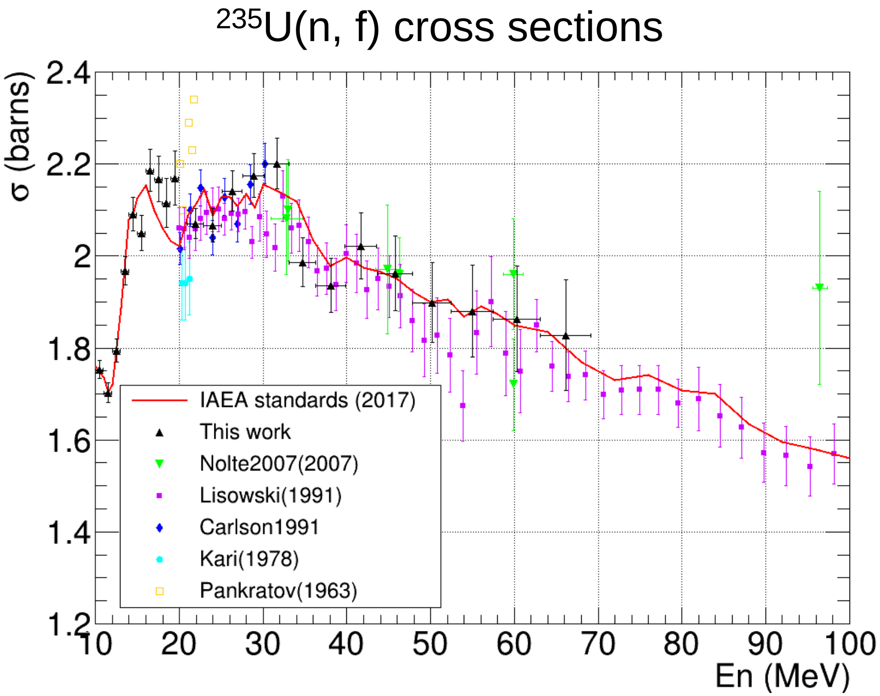
① Sample size is much larger than the beam spot
② Samples' homogeneity and beam profile in this case is not well controlled yet
③ The measurements are normalized to the standards at 14.5 MeV (D-T source)

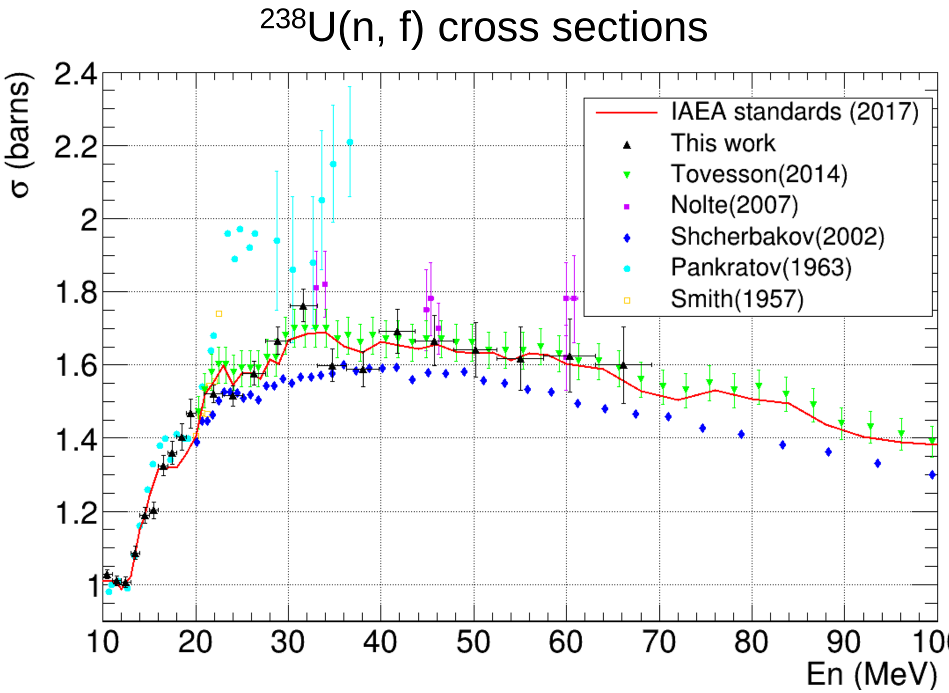
Cross section at 14.5 MeV

Reaction	Library	Cross section (barns)
^{235}U(n, f)	IAEA standards (2017)	2.09
^{238}U(n, f)	IAEA standards (2017)	1.19

Analysis and preliminary results

(3) Preliminary results





The measured shapes of ^{235}U(n, f) and ^{238}U(n, f) XS generally follow the IAEA standards but discrepancies exist at given energy (~20 MeV, ~30 MeV)

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Summary

1. $^{235,\,238}$U (n, f) cross sections from 10 to 70 MeV are measured relative to n-p scattering at CSNS Back-n (A shape measurement normalized to standard).
2. The preliminary results generally follow the IAEA standards (2017) but discrepancies exist at given energy.
3. More detailed analysis will be performed to confirm the discrepancy between our measurement and the standard, which is very important for the next evaluation
4. The measurement energy range will be extended (10-70 MeV -> 7-100 MeV) by upgrading the telescope and increasing the statistics
5. Absolute measurement may be performed in the future with good control on the relation between sample and beam

Thanks, questions?