中国科学院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

CSNS

Progress in the measurement of the neutron-induced fission cross-section at CSNS Back-n

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Outline

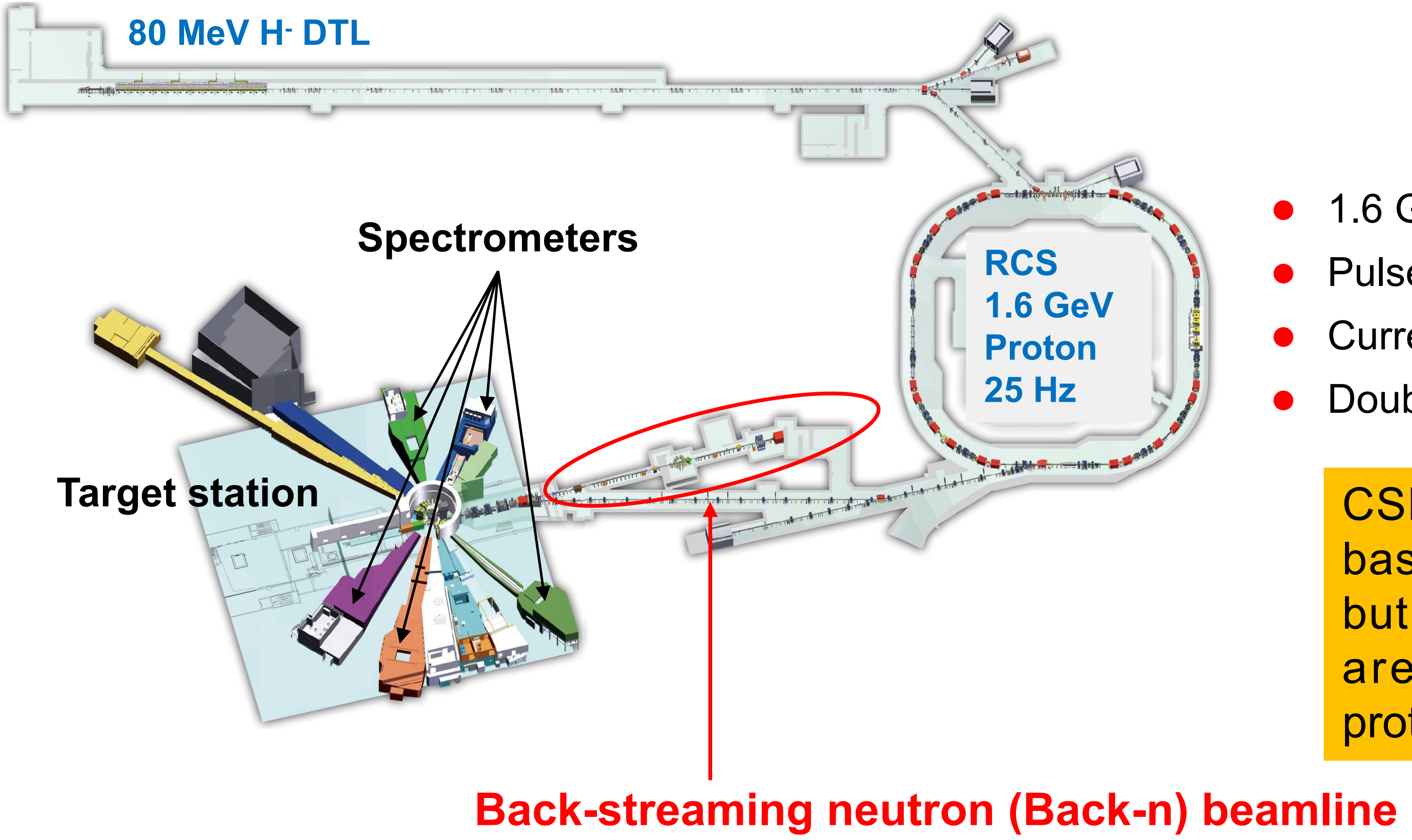
1. CSNS & Back-n facility

2. Progress in the fission XS measurement

3. Prospects

4. Summary

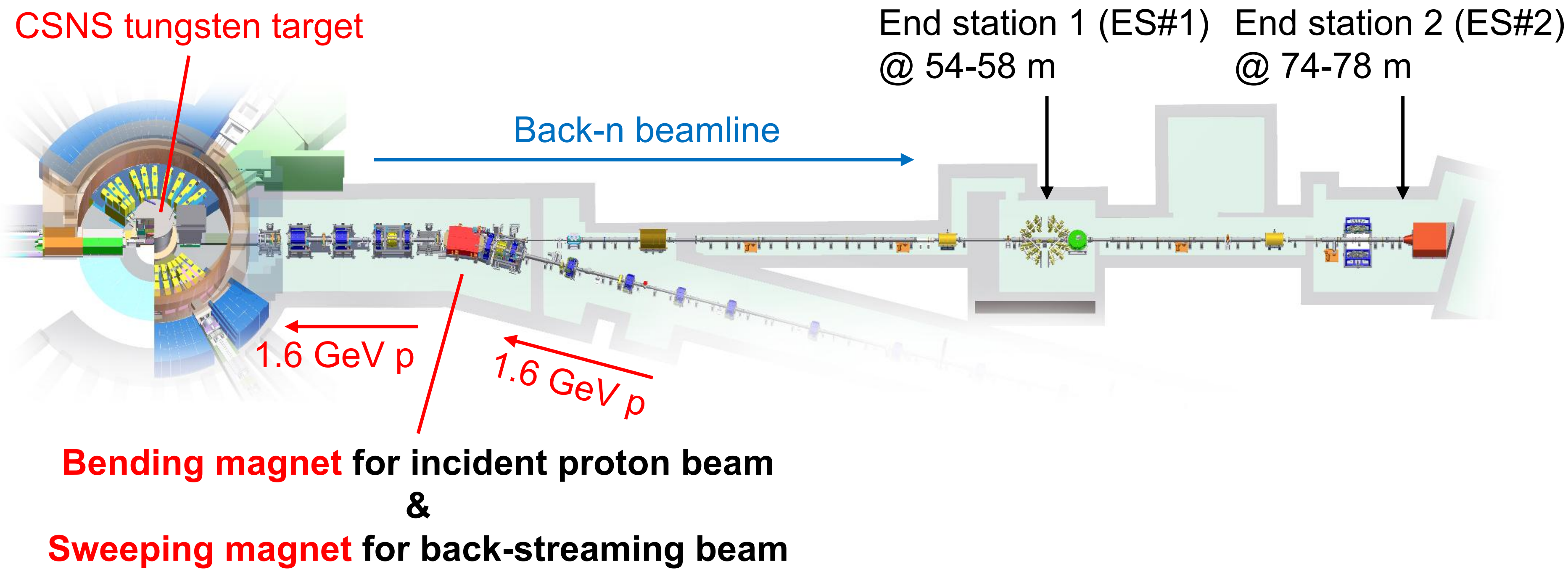
CSNS layout



- 1.6 GeV protons bombard tungsten target
- Pulsed beam with 25 Hz repetition frequency
- Current beam power: ~170 kW (2.65 $\times 10^{13}$ p/pulse)
- Double-bunch/Single-bunch commissioning

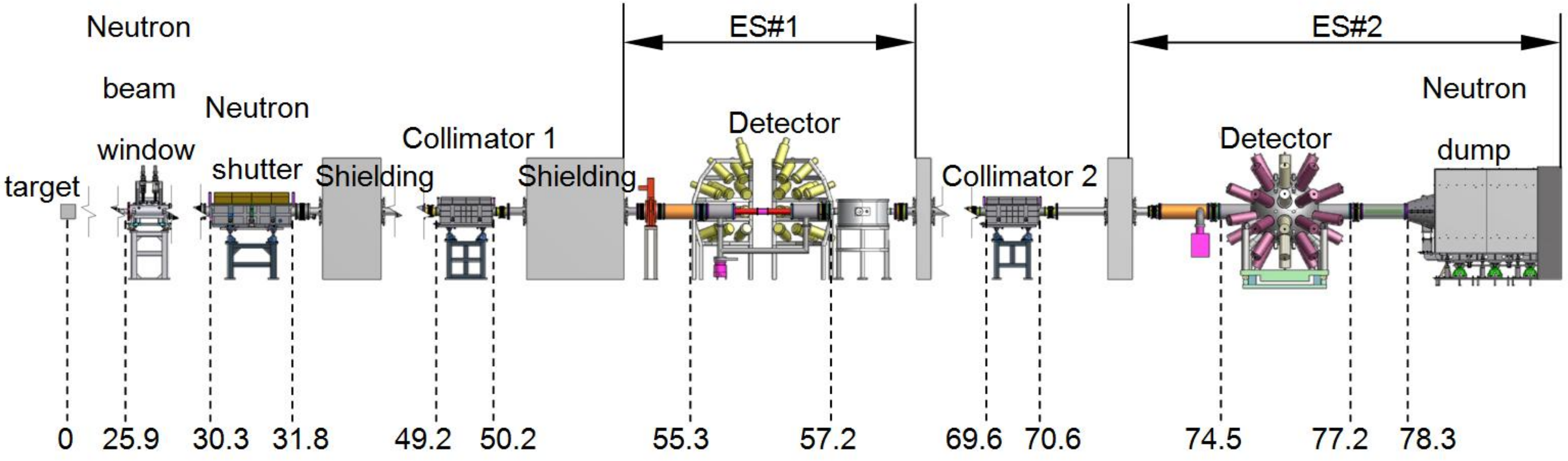
CSNS is Mainly used for material study based on neutron scattering technique, but expanded applications of the beam are involved: **white neutron beam**, proton beam, muon beam, etc.

Back-n facility



- Time-of-flight (TOF) technique
- Two end stations: ES#1 (~56 m) and ES#2 (~76 m)
- Wide neutron energy range (from thermal to ~300 MeV)
- Weak γ-flash due to back-streaming design

Back-n facility



A neutron shutter and two collimators are used together to configure the beam by adjusting their apertures:

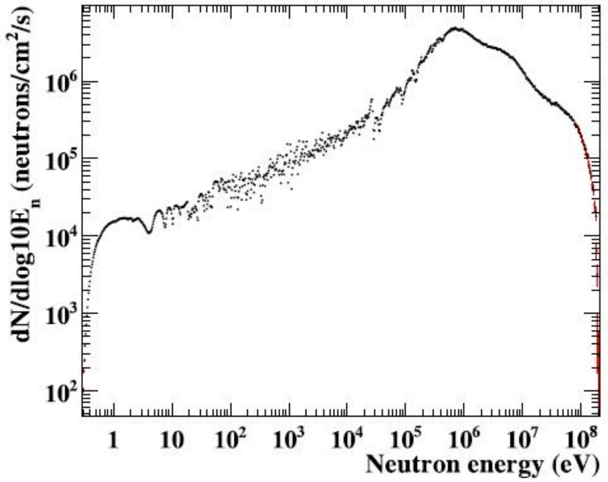
Jingyu Tang et al., *Nucl. Sci. Tech.* (2021) 32: 11

Table 1 Four sets of standard beam spots and neutron fluxes with relevant collimator apertures at Back-n (100 kW) — Simulated data

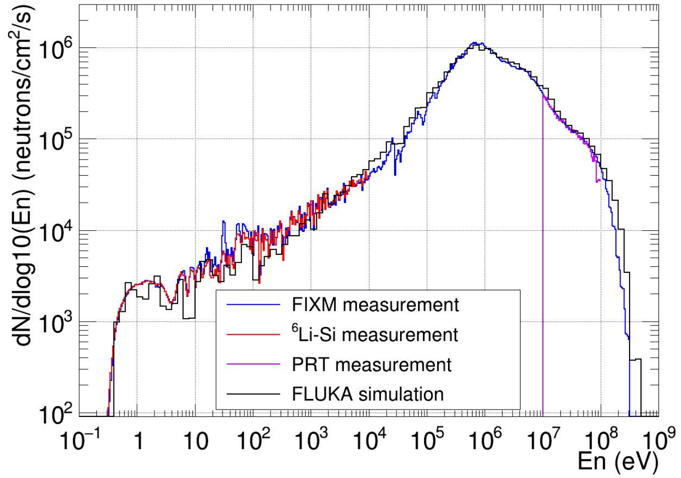
Mode	Shutter (mm)	Coll#1 (mm)	ES#1 spot (mm)	ES#1 flux ($n/cm^2/s$)	Coll#2 (mm)	ES#2 spot (mm)	ES#2 flux ($n/cm^2/s$)
Low intensity	Φ3	Φ15	Φ15	1.3×10^5	Φ40	Φ20	4.6×10^4
Small spot	Φ12	Φ15	Φ20	1.6×10^6	Φ40	Φ30	6.1×10^5
Large spot	Φ50	Φ50	Φ50	1.8×10^7	Φ58	Φ60	6.9×10^6
Imaging	78 × 62	76 × 76	75 × 50	2.0×10^7	90 × 90	90 × 90	8.6×10^6

Back-n facility

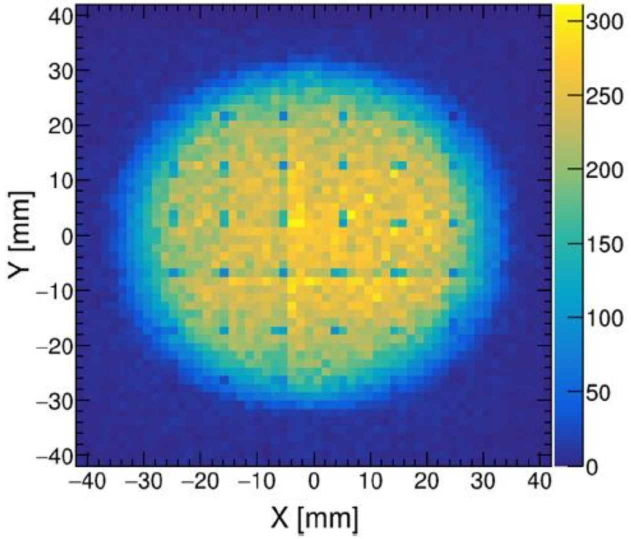
Flux of ES#2 — Big collimators



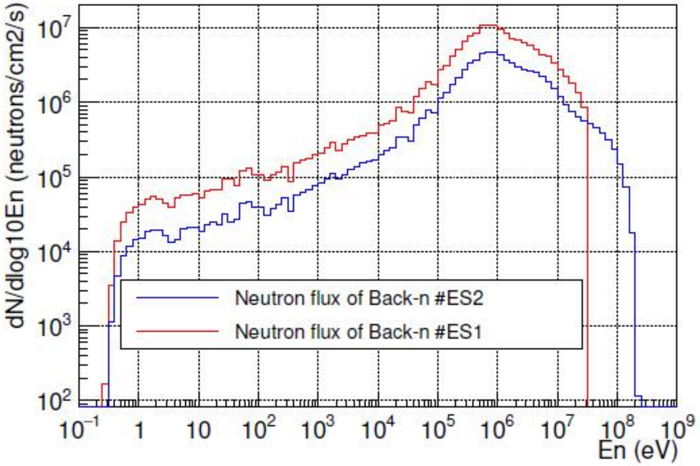
Flux of ES#1 — small collimators



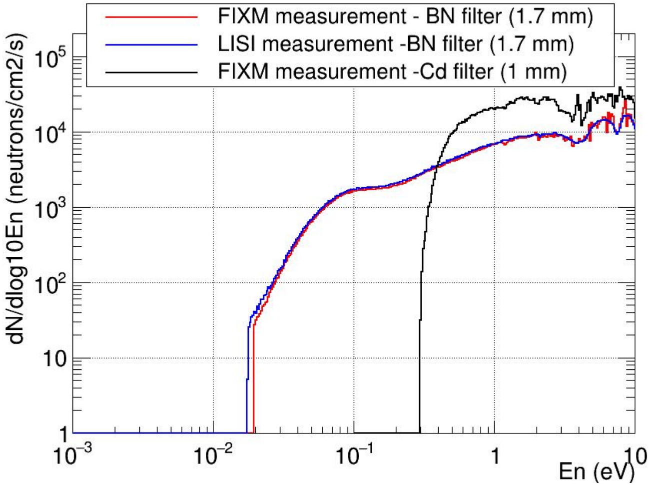
Beam profile of ES#2 — big collimators



Flux comparison of ES#1 and ES#2



Thermal neutron Flux of ES#2

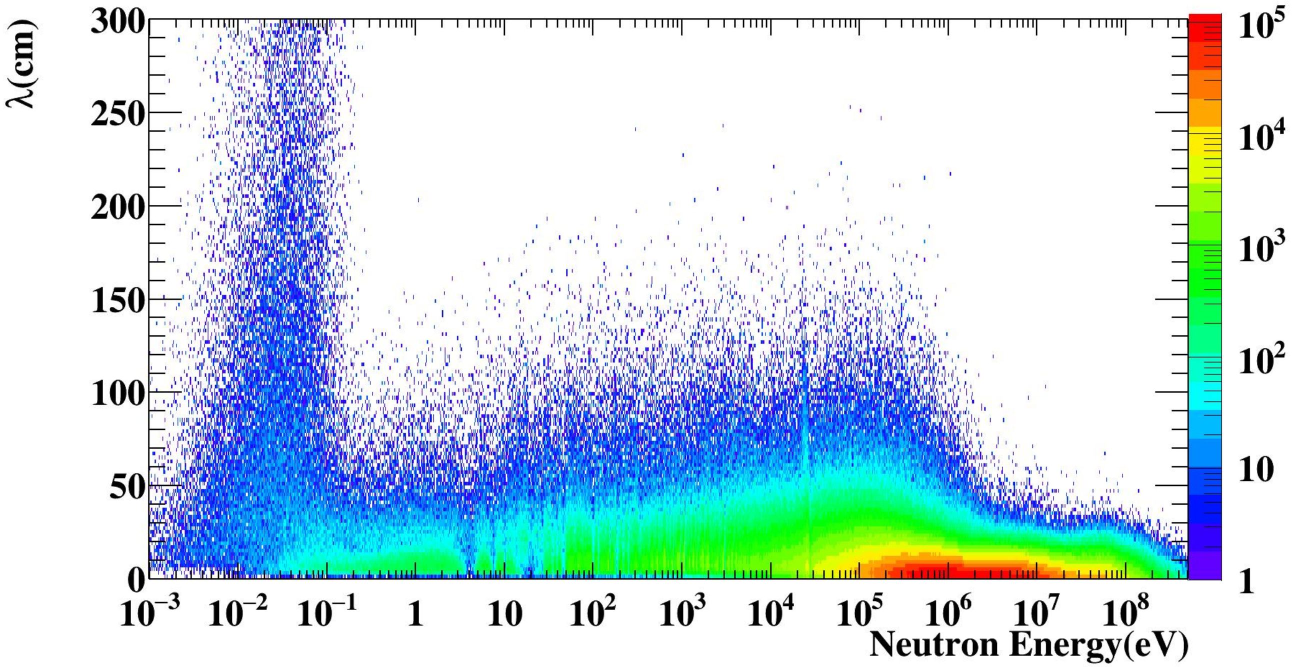


- Yonghao Chen et al., *EPJ.A* (2024) 60: 63
- Yonghao Chen et al., *EPJ Web of Conf.* (2020) 239: 17018
- Yonghao Chen et al., *EPJA* (2019) 55: 115
- Yijia Qiu et al., *NIMA* (2025) 1075: 170383
- Binbin Qi et al., *NIMA* (2020) 957: 163407

Dr. Yijia Qiu
May 27th, Parallel Session 1, 11:25 - 11:40

Back-n facility

Simulation of the equivalent neutron moderation distance in the spallation target



$$\frac{\Delta E}{E} = \gamma(\gamma+1)\sqrt{\left(\frac{\Delta T}{T}\right)^2 + \left(\frac{\Delta L}{L}\right)^2}$$

Proton beam width (ΔT) **Moderation** (ΔL)

Energy resolution at Back-n ES#2

Energy (eV)	ΔT (ns)	ΔL (cm)	ΔE/E
1	25.5	14.5	3.8×10^{-3}
10	25.5	17.4	4.5×10^{-3}
1×10^{2}	25.5	15	3.9×10^{-3}
1×10^{3}	25.5	13.6	3.5×10^{-3}
1×10^{4}	25.5	13.3	3.6×10^{-3}
1×10^{5}	25.5	9.8	3.9×10^{-3}
1×10^{6}	25.5	4.2	9.2×10^{-3}
1×10^{7}	25.5	3.6	2.9×10^{-2}
1×10^{8}	25.5	4.4	9.9×10^{-1}
3×10^{8}	25.5	4.1	19.8×10^{-1}

Shengda Tang
May 27th, Parallel Session 1, 09:40 - 09:55

Outline

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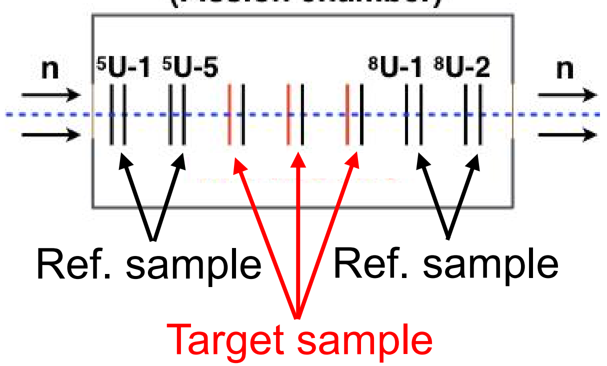
Fission XS measurement at Back-n

Fission cross-section measured at Back-n

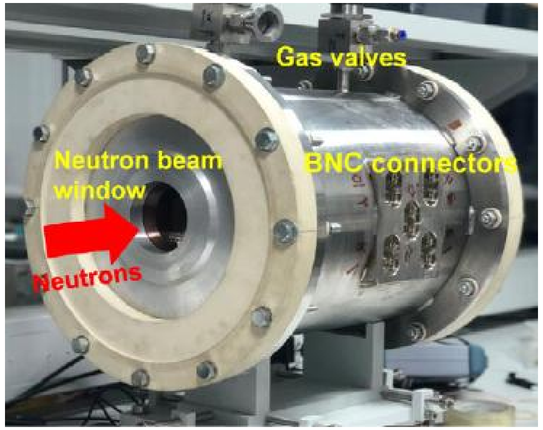
Year	Nucleus	Detector	Reference/Comment
2018	^{235}U	FIXM	**ANE** (2020) 140: 107301 (^{5}U/^{8}U ratio)
2018	^{238}U	FIXM	**EPJA** (2023) 59: 5 (^{5}U/^{8}U ratio)
2018	^{236}U	FIXM	**PRC** (2020) 102: 034604
2019	^{232}Th	FIXM	**NST** (2023) 34: 115
2019	^{239}Pu	FIXM	**PRC** (2023) 107: 024606
2020	^{232}Th	FIXM+PRT	**PLB** (2023) 839: 137832
2021	^{235}U	FIXM+PRT	**EPJ Web of Conf.** (2023) 284: 01013
2021	^{238}U	FIXM+PRT	**EPJ Web of Conf.** (2023) 284: 01013
2023	^{236}U	FIXM	Analysis in progress
2025	^{235}U	TPC+^{6}Li-Si	Analysis in progress

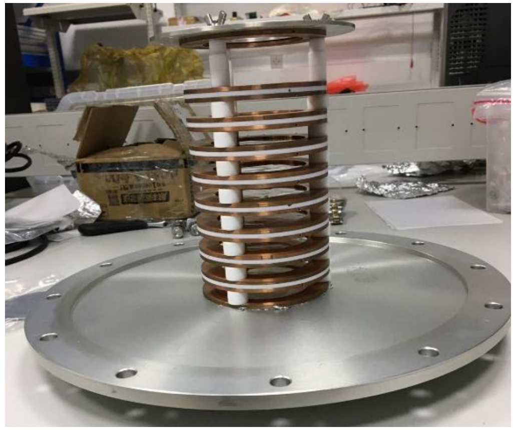


$$\sigma_x(En) = \frac{R_x(En)\varepsilon_s N_s}{R_s(En)\varepsilon_x N_x}\sigma_s(En)$$

(x-Target, s- Ref.)

- E_n Neutron energy
- R Fission rate
- ε Efficiency
- N Sample quantity





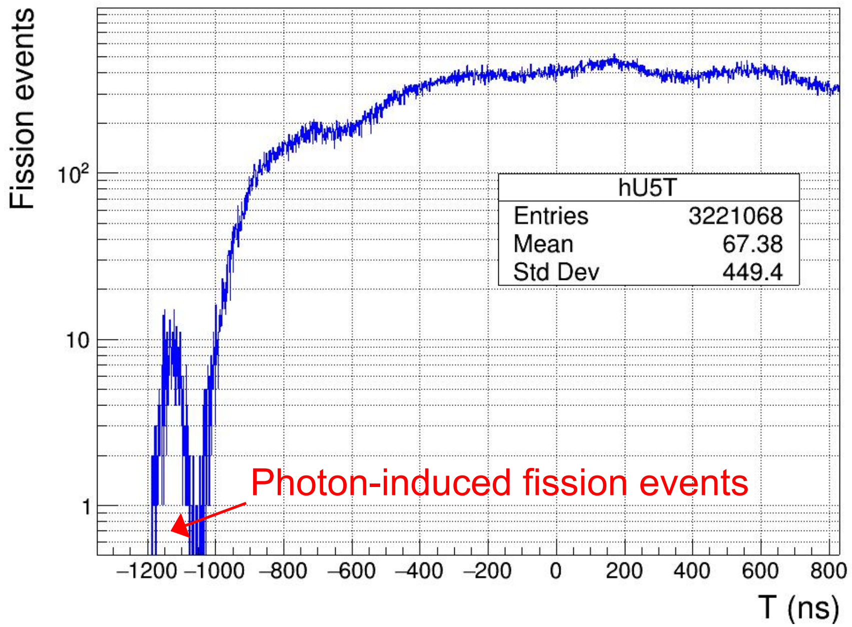
Fission XS measurement at Back-n

TOF method for calibrating neutron energy

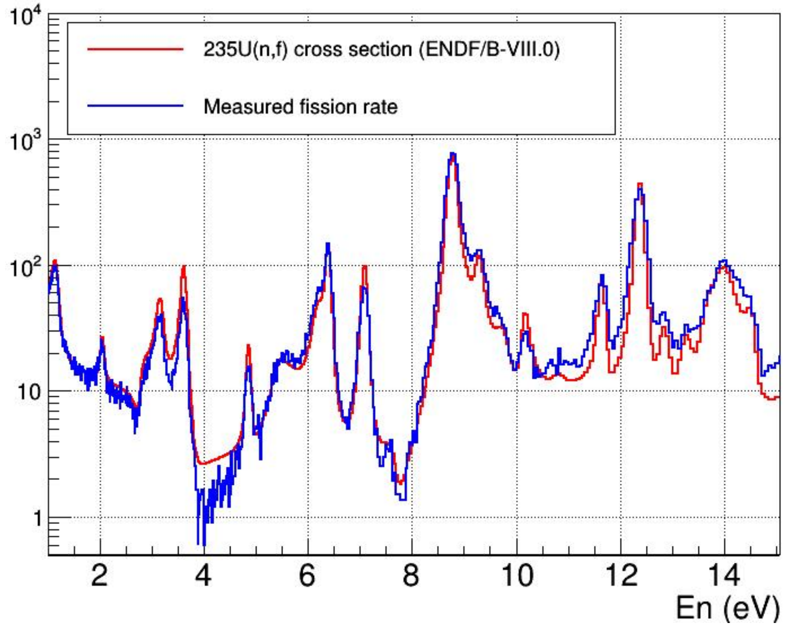
$$v = \frac{L}{TOF} = \frac{L}{T - T_0}$$

- L is determined by the resonance peaks of ^{235}U sample
- T_0 is determined by the γ-flash events

Time distribution of fission events



Comparison of fission rate and cross-section

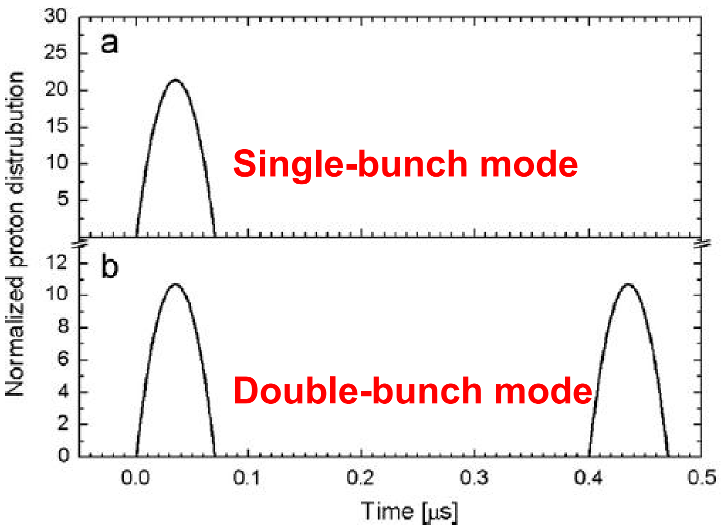


Fission XS measurement at Back-n

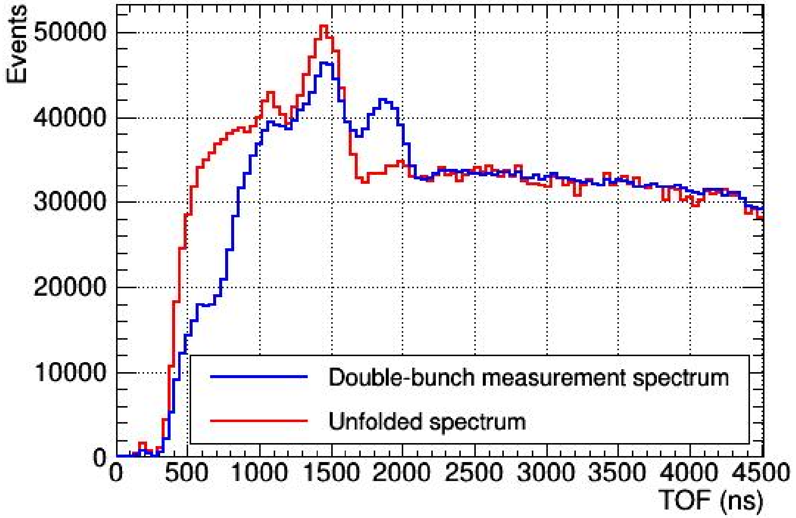
Double-bunch unfolding for TOF correction

- Double-bunch mode: two identical proton bunches with a well-defined interval (410 ns) in one proton pulse
- An uncertainty of 410 ns in TOF measurement is negligible for slow neutrons, but it is not the case for high energy neutrons
- An iterative algorithm based on Bayes' theorem is developed for unfolding the TOF spectrum (Han Yi et al, *JINST* (2019) **14**: 02011)

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



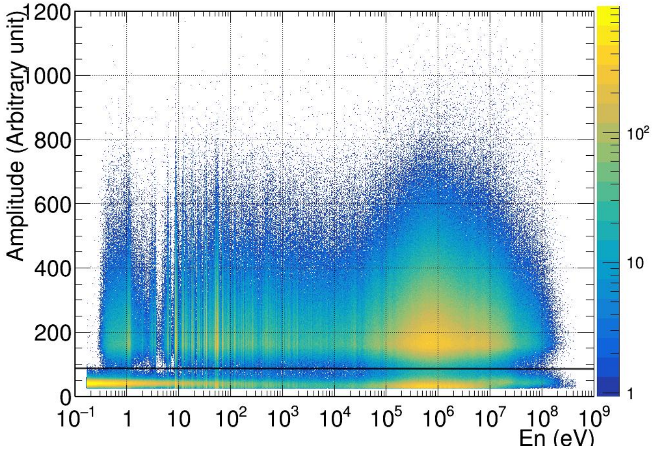
TOF spectrum before and after unfolding

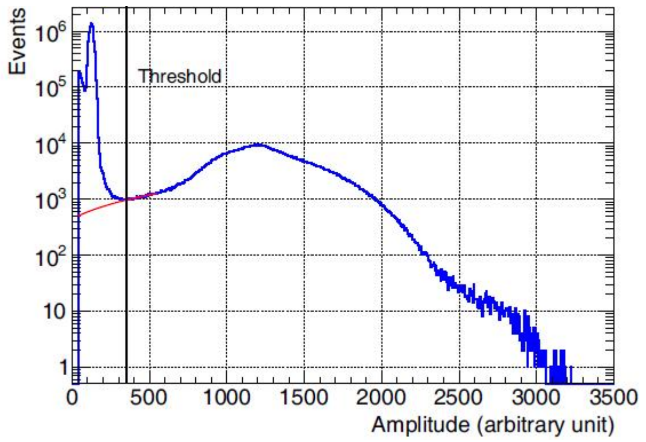


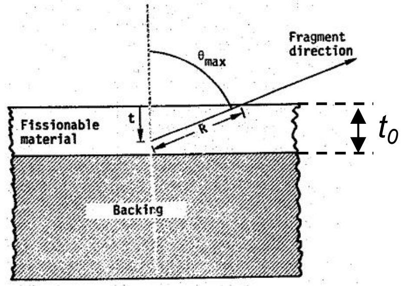
Fission XS measurement at Back-n

Efficiency determination

Efficiency is usually determined based on the amplitude distribution



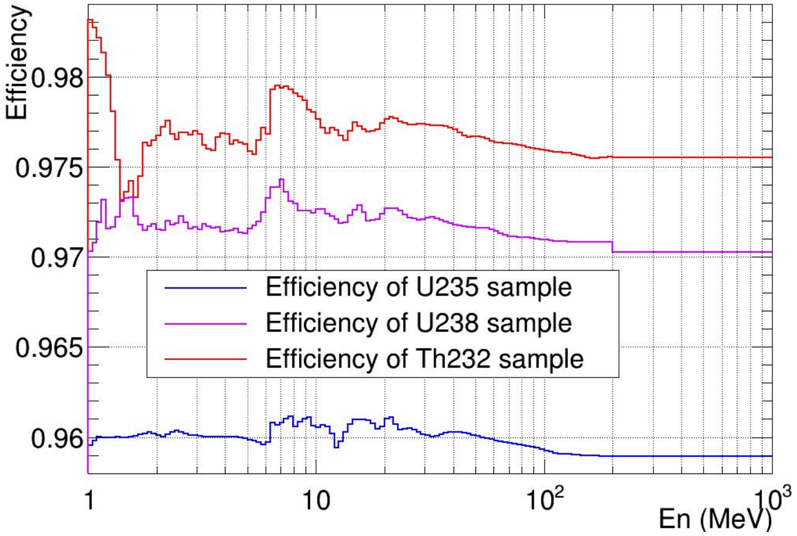




$$\varepsilon(E_n) = \int_0^{t_0}\int_{cos\theta_{max}}^{1} W(cos\theta)dcos\theta dt$$

$$W(cos\theta) = 1 + (A-1)cos^2\theta$$

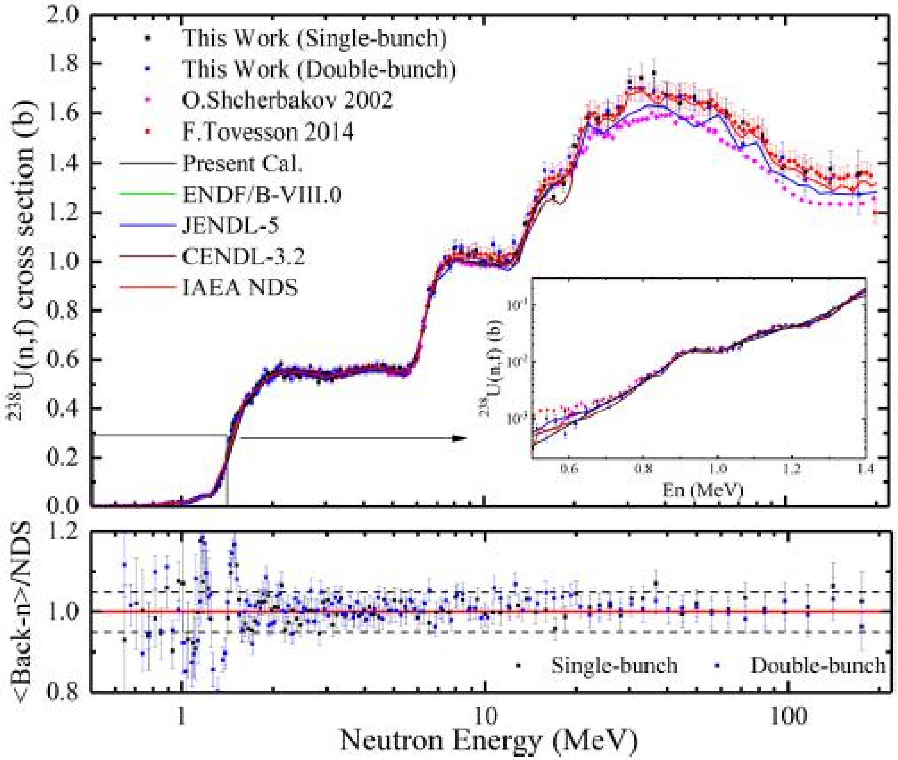
$$A = \frac{W(cos0°)}{W(cos90°)} \quad cos\theta_{max} = \frac{t}{R}$$

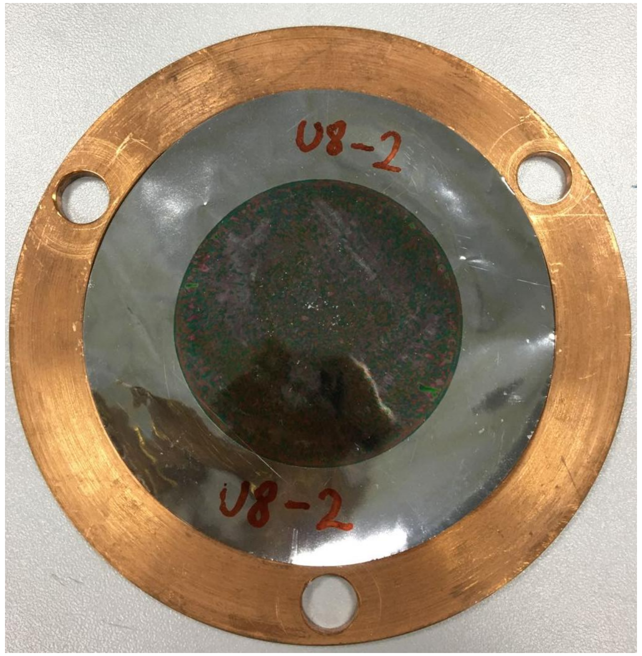


Efficiency determination taking into account the angular distribution of the FFs: the variation due to the anisotropy is less than 1%

Fission XS measurement at Back-n

^{238}U(n, f) XS measurement from 0.5 to 200 MeV





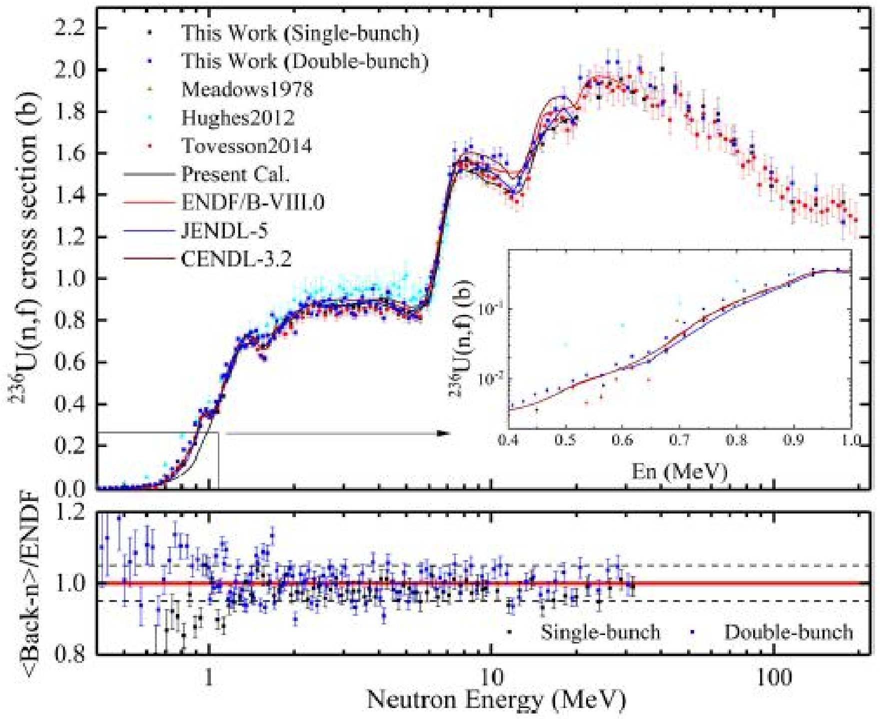
Jie Wen et al., *Annals Nucl. Energy* (2020) 140: 107301

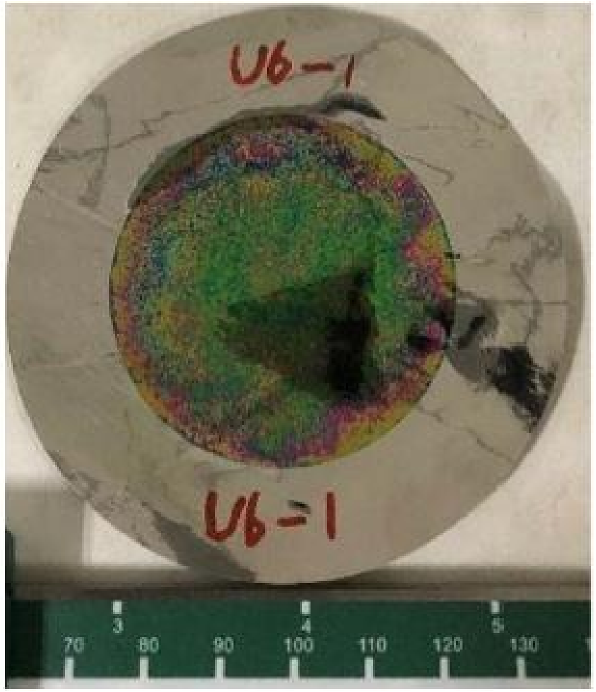
Zhizhou Ren et al., *Eur. Phys. J. A* (2023) 59: 5

- Measurement relative to ^{235}U(n, f) up to 200 MeV
- Important measurement reference in high energy region
- The measurement shows better agreement with IAEA standard and ENDF/B-VIII.0 than JENDL-5 and CENDL-3.2

Fission XS measurement at Back-n

^{236}U(n, f) XS measurement from 0.4 to 200 MeV





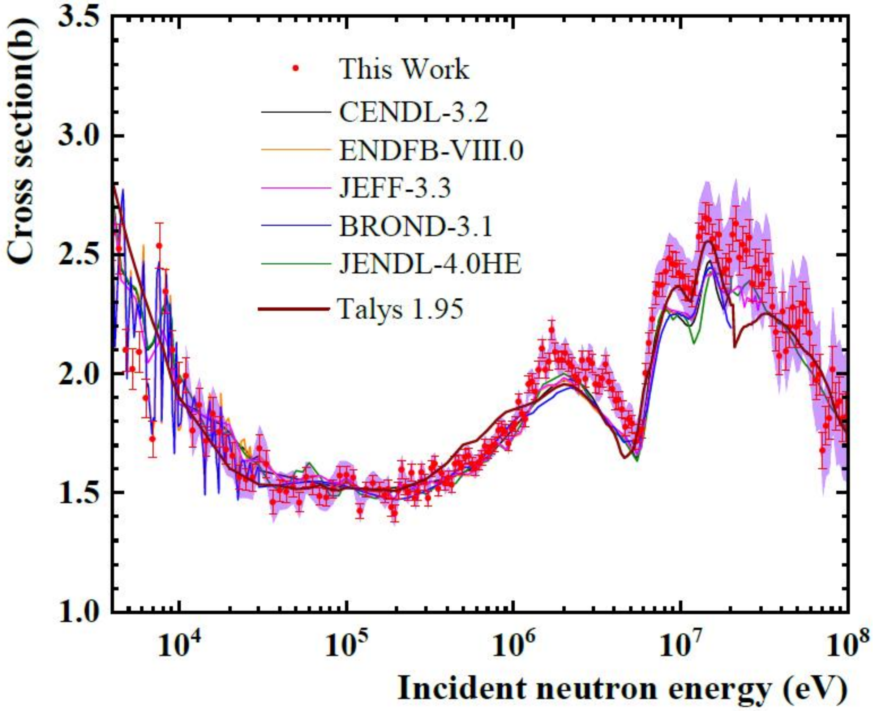
Zhizhou Ren et al., *Phys. Rev. C* (2020) 102: 034604

Zhizhou Ren et al., *Eur. Phys. J. A* (2023) 59: 5

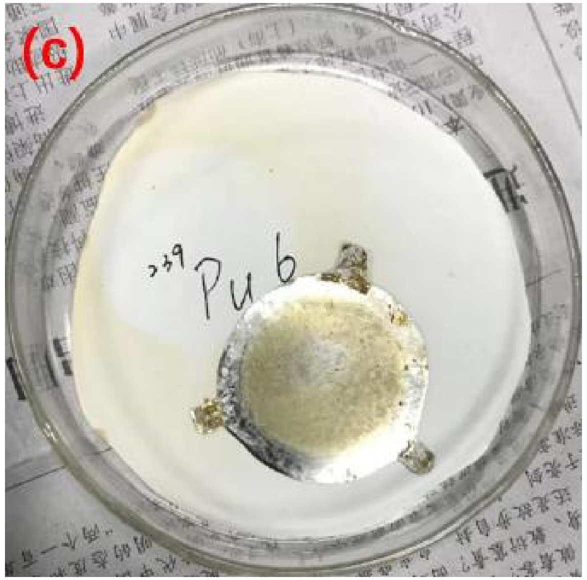
- ^{236}U is of interest because of its build-up in the equilibrium fule composition in the Th/U cycle
- Measurement relative to ^{235}U(n, f) up to 200 MeV
- Important measurement reference in high energy region

Fission XS measurement at Back-n

^{239}Pu(n, f) XS measurement from 4 keV to 100 MeV



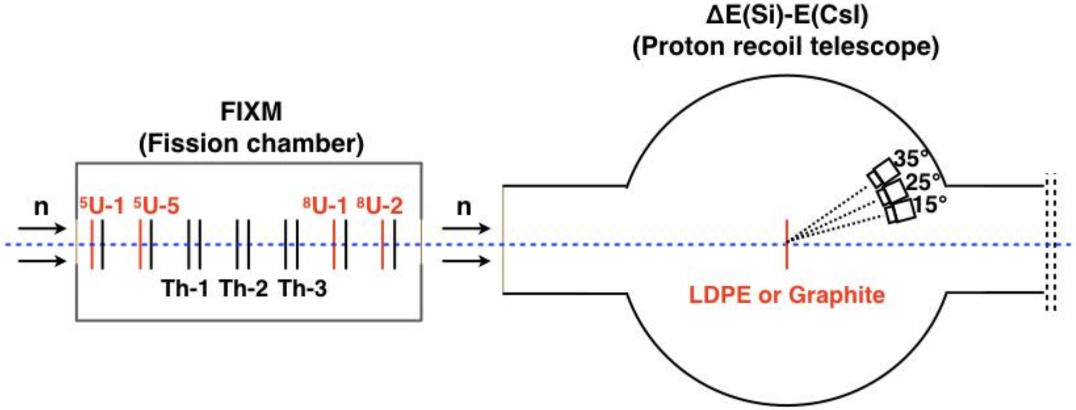
Yijia Qiu et al., *Phys. Rev. C* (2023) 107: 024606



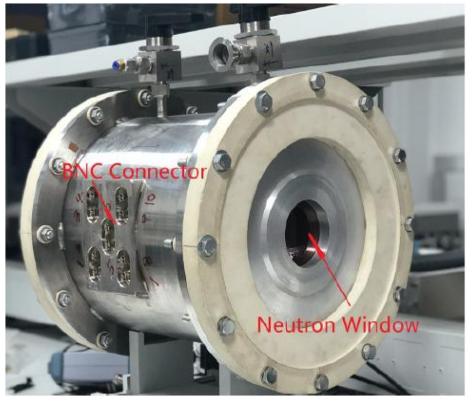
- ^{239}Pu is very important isotope in the U/Pu cycle
- Measurement relative to ^{235}U(n, f) from 4 keV to 100 MeV
- Large systematic uncertainties due to several reasons (sample, beam configuration, etc.)
- An improved measurement is expected to be performed in the future

Fission XS measurement at Back-n

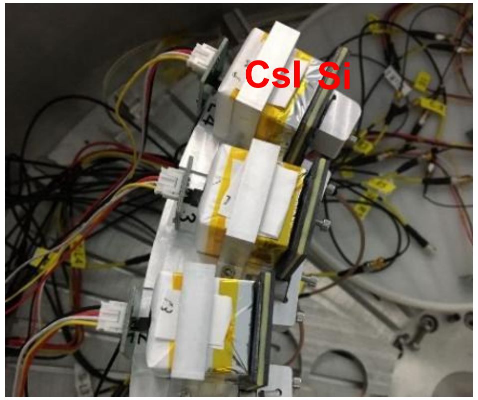
- Measurement combining fission chamber and ΔE-E telescope by taking H(n, n) as reference
- A fission chamber (FIXM) is used for measuring the fission events
- Proton recoil telescope (PRT) is used for measuring the scattering protons



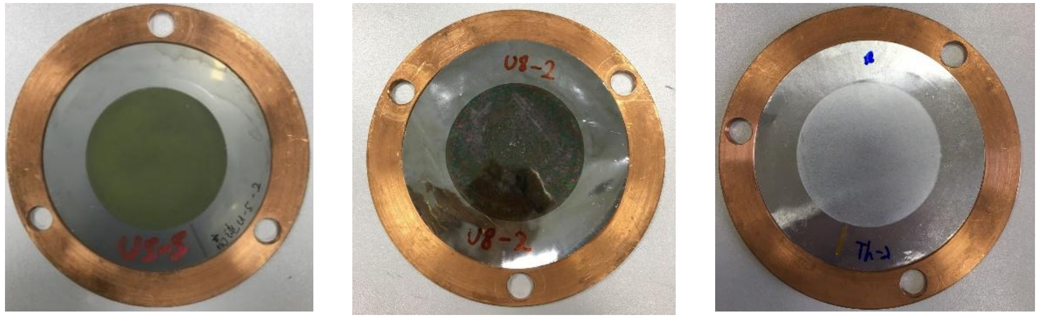
FIXM

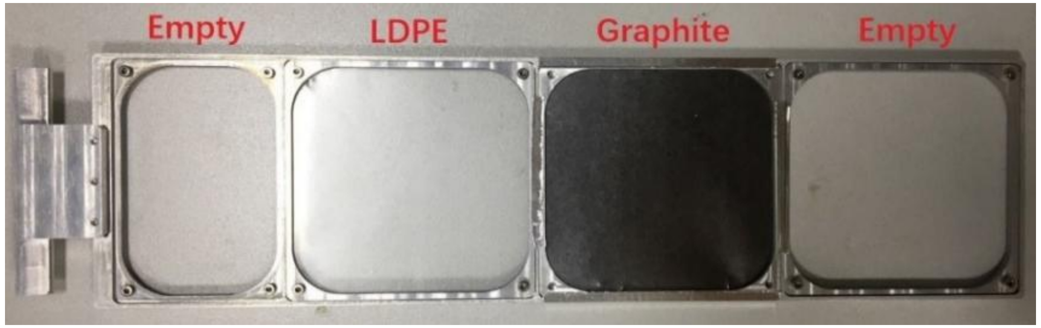


PRT: Si (300 μm)+ CsI (3 cm)



U5 U8 Th232

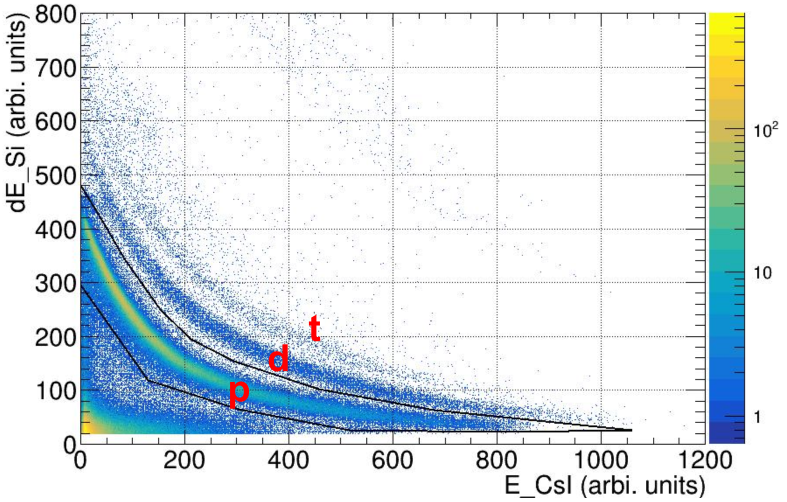




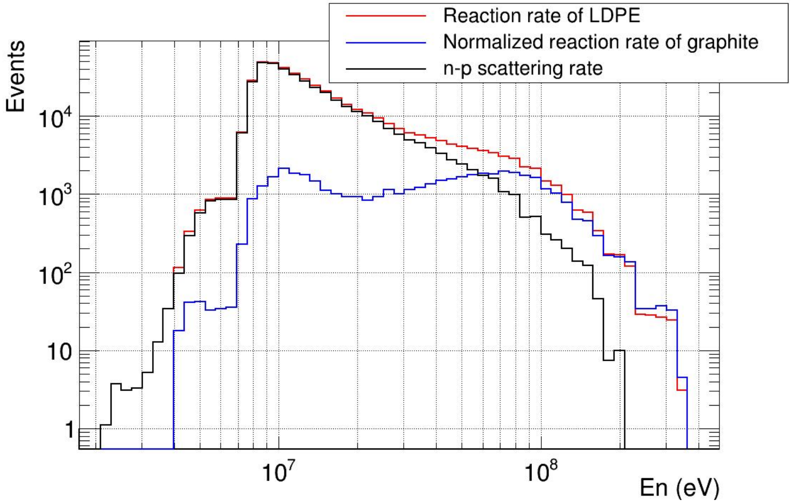
Fission XS measurement at Back-n

- ΔE-E distribution is applied for identifying proton events
- The contribution from $^{12}C(n, p)$ reaction is quantified by measuring a graphite sample
- The effective efficiency of PRT is obtained by Geant4 simulation

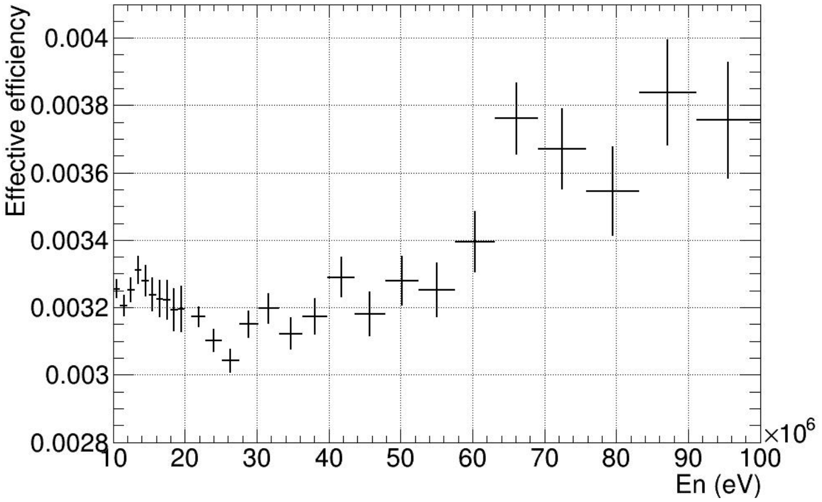
ΔE-E particle identification



Background subtraction



Efficiency simulation

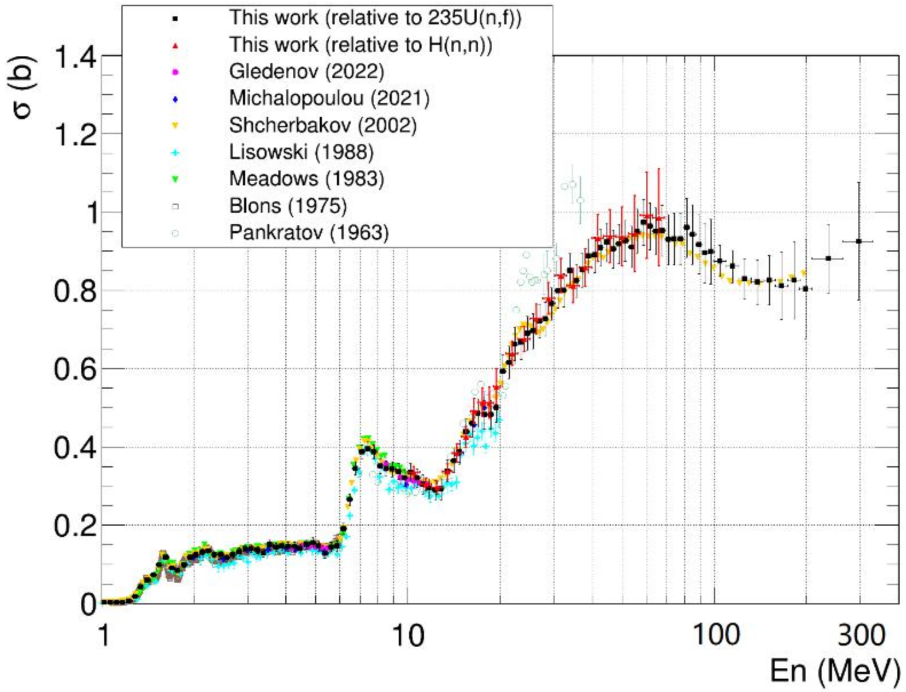


Fission XS measurement at Back-n

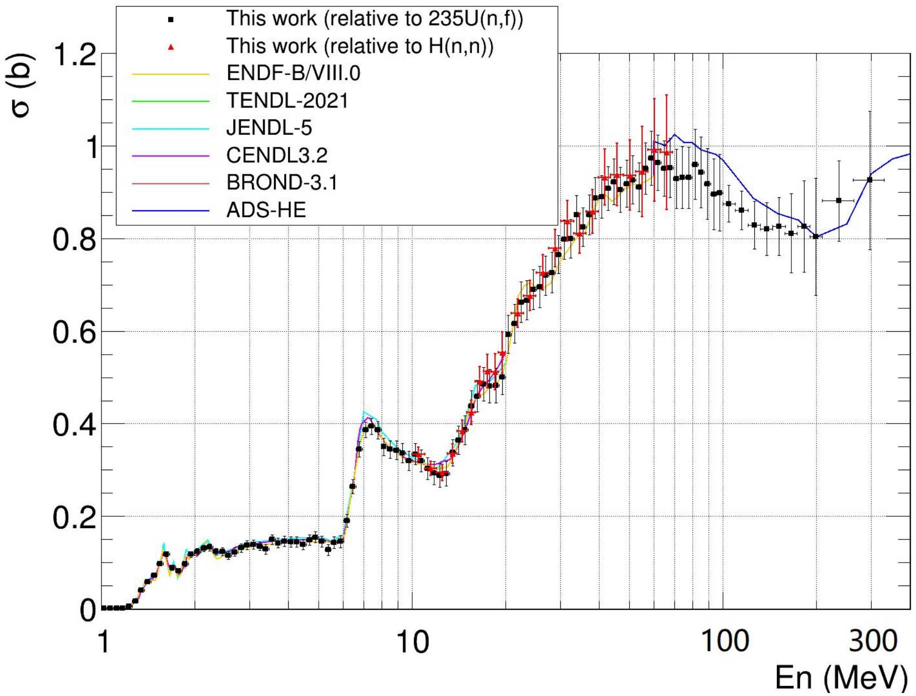
^{232}Th(n, f) XS measurement from 1 to 300 MeV

Yonghao Chen et al., *Phys. Lett. B* (2023) 839: 137832

Comparison with other measurements



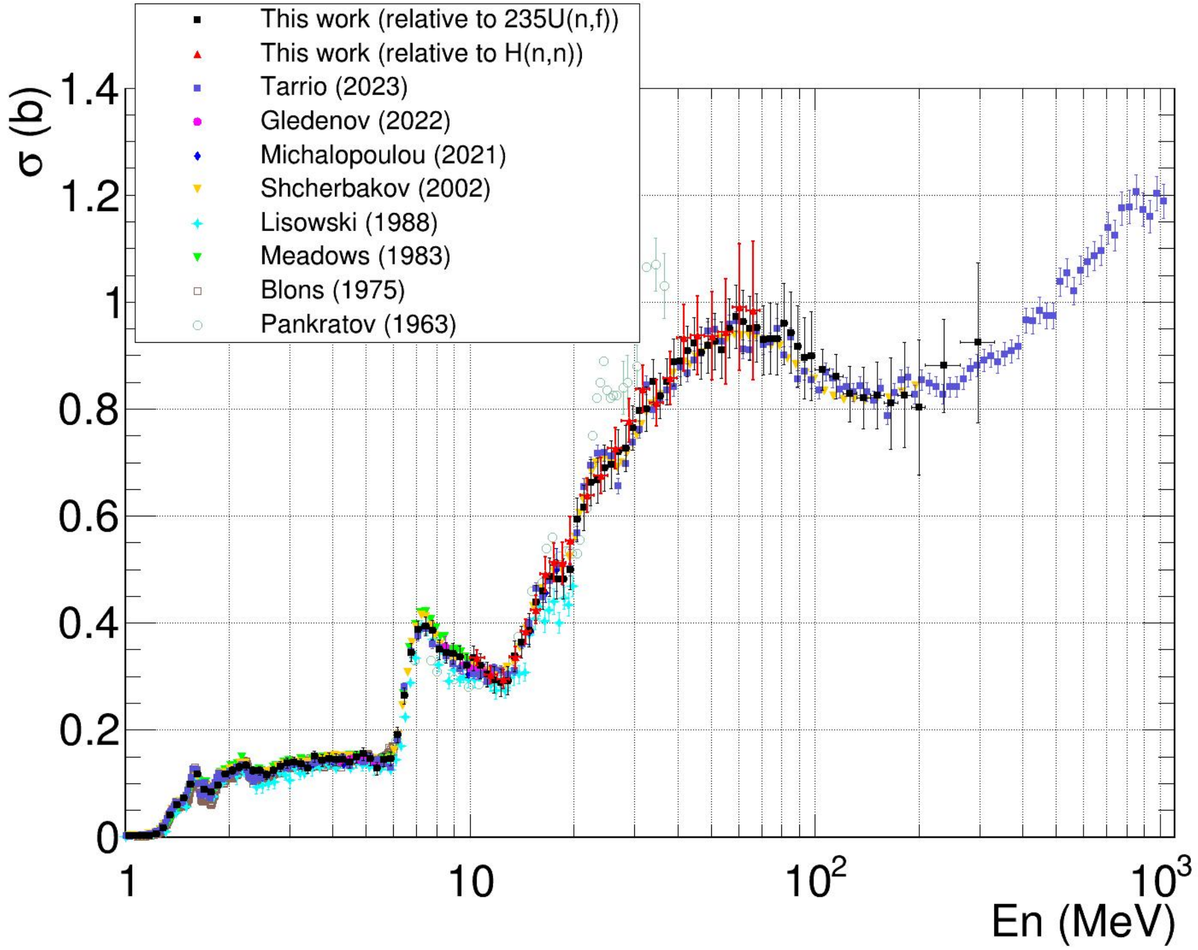
Comparison with evaluations



- Measurement respectively relative to ^{235}U(n, f)【1-300 MeV】and H(n, n)【10-70 MeV】
- Results obtained by two approaches/references agree with each other within uncertainties
- Provide very scarce data in 200-300 MeV region

Fission XS measurement at Back-n

^{232}Th(n, f) XS measurement

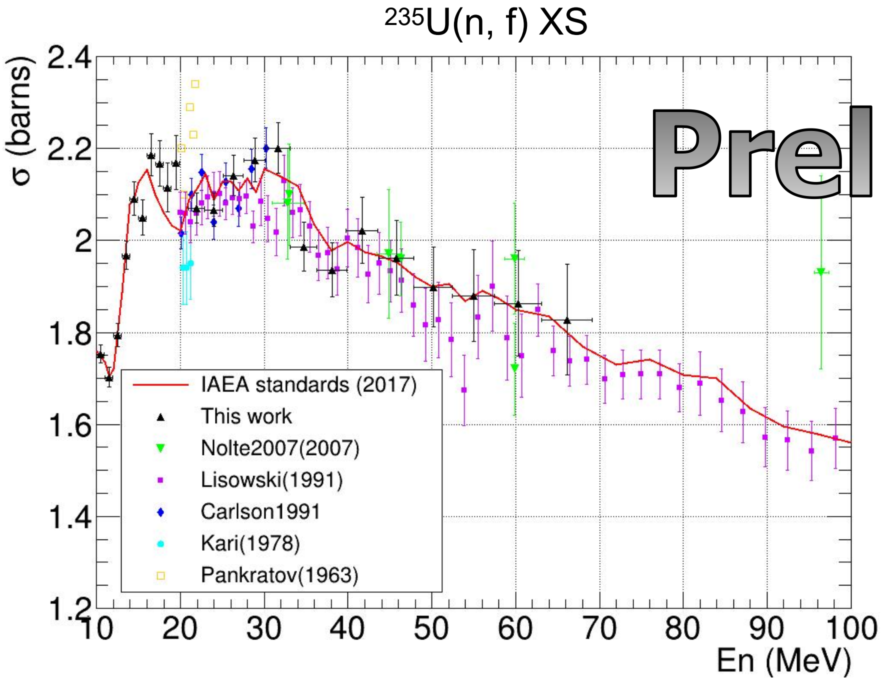


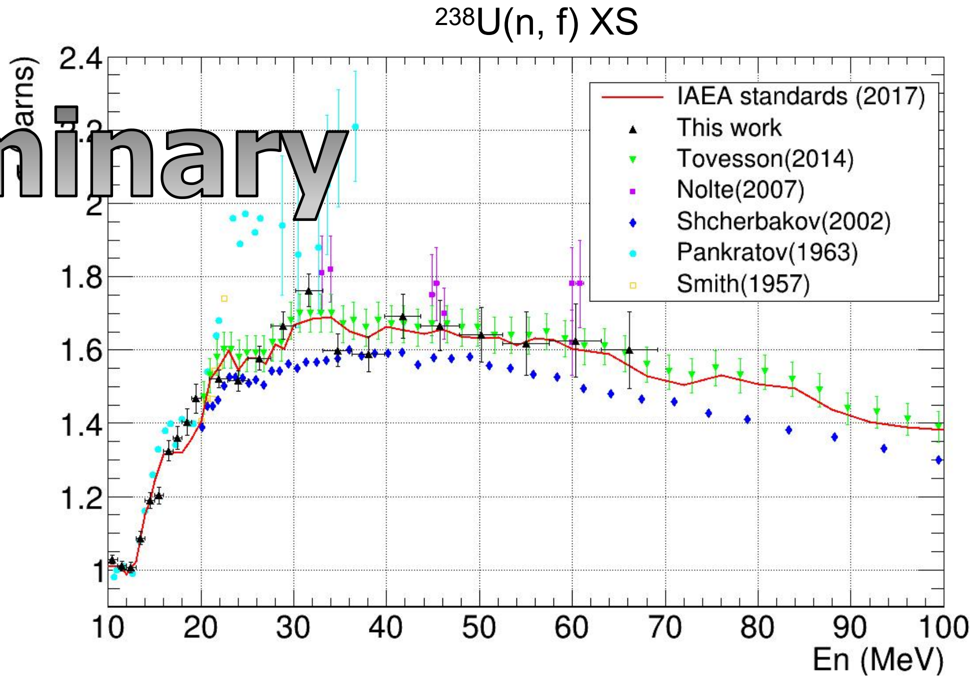
- Coincide with CENR n_TOF data in 200 – 300 MeV region (**D. Tarrio et al., *Phys. Rev. C* (2023) 107: 044616**)
- One of the two datasets above 200 MeV
- Very important references for evaluation in high energy region

Fission XS measurement at Back-n

$^{235, 238}$U(n, f) XS measurement from 10 to 70 MeV relative to n-p scattering

Yonghao Chen et al., *EPJ Web Conf.* (2023) 284: 01013



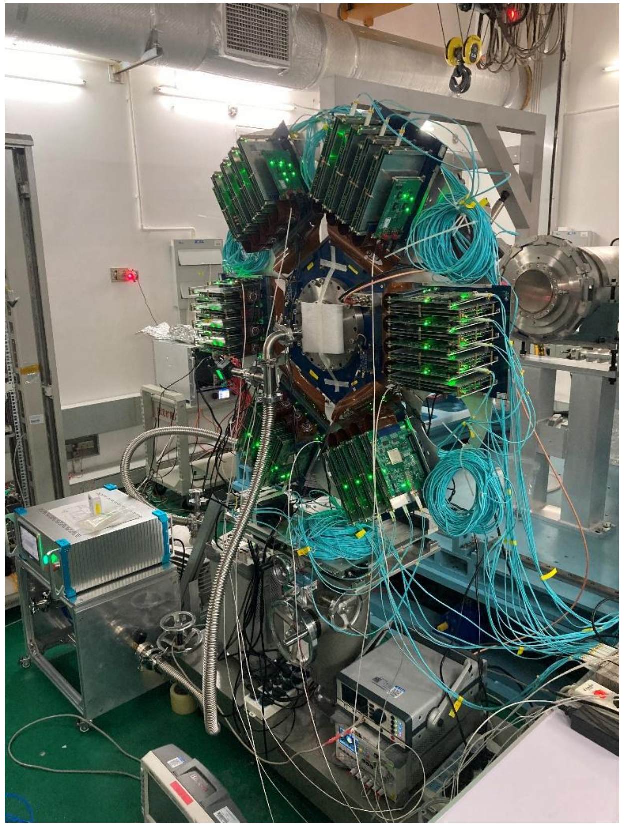


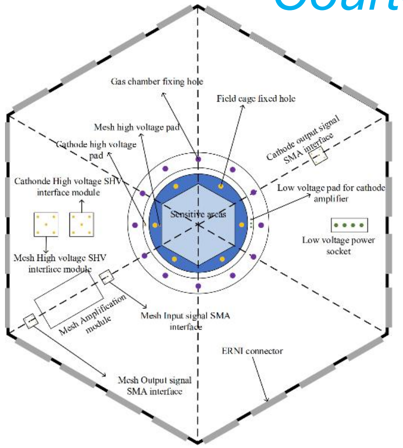
- Very meaningful data for neutron data standards
- The energy range might be extended in the future by upgrading the experimental setup (10-70 MeV -> 7-100 MeV)

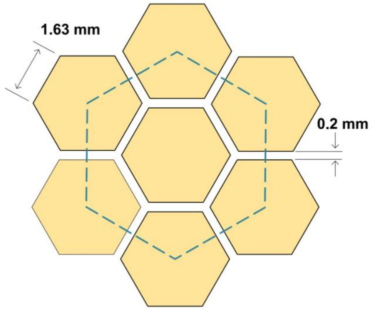
Fission XS measurement at Back-n

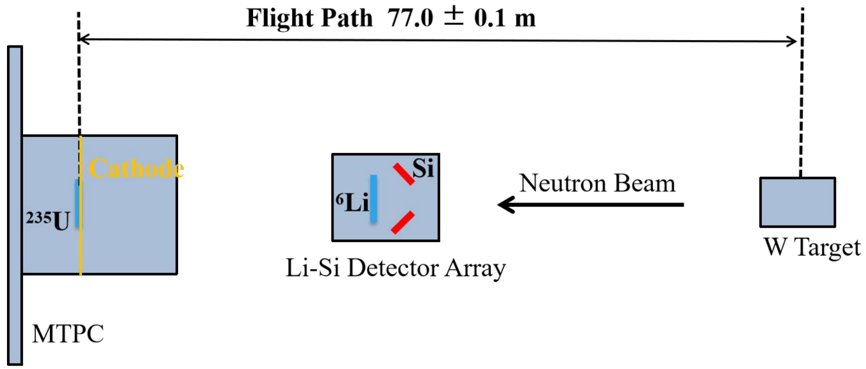
^{235}U(n, f) XS measurement relative to ^{6}Li(n, α) based on a Multi-purpose Time Projection Chamber (MTPC)

Courtesy of: Dr. Haofan Bai









- 0.5 eV ~ 10 keV, 43 energies
- Measured at 170 kW, beam configured with Φ30 mm, duration ~100 h
- $^{235}U(OH)_4$ sample: 1.76×10^{18} number of nuclei, Φ40 mm

- Developed by CSNS Back-n team and USTC
- Gain structure: Micromegas
- Signal: 1519 readout pads + cathode + mesh

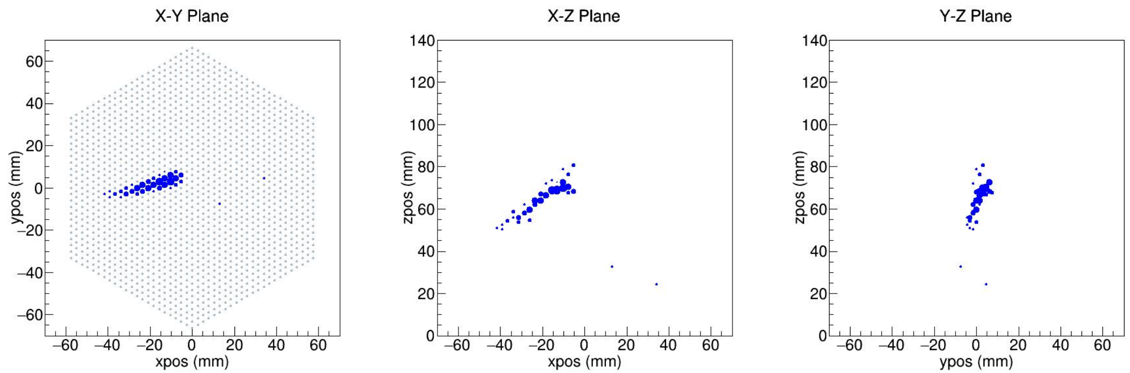
Please refer to Dr. Han Yi's talk for more details of the MTPC detector
May 26th, Parallel Session 1, 09:20 - 09:40

Fission XS measurement at Back-n

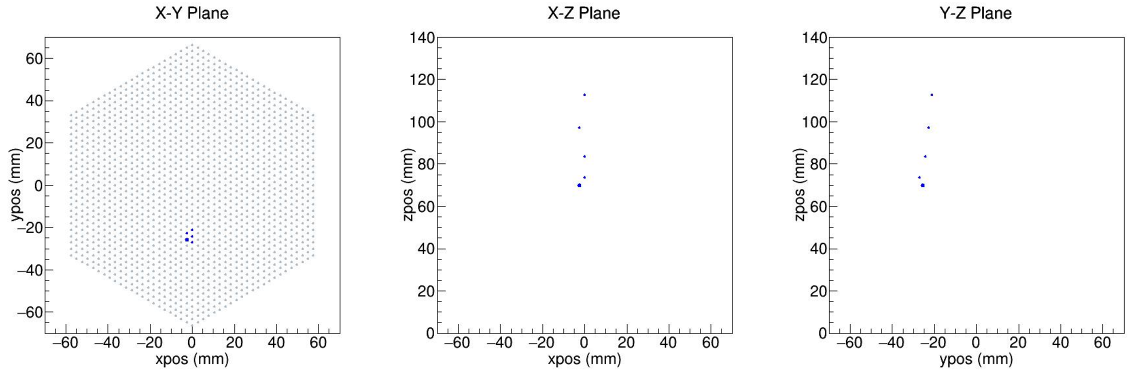
^{235}U(n, f) XS measurement relative to ^{6}Li(n, α) based on a Multi-purpose Time Projection Chamber (MTPC)

Courtesy of: Dr. Haofan Bai

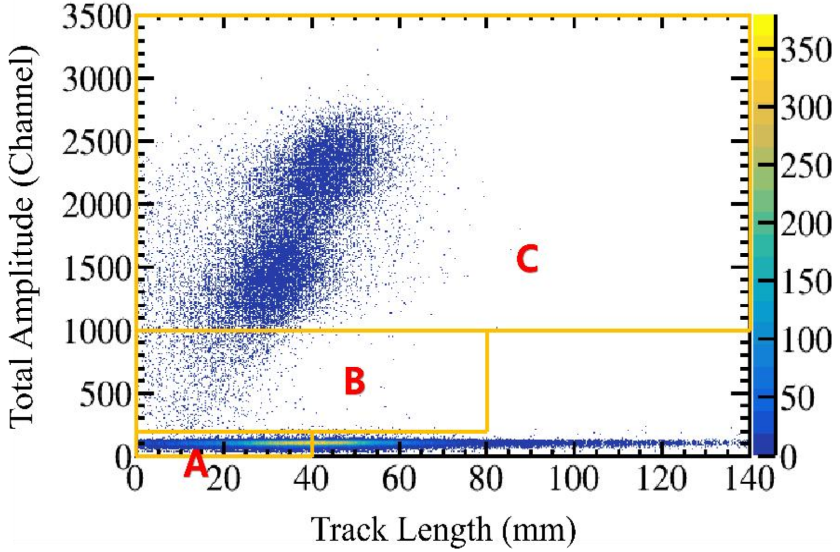
Tracks of Fission Fragments



Tracks of α particles



Amplitude distribution

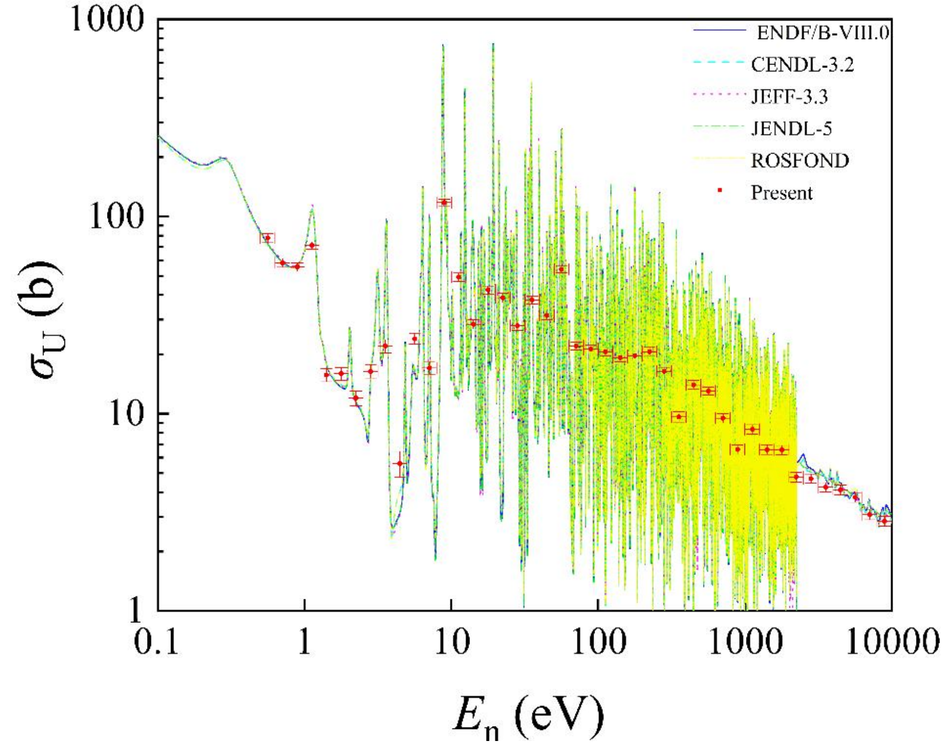


Distinguish fission fragments from α particles based on both track length and amplitude

Fission XS measurement at Back-n

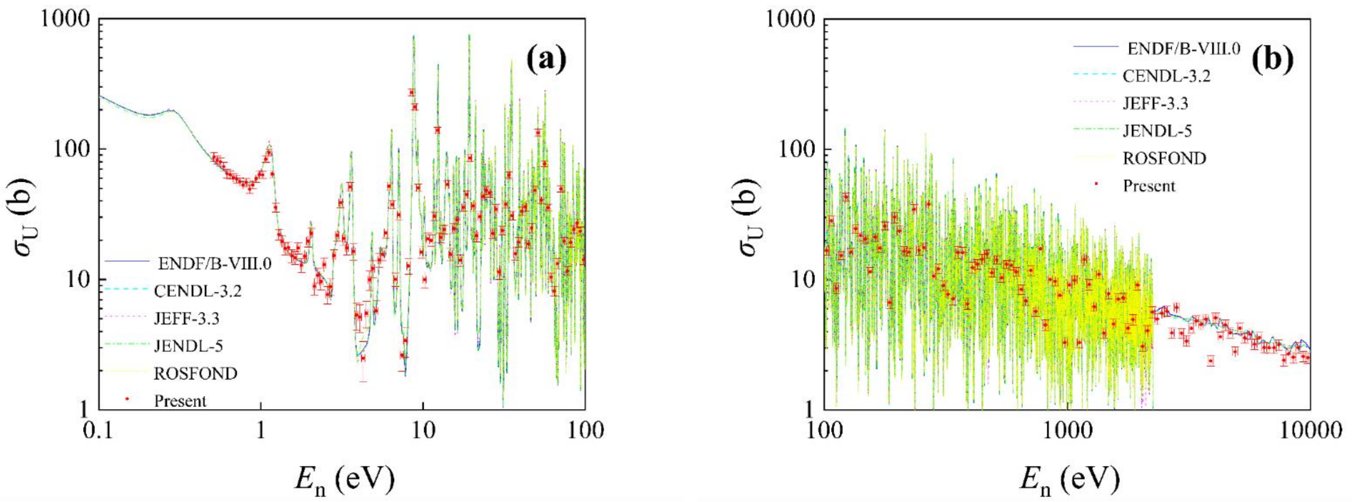
$^{235}U(n, f)$ XS measurement relative to $^{6}Li(n, \alpha)$ based on a Multi-purpose Time Projection Chamber (MTPC)

Courtesy of: Dr. Haofan Bai



0.5 ~ 100 eV, 50 bins per magnitude

0.10 ~ 10 keV, 50 bins per magnitude



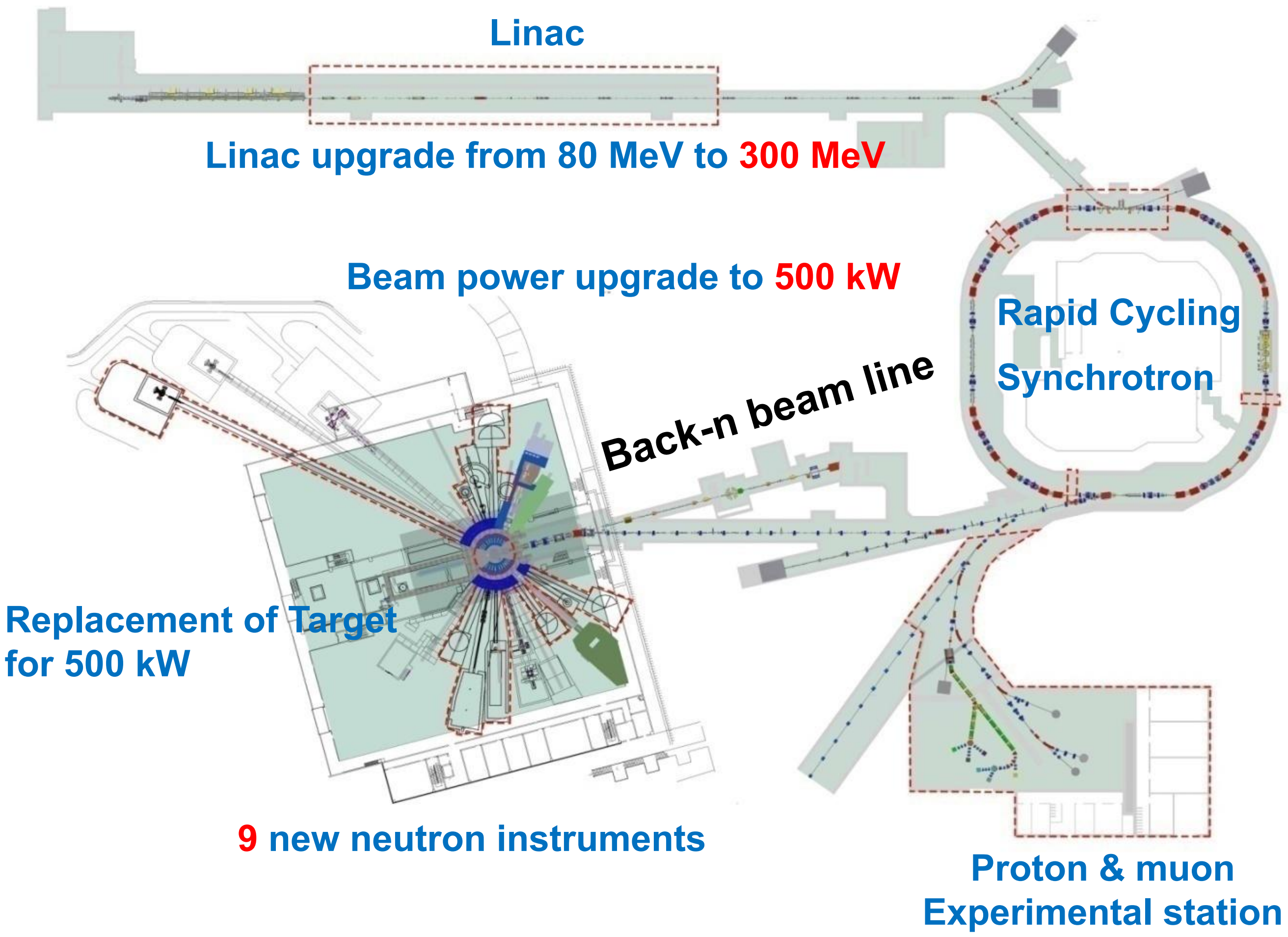
- Consistent with the data from five evaluations (especially for the resonance peak area)
- Uncertainty (10 bins per magnitude): 3.1 ~ 9.0 %

Outline

1. CSNS & Back-n facility
2. Progress in the fission XS measurement
3. **Prospects**
4. Summary

Future prospects

CSNS-II upgrading project: increase the beam power and built new instruments



- Project Budget: 2.9 BCNY (~380 MEUR)
- Funded by central and local government
- Design and R&D completed
- Construction duration (~6 years): 2024.3~2029.12
- User operation will be almost unaffected during CSNS-II construction (beam availability ~5000 h/year)

For Back-n beam line: flux will be increased by a factor of 5, which is advantageous for measurements involving small cross-sections and/or small sample quantities.

Future prospects

Accelerator bunch merging study @ CSNS/RCS: merge two bunches into one

- Double-bunch mode: two identical proton bunches with a well-defined interval (410 ns) in one proton pulse
- Unfolding method works but inevitably introduces systematic error
- Bunch merging (without reducing flux) is extremely important for the measurement of the high energy neutrons

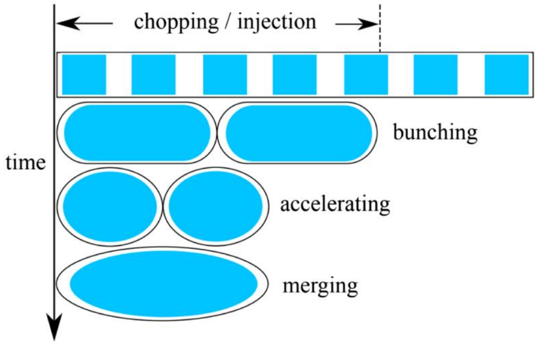
Challenges for bunch-merging in the high intensity RCS

- Strong high-intensity effect → beam dipole oscillation
- Very short merging time → emittance growth

} Beam loss

A fast bunch merging has been proposed

- Desynchronization between the dipole and rf system → increasing the limited merging time
- Optimization/adjustment of the rf phase → compensation of the high-intensity effects



The newly-installed magnet alloy rf cavity for the CSNS-II (Sep. 2022)

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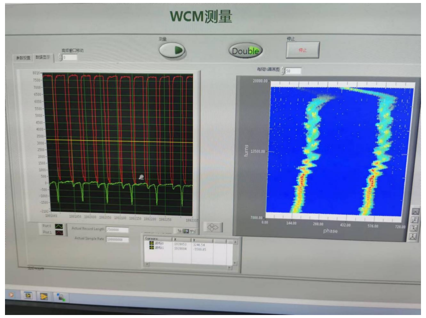

Future prospects

More kinds of samples will be measured, and more types of detectors will be developed

Thanks to the increase of the neutron flux, we will be able to measure more kinds of samples like:

- Small cross-sections
- Small sample quantities
- … …

For example, minor actinides with small quantities.

PPAC (Parallel Plate Avalanche Counter) is a good candidate that aligns with the future direction of fission measurement at Back-n, due to its good performance (fast signal, position sensitivity, and high counting rate, etc.)

PPAC @ IPN Orsay/ CERN n_TOF

Outline

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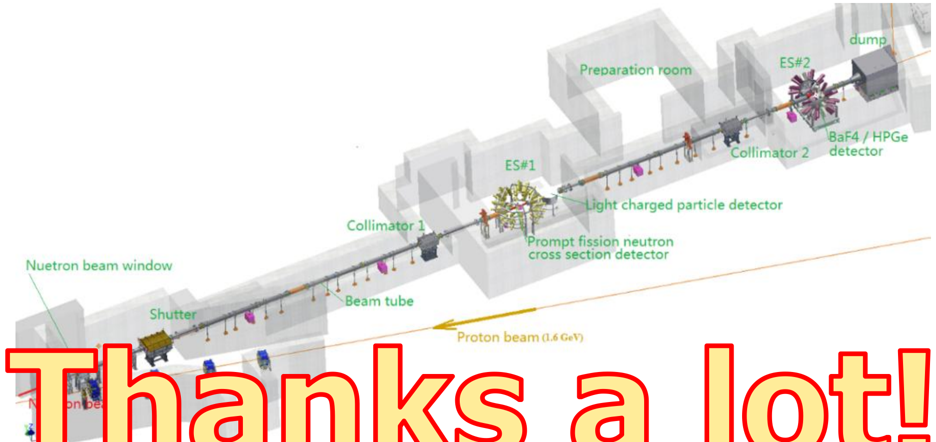
Summary

- A series of fission cross-sections have been measured at CSNS Back-n, and we continue to make contributions to nuclear data community
- The Back-n facility performance (flux, energy resolution) will be largely improved with the CSNS-II upgrading project
- More kinds of samples and more types of detectors will be developed, adapting to the improvement of the facility



Thanks a lot!

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