CSNS Back-n中子全截面测量研究及相关进展

陈永浩

中国科学院高能物理研究所
散裂中子源科学中心

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Outline

1. Motivations

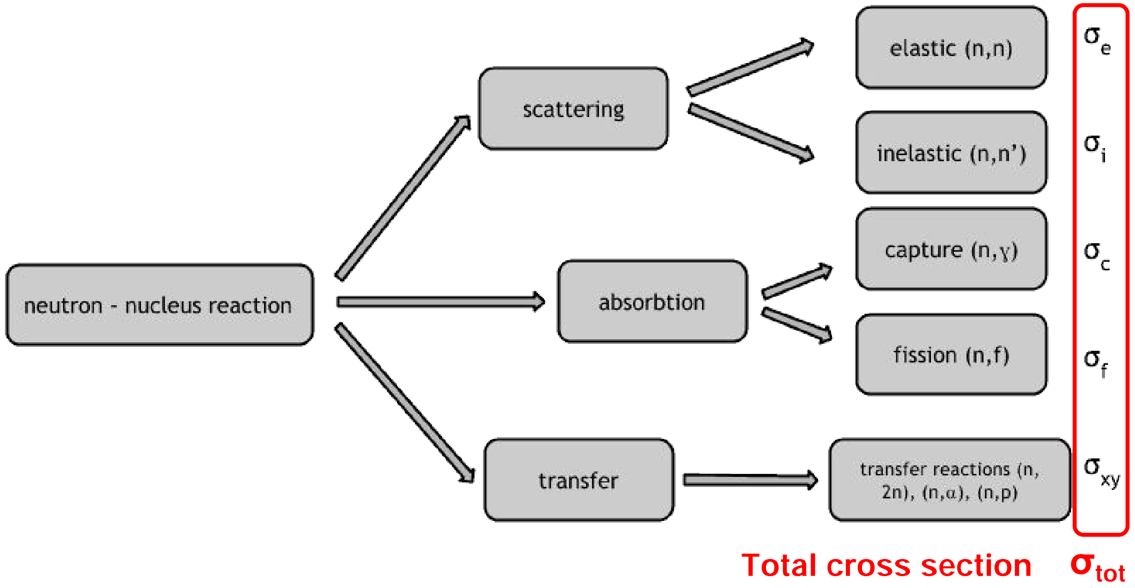
2. CSNS Back-n facility

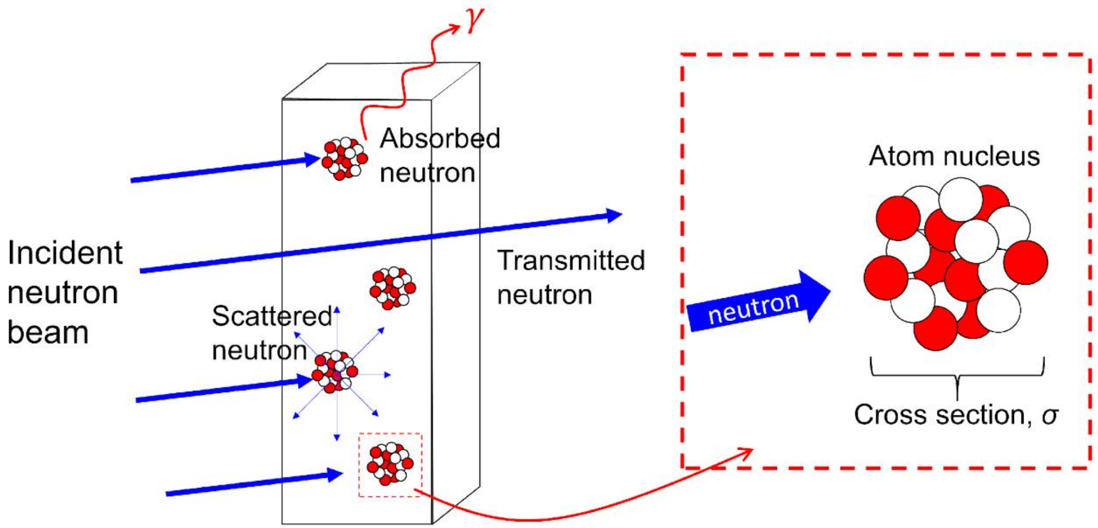
3. Neutron total XS measurement at CSNS Back-n

4. Summary and prospects

Motivations

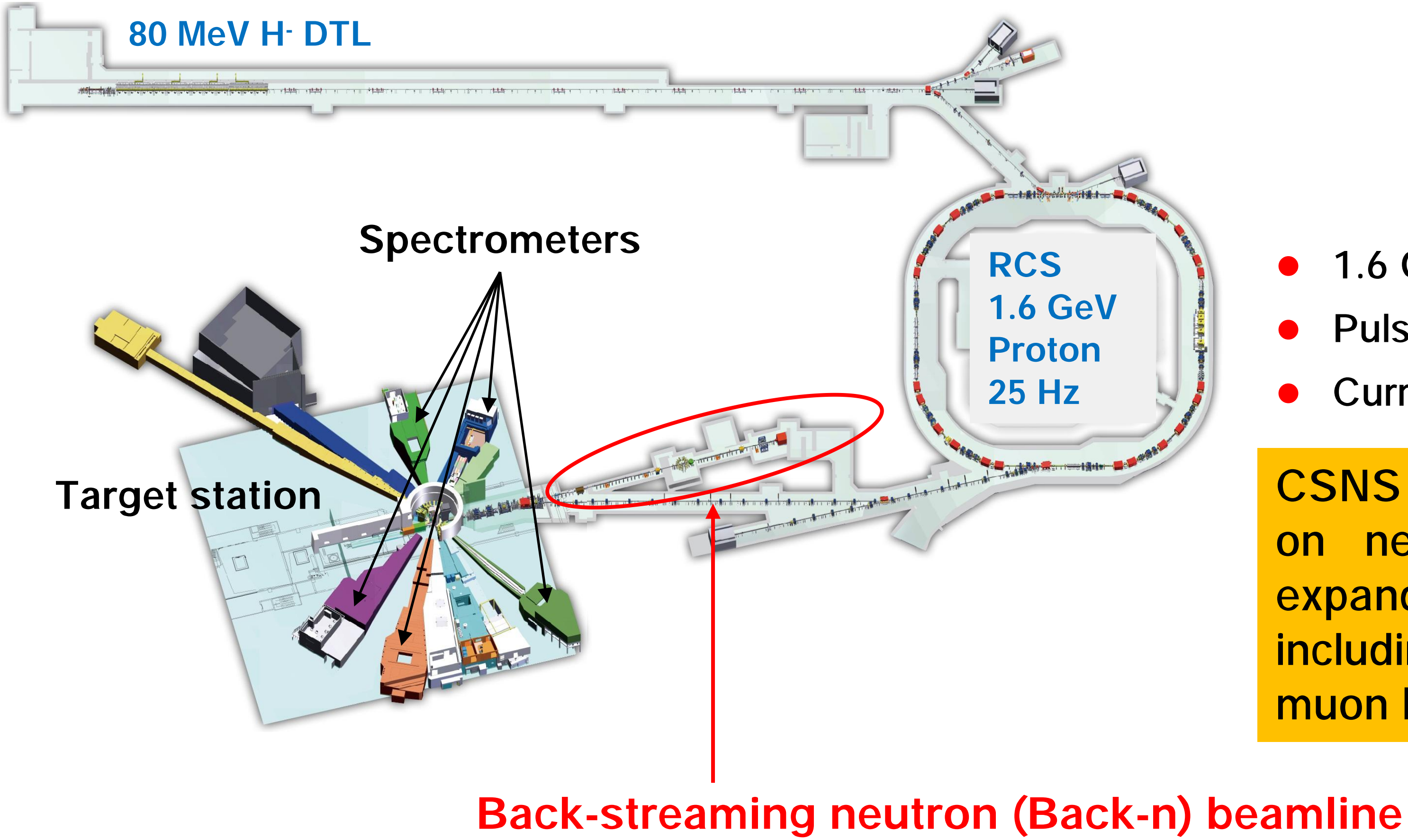
- The total cross section measures the probability of any interaction occurring when a neutron interacts with a target nucleus.
- *"Neutron total cross sections are perhaps the most fundamental measures of the nuclear interaction"* [*P. W. Lisowski et al. Nucl. Sci. Eng. (2024) 198: 1901-1910*], resulting in a strong constraint on nuclear models.
- The neutron total cross section is usually measured by the transmission method, which is an absolute measurement of high accuracy, making it highly valuable data.





Outline

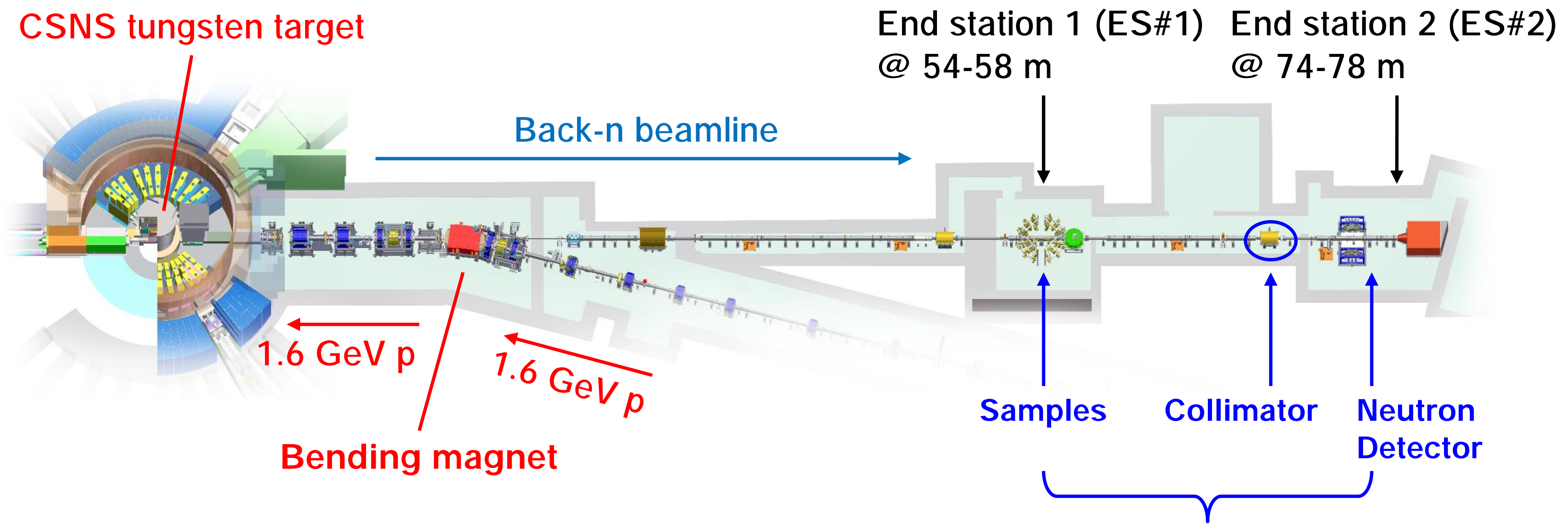
CSNS layout



- 1.6 GeV protons bombard tungsten target
- Pulsed beam with 25 Hz repetition frequency
- Current beam power: ~185 kW (2.88×10^{13} p/pulse)

CSNS is mainly used for material study based on neutron scattering technique, but beam expanded applications are actively involved, including **white neutron beam**, proton beam, muon beam, etc.

Back-n facility

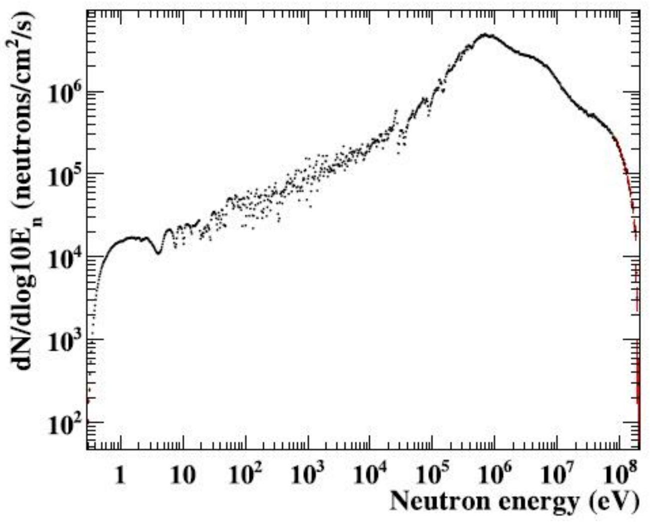


Suppress the multi-scattering background and only measure the transmitted neutrons!

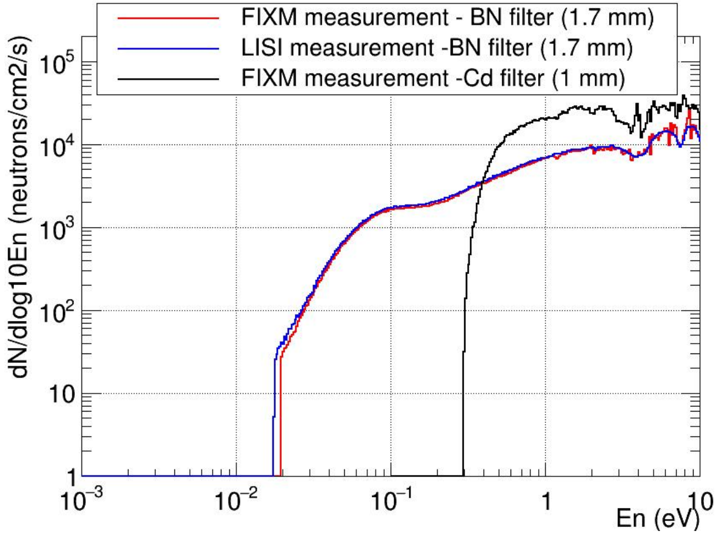
- Time-of-flight (TOF) technique
- Two end stations: ES#1 (~56 m) and ES#2 (~76 m)
- Wide neutron energy range (from thermal to ~300 MeV)
- Weak γ-flash due to back-streaming design
- **Ideally suited for total XS measurement due to its unique design**

Back-n beam characterization

Neutron flux of ES#2 (~10^7 n/cm²/s)



Thermal neutron Flux of ES#2



Yijia Qiu, <u>Yonghao Chen*</u> et al., NIMA (2025) 1075: 170383

Energy resolution at Back-n ES#2

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

Proton beam width Moderation

Resolution is better than 1% up to 1 MeV

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}

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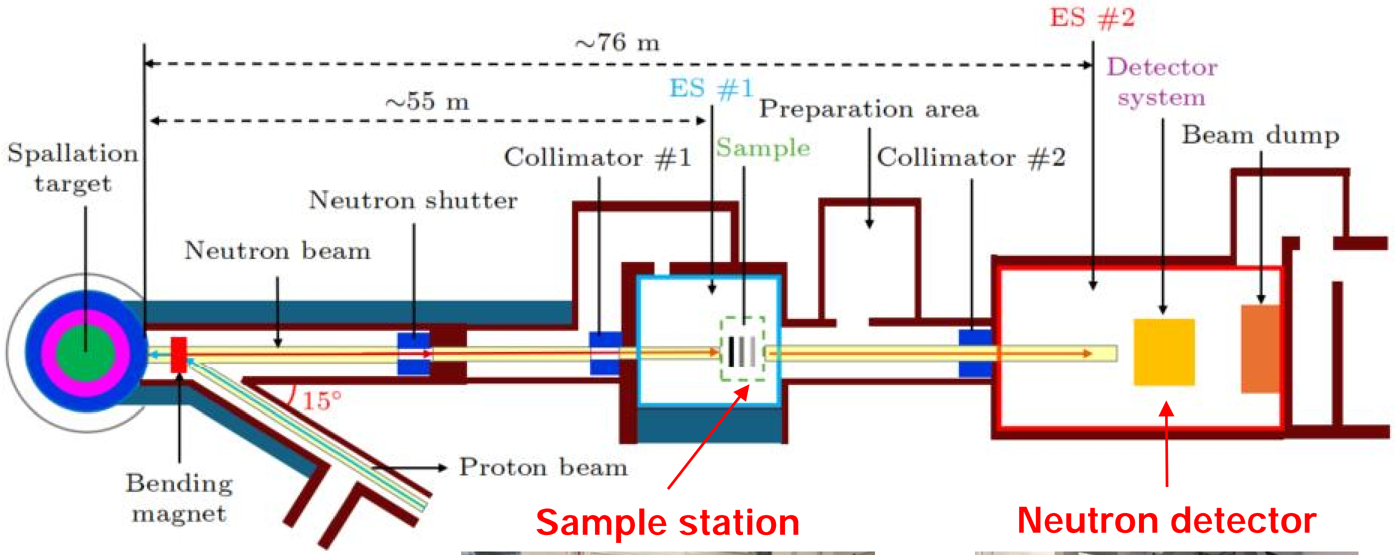
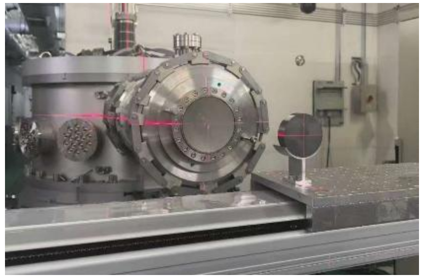
The experimental setup at CSNS Back-n



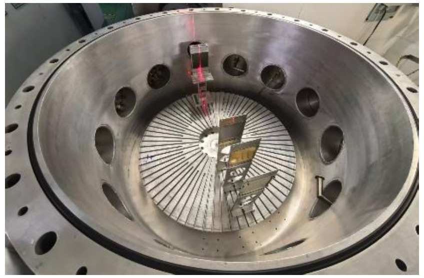
Sample station

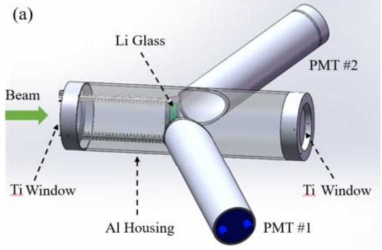
Neutron detector



Fission chamber (FIXM)

^{235}U converter





^{6}Lithium-glass (Li-GS)

$$\sigma_{tot}(E_n) = -\frac{1}{N_s}\ln T(E_n)$$

$$T(E_n) = \frac{N_{sample-in}(E_n) - B_{sample-in}(E_n)}{N_{sample-out}(E_n) - B_{sample-out}(E_n)}$$

- E_n Neutron energy
- N_s Sample quantity
- T Transmission rate
- $N_{sample\text{-}in}$ Neutron counts with sample-in
- $B_{sample\text{-}in}$ Background counts with sample-in

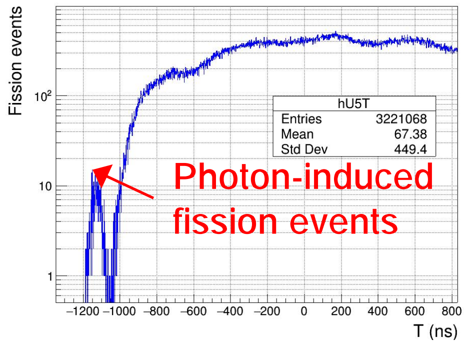
Neutron TOF technique

TOF method for calibrating neutron energy

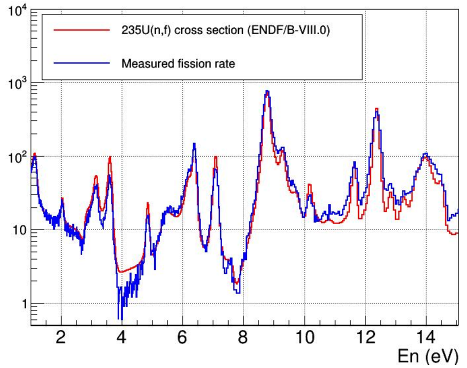
$$v = \frac{L}{TOF} = \frac{L}{T - T_0}$$

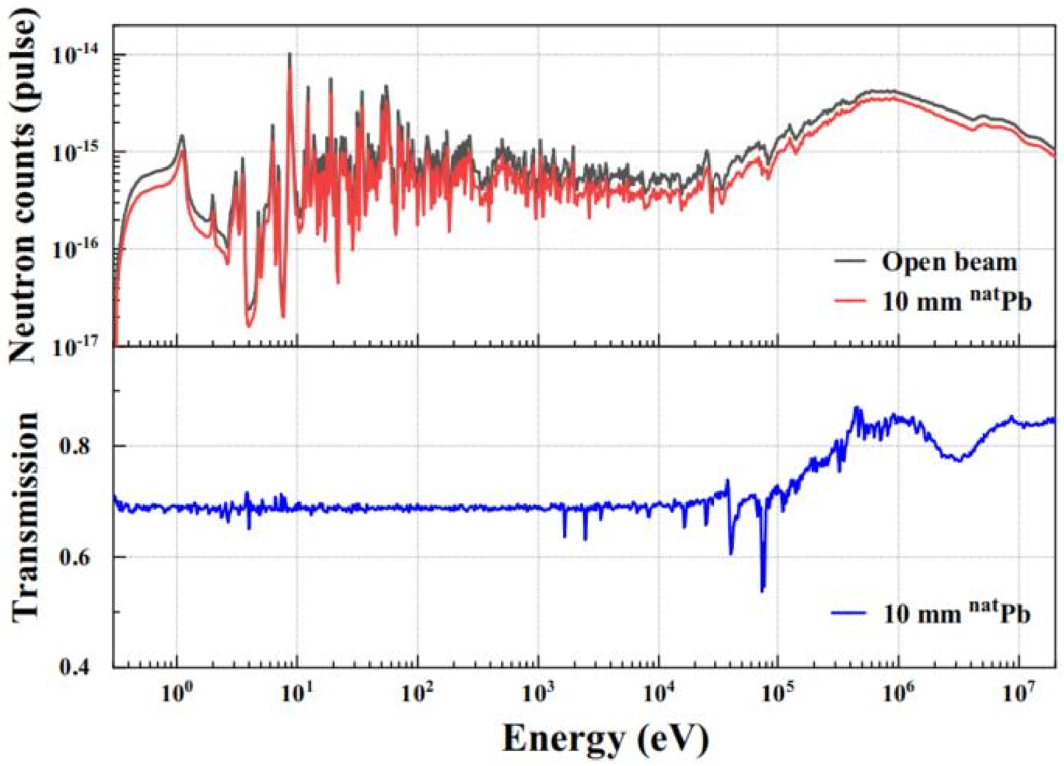
- L is determined by the resonance peaks of ^{235}U sample
- T_0 is determined by the γ-flash events

Time distribution of fission events



Comparison of fission rate and cross-section

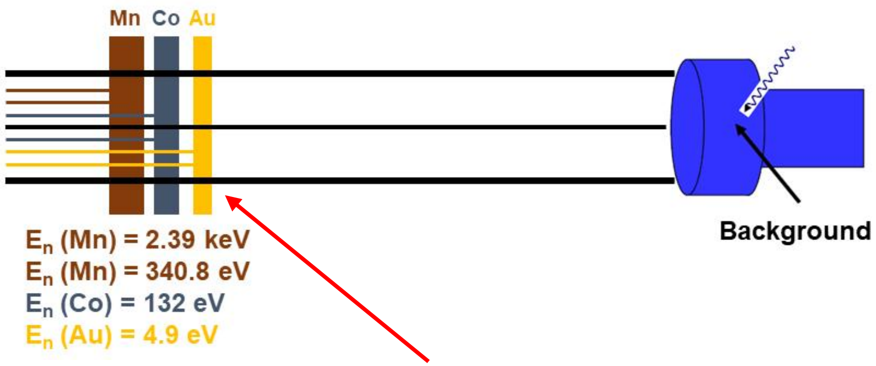




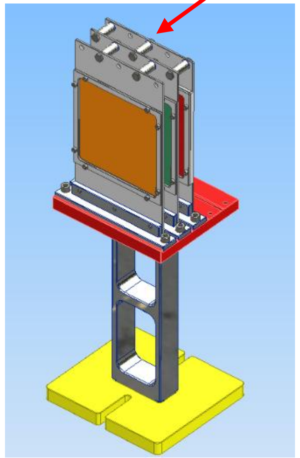
J. M. Xue et al., Nucl. Sci. Tech. (2024) 35: 18

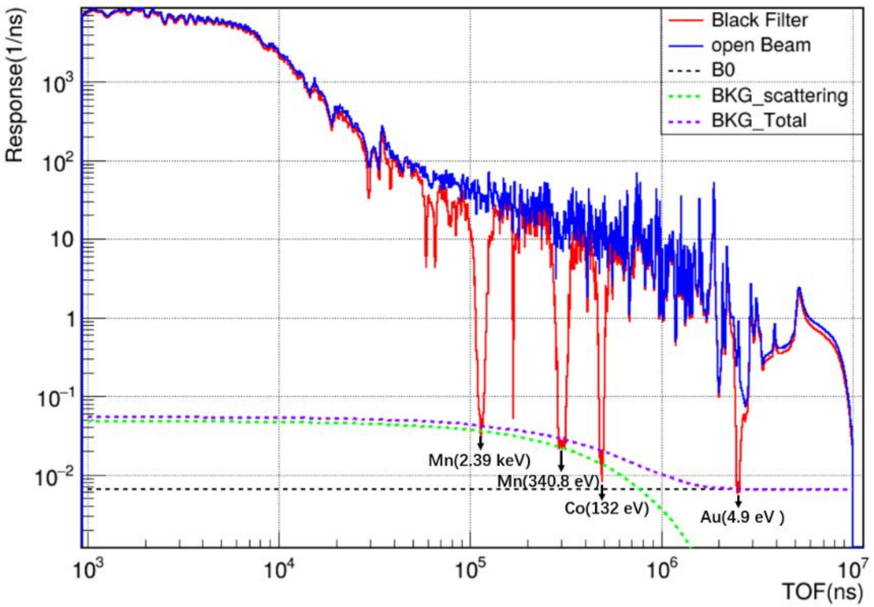
Background evaluation

Background evaluation based on the black resonance technique



Black resonance filters





$$B(t) = b_0 + b_1 e^{-\lambda_1 t}$$ **(GELINA JRC-Geel)**

- b_0 time independent background
- $b_1 e^{-\lambda_1 t}$ scattered neutron background

Background is negligible for most of the cases measured by the fission chamber

Uncertainty estimation

$$\sigma_{tot}(E_n) = -\frac{1}{N_s}\ln T(E_n)$$

Statistical errors

Weighting factor
$(1/\ln T)^2 < 0.19$

- Transmission rate: ~2%
- Background: ~0.2%
- Flux normalization: <0.1%

~2%

Systematic errors

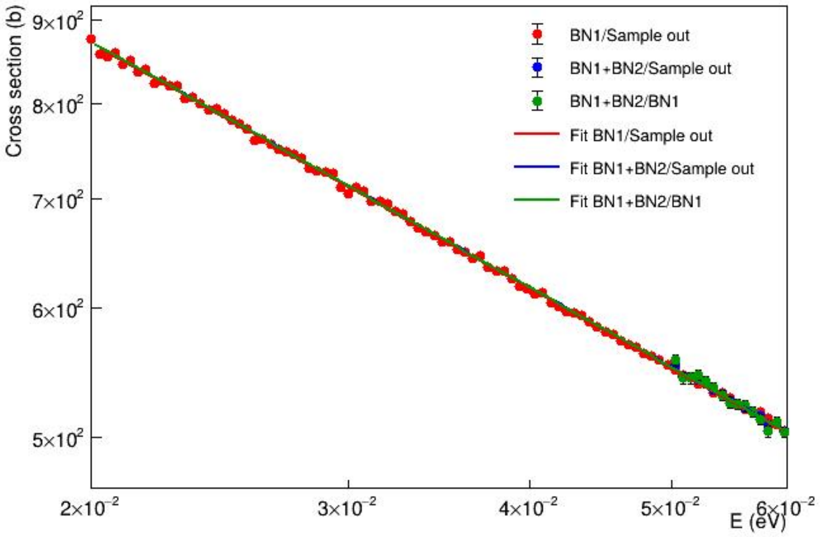
- Sample mass: negligible
- Sample area: negligible
- Impurities: <0.1%
- inhomogeneity of sample and beam profiles: ~0.5%

~0.51%

$$\frac{\Delta\sigma_{tot}}{\sigma_{tot}} = \sqrt{\left(\frac{1}{\ln T}\right)^2\left(\frac{\Delta T}{T}\right)^2 + \left(\frac{\Delta N_s}{N_s}\right)^2}$$

Total uncertainty: <1%

Example: ^{nat}B(n, tot) XS



Low transmission suppresses the statistical error, and vice versa

Total XS measurement at CSNS Back-n

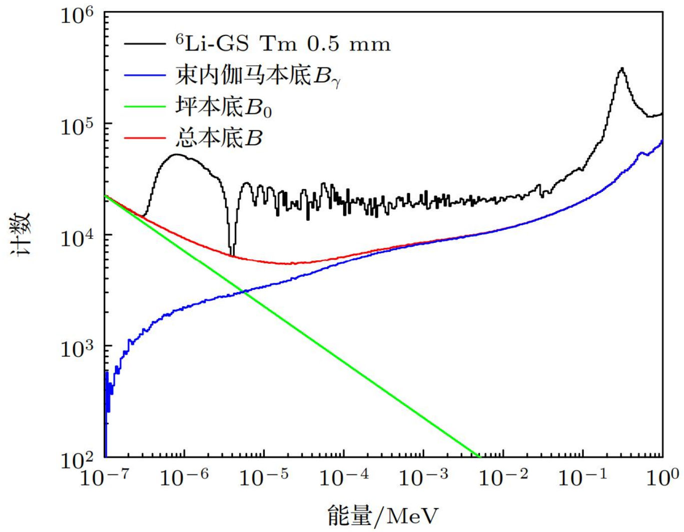
List of publications

Year	Nucleus	Detector	Energy range	Resonance parameters	User affiliation	Reference
2019	^{nat}C	FIXM	1 eV – 20 MeV	–	九院二所	*Nucl. Sci. Tech.* (2019) 30: 139
2021	^{27}Al	FIXM	1 eV – 20 MeV	–	九院二所	*Eur. Phys. J. A* (2021) 57: 232
2022	^{nat}Li	FIXM	0.4 eV – 20 MeV	Yes	上海应物所	Acta Phys. Sin. (2022) 71: 052901
2023	^{209}Bi	FIXM	0.3 eV – 20 MeV	Yes	南华大学	*Chin. Phys. C* (2023) 47: 124001
2024	^{9}Be	FIXM	0.3 eV – 120 MeV	–	九院二所	*Chin. Phys. C* (2024) 48: 084001
2024	^{nat}Cr	FIXM	0.3 eV – 20 MeV	–	南华大学	*Chin. Phys. C* (2024) 48: 104002
2024	^{nat}Pb	FIXM	0.3 eV – 20 MeV	–	南华大学	*Nucl. Sci. Tech.* (2024) 35: 18
2025	^{nat}Fe	FIXM	0.3 eV – 150 MeV	–	九院二所	*Phys. Lett. B* (2025) 863: 139355
2026	^{nat}Ag	FIXM	10 – 100 eV	Yes	散裂	物理学报 (2026) 75: 020110
2026	^{169}Tm	Li-GS	1 – 100 eV	Yes	原子能院	物理学报 (2026) 75: 020103

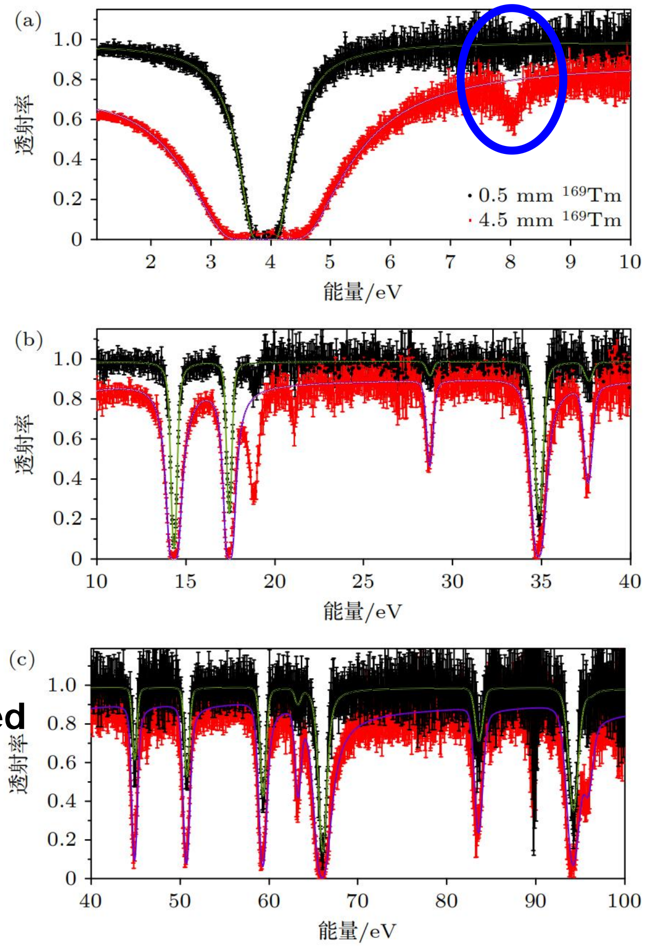
Total XS measurement at CSNS Back-n

^{169}Tm (n, tot) measurement (原子能院)

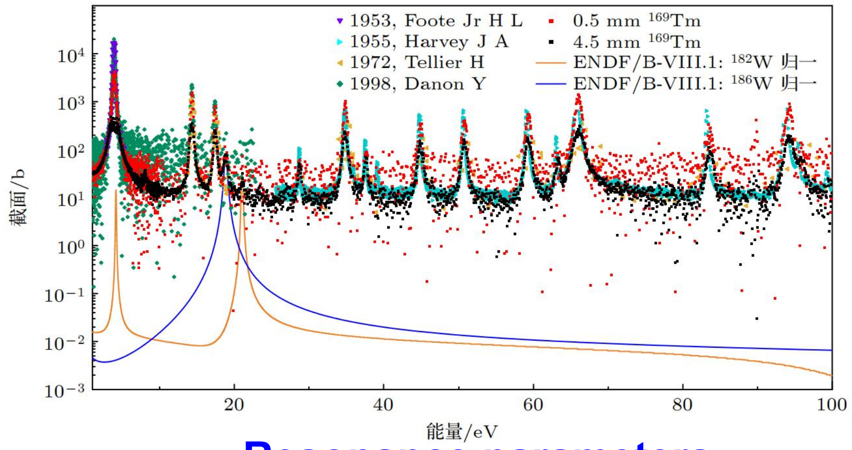
Background



Transmission rate



Total XS



Resonance parameters

E_n /eV		Γ_n /meV		Γ_γ /meV		k		J
本工作	ENDF/B-VIII.1	本工作	ENDF/B-VIII.1	本工作	ENDF/B-VIII.1	本工作	ENDF/B-VIII.1	
3.908±0.002	3.906	7.38±0.24	7.47	105.70±7.40	102.4	5.17±0.21	5.22	1
14.33±0.01	14.32	9.13±0.16	9.12	98.80±6.92	97.1	2.09±0.14	2.08	0
17.43±0.01	17.42	5.46±0.04	5.74	81.40±5.70	81.4	1.28±0.04	1.34	0
28.73±0.26	28.90	0.21±0.01	0.21	93.70±6.56	95.0	0.16±0.01	0.16	1
34.85±0.01	34.79	6.86±0.06	5.87	86.00±6.02	86.0	4.76±0.06	4.12	1
37.64±0.06	37.51	0.45±0.02	0.46	123.96±8.68	86.0	0.34±0.02	0.34	1
44.88±0.01	44.79	2.91±0.18	3.47	99.00±6.93	93.0	2.12±0.17	2.51	1
50.74±0.07	50.58	5.06±0.37	5.40	89.01±6.23	79.0	3.59±0.33	3.79	1
59.29±0.02	59.07	10.13±0.21	10.0	86.00±6.02	84.0	6.80±0.18	6.70	1
63.17±0.01	62.97	0.96±0.06	1.00	78.02±5.46	78.0	0.71±0.06	0.74	1
65.98±0.01	65.75	139.18±0.49	113	83.00±5.81	83.0	13.00±2.28	11.96	0
83.55±0.13	83.18	7.50±0.09	7.53	85.00±5.95	85.0	5.17±0.09	5.19	1
94.16±0.06	94.10	35.08±1.92	32.0	119.12±8.14	86.0	18.56±1.19	17.49	1
95.95±0.02	95.40	4.25±0.32	3.80	71.00±4.97	71.0	1.00±0.29	0.90	0

- One of important rare-earth element
- Reactor neutron poison
- The resonance at 8.037 eV (not included in the library) is confirmed

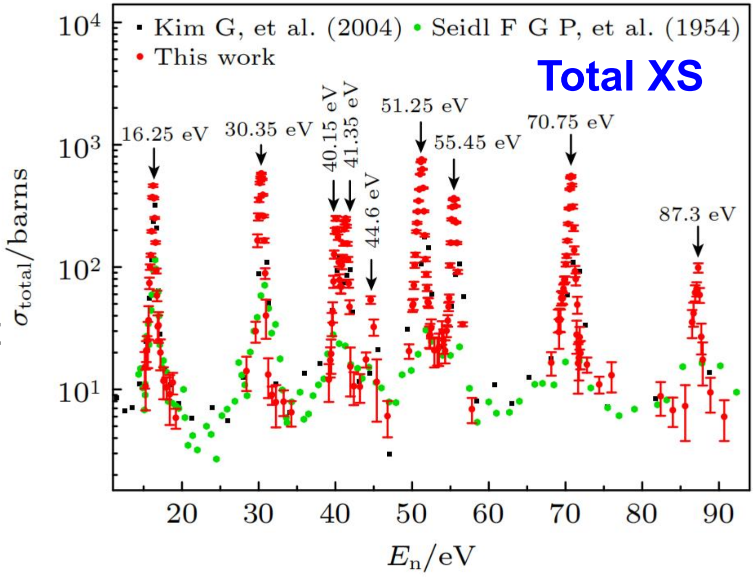
杨皓岚等, 物理学报 (2026) 75: 020103

Total XS measurement at CSNS Back-n

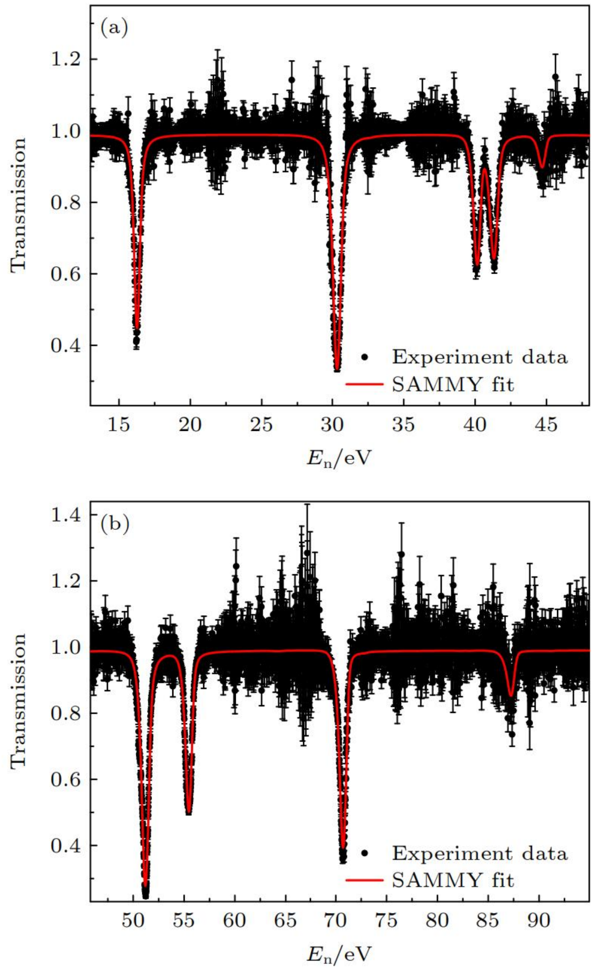
^{nat}Ag (n, tot) measurement (散裂中子源科学中心)

- Important element in archaeometry
- Large discrepancies exist in current literature between measurements and evaluations
- Resonance parameters from 1 to 100 eV are obtained

唐生达, **<u>陈永浩*</u>** 等,
物理学报 (2026) 75: 020110



Transmission rate



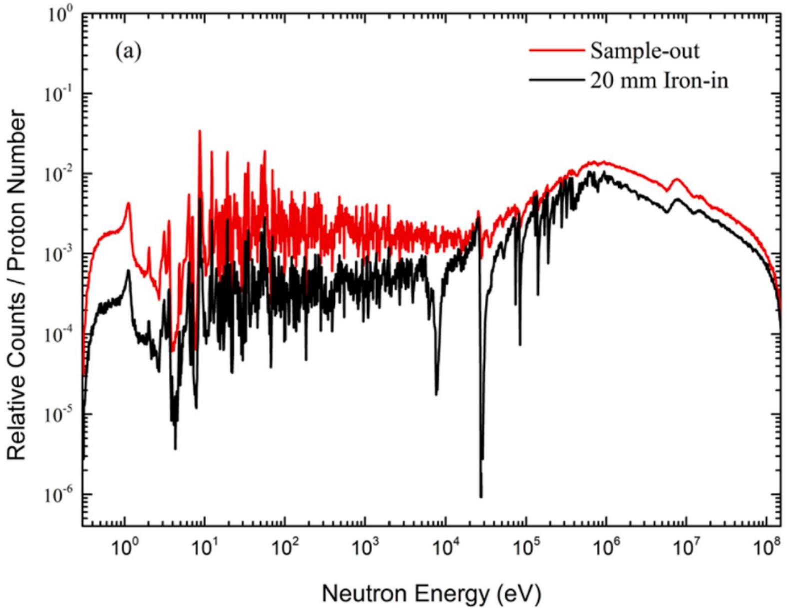
Resonance parameters

	E_{res} /eV				Γ_n/meV			
	This work	Li et al.[28]	ENDF/B-VIII.0	CENDL3.2	This work	Li et al.[28]	ENDF/B-VIII.0	CENDL3.2
^{107}Ag	16.33	16.34	16.30	16.30	7.16	13.70	11.6	11.80
	41.52	41.57	41.57	41.50	4.60	4.40	5.37	5.40
	44.90	44.92	44.90	44.80	1.10	1.3	1.2	3.40
	51.44	51.57	51.56	51.40	21.97	21.8	23.9	21.60
^{109}Ag	30.51	30.57	30.60	30.40	7.66	10.58	7.33	7.30
	40.33	39.88	40.30	40.10	4.60	5.31	5.3	6.20
	55.72	55.92	55.80	55.70	38.32	31.96	37.20	36.80
	71.04	—	71.0	70.08	26.15	—	24.14	26.40
	87.57	—	87.70	87.70	5.13	—	6.40	6.20

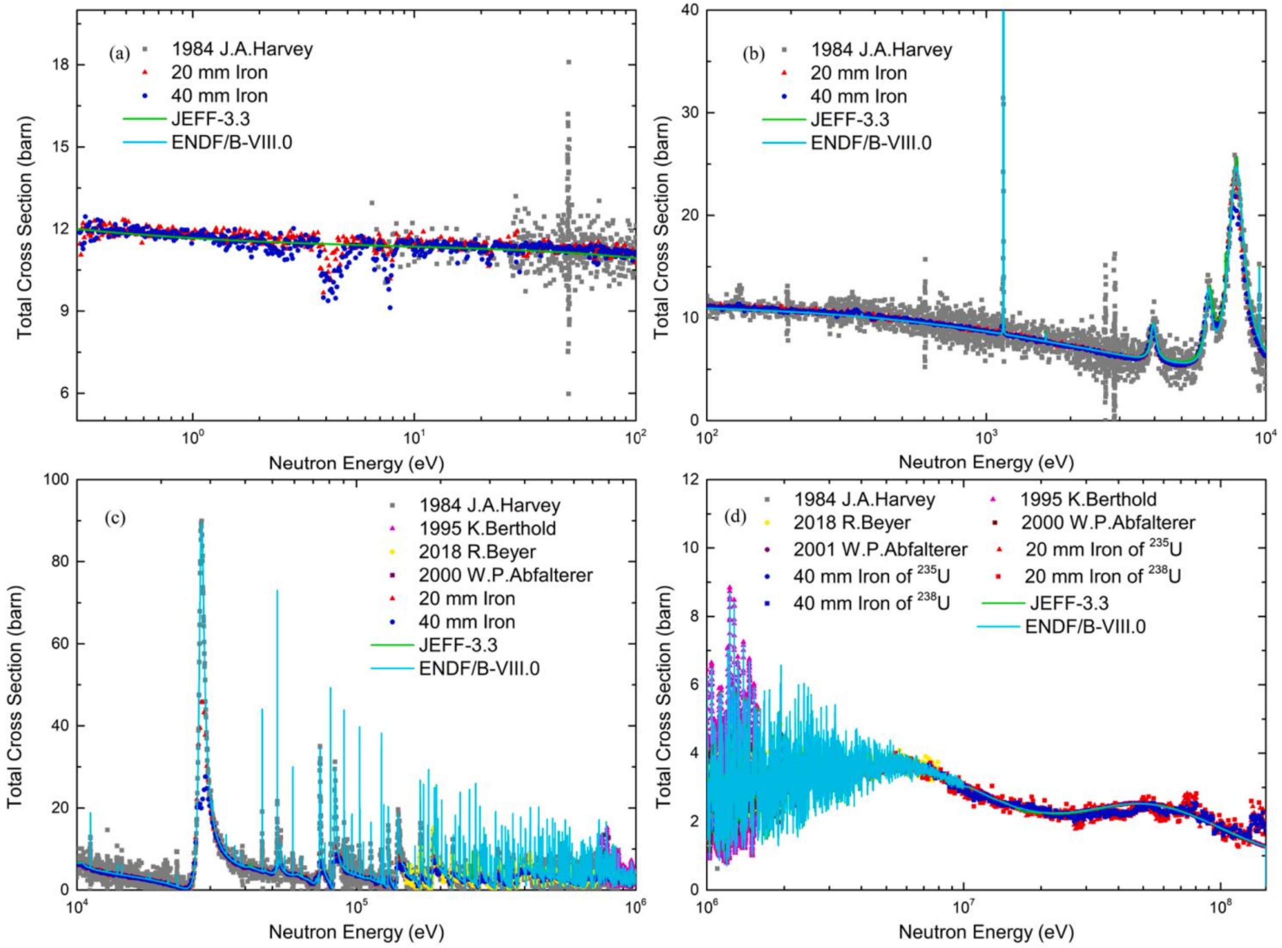
Total XS measurement at CSNS Back-n

natFe (n, tot) measurement (九院二所)

Sample-in/sample-out measurement



Total XS



- Iron is widely used as the structural and shielding materials of nuclear devices
- The total XS in a wide range, from 0.3 eV to 150 MeV, is obtained with high accuracy (<2%)

J. B. Bai et al., *Phys. Lett. B* (2025) 863: 139355

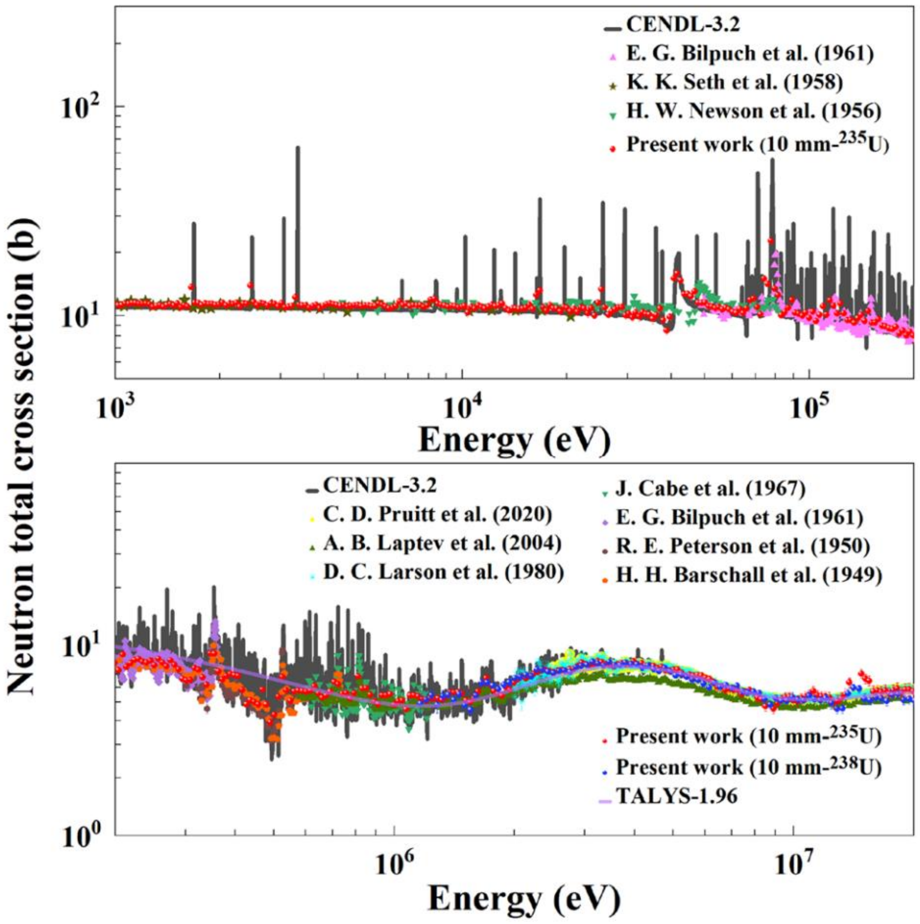
Total XS measurement at CSNS Back-n

^{nat}Pb (n, tot) and ^{209}Bi (n, tot) measurement (南华大学)

- Coolant of the lead-cooled fast reactor
- The total xs from 0.3 eV to 20 MeV is obtained
- Resonance parameters of ^{209}Bi from 0.5 to 20 keV are obtained

J. M. Xue et al., *Chin. Phys. C* (2023) 47: 124001
J. M. Xue et al., *Nucl. Sci. Tech.* (2024) 35: 18

^{nat}Pb (n, tot) XS



Resonance parameters of ^{209}Bi

Table 4. Extracted neutron resonance parameters of ^{209}Bi.

Reference	E_{res}/eV	Γ_γ/eV	Γ_n/eV
Present	800.5	0.0342	4.9883
ENDF/B-VIII.0	800.0	0.0387	4.6364
C. Domingo-Pardo [16]	801.6	0.0333(0.012)	4.309(0.145)
A. R. De [5]	800.0	–	4.655(0.05)
U. N. Singh [17]	800.0	–	4.6(0.4)
Present	2340.5	0.0349	27.325
ENDF/B-VIII.0	2310.0	0.046	17.889
C. Domingo-Pardo	2323.8	0.0268(0.017)	17.888(0.333)
A. R. De	2312.0	–	18.1(0.3)
U. N. Singh	2312.0	–	19.5(1.0)
Present	5110.5	0.0666	3.6903
ENDF/B-VIII.0	5114.0	0.065	5.64
C. Domingo-Pardo	5114.0	0.065(0.002)	5.64(0.27)
A. R. De	5108.0	–	5.74(0.14)
U. N. Singh	5112.0	–	5.4(0.6)
R. Macklin [18]	5113.0	–	6.49(0.14)
J. Morgenstern [19]	5084.0	–	6.05
Present	12042	0.1191	280.98
ENDF/B-VIII.0	12098	0.117	258.889
A. R. De	12123	–	259.0(6.0)
U. N. Singh	12150	–	270.0(45.0)
R. Macklin	12100	–	292.0(26.0)
J. Morgenstern	12100	–	267.0
Present	15476	0.1142	87.601
ENDF/B-VIII.0	15510	0.11	114.444
A. R. De	15548	–	129.0(2.0)
U. N. Singh	15540	–	118.0(20.0)
R. Macklin	15510	–	126.0(11.0)
J. Morgenstern	15470	–	118.0

$^{10}B(n, \alpha)$ measurement at thermal region at CSNS Back-n

- 绝大大部分中子核反应截面是以标准截面为参考的相对测量，**标准截面自身的误差是不可避免的系统误差。**
- $^{10}B(n,\alpha)$ 是常用的标准截面，但是在热中子能区EXFOR库只收录了一组实验测量 (Prosdocimi A et al., 1963), 使其成为**标准截面体系中最弱的点** (IAEA Report, INDC (NDS)-0865)。
- $^{10}B(n, \alpha)$ 反应截面决定BNCT中的照射剂量，是反应堆控制与反应性调节的核心物理机制，是中子探测和成像技术的关键转换材料。

➢ **通过^{10}B全截面高精度测量热中子能区$^{10}B(n, \alpha)$反应截面**

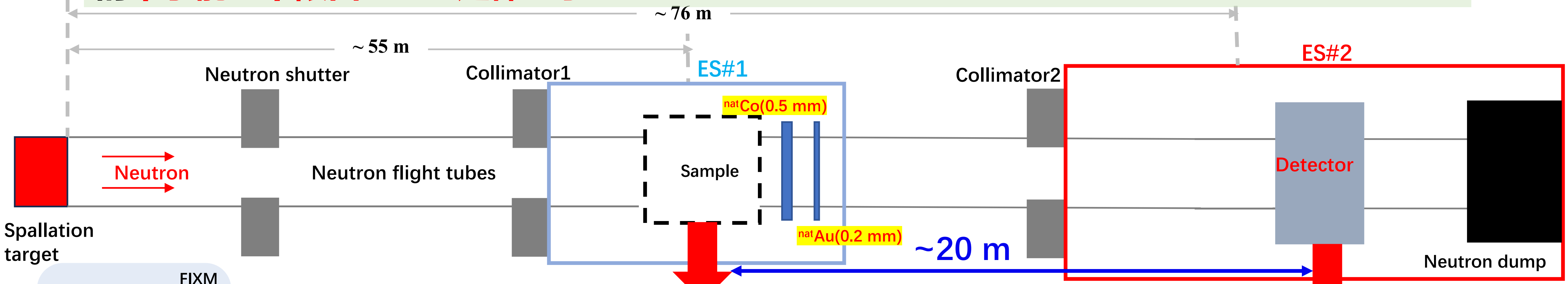
$$^{10}B(n, tot) \begin{cases} ^{10}B(n, \alpha)^{7}Li & \sim 3844.12\ b\ (0.0253\ eV) \\ ^{10}B(n, el) & \sim 2.19\ b\ (0.0253\ eV) \\ ^{10}B(n, \gamma) & \sim 0.40\ b\ (0.0253\ eV) \end{cases}$$

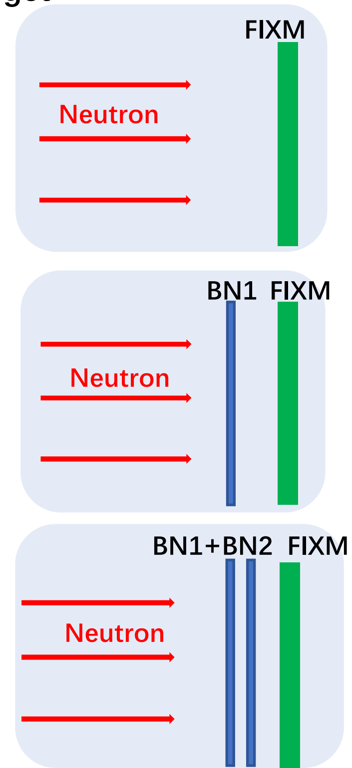
$^{10}B(n,el)$ and $^{10}B(n,\gamma)$ 反应截面对全截面的贡献小于0.1%，通过测量全截面后进行微小修正即可得到$^{10}B(n,\alpha)$ 反应截面。**基于透射法的全截面测量是精度非常高的绝对测量，不依赖于任何其他参考截面。**

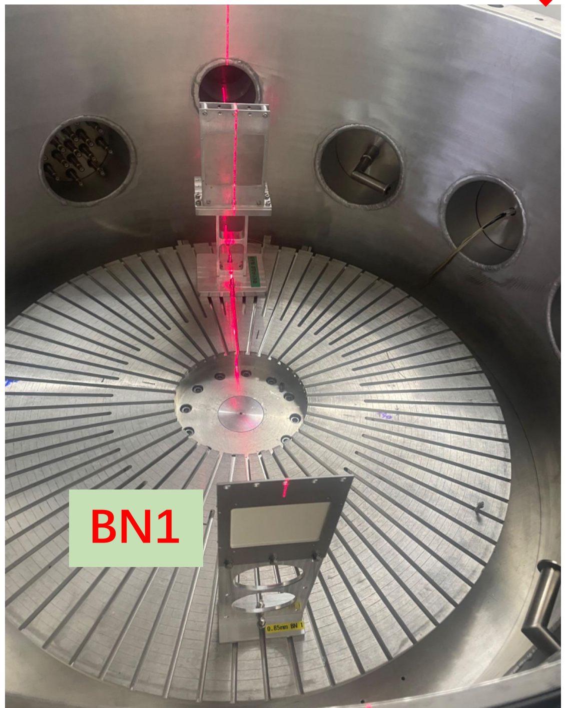
$$(n,\alpha) = (n,tot) - (n,el) - (n,\gamma)$$

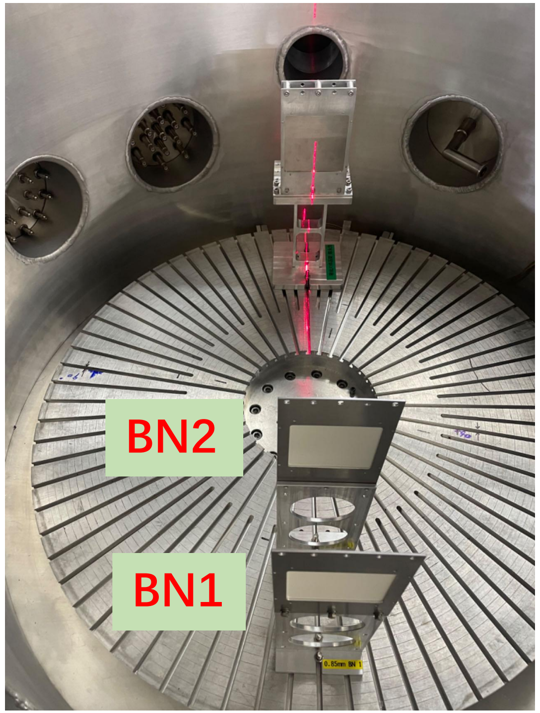
^{10}B(n, α) measurement at thermal region at CSNS Back-n

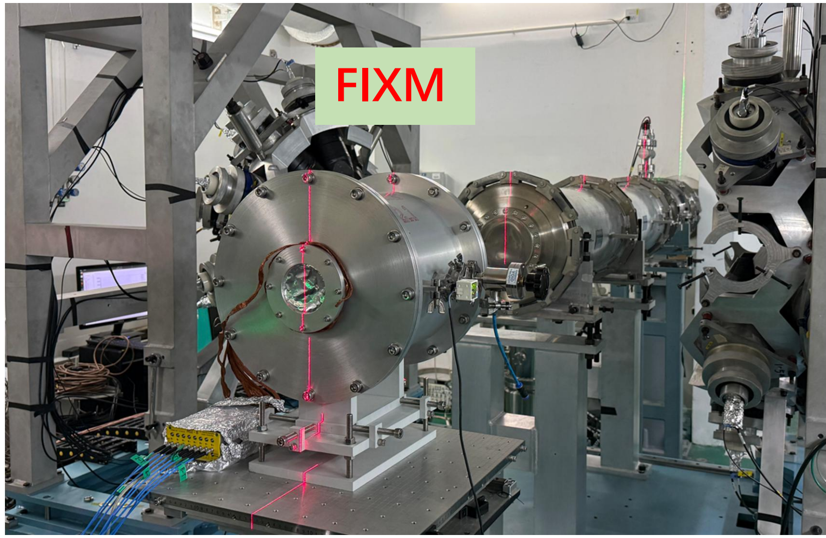
本实验是Back-n在热中子能区的首次测量，通过移除前端镉吸收片，我们将Back-n束流的**中子能量下限由0.3 eV延伸至了0.02 eV**！



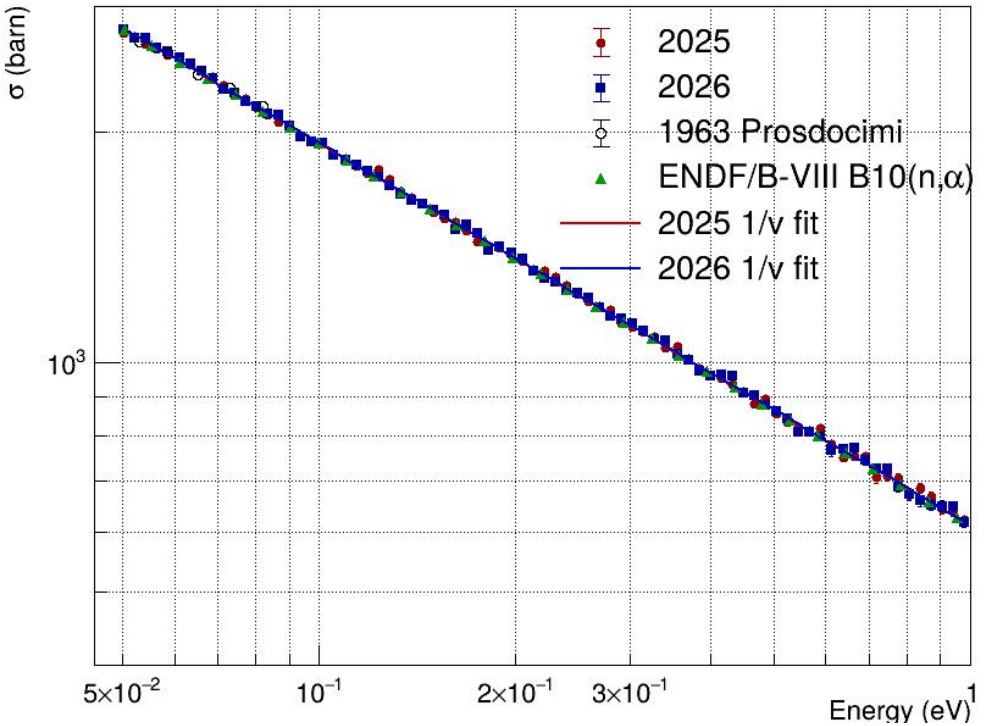


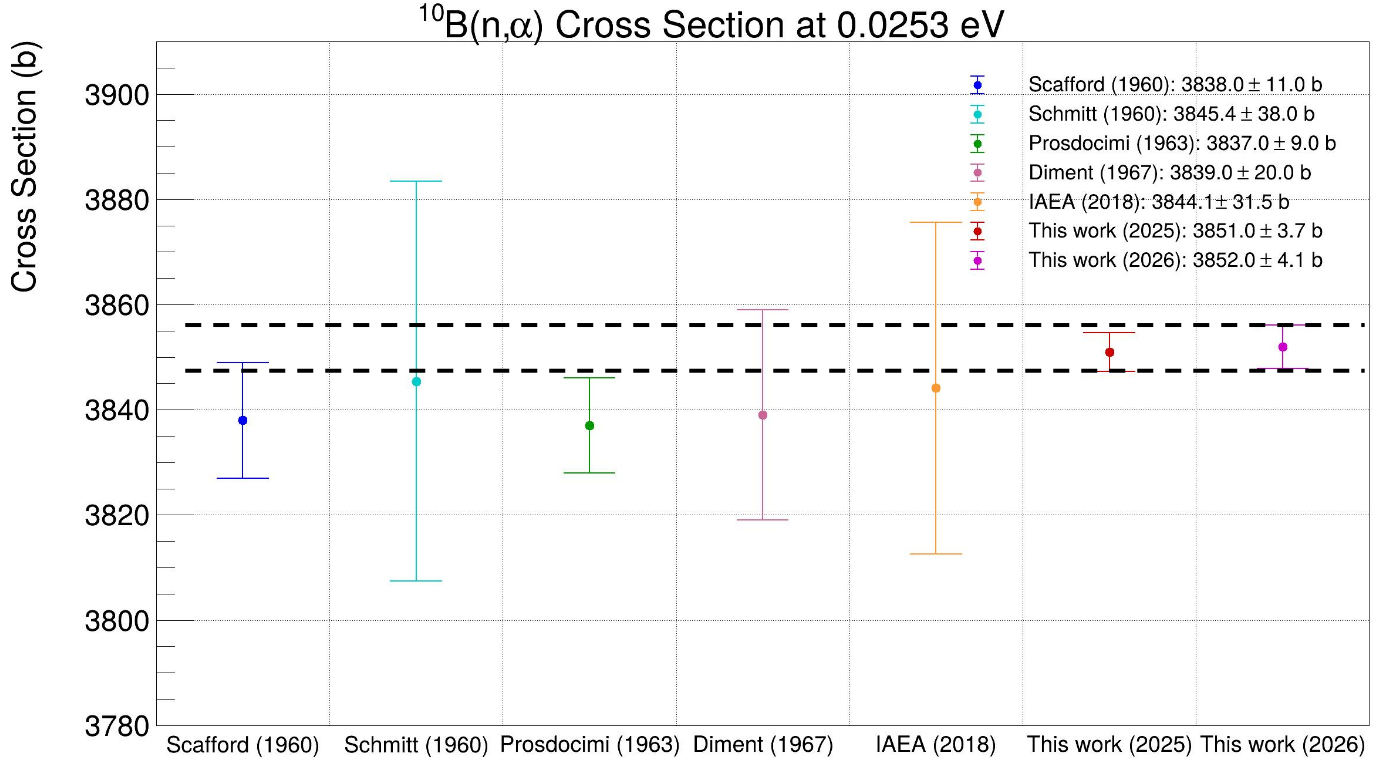






$^{10}B(n, \alpha)$ measurement at thermal region at CSNS Back-n





提供最新高精度测量结果

与早期实验有明显偏差

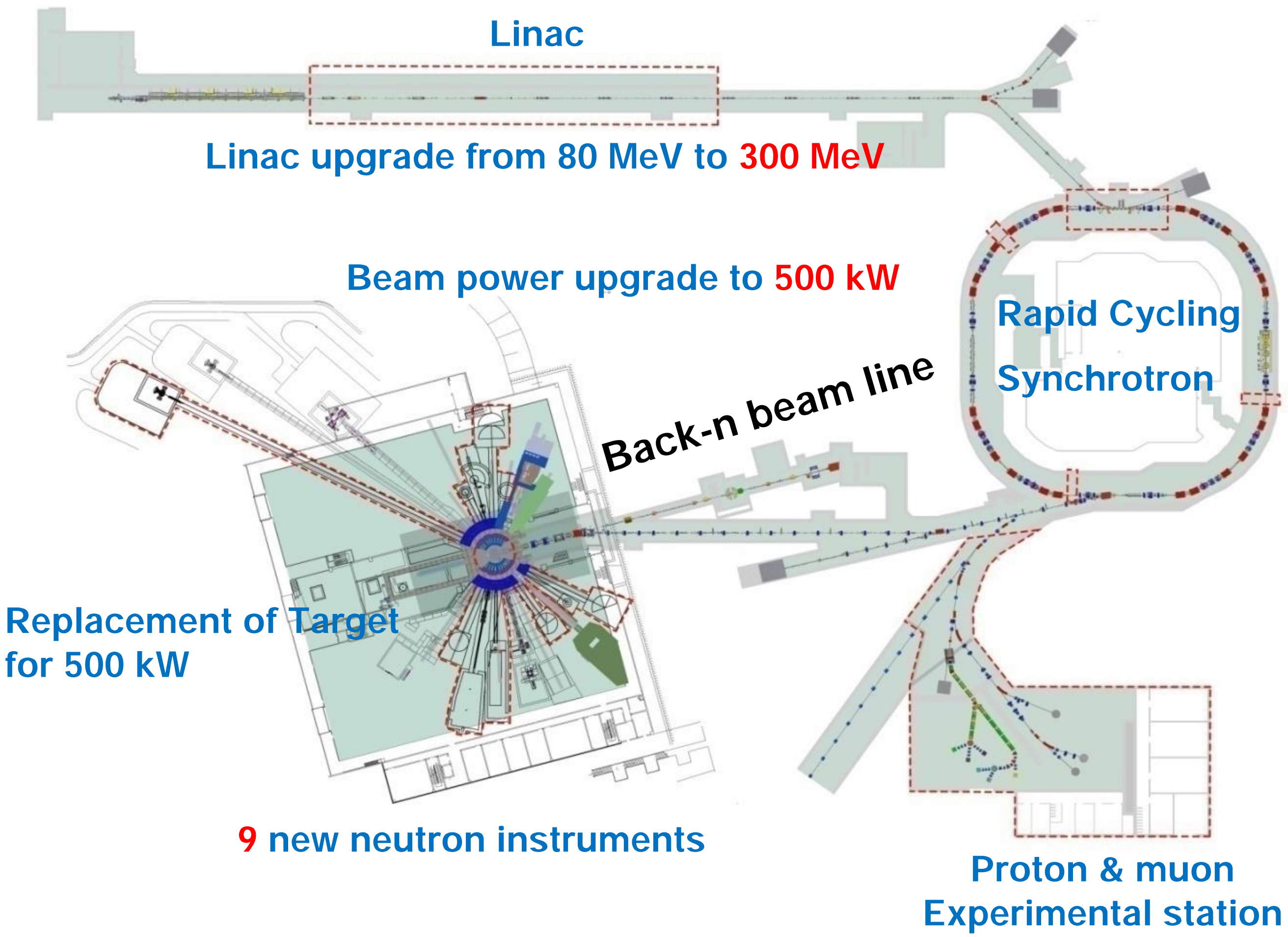
有望补齐IAEA标准截面体系最弱短板

详见彭俊勇报告：7月16日下午，分会场三

Outline

Summary and prospects

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

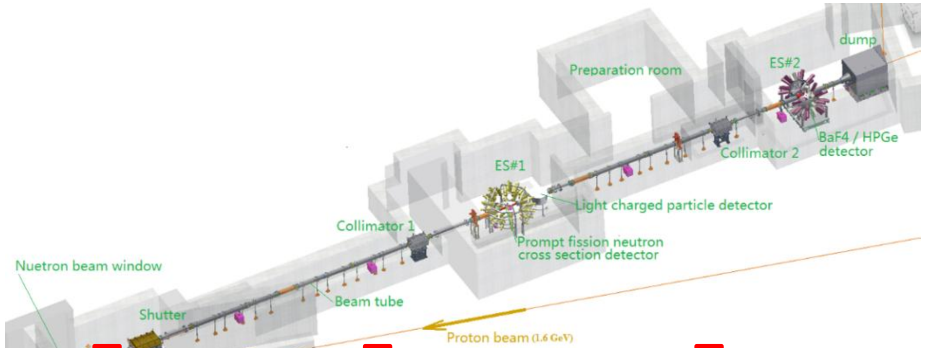


- Project Budget: 2.9 BCNY (~380 MEUR)
- Construction duration (~6 years): 2024.3~2029.10
- New spectrometers and end stations will be built

For Back-n beam line, the flux will be increased by a factor of 5, which will facilitate measurements involving small cross sections or small sample quantities.

Summary and prospects

- CSNS Back-n is ideally suited for neutron total XS measurement owing to its unique geometric design
- A series of total cross sections have been measured with high accuracy, and we continue to make contributions to nuclear data community
- The Back-n facility performance will be largely improved with the CSNS-II upgrading project
- More kinds of samples will be measured and more types of detectors will be developed, adapting to the improvement of the facility
- The total cross-section measurement can be combined with other reaction measurement (^{10}B case)



Thanks a lot!

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