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

CSNS

热中子能区$^{10}B(n,\alpha)$截面的实验测量

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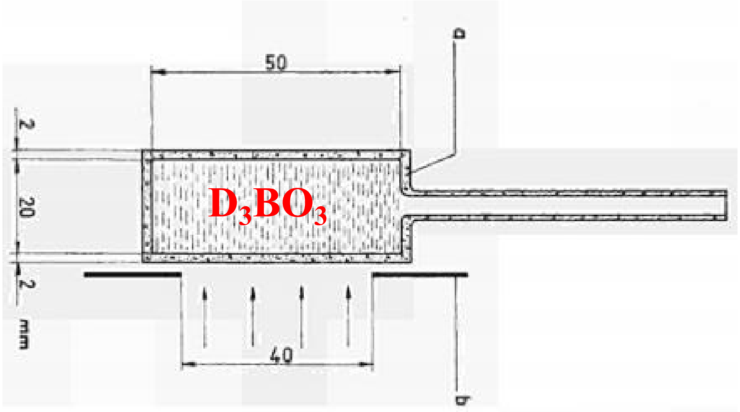
Outline

Motivation

- Neutron reaction cross sections are always measured relative to neutron cross-section standards (σ_{std}). Relative measurement avoids measuring the neutron flux but is limited by the precision of the σ_{std}.
- The ^{10}B(n,α) cross-section is one of the commonly used σ_{std}. **However, there is only one dataset (Prosdocimi A et al., 1963) in EXFOR** provides the ^{10}B(n, α) cross section in the thermal region, making it one of the weakest points in the neutron standards.
- **In BNCT**, **the ^{10}B(n, α) cross section** determines the tumor dose accuracy; in **reactors**, it governs control rod and soluble boron safety; in **detection and imaging**, it defines neutron conversion sensitivity; in **neutron sources**, it controls thermal-neutron filtering and beam quality.

➢ Comparison with previous measurement

Prosdocimi A et al., Nuclear Energy. Parts A/B. Reactor Science and Technology, 1963, 17(2): 83-87.



	Previous measurement	Back-n measurement	
Sample:	D_3BO_3 solution	BN sheet (~1 mm)	**Less impurities**
Neutron Source:	Reactor Neutron Source	Spallation Neutron Source	**High resolution (<0.1% at thermal)**

➢ Determine the $^{10}B(n, \alpha)$ cross section based on the total cross-section measurement

^{10}B(n, tot) →
- ^{10}B(n, α)^{7}Li ~ 3844.12 b (0.0253 eV)
- ^{10}B(n, el) ~ 2.19 b (0.0253 eV)
- ^{10}B(n, γ) ~ 0.40 b (0.0253 eV)

The ^{10}B(n,el) and (n,γ) cross sections contribute less than **0.1%** to the total cross section at thermal energy. Thus, the ^{10}B(n, α)^{7}Li cross section can be accurately deduced from the total cross section, which is supposed to be **very precise absolute measurement via the transmission measurement**.

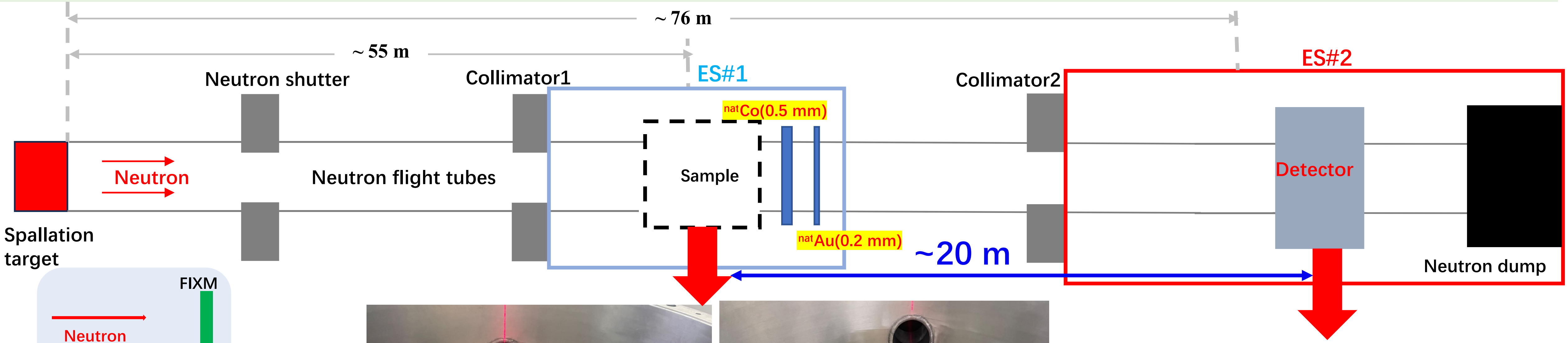
$$(n,\alpha) = (n,tot) - (n,el) - (n,\gamma)$$

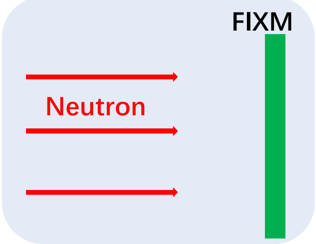
➢ Literatures of $^{10}B(n, tot)$ cross section measurement

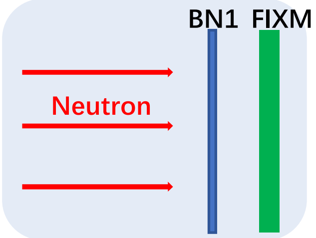
	Safford (1960)	Schmitt (1960)	Diment (1967)
^{10}B(n, tot) (b)	3841 ± 12 (absorption)	3848 ± 38	3839 ± 20
^{10}B(n, α) (b)	3838	3845	3836

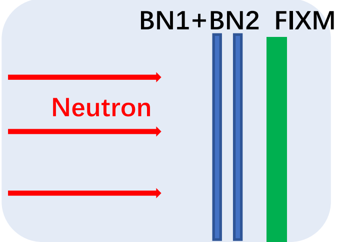
Experimental setup

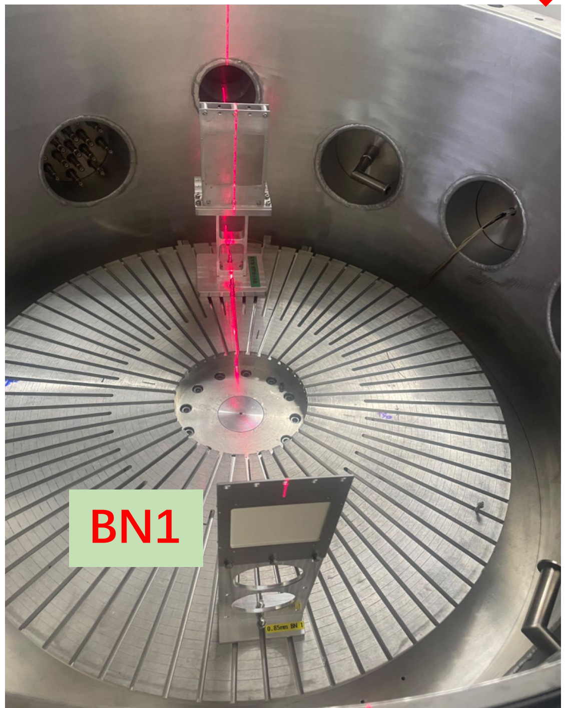
This work presents the first thermal neutron measurement ever conducted at the Back-n facility. A Cd filter previously placed in the beam absorbed neutrons below **0.3 eV**. The accessible energy range has now been extended down to **0.02 eV by removing the Cd filter.**

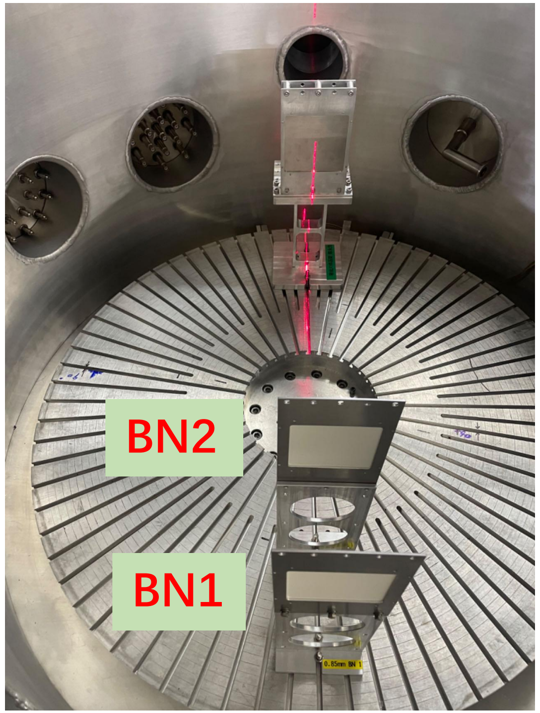


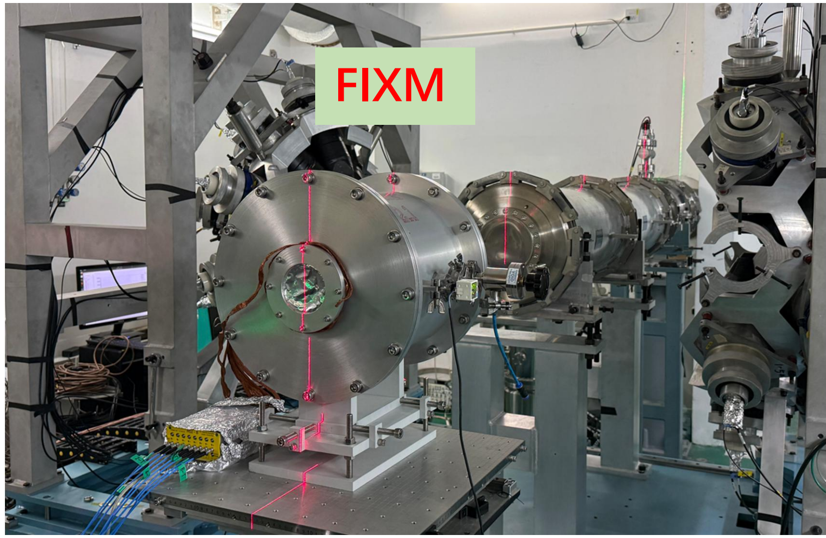










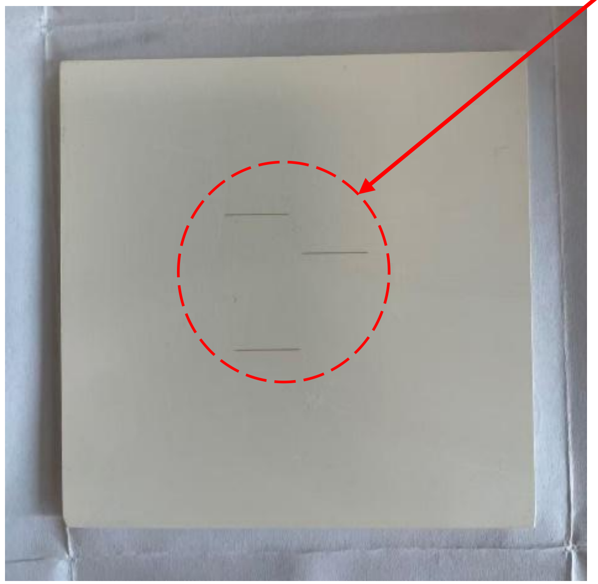


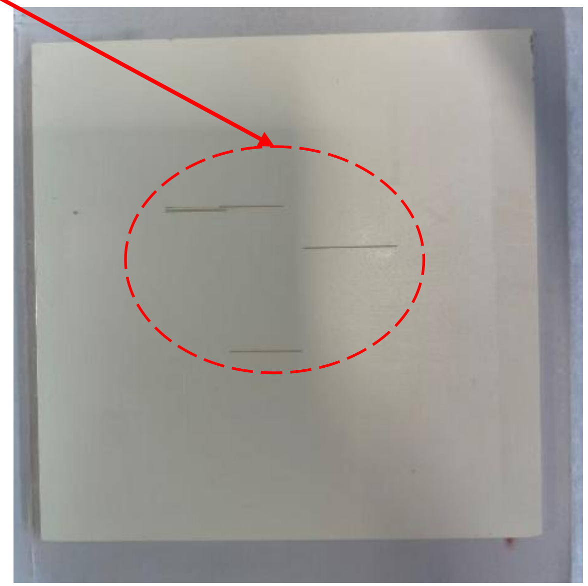
Experimental setup

➢ ^{nat}BN sample

	BN1	BN2
Mass (g)	13.031±0.00025	12.9485±0.00033
Area (cm^2)	64.3204	64.3236
Isotopic abundance ($^{10}B/B$)	0.1983±0.00002	
^{nat}BN Purity(%)	**99.50%±0.056%**	

Matrix-Array Femtosecond Laser Ablation by commercial company for determining the purity of the BN after the measurement





The thermal neutron total cross sections of ^{14}N (~12.17 b) 、 ^{15}N (~4.56 b) and ^{11}B (~5.07 b) are significantly smaller than that of ^{10}B (n, α) (3844.12 b) , which accounts for about 97.7% for the σ_{BN}^{tot}. Corrections were made to eliminate the contributions from above impurities based on the evaluated libraries (ENDF/B-VIII.0, JEFF-3.3, JENDL-5, ROSFOND-2010, CENDL-3.2).

Experimental setup

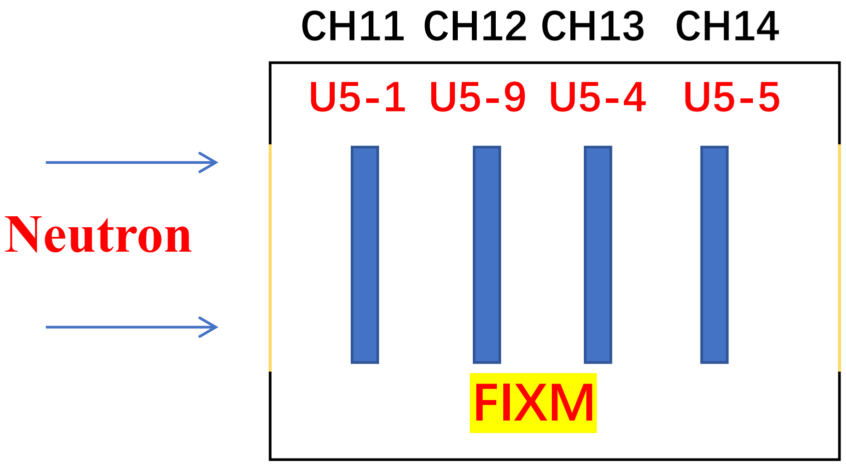
样品号 (ppm)		B10/B11	Li7	Be9	B10	B11	N (根据化学式计算得出)	Na23	Mg24	Al27	Si29	P31	S34	Cl35	K39	Ca43	Sc45
sample1-A 面																	
line-1	不预剥蚀	0.22	-	-	436940	434348	562924	31.29	8.39	27.88	382.87	73.80	-	25.50	23.16	-	0.044
line-2	预剥蚀	0.22	-	-	436876	434181	562708	8.12	4.58	15.02	654.99	95.89	-	199.46	5.15	-	0.027
line-3	预剥蚀	0.22	-	-	437251	434472	563085	14.16	5.14	14.20	463.11	76.48	-	131.71	14.74	-	0.042

样品号 (ppm)		Ti49	V51	Cr52	Mn55	Fe57	Co59	Ni60	Cu63	Zn66	Ga69	Ge72	As75	Rb85	Sr88	Y89	Zr90
sample1-A 面																	
line-1	不预剥蚀	1.557	1.093	0.532	0.314	11.775	0.151	0.402	0.471	1.796	0.016	-	-	0.067	0.343	0.148	0.365

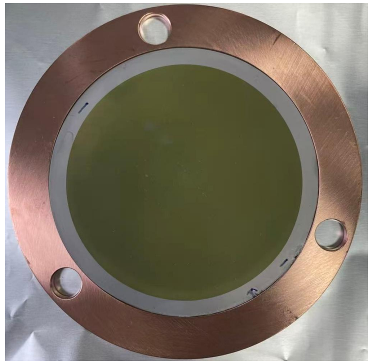
样品号 (ppm)		Nb93	Mo95	Rh103	Pd105	Ag107	Cd111	In113	Sn118	Sb121	Cs133	Ba137	La139	Ce140	Pr141	Nd146	Sm147	Eu153	Gd157
sample1-A 面																			
line-1	不预剥蚀	0.003	0.010	-	-	0.227	0.001	0.057	153	0.045	0.003	0.855	0.181	0.223	0.021	0.084	0.022	0.001	0.025

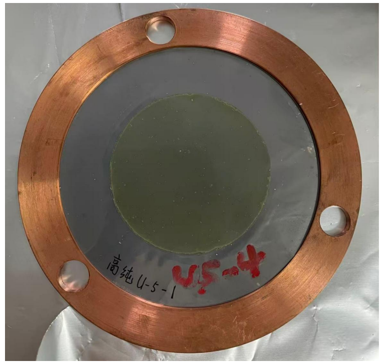
样品号 (ppm)		Tb159	Dy163	Ho165	Er166	Tm169	Yb172	Lu175	Hf178	Ta181	W182	Re185	Pt195	Au197	Tl205	Pb208	Bi209	Th232	U238
sample1-A 面																			
line-1	不预剥蚀	0.003	0.019	0.006	0.010	0.002	0.010	0.002	0.013	0.002	0.260	0.000	-	0.125	0.001	11.815	0.517	0.022	0.009

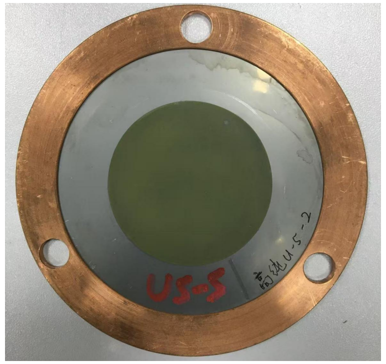
➢ FIXM

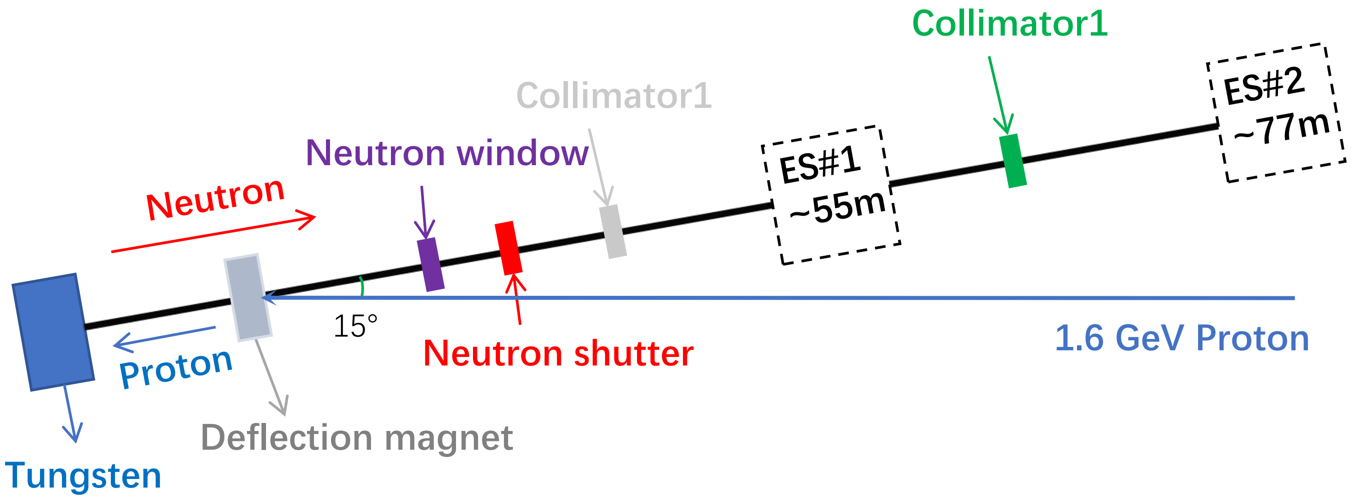


	U5-1	U5-9	U5-4	U5-5
Mass (mg)	23.091	23.091	6.331	6.319
Diameter of sensitive area (mm)	70	70	50	50
U5 isotopic abundance	90%	90%	99.985%	99.985%









The prompt γ-rays (γ-flash) can be utilized to calibrate the neutron time of flight.

$$TOF_N = T_N - T_{N_0} = T_N - (T_{gamma} - TOF_{gamma})$$

$$TOF_{gamma} = \frac{L}{C}$$

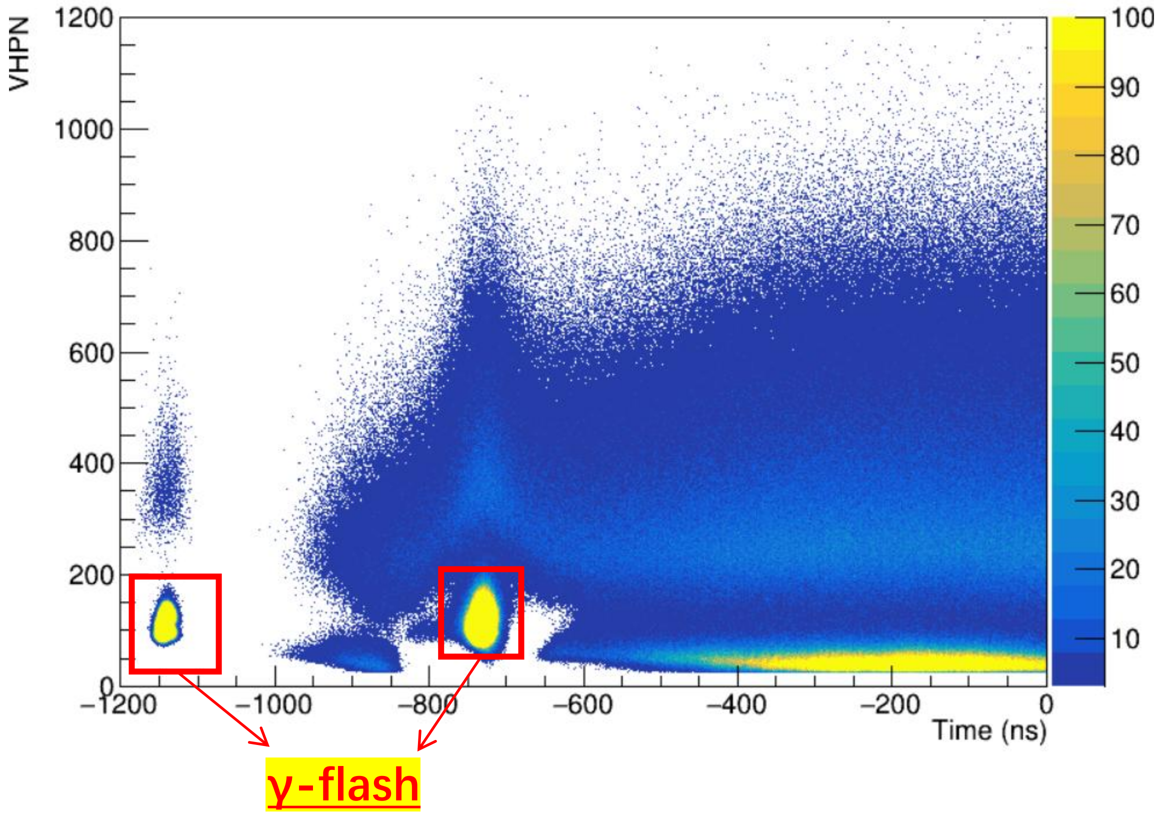
$$T_N = \ Neutron\ arrive\ time$$

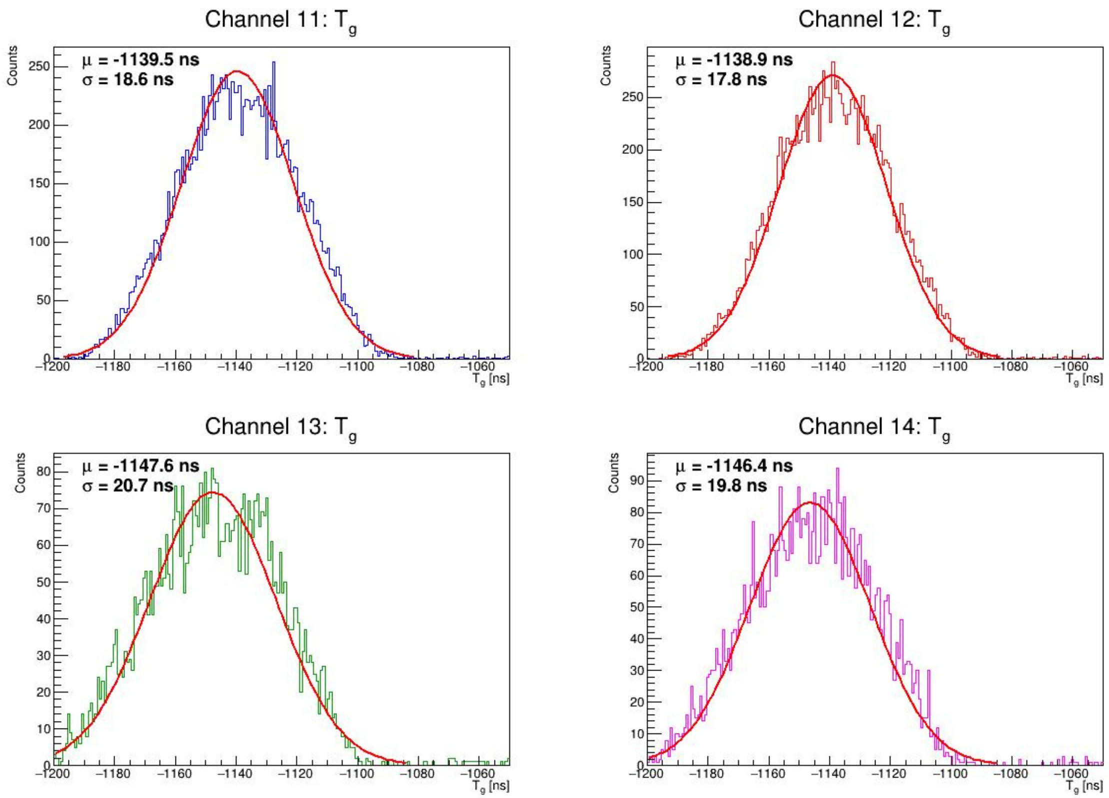
$$T_{N_0} = \ Neutron\ generation\ time$$

$$T_{gamma} = \ \gamma\text{−}flash\ detection\ time$$

$$TOF_{gamma} = \ \gamma\text{−}flash\ \ time\ of\ flight$$

Determining the γ-Flash Timing





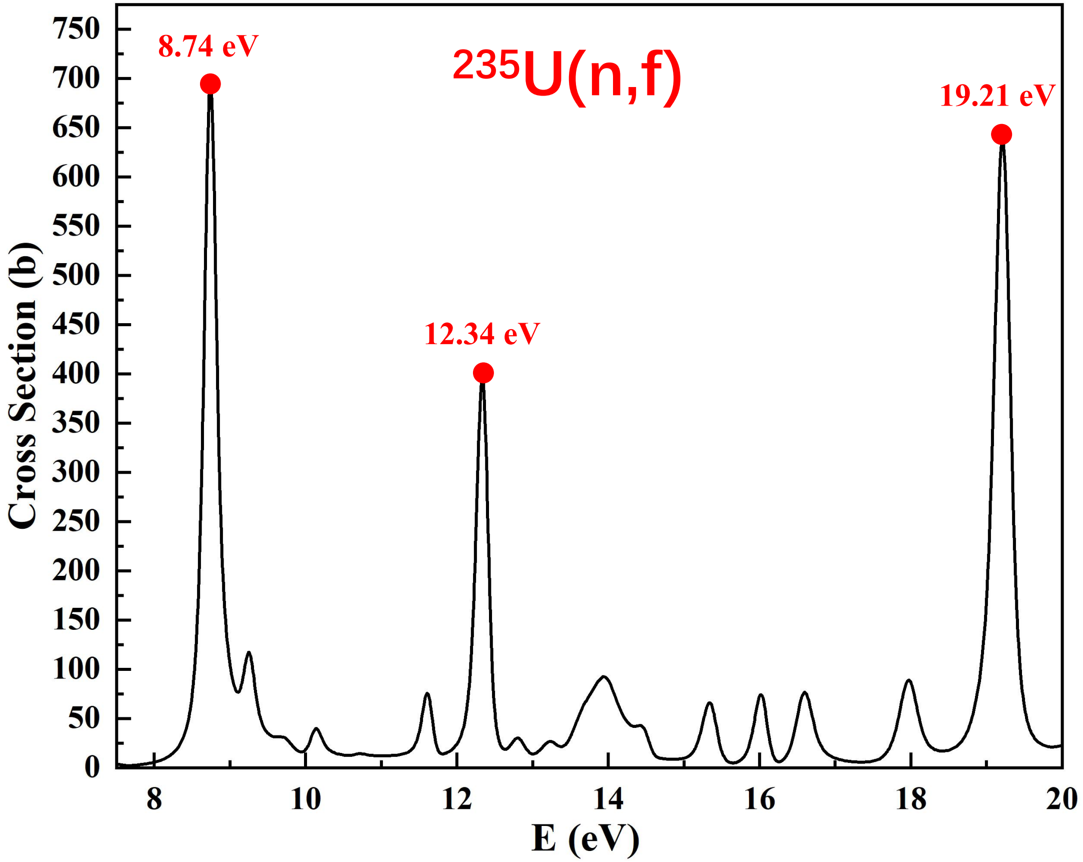
The double-bunch structure (2 identical incident proton bunch with a well-defined 410 ns interval) is negligible for thermal neutrons with a TOF of ~35 ms.

	Ch 11 U5-1	Ch 12 U5-9	Ch 13 U5-4	Ch 14 U5-5
T_g (ns)	-1139.5+205	-1138.9+205	-1147.6+205	-1146.4+205

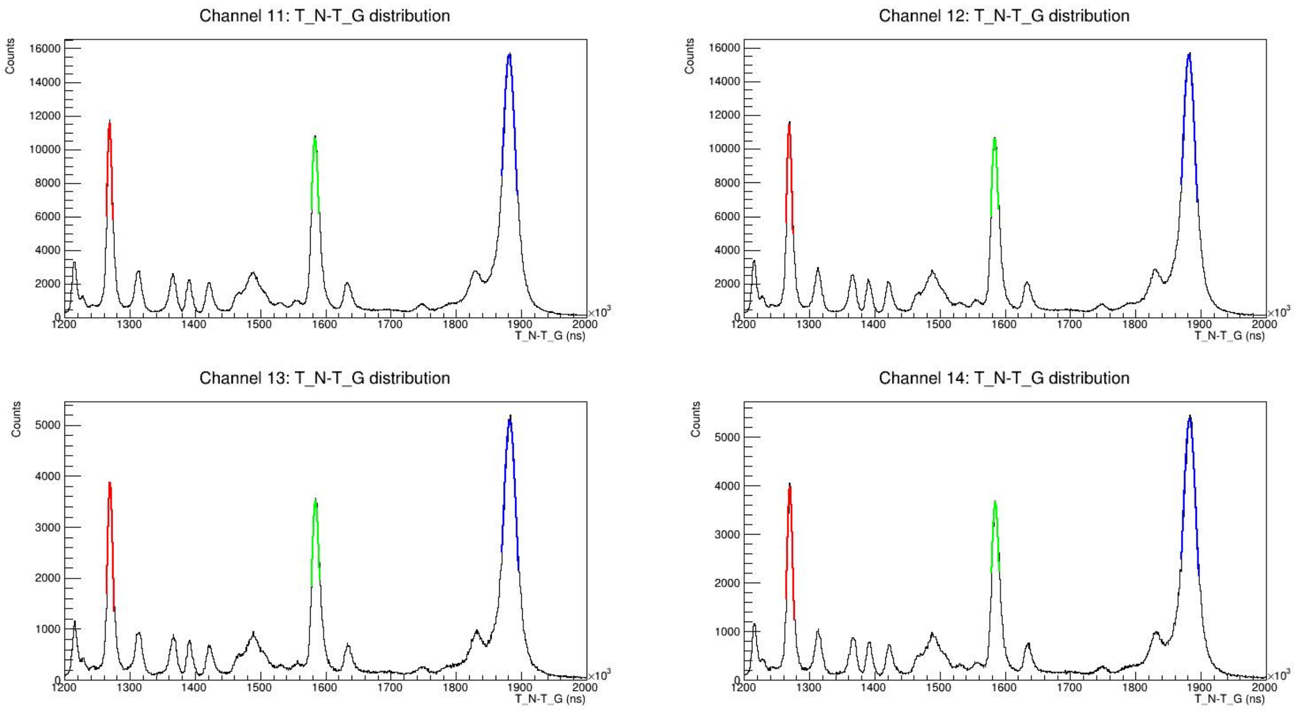
Flight Distance calibration

- The ^{235}U(n, f) resonances are used for calibrating the neutron flight length

$$T_n - T_g = \frac{L}{c}\left[\frac{1}{\sqrt{1-\frac{1}{\left(\frac{E_n}{m_n c^2}+1\right)^2}}}-1\right]$$



- $(T_n - T_g)$



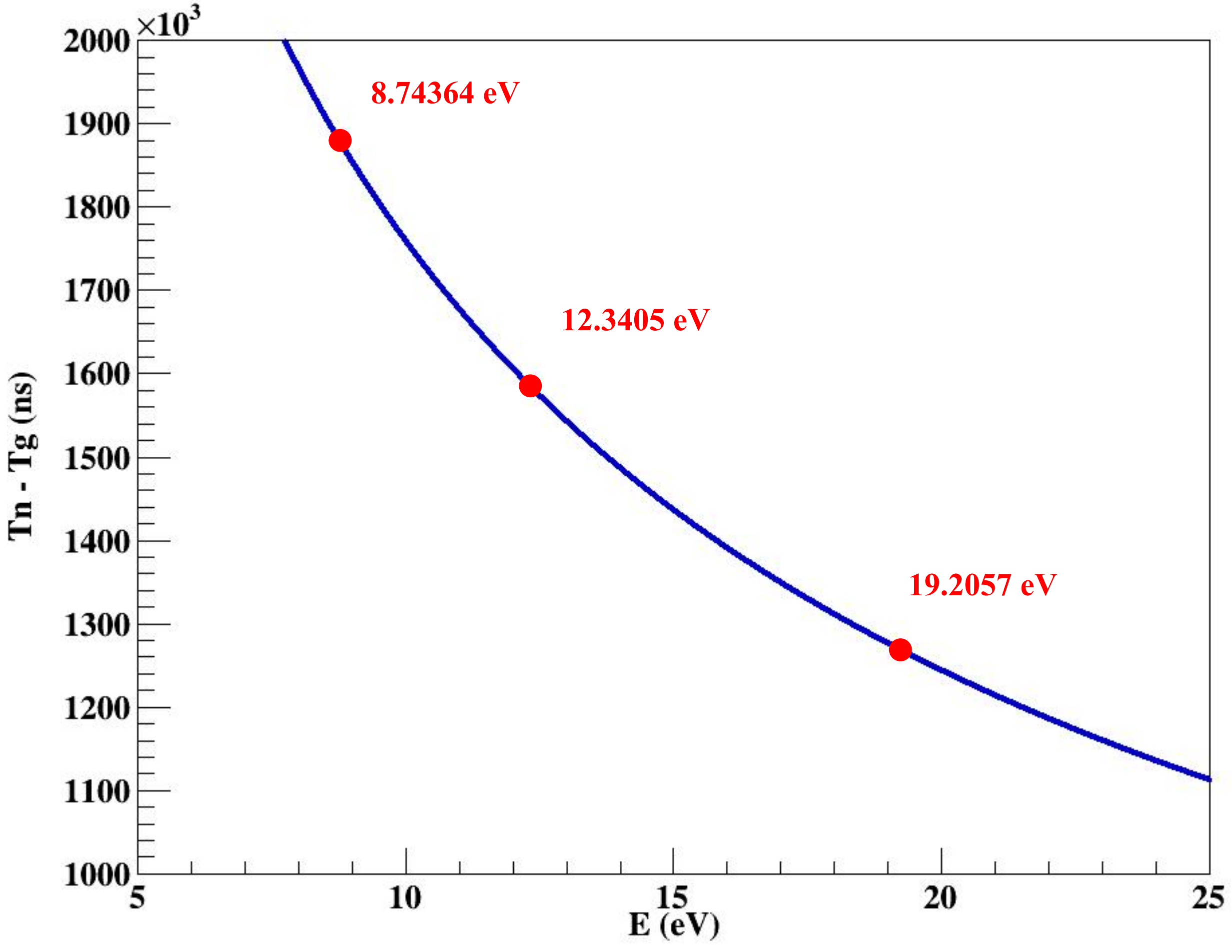
19.21eV	T_n-T_g (ns)
ch 11	1268918.83
ch 12	1269232.52
ch 13	1269495.22
ch 14	1269933.80

12.34eV	T_n-T_g (ns)
ch 11	1583888.36
ch 12	1584200.22
ch 13	1584653.70
ch 14	1585104.77

8.74eV	T_n-T_g (ns)
ch 11	1881466.92
ch 12	1881985.39
ch 13	1882437.62
ch 14	1883022.38

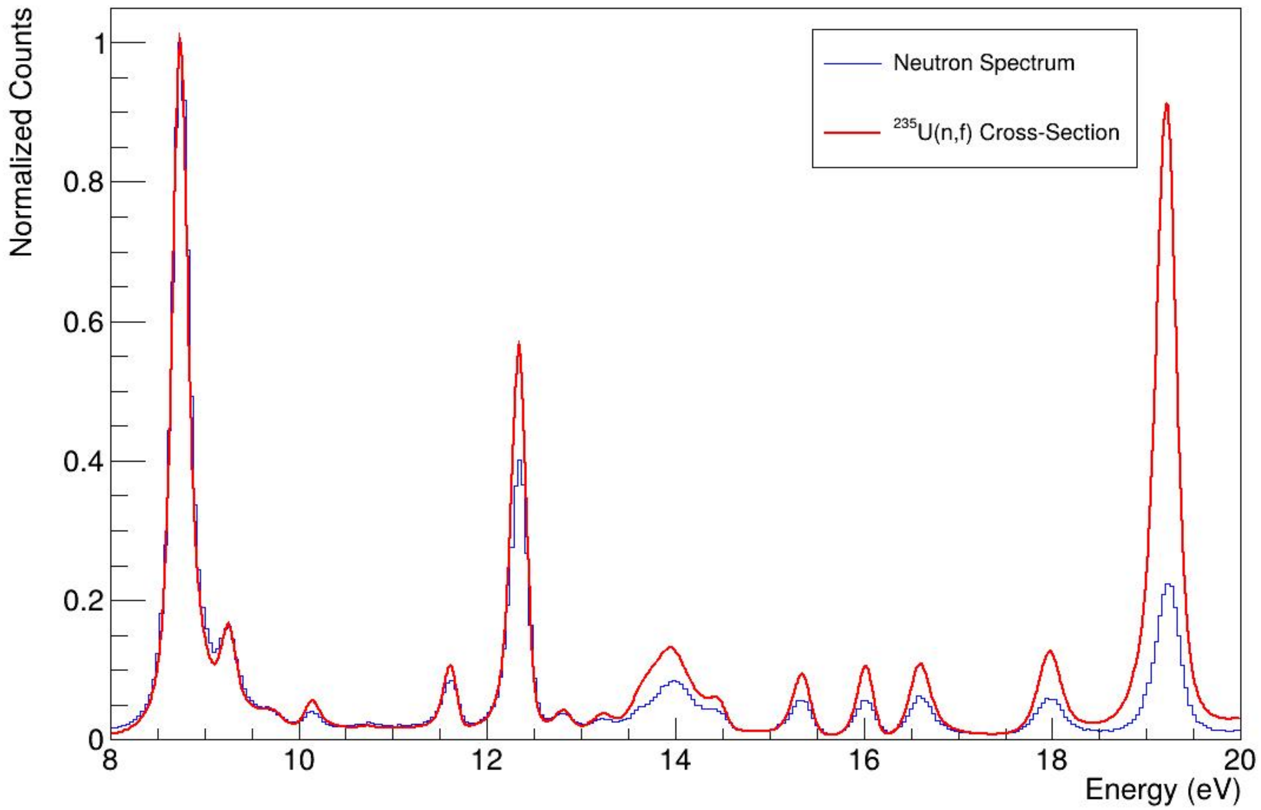
Flight Distance calibration

➢ Flight Distance Fitting



ch	11	12	13	14
L (m)	76.9589	76.9777	76.9968	77.0207

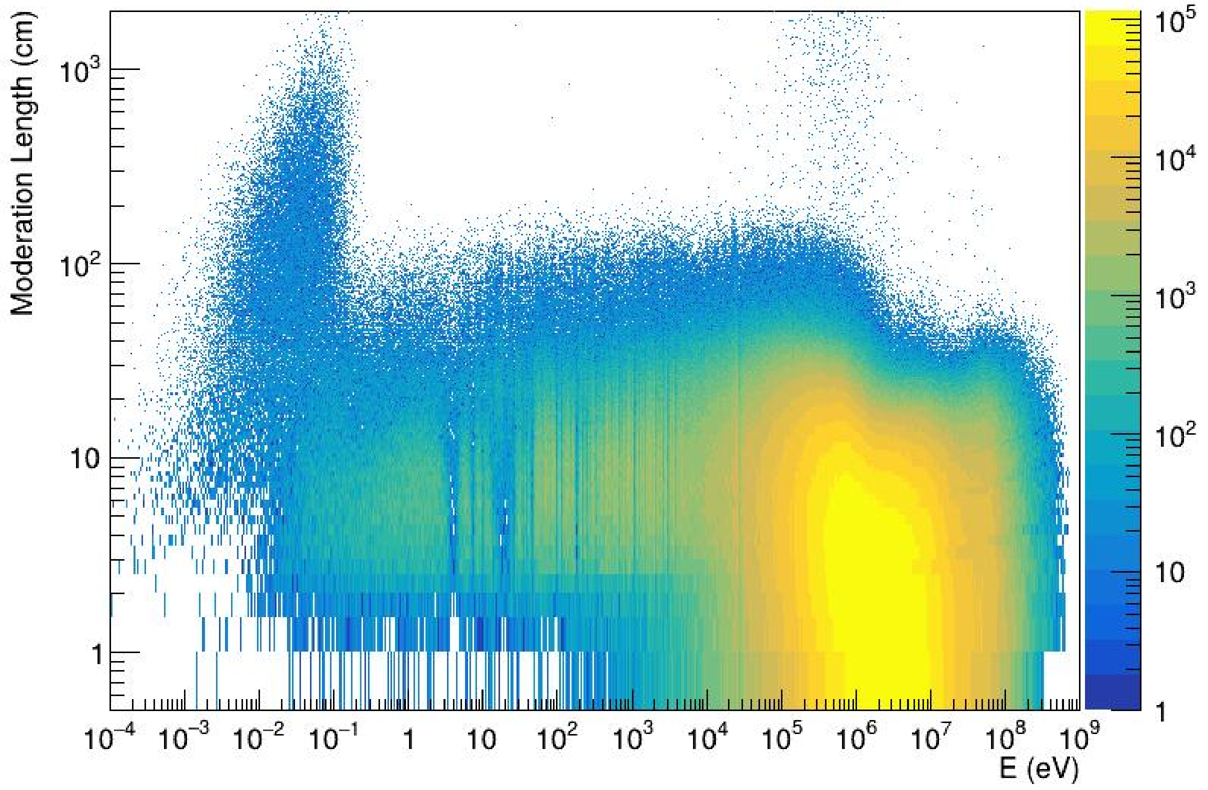
➢ Verify flight distance



Flight Distance calibration

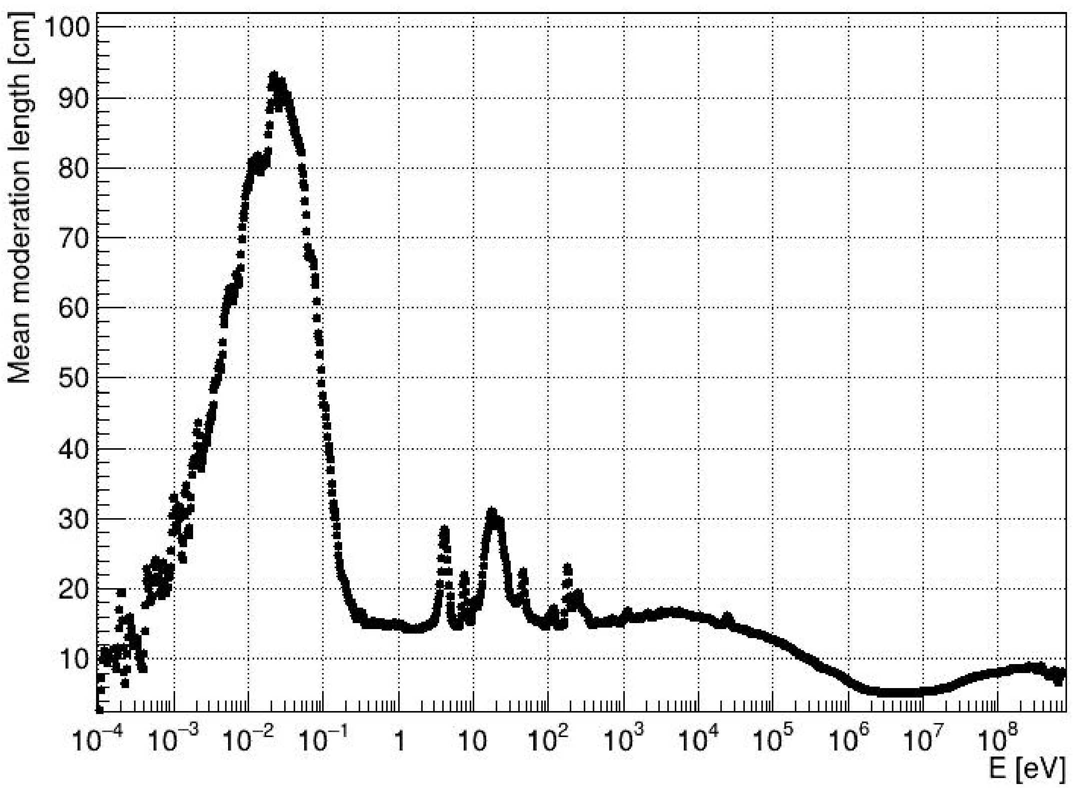
➤中子平均慢化长度随能量分布(Geant 4模拟结果)

中子慢化长度vs中子能量



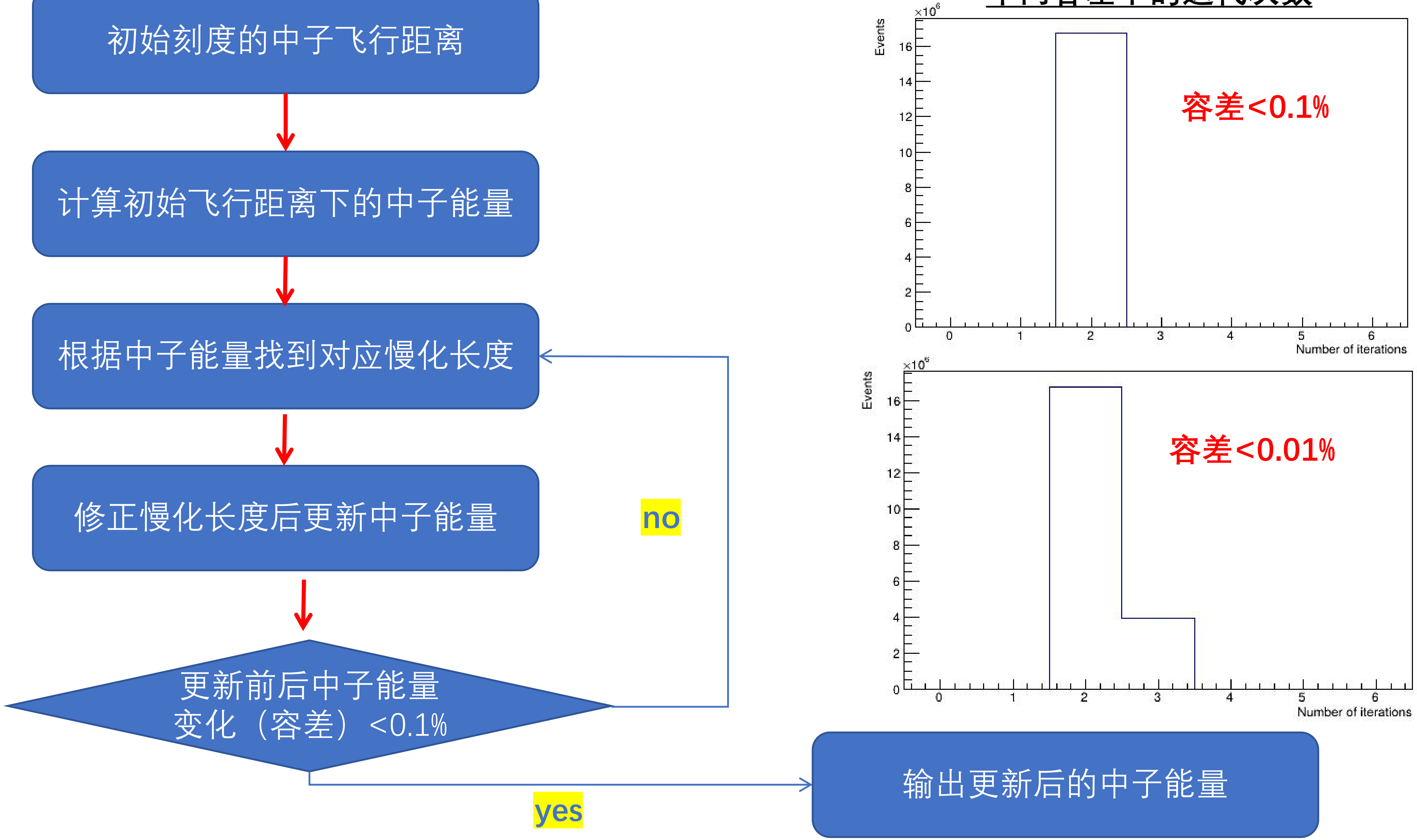
由课题组成员唐生达模拟

中子平均慢化长度分布



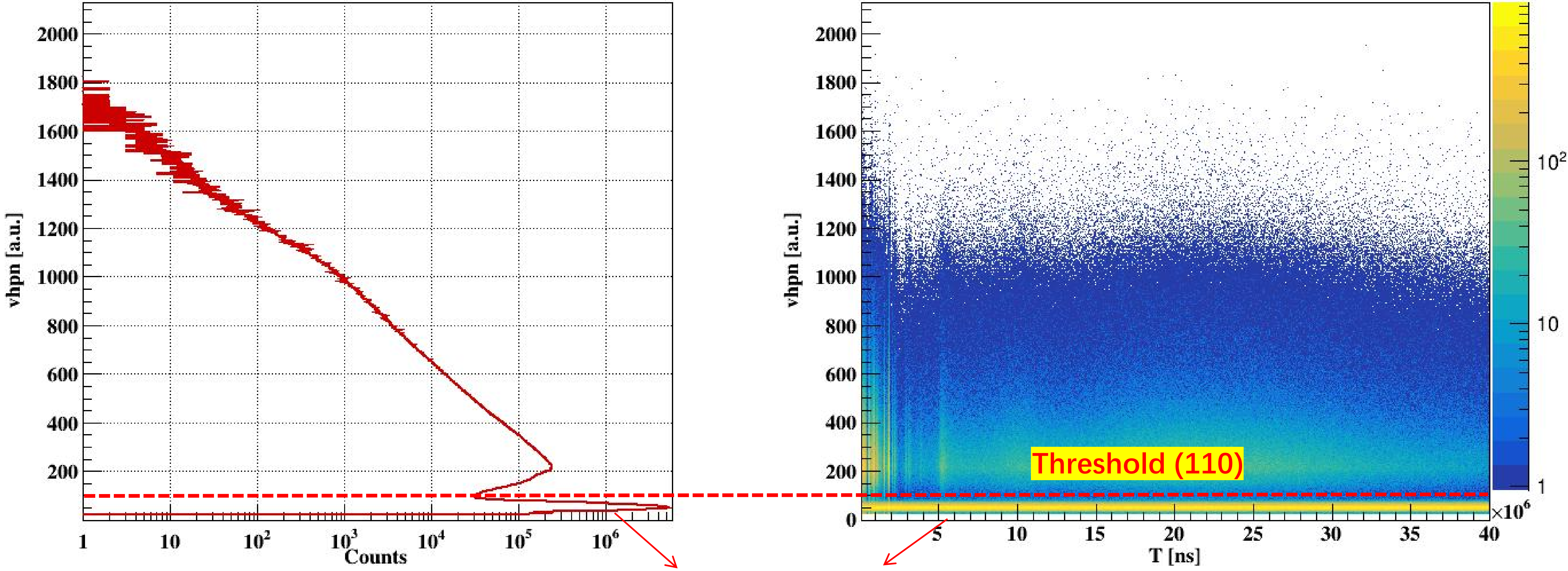
考虑中子慢化长度后的中子飞行距离

不同容差下的迭代次数



α background discrimination

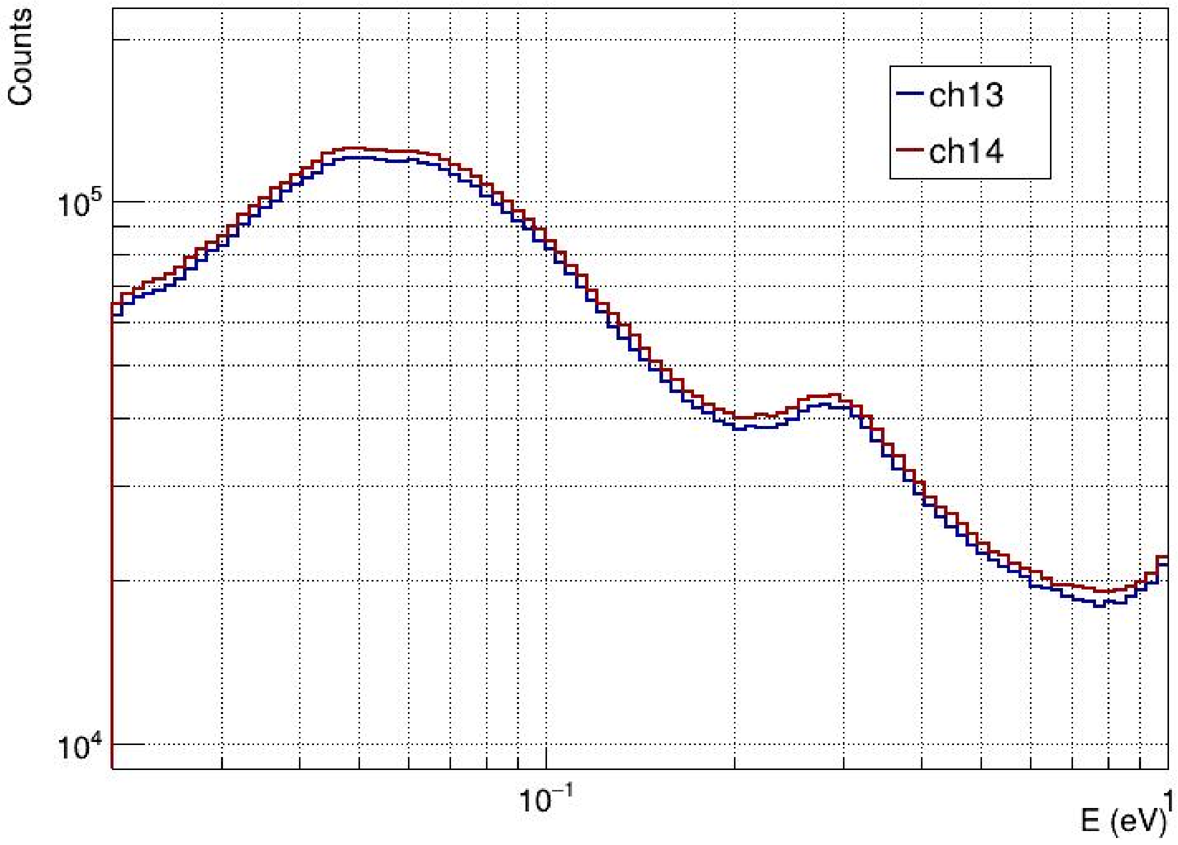
- Using the pulse amplitude to cut the alpha background

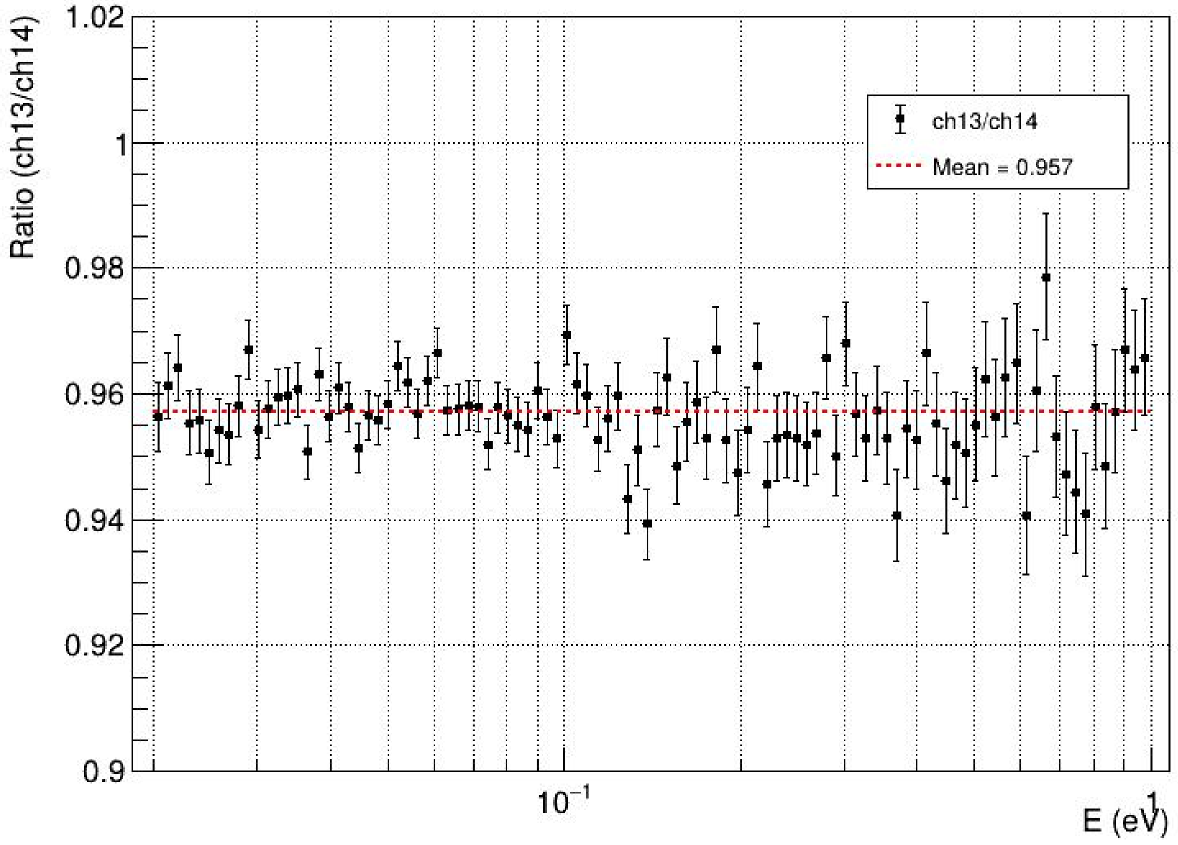


α background

➢Fission rate comparison of U5-4 (CH13) and U5-5 (CH14)

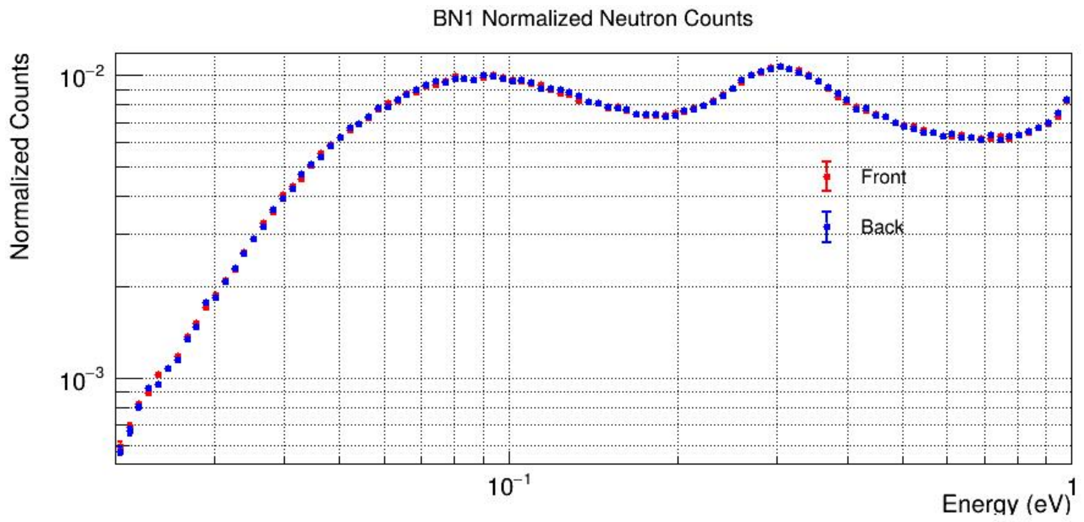
U5-4与U5-5计数率比值

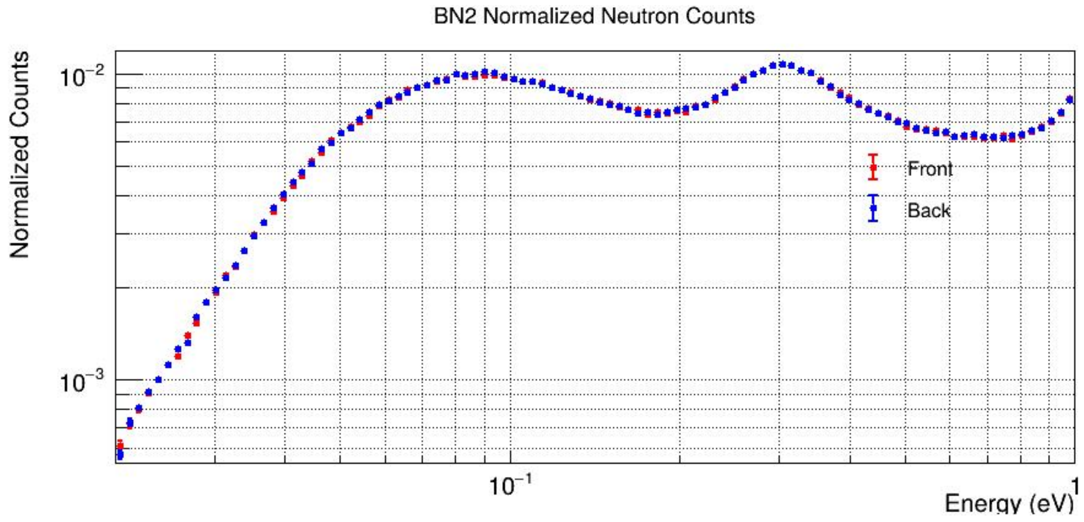


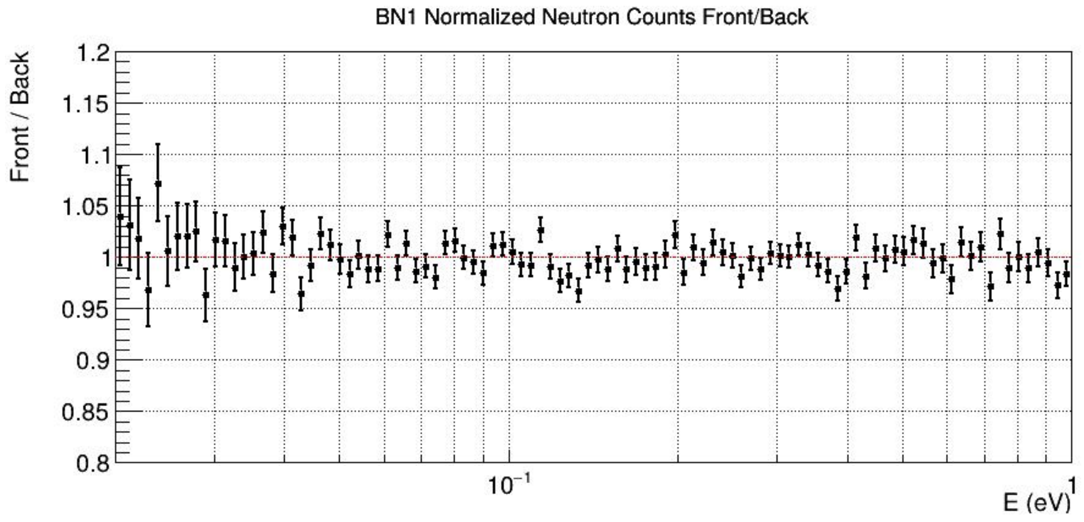


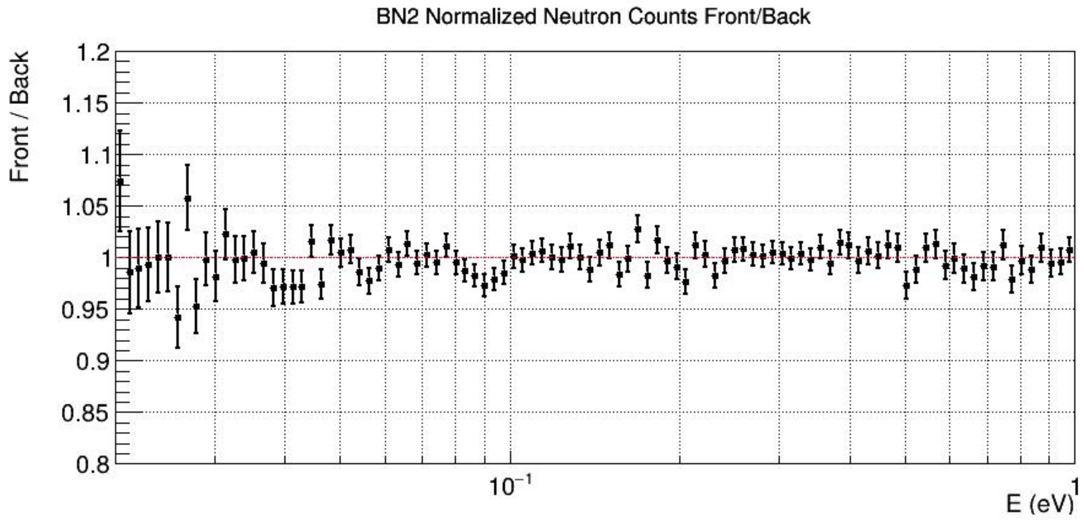
Verification of sample and beam uniformity

➢BN1以及BN2的正反面测量计数对比







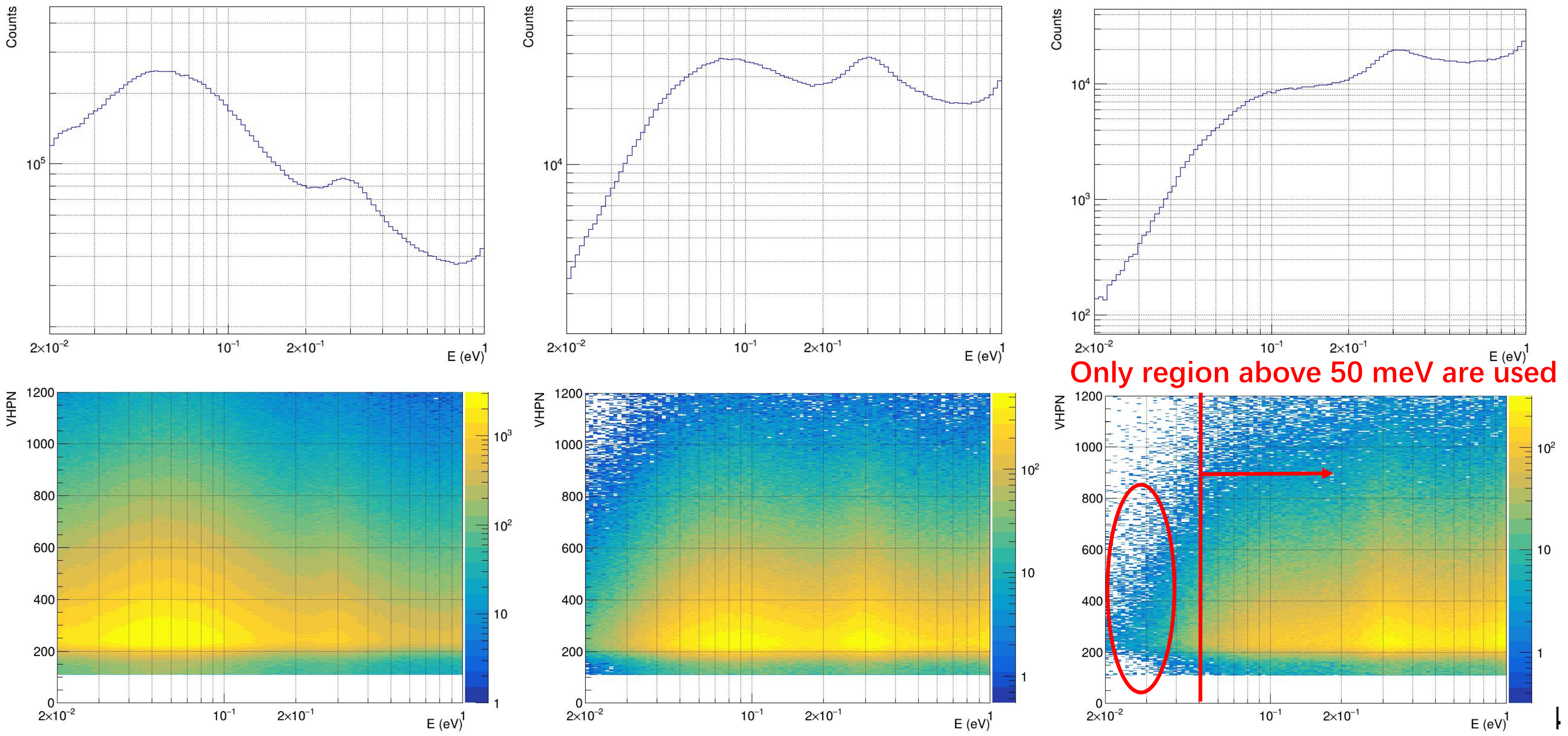


Fission rates with different samples (2025)

Open beam (sample out)

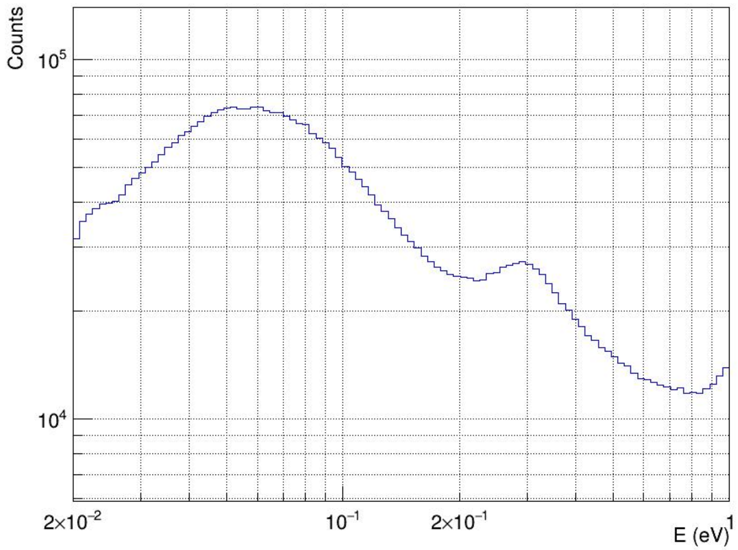
BN1

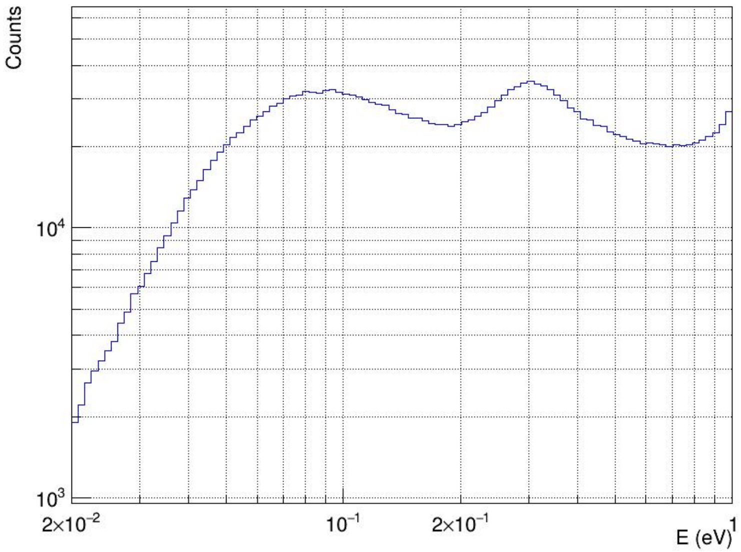
BN1+BN2

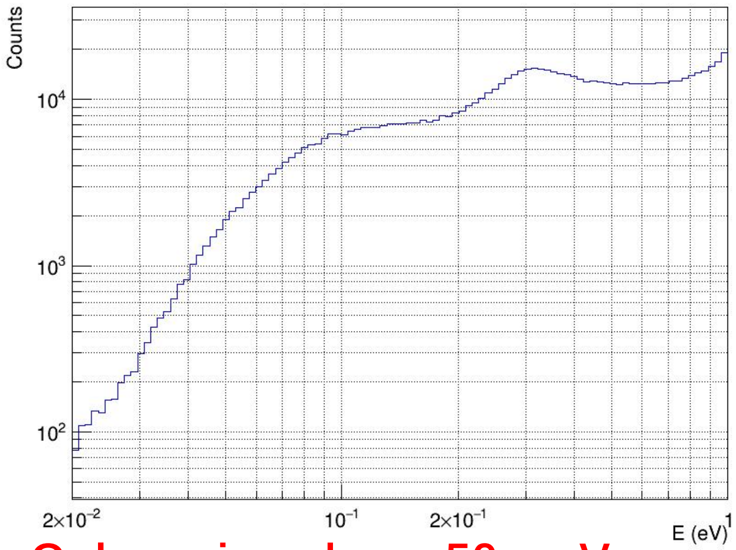


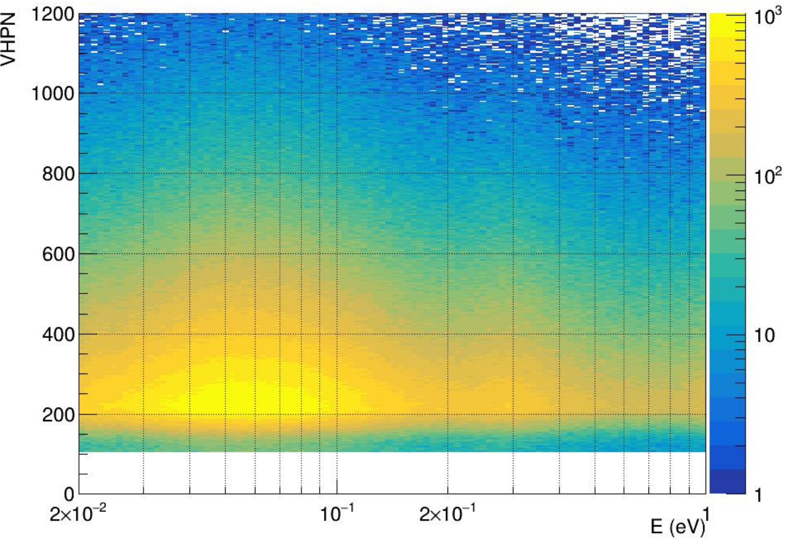
Fission rates with different samples (2026)

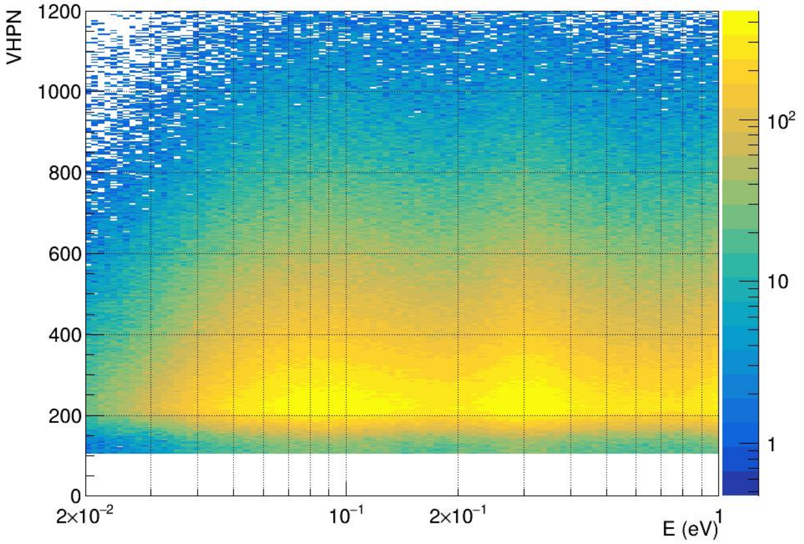
Open beam (sample out) | BN1 | BN1+BN2



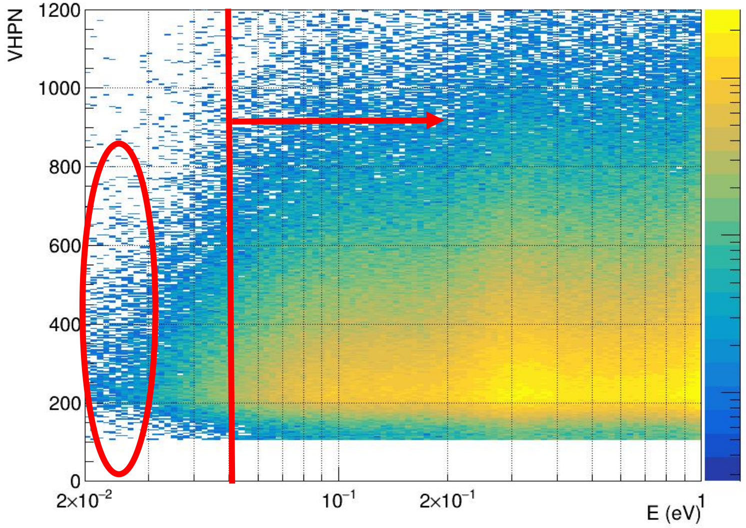




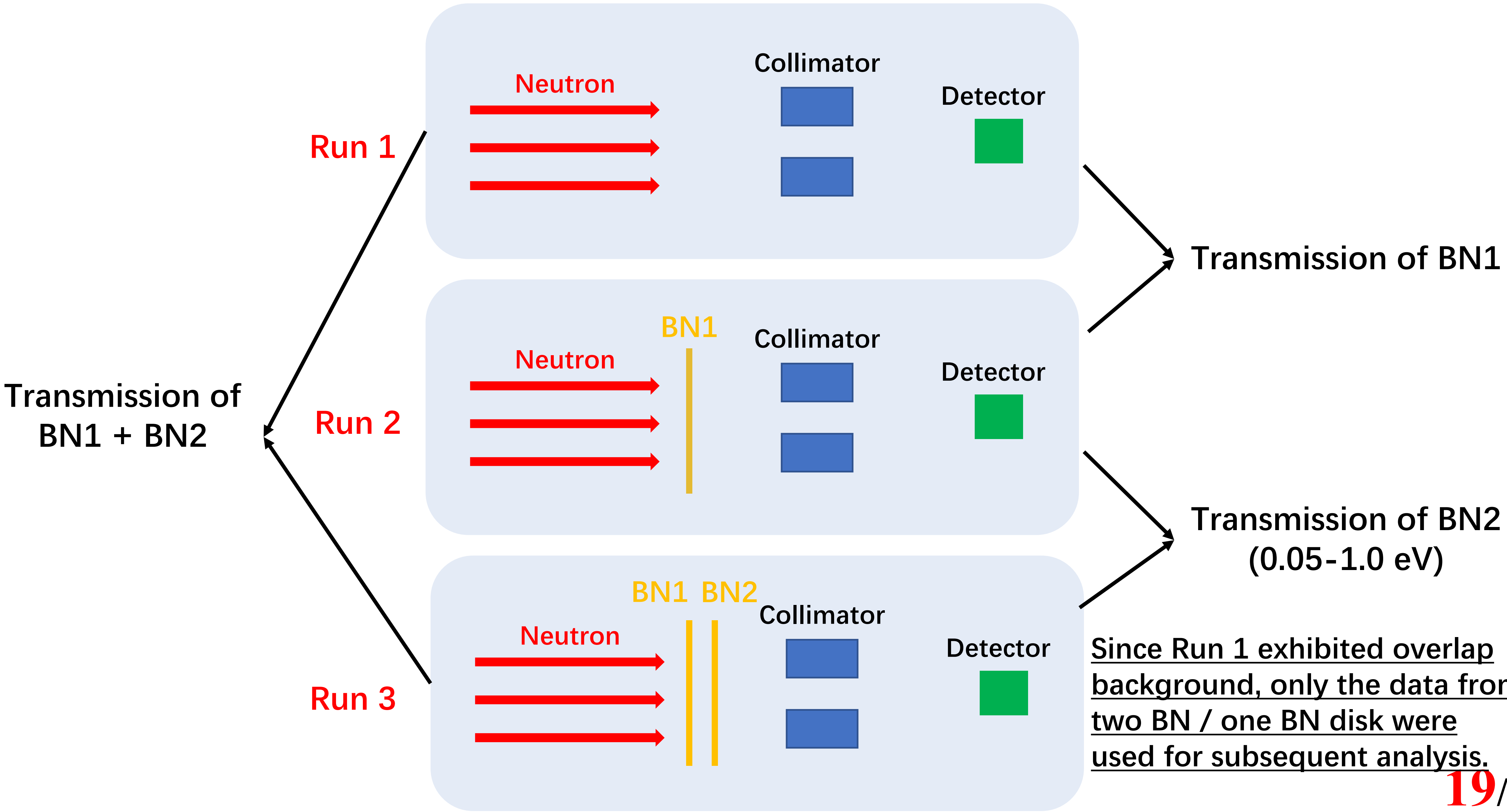




Only region above 50 meV are used



Cross-section



<u>Since Run 1 exhibited overlap background, only the data from two BN / one BN disk were used for subsequent analysis.</u>

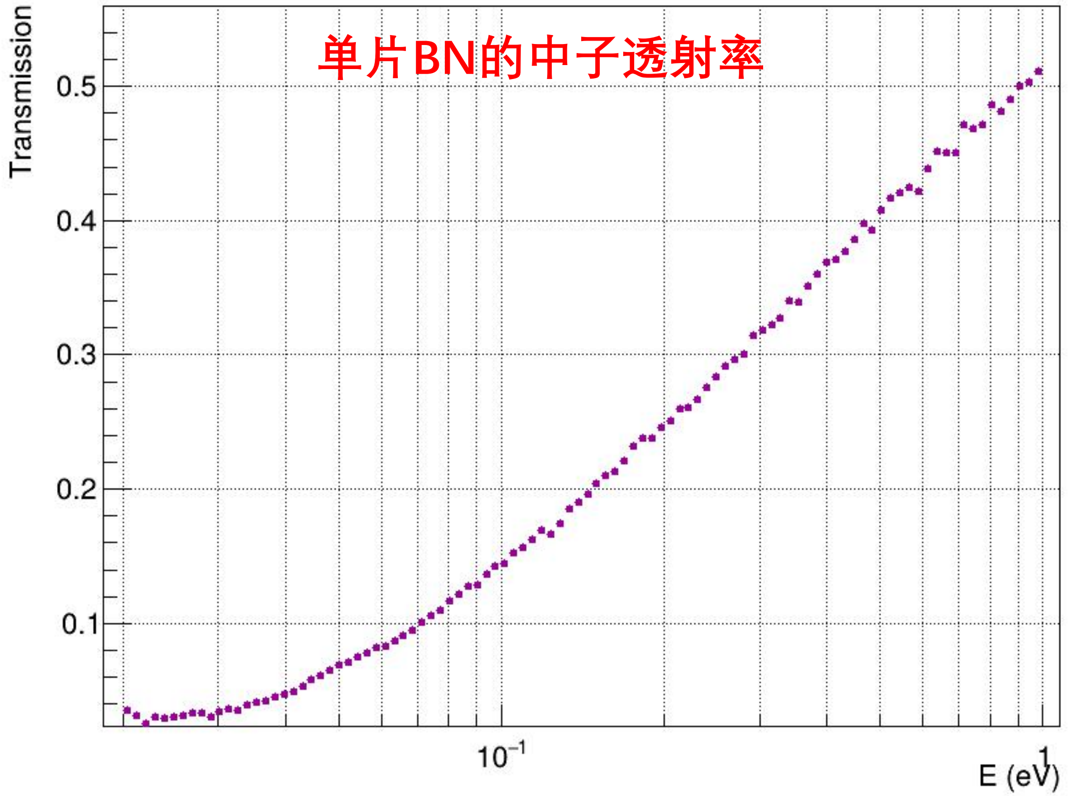
➢ Total Cross Section and Correction

$$\sigma_{{nat}_{BN(n,tot)}} = \frac{-lnT}{N_s}$$

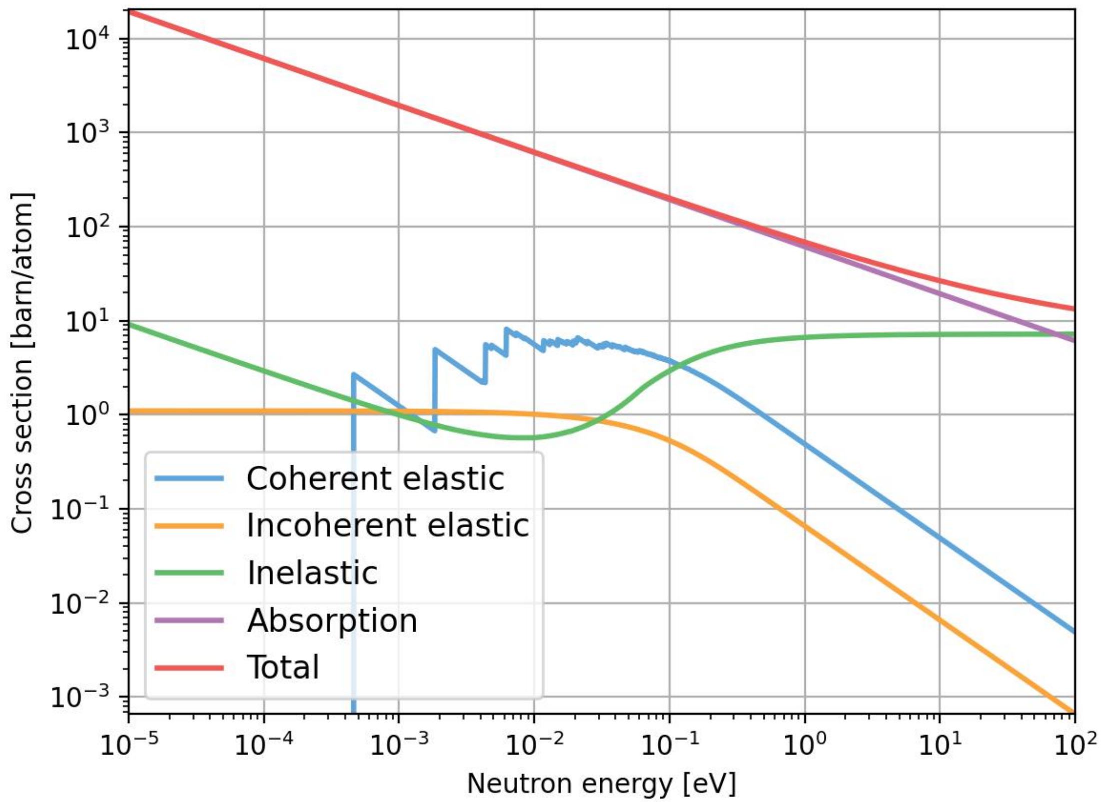
$$\sigma_{{}^{10}B(n,\alpha)} = \frac{\left[\sigma_{{}^{nat}BN(n,tot)} - \sigma_{{}^{nat}BN(n,scatter)} - (\sigma_{{}^{nat}N(n,tot)} - \sigma_{{}^{nat}N(n,scatter)}) - C_{{}^{11}B} \bullet (\sigma_{{}^{11}B(n,tot)} - \sigma_{{}^{11}B(n,scatter)})\right]}{C_{{}^{10}B}} - \sigma_{{}^{10}B(n,\gamma)}$$

N_s 代表BN的原子面密度，C_i 表示同位素丰度。

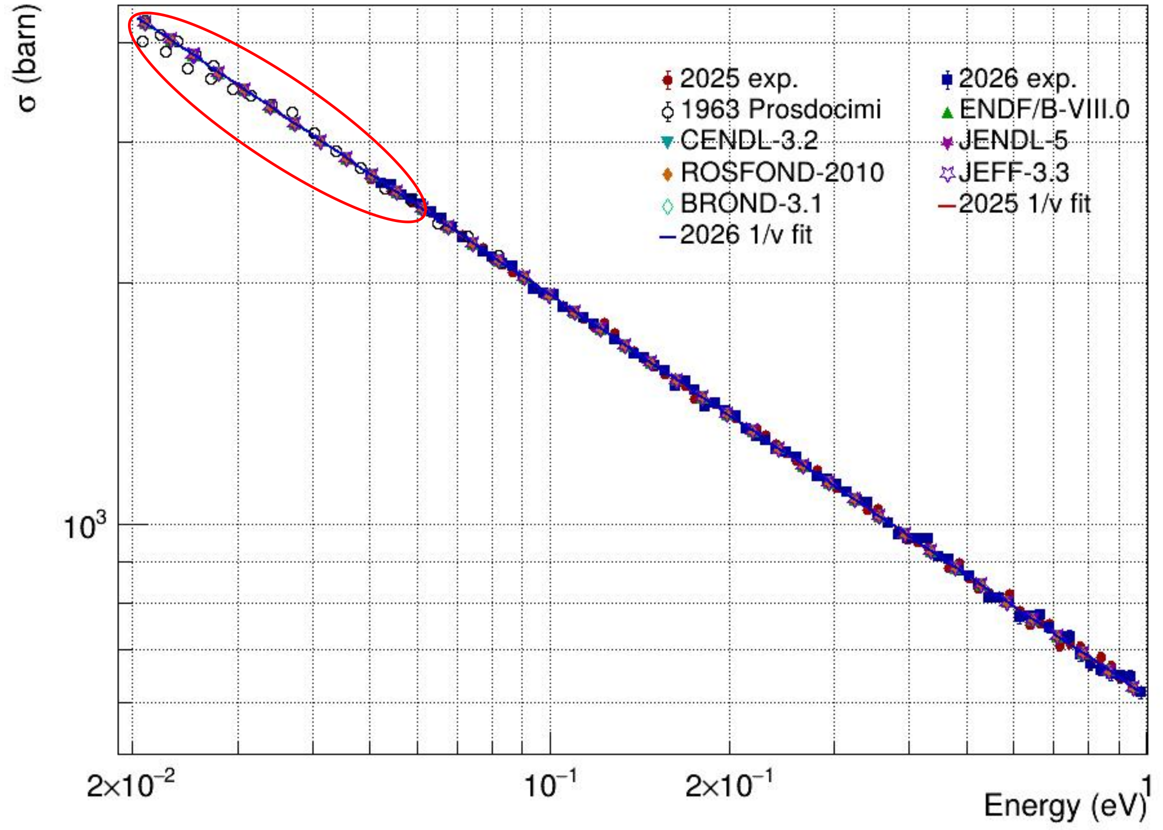
单片BN的中子透射率



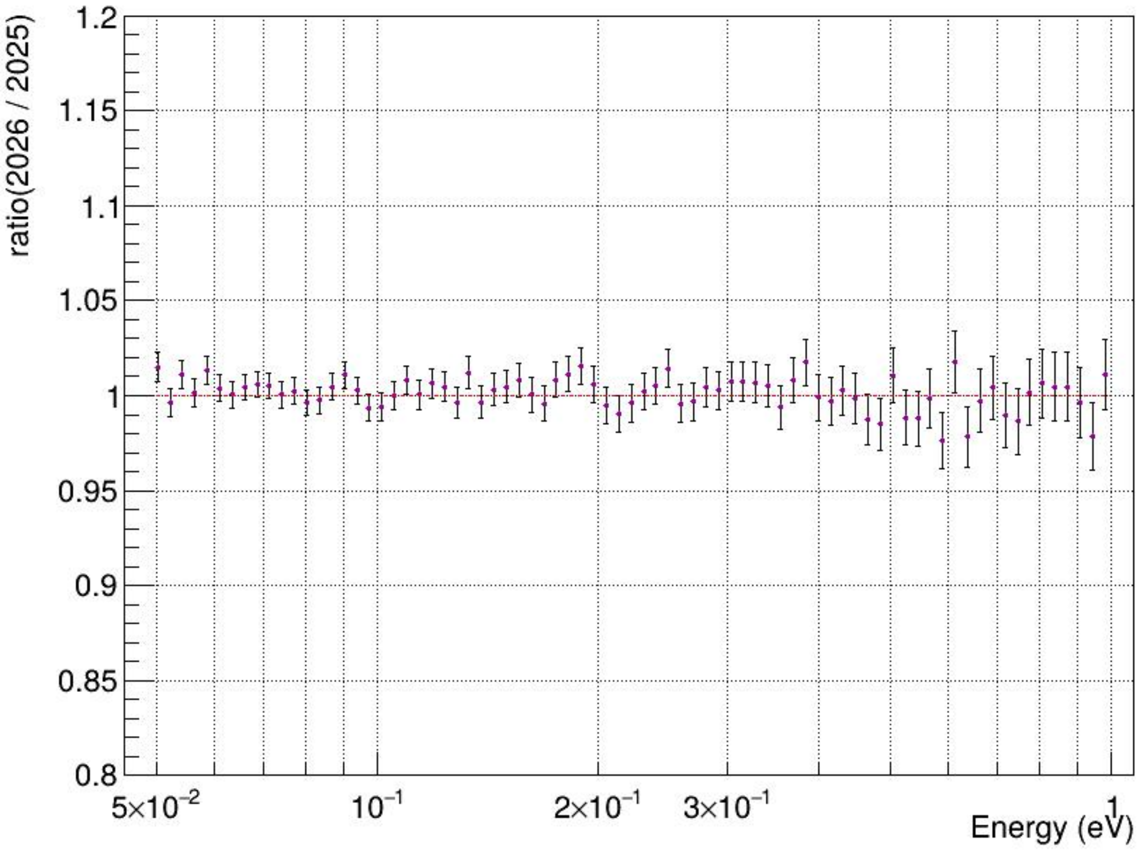
使用Ncrystal计算的BN多晶散射截面



$^{10}B(n,\alpha)$截面测量结果比较



2026年与2025年测量结果逐点比值

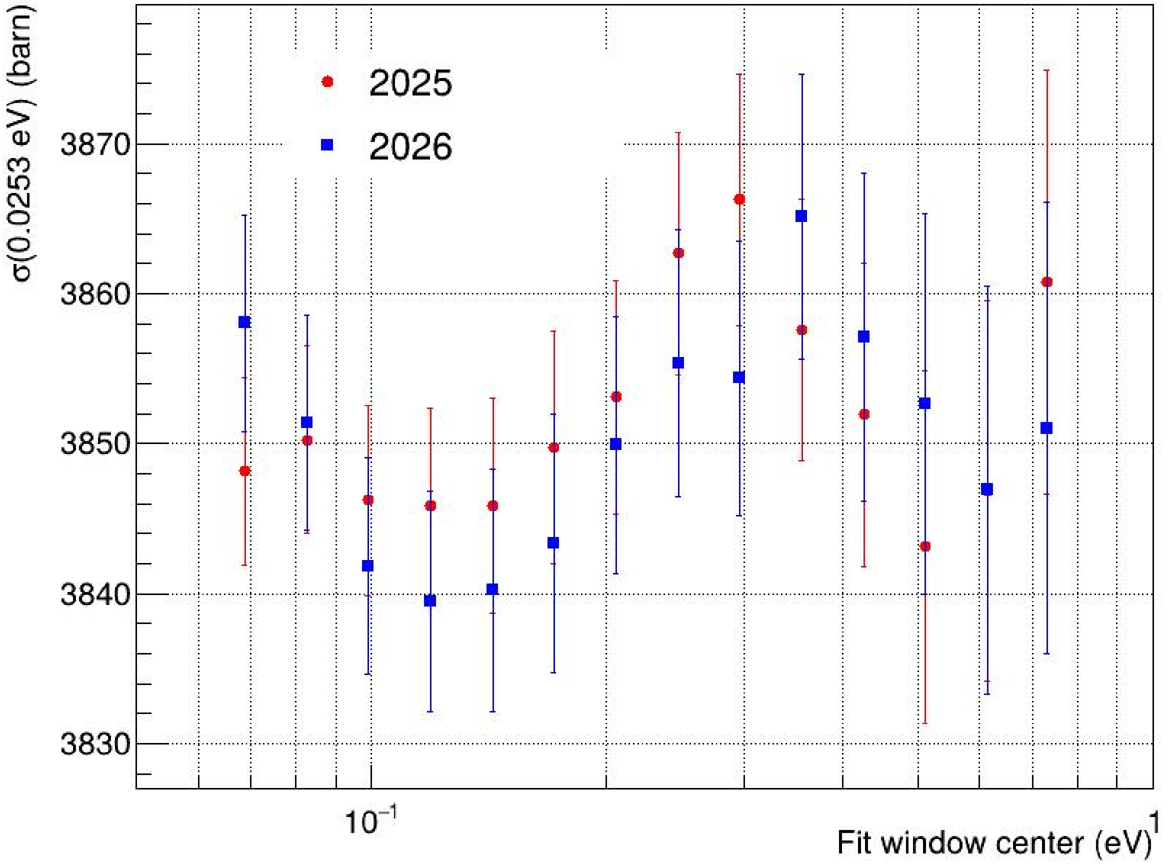


FitMin(eV)	FitMax(eV)	25年实验截面(b)(@0.0253 eV)	26年实验截面(b)(@0.0253 eV)
0.05	1.0	3851±3.68 b	3852±4.13 b

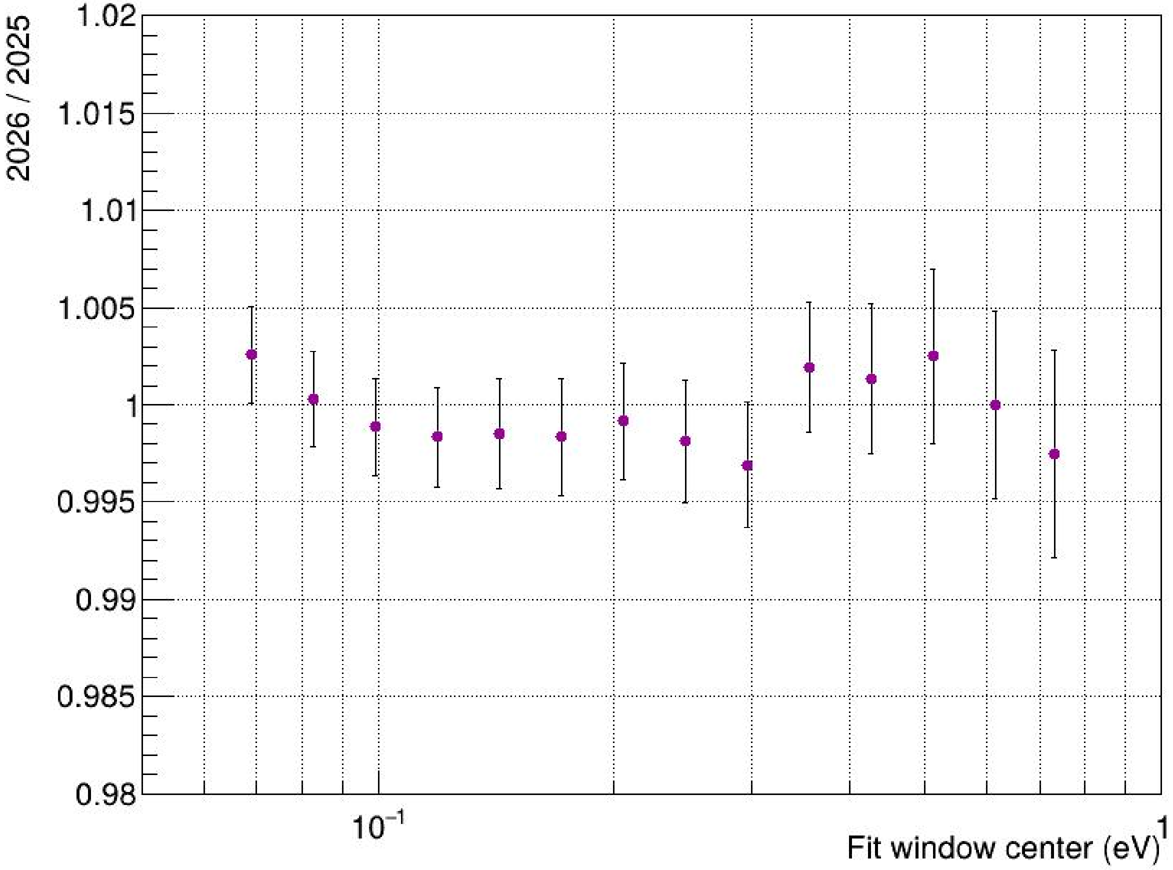
Cross-section

➢ 在不同能段对热中子能点(0.0253eV)截面进行拟合(FitMin = FitMin*1.3 FitMax = FitMin*1.9)

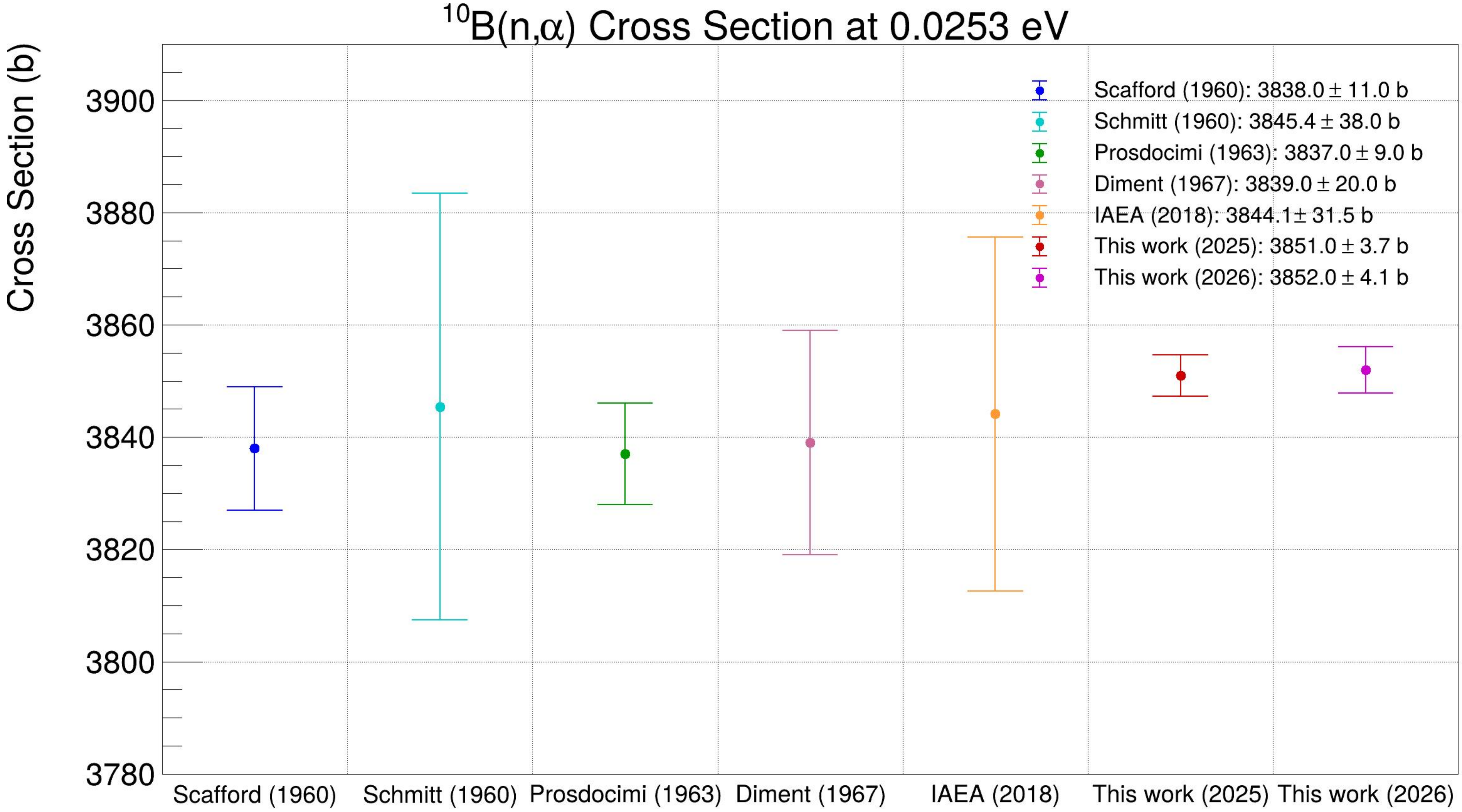
不同能段的拟合截面结果



2026年实验与2025年实验结果比值



Cross-section



Error analysis

- Uncertainty estimation

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

$$\frac{\Delta\sigma_{natB(n,tot)}}{\sigma_{natB(n,tot)}} = \frac{\sqrt{\Delta\sigma_{BN(n,tot)}^{\ 2} + \Delta\sigma_{natN(n,tot)}^{\ 2}}}{\sigma_{natB(n,tot)}}$$

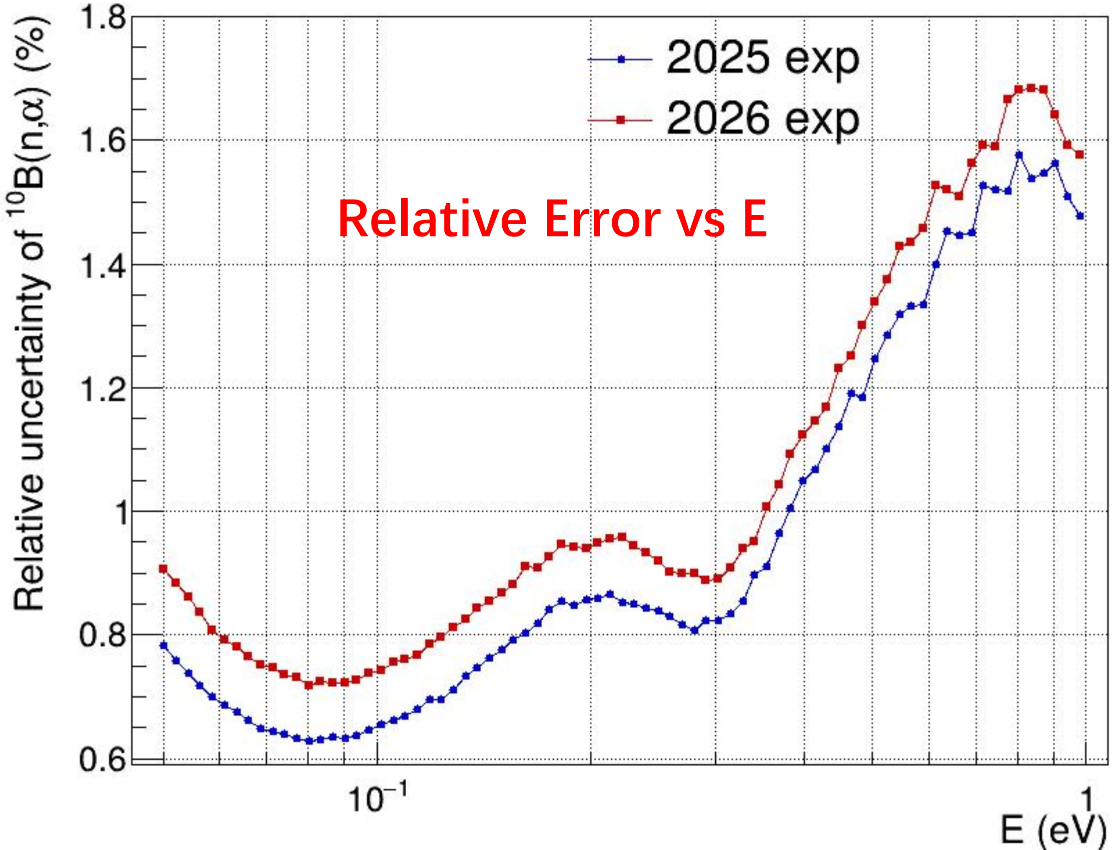
$$\frac{\Delta\sigma_{10B(n,tot)}}{\sigma_{10B(n,tot)}} = \frac{\sqrt{\Delta\sigma_{natB(n,tot)}^{\ 2} + (\Delta\sigma_{B11} \cdot C_{B11})^2}}{\sigma_{10B(n,tot)} \cdot C_{B10}}$$

$$\frac{\Delta\sigma_{10B(n,\alpha)}}{\sigma_{10B(n,\alpha)}} = \frac{\sqrt{\Delta\sigma_{10B(n,tot)}^{\ 2} + \Delta\sigma_{10B(n,el)}^{\ 2} + \Delta\sigma_{10B(n,\gamma)}^{\ 2}}}{\sigma_{10B(n,\alpha)}}$$

- Sources of uncertainty

1. Statistics → Primary
2. Sample mass
3. Sample surface area
4. Cross-section library data
5. Sample purity

(2–5) → Minor



Conclusions

1. A new absolute cross section measurement of $^{10}B(n, \alpha)$ in thermal region (0.05 - 1.0 eV) were campaigned at CSNS Back-n.

2. The measured cross section of $^{10}B(n, \alpha)$ at the thermal point deviates from the IAEA standard by 7 b (0.18 %).

3. The experiments in 2025 and 2026 used the same samples, and the measurement results were very close. However, the deviations between this measurement and those from the 1960s are significant.

Future works

1. A highly enrich ^{10}B sample (like $^{10}BC_4$) should be measured in the future.

中国散裂中子源

China Spallation Neutron Source

Thank you !

恳请各位专家批评指正

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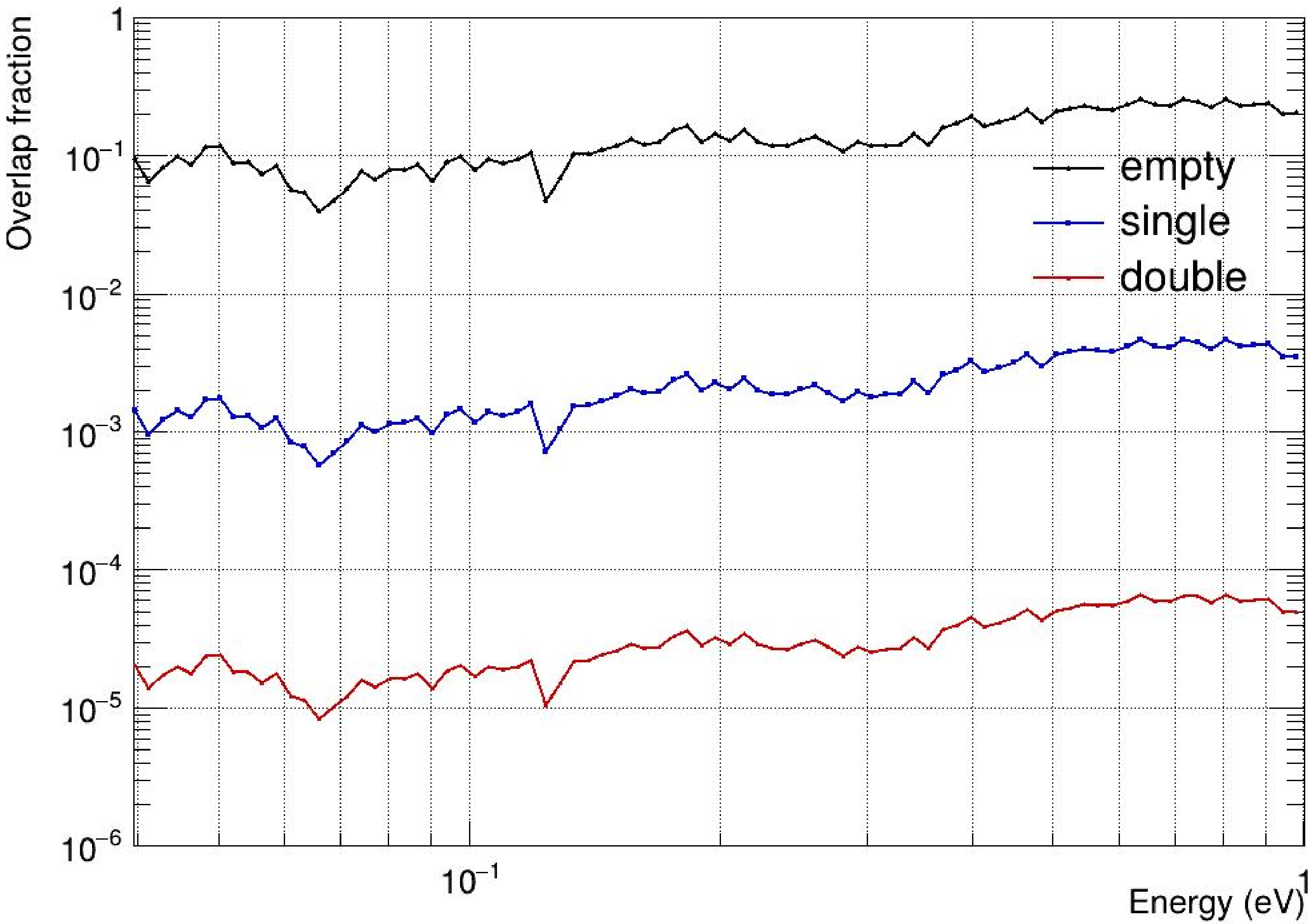
10-th CSNS Back-n User Conference. July 15-17,2026

设实验测量的空样品、一片BN、两片BN计数分别为C_0、C_1、 C_2。对应的overlap本底为B_0 B_1 B_2，其中$B_2=B_1*\exp(-\sigma_{overlap}*N_s)=B_0*\exp(-2*\sigma_{overlap}*N_s)$。 σoverlap来自ENDF/B VIII.0数据。可粗略估计overlap本底占比大小

$$\frac{C_1 - B_1}{C_0 - B_0} = \frac{C_2 - B_2}{C_1 - B_1}$$

$$B_0 = \frac{C_0 C_2 - C_1^2}{C_0 f^2 + C_2 - 2C_1 f}$$

其中$f=\exp(-\sigma_{overlap}*N_s)$，即overlap本底经过一片BN的衰减因子。



Neutron energy resolution (0.0253 eV)

$$\frac{dv}{v} = \sqrt{(\frac{\Delta L}{L})^2 + (\frac{\Delta T}{T})^2} = 0.045\%$$

$$\frac{dE}{E} = \gamma(\gamma + 1)\sqrt{(\frac{\Delta L}{L})^2 + (\frac{\Delta T}{T})^2} = 0.091\%$$

ΔL = 3.5 cm，ΔT = 205 ns，
L = 76.9589 m，T = 34980813 ns

$$\begin{cases} C_0 = S_0 + B_0 \\ C_1 = S_0 f_s + B_0 f_b \\ C_2 = S_0 f_s^2 + B_0 f_b^2 \end{cases}$$