Sm/Yb/Ag中子俘获截面实验研究进展

2025

李鑫祥

南华大学

Content

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Motivation

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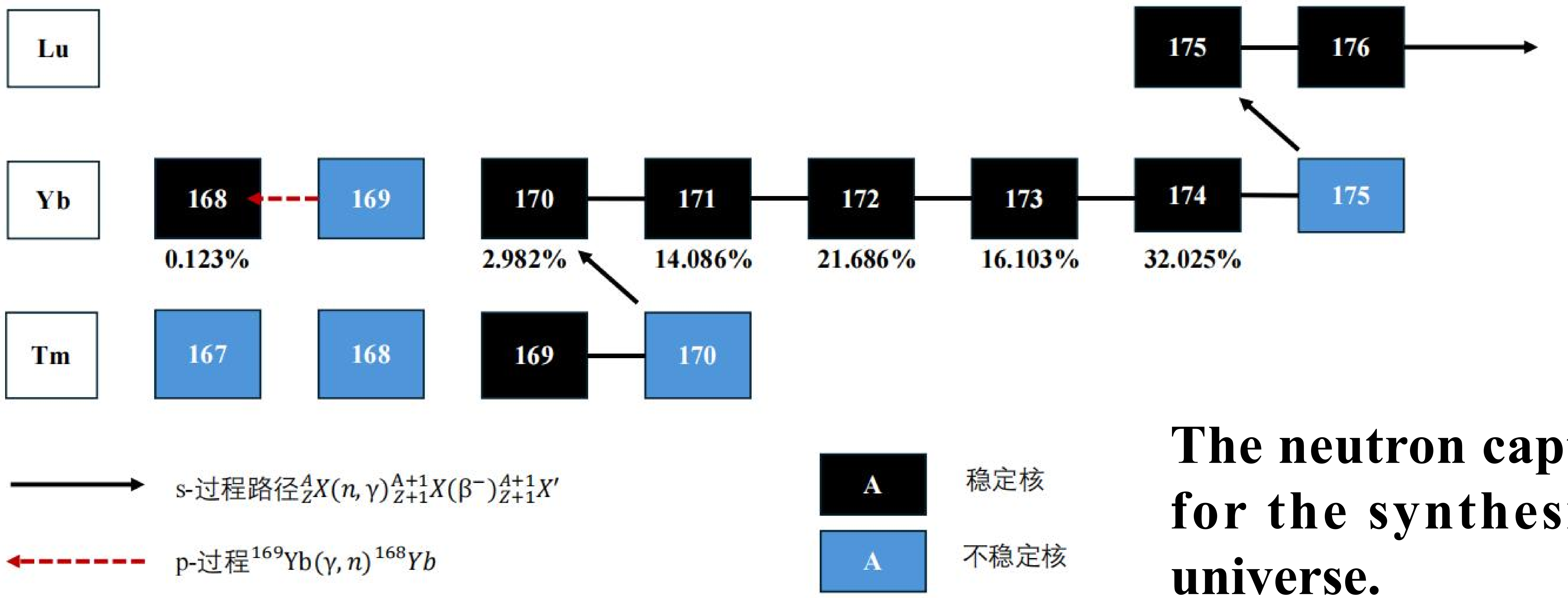
Motivation: Nuclear Astrophysics

How are elements heavier than iron produced in the universe?

——One of the unsolved problems of physics in 21st century



- Neutron is no charged;
- The neutron capture cross section of nuclide tends to increase with decreasing energy;

The neutron capture reaction is the main pathway for the synthesis of superiron elements in the universe.

Neutron capture cross section of superiron elements is the key parameters for nuclear astrophysics

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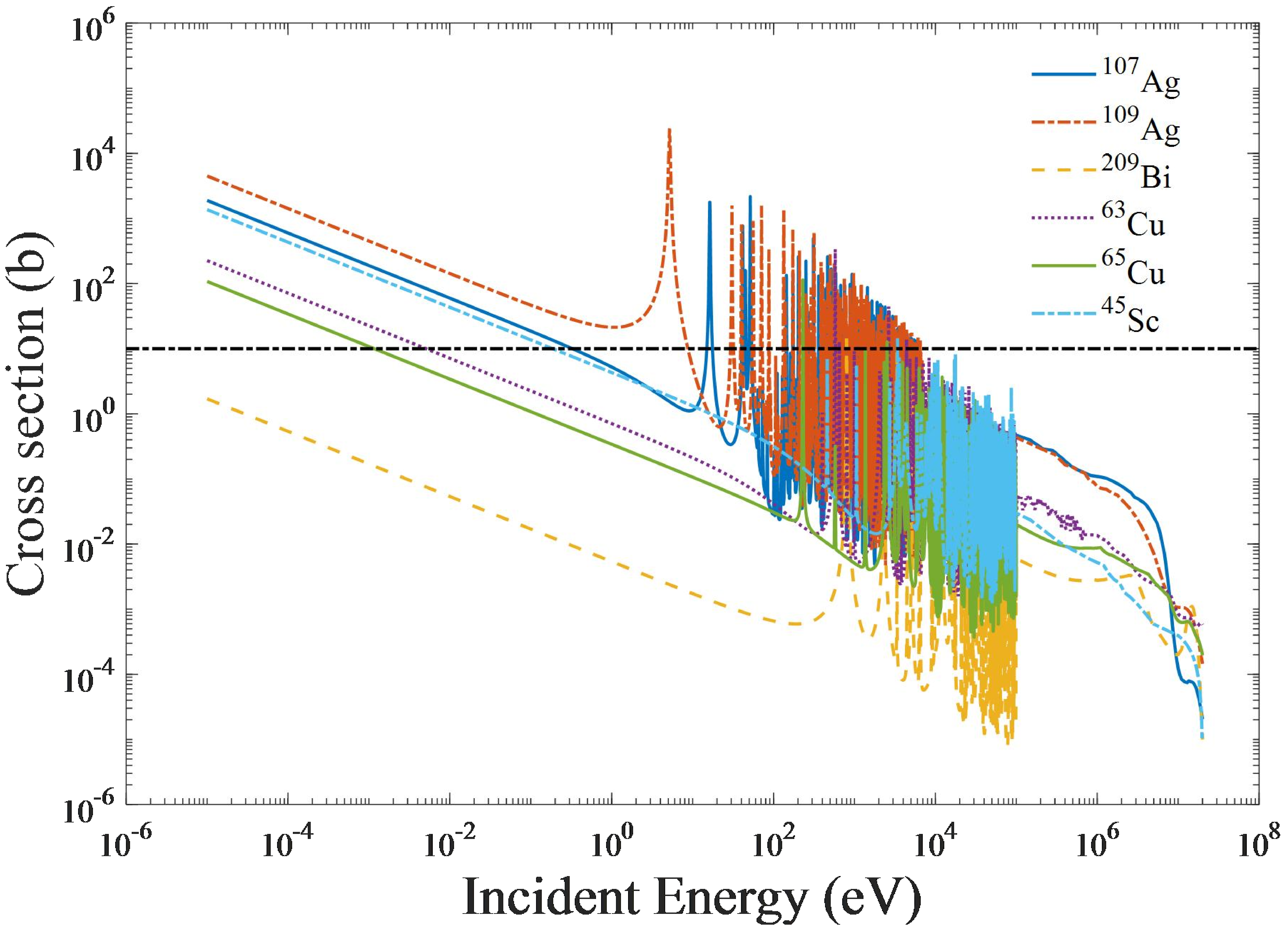
Motivation: Nuclear Data



- Back-n装置目前发表的中子俘获截面实验数据中，共振峰低于10 b的截面数据极少；
- 我们从2020年开始测量Cu/Ag等低截面同位素靶(n,g)截面，遇到困难；
- 从2022年起，我们系统性开展了一系列低截面同位素靶的(n,g)截面测量（^{107}Ag、^{109}Ag、^{209}Bi、^{63}Cu、^{65}Cu、^{45}Sc）
- 从这些数据的综合分析中，探索一条在现有条件下能够完成的低截面靶的实验和分析方法；

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Method & Material

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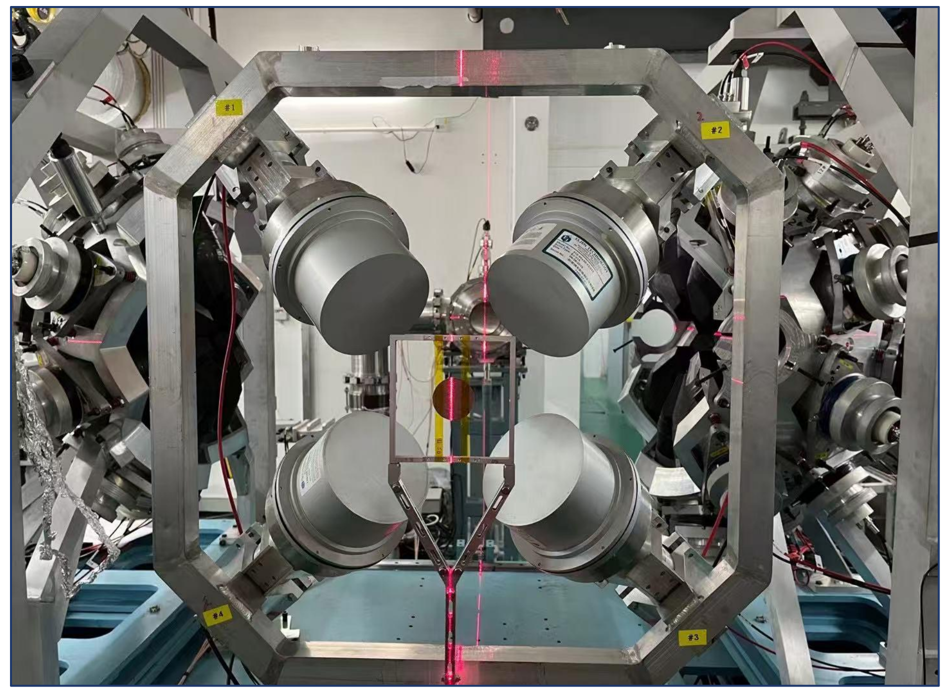
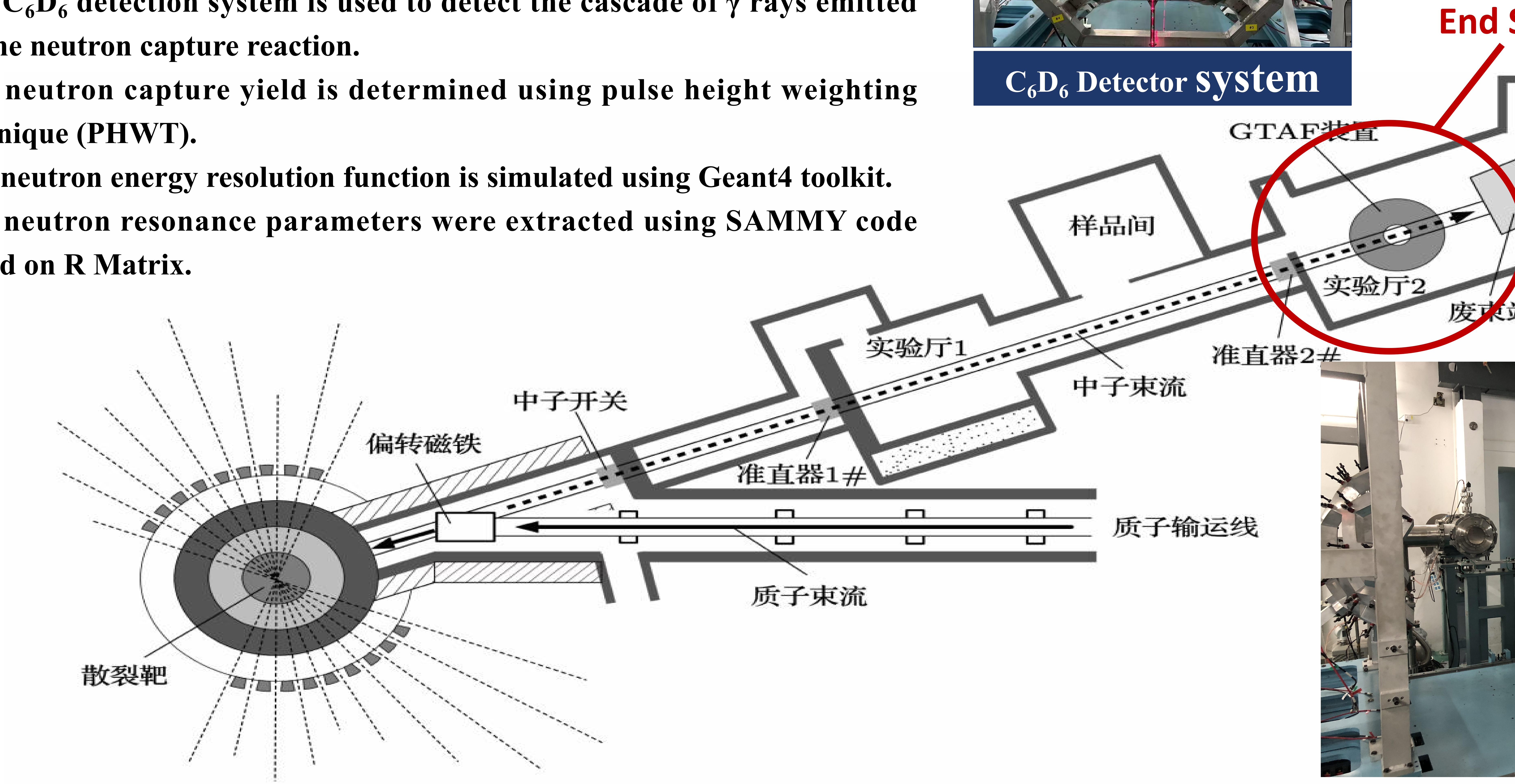
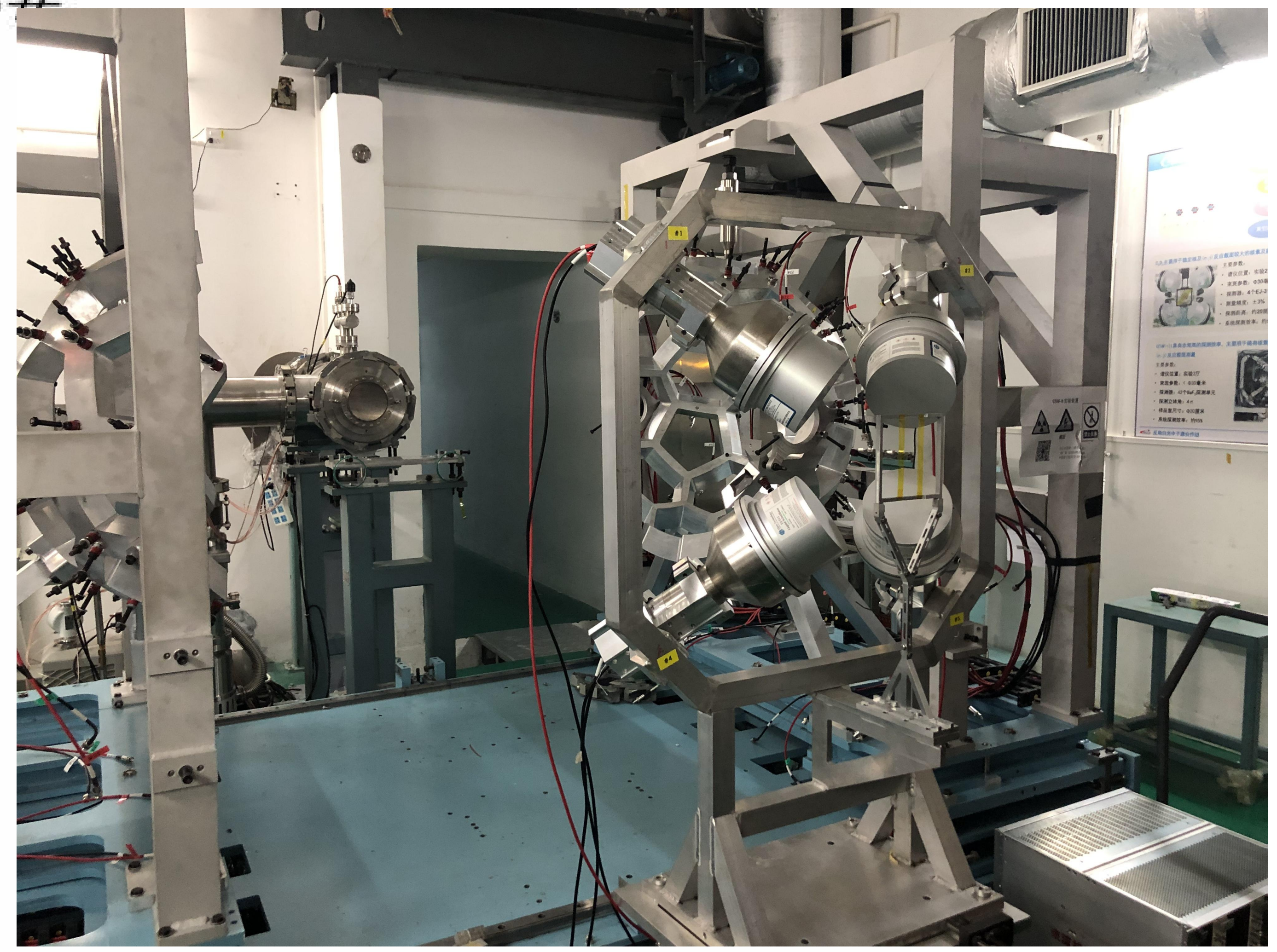
Experimental setup

- The C_6D_6 detection system is used to detect the cascade of γ rays emitted by the neutron capture reaction.
- The neutron capture yield is determined using pulse height weighting technique (PHWT).
- The neutron energy resolution function is simulated using Geant4 toolkit.
- The neutron resonance parameters were extracted using SAMMY code based on R Matrix.



C_6D_6 Detector system





* Figure from reference: Q.W. Zhang et al., Acta Phys. Sin. 70(22): 222801. (2021)

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Overview of Experimental Research on Neutron Capture Cross Section Conducted by USC&SARI at Back-n Facility(As of May.2025)

Date	Target	Diameter (mm)	Thickness (mm)	BeamPower (kW)	Publish
2019.01	^{197}Au	50.0	1.0	~34	X.R. Hu et al., Nucl. Sci. Tech. (2021)
	^{nat}Se	50.0	2.0		X.R. Hu et al., Chin. Phys. B (2022)
	^{89}Y	50.0	1.0		Analyzing by CDUT
2019.05	^{197}Au	30.0	1.0	~50	X.X. Li et al., Nuclear Techniques (in Chinese)
	^{nat}Er	50.0	1.0		X.X. Li et al., Phys. Rev. C (2021， 2022)
2019.05	^{nat}Sm	50.0	1.0	~50	X.X. Li et al., Nucl. Sci. Tech. (2025)
2020.10	^{63}Cu	30.0	0.1	~80	Analyzing
	^{65}Cu	30.0	0.1		
2021.04	^{107}Ag	30.0	0.1	~100	X.X. Li et al., Chin. Phys.B (2022)
	^{109}Ag	30.0	0.1		
2022.07	^{nat}Ag	30.0	0.1	~150	Analyzing
2022.11	^{nat}Yb	30.0	0.1	~150	Y.J. Chen et al., Phys. Rev. C (2025)
2023.10	^{65}Cu	30.0	0.1	~150	Analyzing
	^{209}Bi	40.0	1.0		
2024.11	^{45}Sc	50.0	0.2, 1.0	~170	

Key Step: Background Determination

- The general experimental process and data analysis methods have been introduced in the previous reports.
- This report will introduce something different in experimental data analysis.

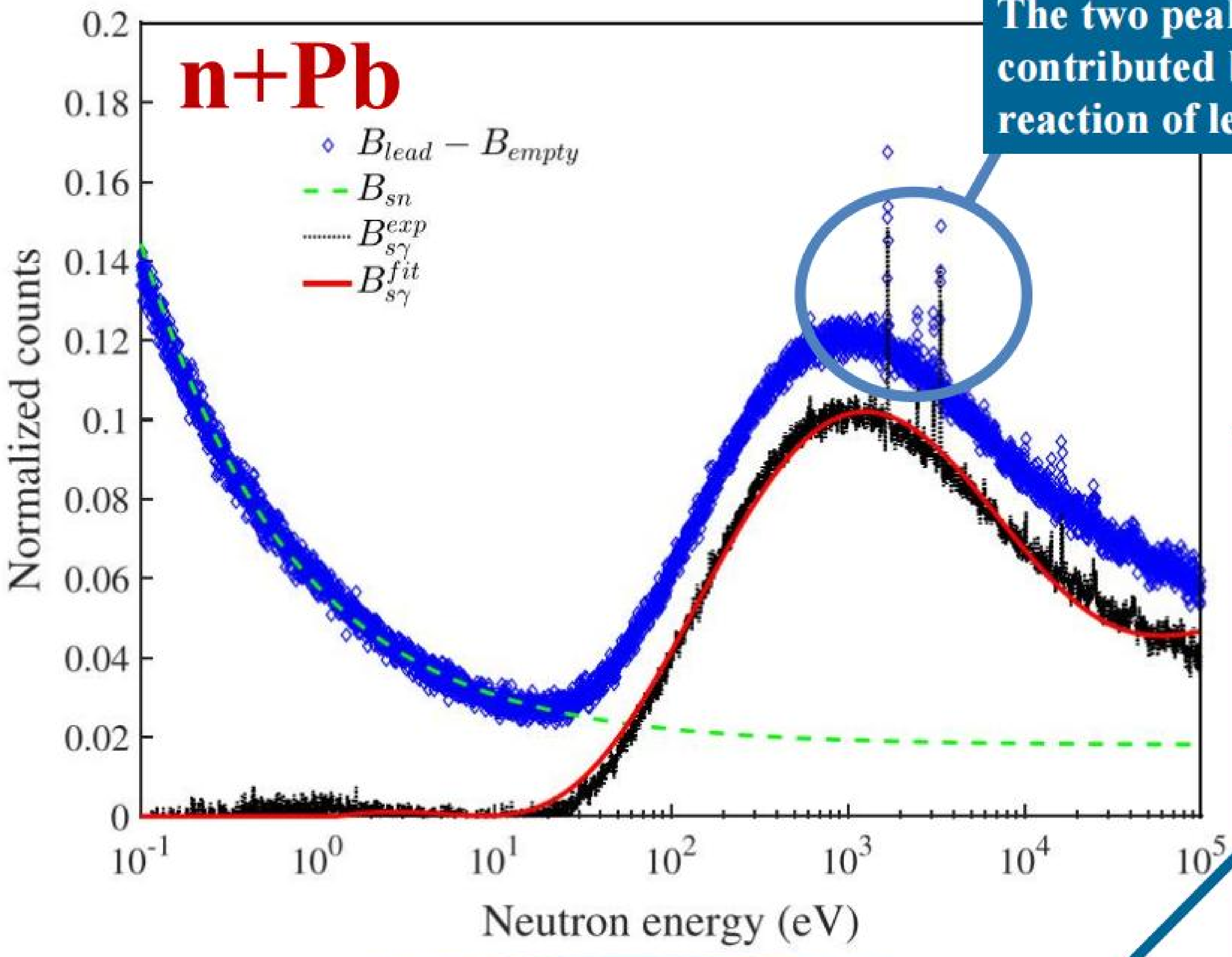
Background composition in the neutron capture cross-section experiment.

BKG	Meaning	Measurement
B_0	Activation background	no beam
$B_{empty}(t_n)$	Target-independent background	n+empty
$B_{sn}(t_n)$	Scattered neutron background	n+carbon/lead
$B_{s\gamma}(t_n)$	In-beam gamma background	n+lead

$$B_{total} = B_0 + B_{empty}(t_n) + B_{sn}(t_n) + B_{s\gamma}(t_n)$$

The most complex one among these backgrounds

For in-beam γ background, n+lead target can determine its shape (time structure)



The two peaks are contributed by the (n,g) reaction of lead target.

$$B_{s\gamma}^{fit} = \frac{a_1}{\sqrt{E_n}} + a_2 e^{a_3/\sqrt{E_n}} + a_4 e^{a_5 \times \sqrt{E_n}} + a_6, \quad (2)$$

where E_n is the neutron energy in units of MeV and a_i are the fitting parameters: $a_1 = -5.343 \times 10^6$, $a_2 = 0.141$, $a_3 = -0.0155$, $a_4 = 0.121$, $a_5 = -16.7$, $a_6 = -0.115$.

we use this euqation to describe the in-beam gamma background in order to eliminate the influence of neutron capture reaction of lead target.

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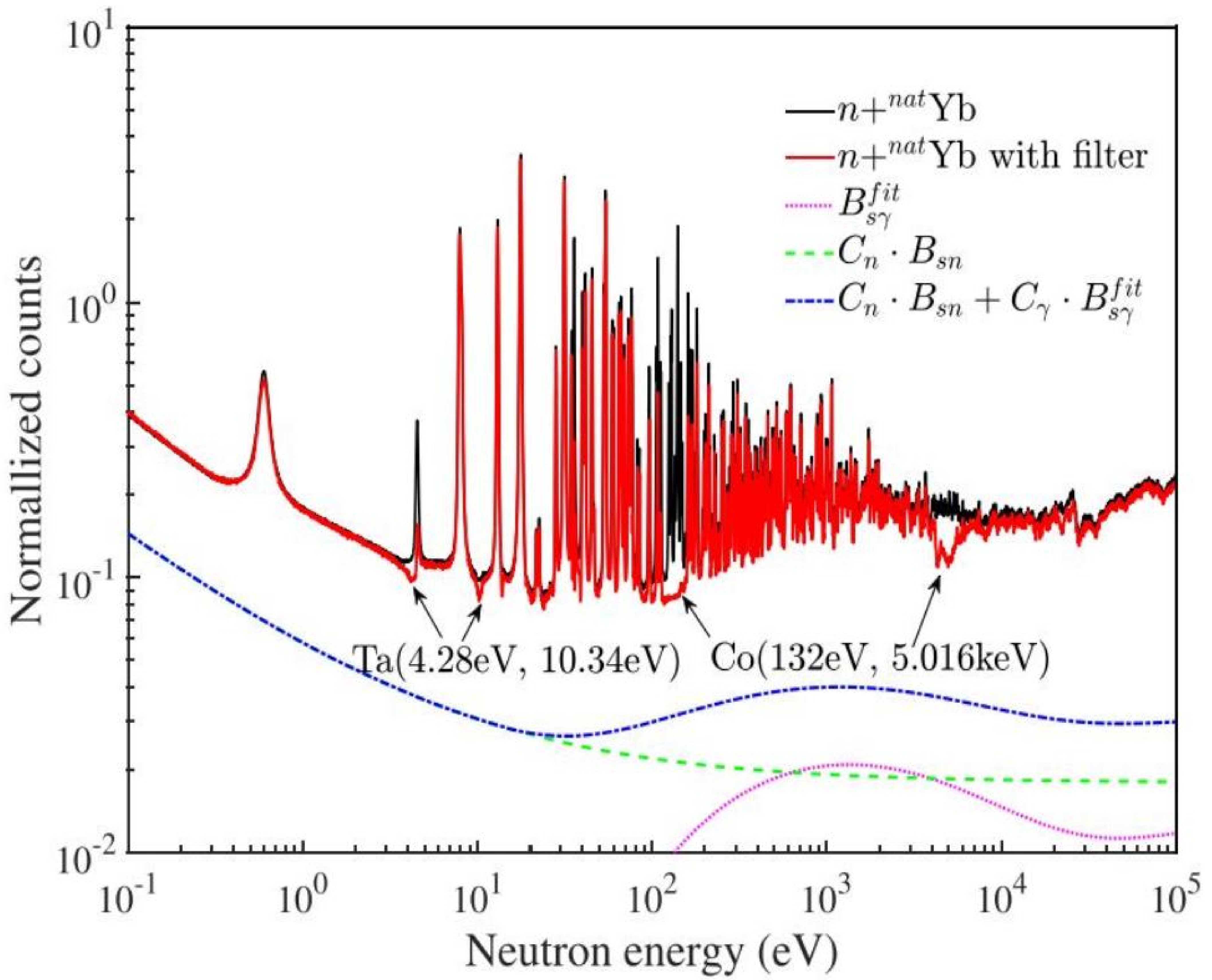
Key Step: Background Determination

The scale of in-beam γ background is determined by the "black resonance" method.



- **Tantalum and cobalt filters, each with a thickness of 1 mm, are placed in the beam line to absorb neutrons at specific energies.**
- **The neutron at 4.28 eV, 10.34 eV, 132 eV and 5.02 keV will be absorbed by filter.**
- **The experimental results is the results of the interaction between the gamma rays and the target.**

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Key Step: S_n for natural target

For the caculation of S_n for natural target, different references provide different methods.

- **Phys. Rev. C 85, 044615 (2012)**

$^{nat}Sn = {^i}Sn, i = find(NA_i = max(NA))$

As shown in Eq. (3), the efficiency, and, hence, the calculated capture yield, is inversely proportional to E_c. However, only a single S_n (typically chosen to be that of the most abundant isotope in the sample) can be used in weighting the data. Therefore, in the analysis of the capture data, the abundances of the other Mg isotopes in the sample must be scaled according to their S_n value. In particular, the neutron separation energies used were 7.33, 11.09, and 6.44 MeV for ^{25}Mg, ^{26}Mg, and ^{27}Mg, respectively.

^{nat}Sn is the same as that of the isotope with the greatest abundance.

- **Chin. Phys. B 31, 080101 (2022)**

$^{nat}Sn = mean(NA_i * {^i}Sn)$

the measurement of the saturated 4.9 eV resonance in the thick ^{197}Au sample. ε_{E_n} is the detection efficiency, which for weighted counts is equal to the excitation energy ($S_n + E_n$) according to Eq. (3), and $S_n = 7.054$ MeV for ^{nat}Se. C_W and B_W are the weighted pulse height spectra for the ^{nat}Se sample and the total background, respectively. The neutron fluence was

^{nat}Sn is euqal to the weighted average of isotope Sn according to their abundances.

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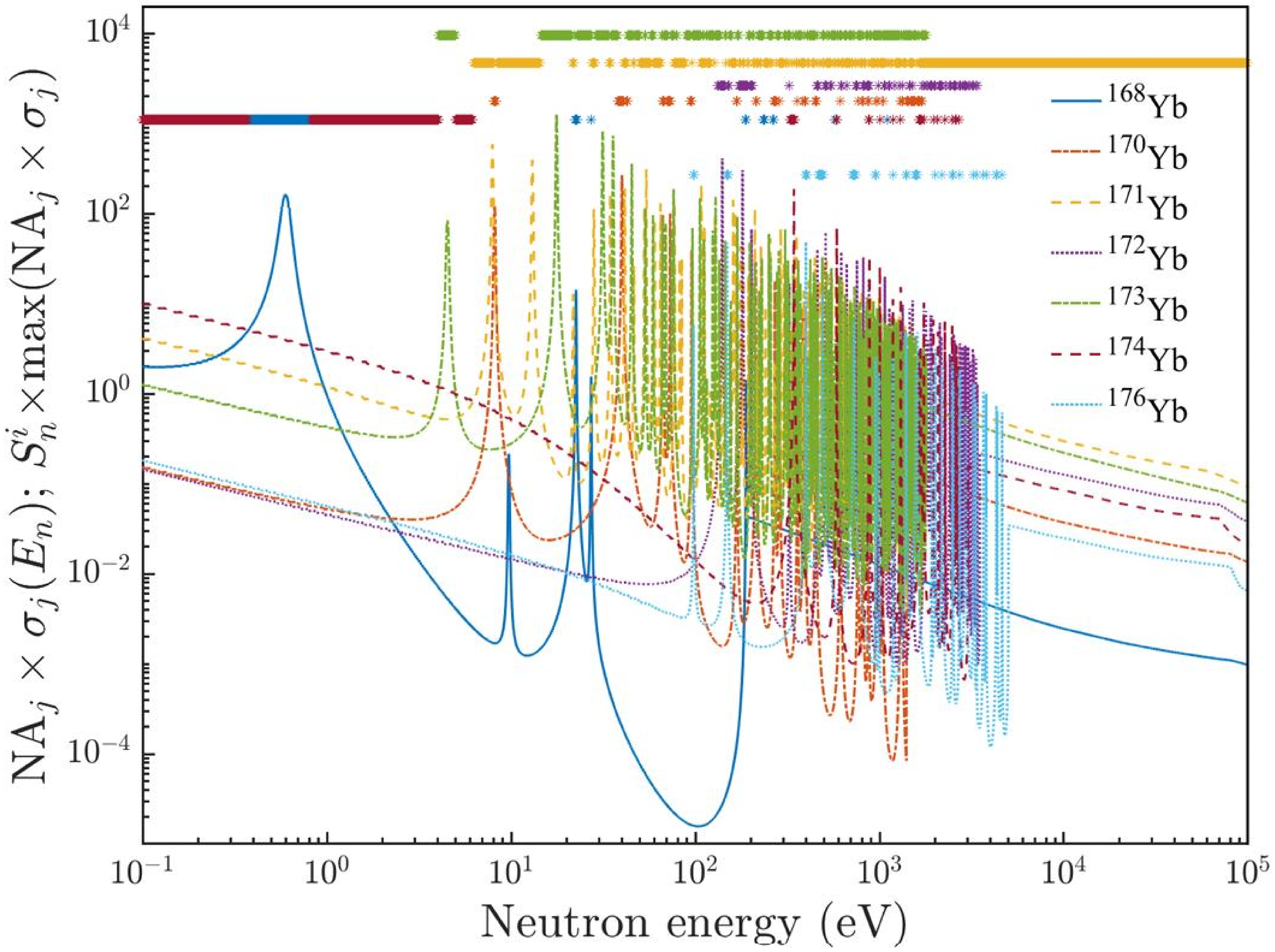
Key Step: S_n for natural target

In the above calculations, natural Sn is a constant independent of the neutron energy.

- Actually, for natural target, differennt resonance peaks are contributed by different isotopes. So the natural Sn should be changed in different resonance energies.
- In this work, the neutron separation energy for natural target is determined by following equation:

$^{nat}Sn(E) = {}^{i}Sn$, $i = find(A_i = max(A))$;

$A = NA_i * \sigma_i$



Y.J. Chen, X.X. Li*, W. Luo* et al., Phys. Rev. C 111, 054607 (2025)

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Key Step: S_n for natural target

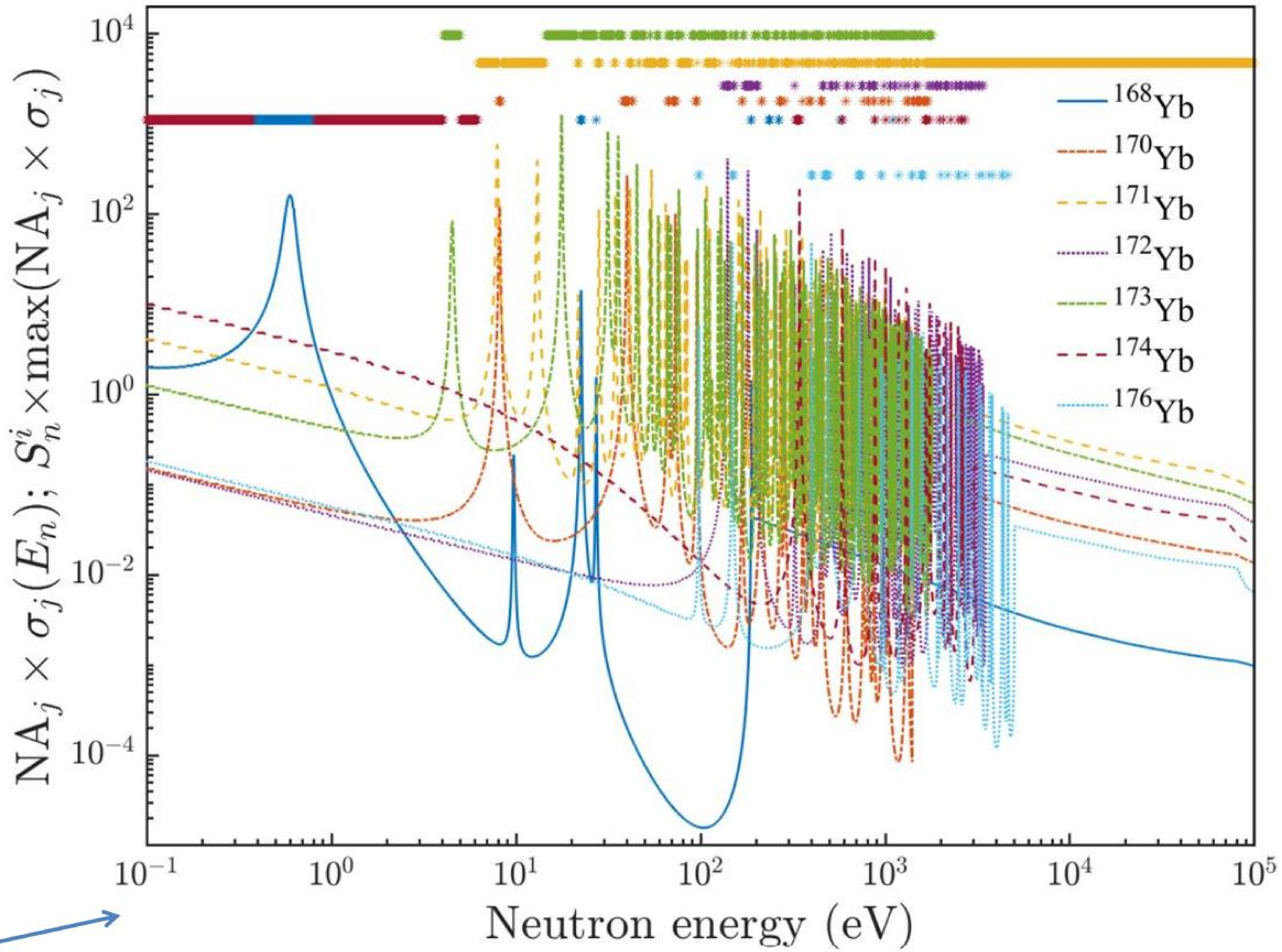
Selection of evauation database

The resonance positions and values can vary across different evaluation databases, which may impact the calculation results of Sn. We compared the results of mai evaluation databases and selected the appropriate ones.

Eliminate inconsistent evaluation databases based on the positions of the formant peaks in the experiment

Database	The peak position is consistent with the experiment?	Results
ENDF/B-VIII.0	Y	Sn1(E)
JEFF-3.3	N	excluded
JENDL-5	Y	Sn2(E)
TENDL-2023	N	excluded
BROND-3.1	Y	Sn3(E)

- **In this case, the database of JEFF-3.3 and TENDL-2023 was excluded, and Sn1(E) == Sn2(E) == Sn3(E).**
- **The selection of the three evaluation databases ENDF/B-VIII.0, JENDL-5 and BROND-3.1 will not affect the result of Sn.**
- **The result of ENDF/B-VIII.0 is shown in the figure.**



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Results

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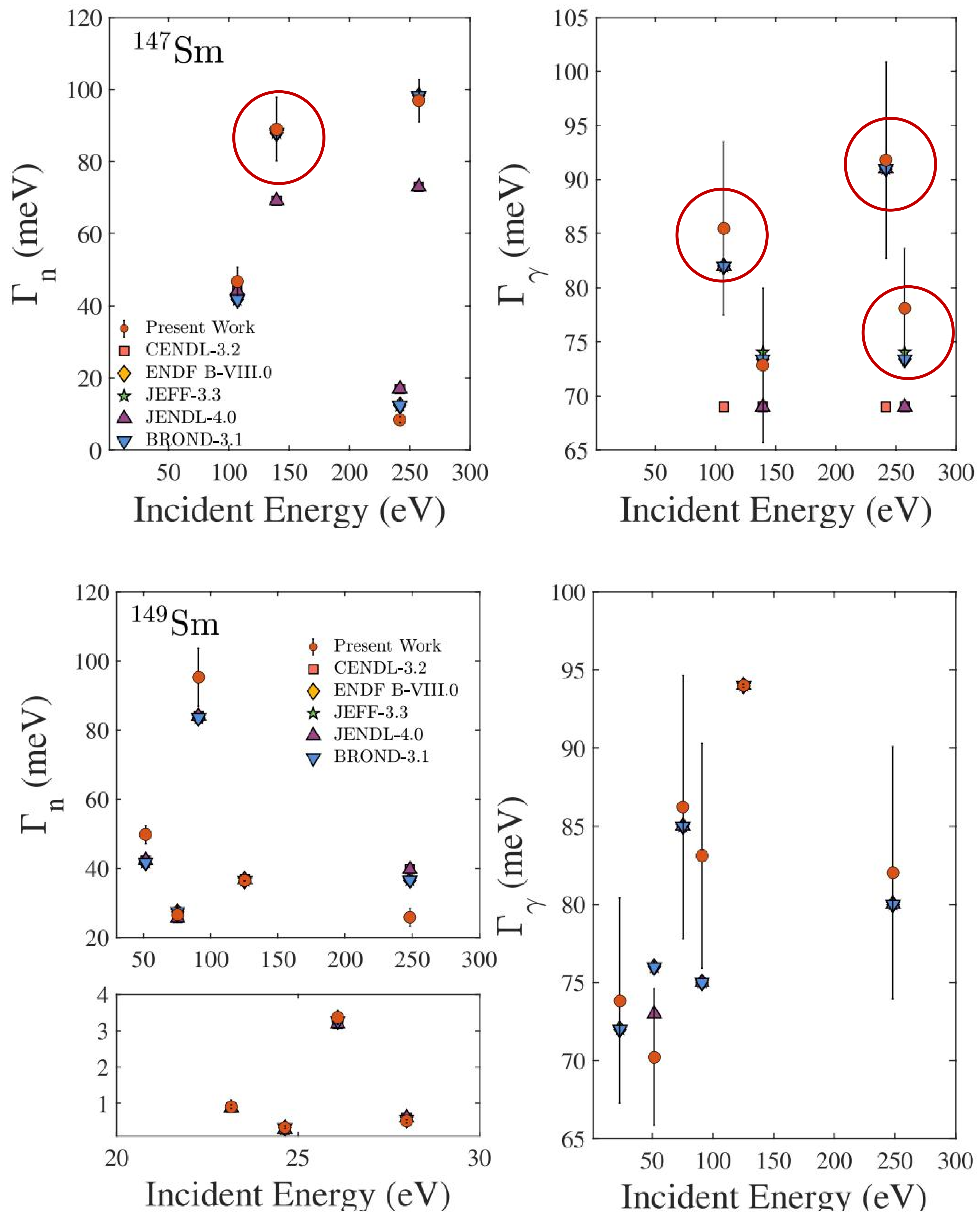
Results: Sm



DB#1-5 representing **CENDL-3.2, ENDF/B-VIII.0, JEFF-3.3, JENDL-4.0, BROND-3.1**

Table 3 Clarification of differences between different evaluation databases

Mass	E_n (eV)	Γ_n						Γ_γ					
		Present work	DB#1	DB#2	DB#3	DB#4	DB#5	Present work	DB#1	DB#2	DB#3	DB#4	DB#5
147	107.0	46.8 ± 4.0	44.2	41.8	41.8	44.2	41.8	85.5 ± 8.0	69.0	82.0	82.0	82.0	82.0
	139.4	89.0 ± 8.8	69.1	88.0	88.0	69.1	88.0	72.9 ± 7.1	69.0	73.4	74.1	69.0	73.4
	241.7	8.4 ± 0.8	17.0	12.4	12.4	17.0	12.4	91.8 ± 9.2	69.0	91.0	91.0	91.0	91.0
	257.3	96.9 ± 6.5	73.0	98.3	98.3	73.0	98.3	78.1 ± 5.8	69.0	73.4	74.1	69.0	73.4
149	23.2	0.9 ± 0.1	0.9	7.9	7.9	0.9	7.9	73.8 ± 6.8	62.0	72.0	72.0	62.0	72.0
	24.6	0.3 ± 0.1	0.3	0.3	0.3	0.3	0.3	39.4 ± 3.9	62.0	40.0	40.0	62.0	40.0
	26.1	3.4 ± 0.3	3.2	3.3	3.3	3.2	3.3	51.7 ± 5.0	62.0	49.0	49.0	62.0	49.0
	28.0	0.5 ± 0.1	0.6	0.5	0.5	0.6	0.5	39.7 ± 4.0	62.0	40.0	40.0	62.0	40.0
	51.5	49.8 ± 3.2	42.3	41.8	41.8	42.3	41.8	70.2 ± 5.1	62.0	76.0	76.0	73.0	76.0
	75.2	26.5 ± 2.3	25.6	27.4	27.4	25.6	27.4	86.2 ± 8.4	62.0	85.0	85.0	85.0	85.0
	90.9	95.3 ± 8.8	84.1	83.6	83.6	84.1	83.6	83.1 ± 7.2	62.0	75.0	75.0	75.0	75.0
	125.3	36.4 ± 4.0	36.8	36.4	36.4	36.8	36.4	94.0 ± 9.8	62.0	94.0	94.0	94.0	94.0
	248.4	25.8 ± 2.6	39.7	36.6	36.6	39.7	36.6	82.0 ± 8.1	62.0	80.0	80.0	80.0	80.0

- **the neutron resonance parameters for various Sm isotopes from 20 to 300 eV were extracted using the SAMMY code based on the R-matrix theory.**
- **For the parameters Γn and Γg in these energies of ^{147,149}Sm, the percentages consistent with the results of the CENDL-3.2, ENDF/B-VIII.0, JEFF-3.3, JENDL-4.0, and BROND-3.1 database are 27%, 65%, 65%, 42%, and 58%, respectively.**
- **However, 27% of the results were inconsistent with those of the major libraries.**

X.X. Li*, H.W. Wang*, W. Luo* et al., Nucl. Sci. Tech. 36:178 (2025)

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Results： Yb

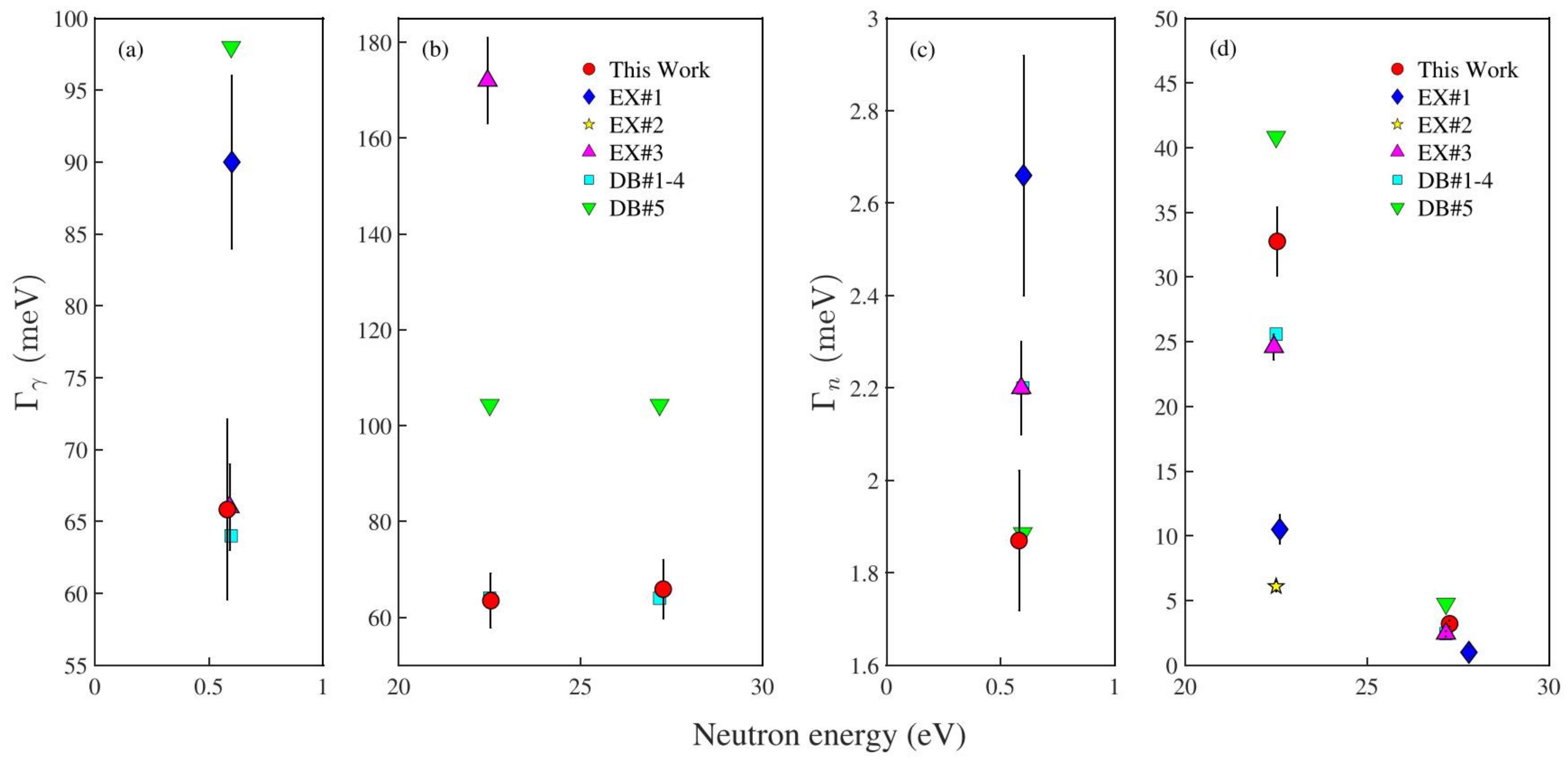

TABLE III: Resonance parameters of ^{168}Yb extracted from the SAMMY code of experimental data.

	E_R (eV)	Γ_γ (meV)	Γ_n (meV)	k
This work	0.58±0.01	65.83±1.27	1.87±0.02	1.82±0.15
EX#1	0.600±0.008	90±6	2.66±0.26	2.58±0.24
EX#2	-	-	-	-
EX#3	0.590±0.005	66±3	2.2±0.1	2.12±0.10
DB#1-4	0.60	64.00	2.20	2.13
DB#5	0.60	98.01	[illegible]	1.85
This work	22.53±0.45	63.48±4.69	32.76±0.66	21.61±1.81
EX#1	22.60±0.05	-	10.5±1.1	-
EX#2	22.5±0.04	-	6.1±0.4	-
EX#3	22.44±0.05	24.6±1.0	172±90	21.52±0.99
DB#1-4	22.50	64.00	25.60	18.29
DB#5	22.50	104.34	40.84	29.34
This work	27.27±0.55	65.88±6.12	3.21±0.24	3.06±0.23
EX#1	27.48±0.1	-	1±0.4	-
EX#2	-	-	-	-
EX#3	27.17±0.06	-	2.45±0.20	-
DB#1-4	27.17	64.00	2.45	2.35
DB#5	27.17	104.34	4.76	4.55

DB#1-5：ENDF/B-VIII.0，JENDL-4.0，BROND-3.1，JEFF-3.3，TENDL-2019

Since JENDL-5 and TENDL-2023 do not include resonance parameters of ^{168}Yb, JENDL-4.0 and TENDL-2019 were used.

EX#1：V. P. Vertebnyj et al. (Neutron Phys. Conf. 1, 181 (1971))

EX#2： H. I. Liou et al. (Phys. Rev. C 7, 823 (1973))

EX#3：V. A. Anufriev et al. (Sov. At. Energy 49, 560 (1980))

The data of DB#1-4 are consistent and have been merged.

- **The results extracted from the experiment are inconsistent with all evaluation databases and existing experimental data.**
- **The existing experimental results are all inconsistent.**
- **None of the experiments is consistent with the results of any evaluation library.**
- **There are significant differences between DB#1-4 and DB#5.**

- **The first experimental extraction of the resonance parameters of ^{168}Yb at 27.3 eV.**
- **The experimental results are consistent with DB1-4 rather than DB5.**

Y.J. Chen, X.X. Li*, W. Luo* et al., Phys. Rev. C 111, 054607 (2025)

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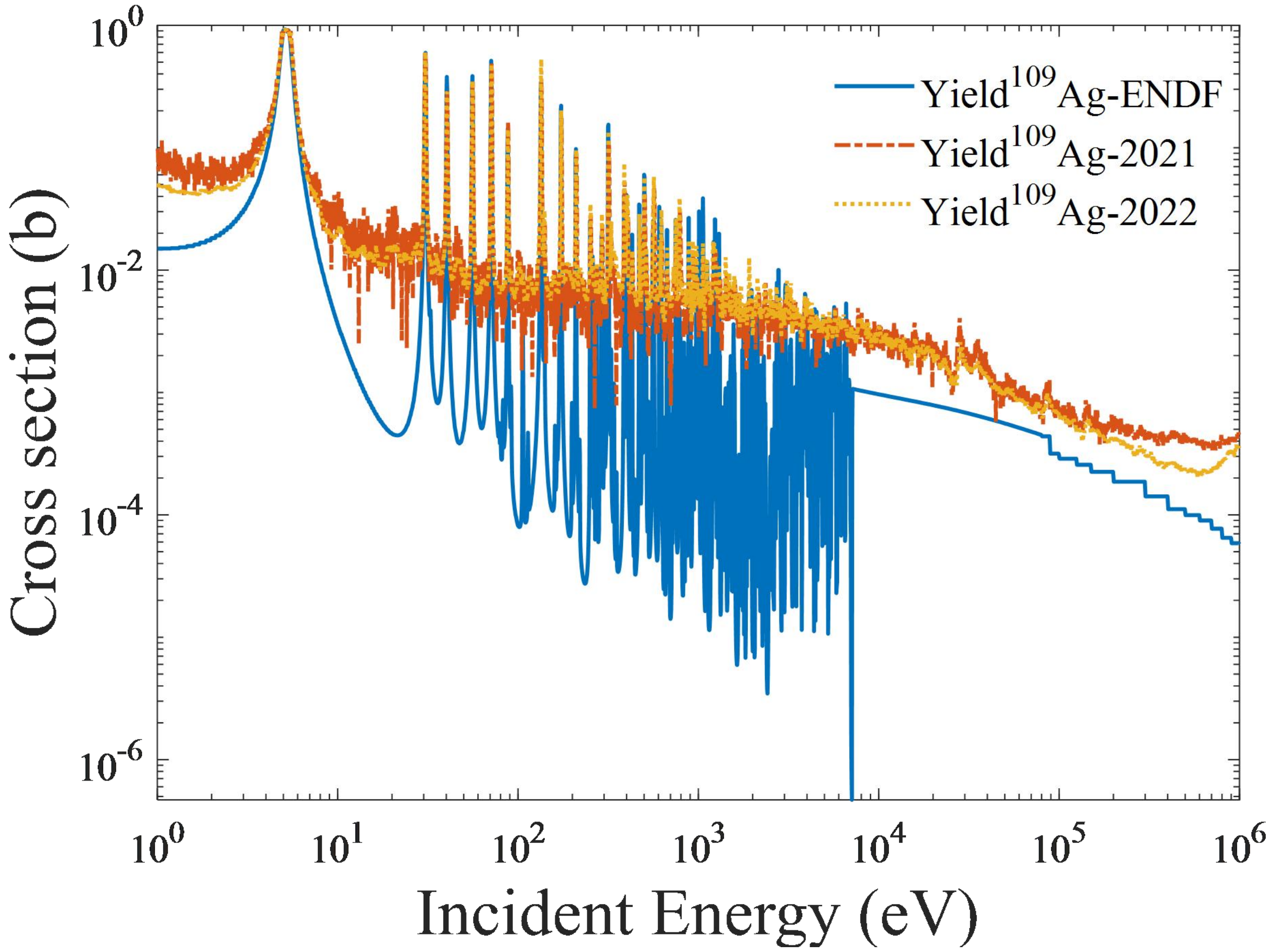
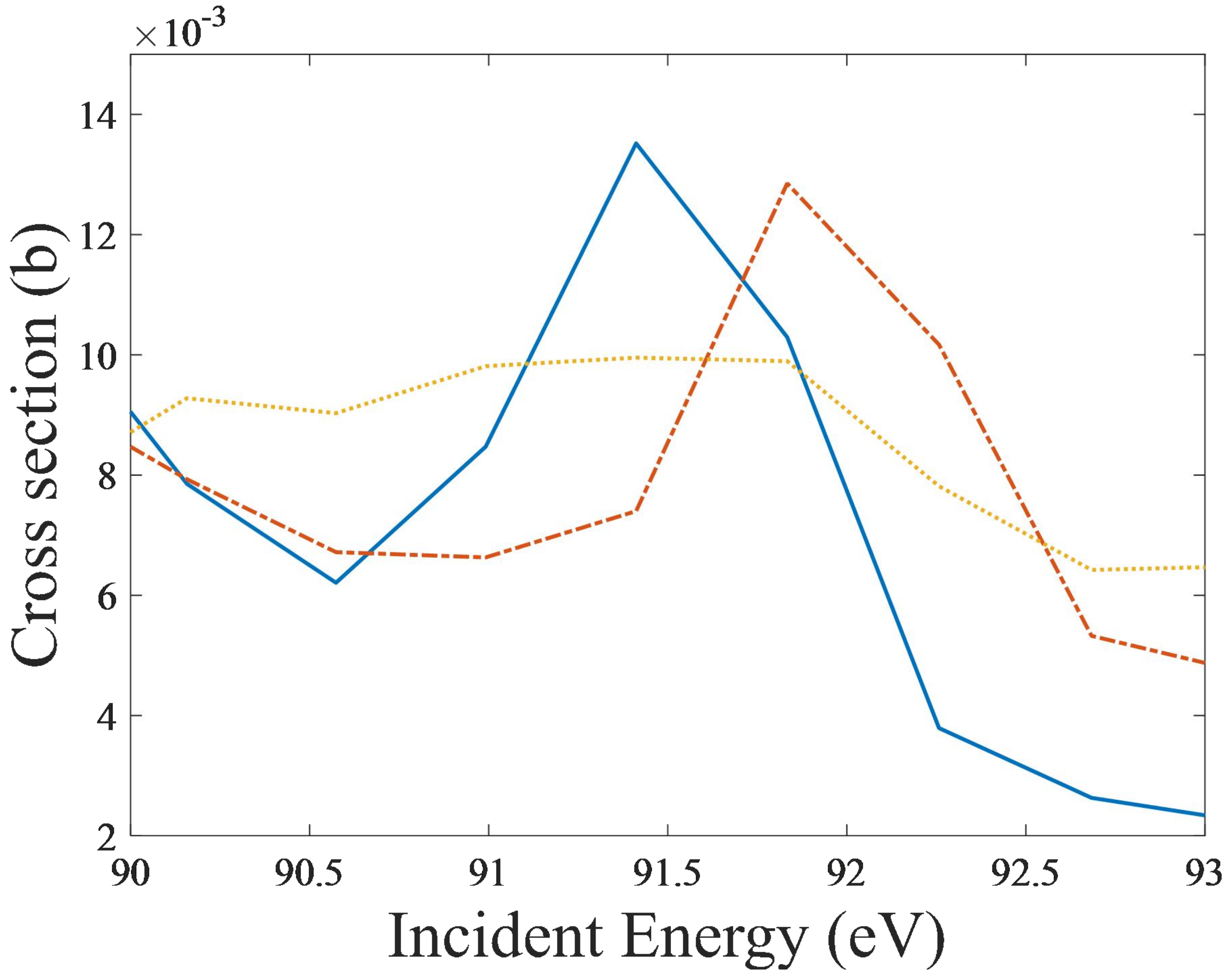
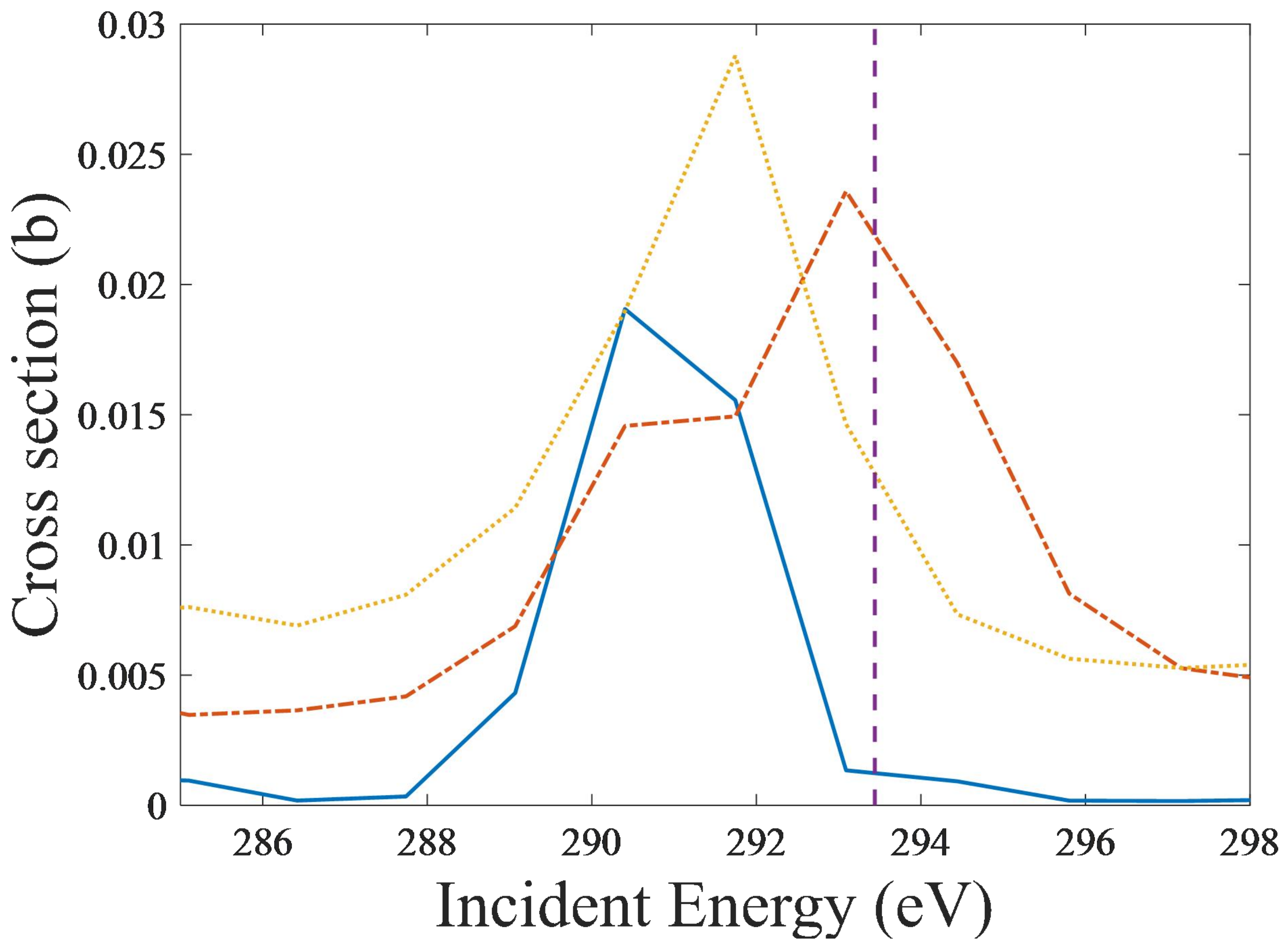
Results： Ag



E_R (eV)	2022	2021	ENDF/B-VIII.0	CENDL-3.2	JENDL-4.0	JEFF-3.3	BROND-3.1
				Γ_γ			
91.64	154.00 ±14.18	177.63 ±14.79	163.00	130.00	130.00	132.00	163.00
293.44	167.72 ±16.77	188.84 ±17.[illegible]8	163.00	130.00	130.00	132.00	163.00
				Γ_n			
91.64	0.13 ±0.01	0.14 ±0.01	0.02	0.10	0.02	0.03	0.02
293.44	0. 46 ±0.03	4. 94 ±0. 34	0.40	0.6[illegible]	0.40	0.23	0.40





- 初步对比了2021年和2022年^{109}Ag的中子俘获截面实验产额；
- 在部分能量点，21年和22年的实验产额存在明显区别，所提取的共振参数也存在差异；
- 本底的精细化确定与扣除等工作有待完成；

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4

Summary

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Summary

- 经过几年的发展，基于Back-n装置的高截面靶的(n,g)截面实验测量与分析方法已经成熟，Yb/Sm/Er等高截面靶实验能取得较好的结果；
- 低截面和低丰度靶的实验测量和数据分析方法有待进一步研究；
- 通过一系列低截面靶实验数据的综合分析（如Ag、Cu、Bi、Sc），有望提取实验结果的共性，发现未曾理解的实验本底信息，为后续低截面靶处理方法发展奠定基础。

Collaboration

We appreciate support from all collaborators.
We thank the staff members of the Back-n white neu_x0002_tron facility (https://cstr.cn/31113.02.CSNS.Back-n) at the China Spallation Neutron Source (CSNS) (https://cstr.cn/31113.02.CSNS), for providing technical

W. Luo, S. Feng, X.X. Li, B. Jiang, Z.C. Li, W. Xie, Z.A. Lin, T. Wu, T. Jiang et al.

H.W. Wang, G.T. Fan, L.X. Liu, Y. Zhang, Z.R. Hao

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THANKS