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Experimental Extraction of Neutron Resonancce Parameters for ^{168}Yb

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Content

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Motivation

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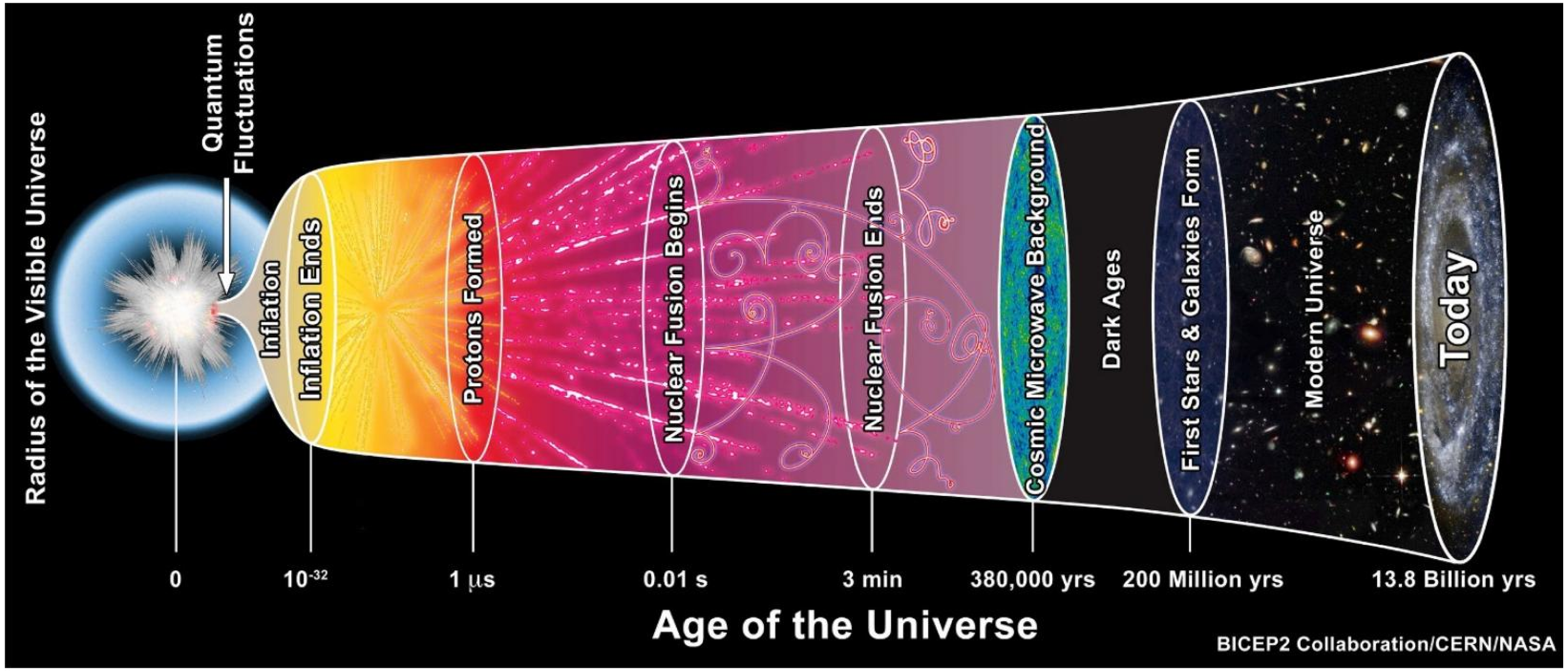
Motivation: Nuclear Astrophysics

How are elements heavier than iron produced in the universe?

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

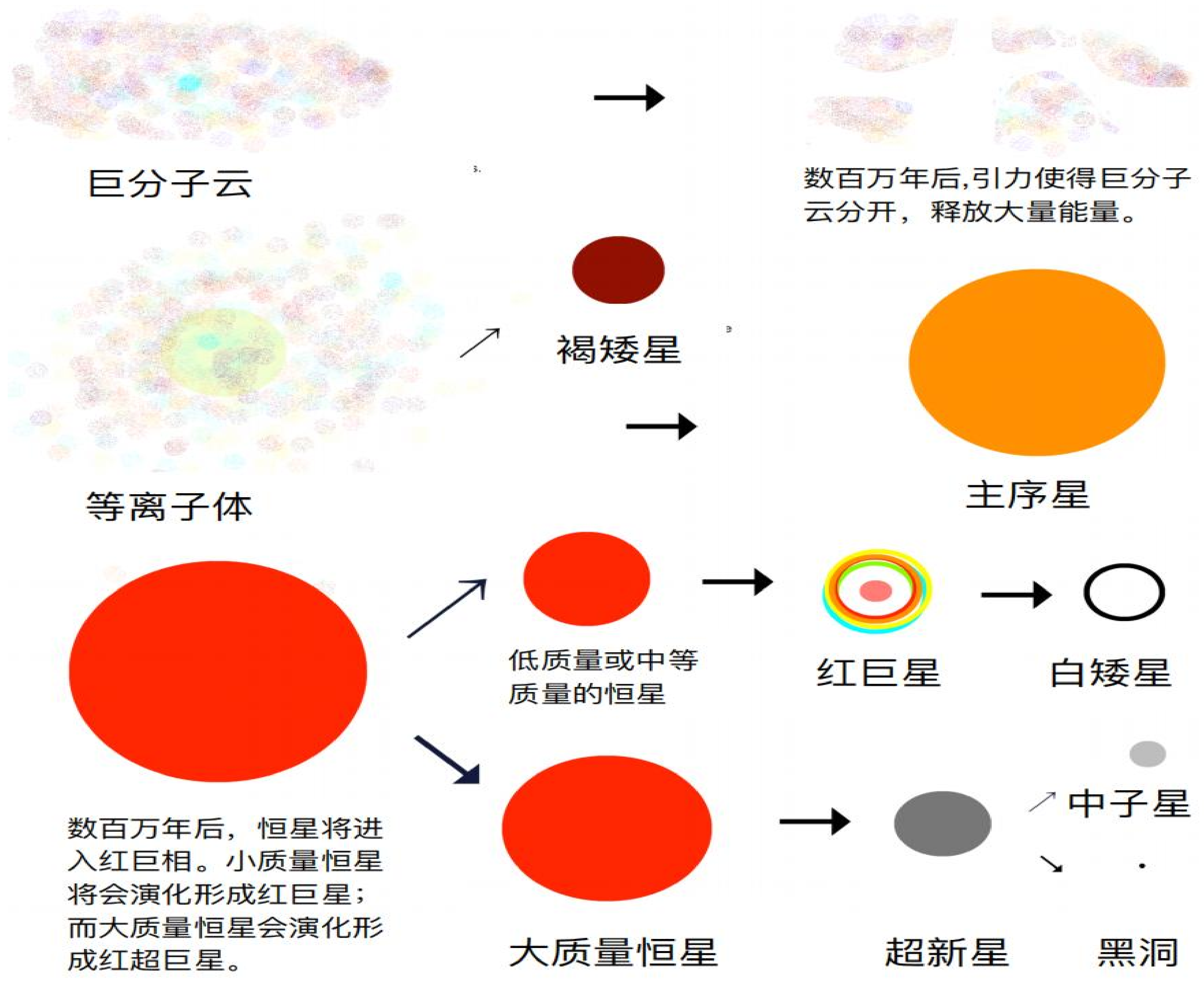


The Big Bang Theory can explain the origin of light elements such as H, He, Li et al.

Motivation: Nuclear Astrophysics

How are elements heavier than iron produced in the universe?

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



The origin of the element from cabon to iron can be explained by the nuclear fusion process in star.

- **For the superiron elements, two factors have caused the nuclear fusion process in stars unable to produce them.**
- **Coulomb barrier**
- **Binding energy**

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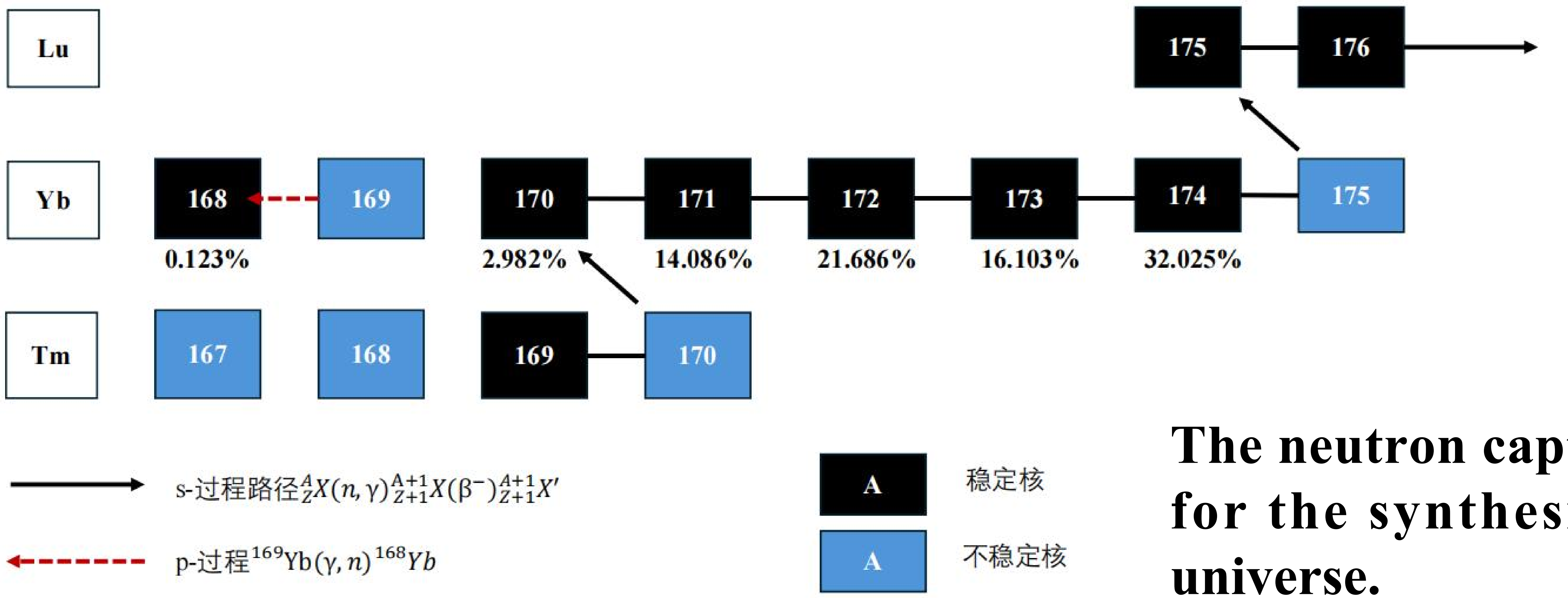
Motivation: Nuclear Astrophysics

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 nuclieds tend 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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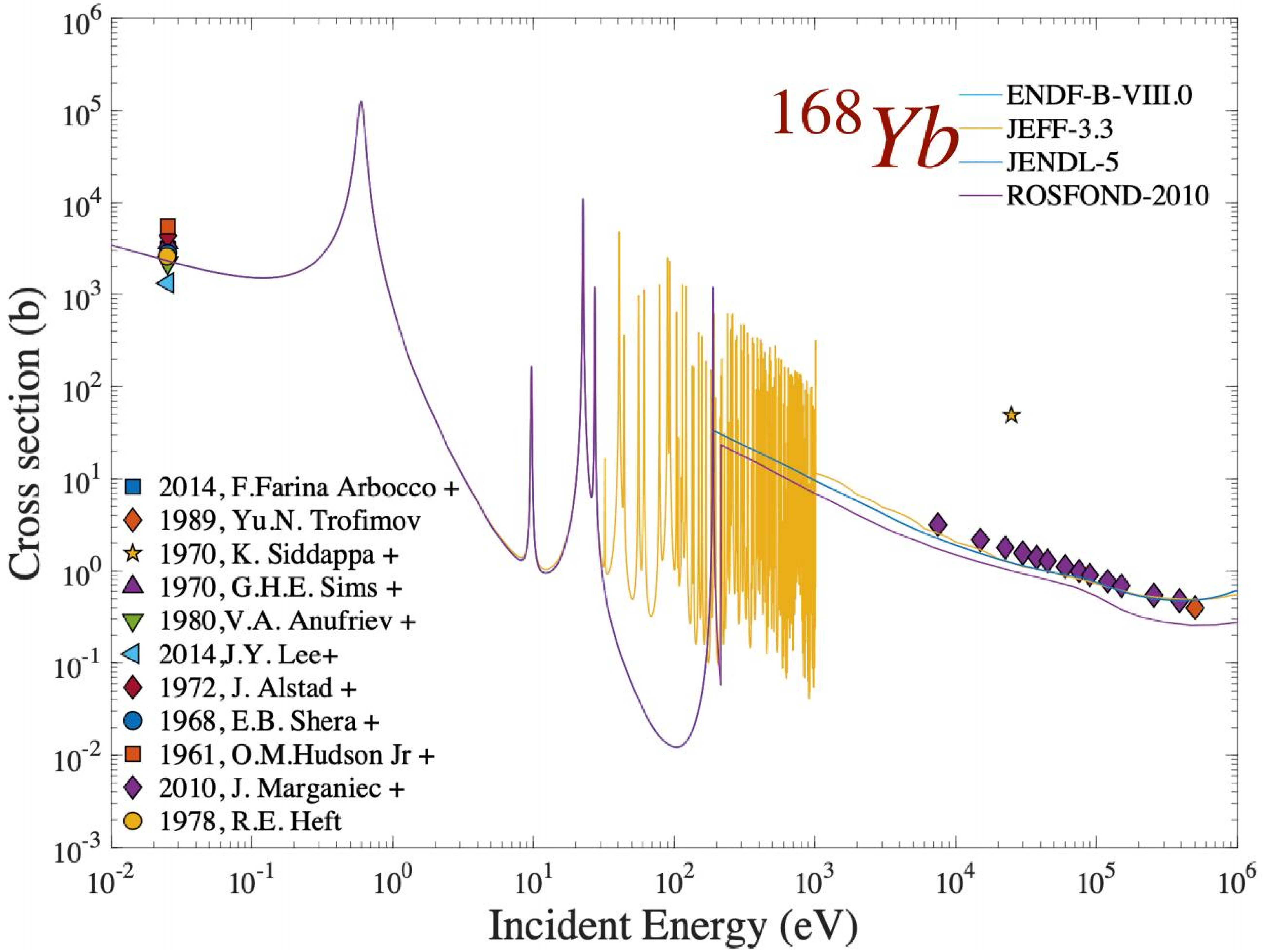
Motivation: Nuclear Data

Experimental data is needed to clarify the differences between evaluation database.



- **Experimental data in resonance energy region needs to be supplemented;**
- **There are obvious differences among different evaluation databases, and high-priecision experimental data clarification is needed;**
- **The experiments in Back-n can provide the experimental support for new version of CENDL database.**

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Method & Material

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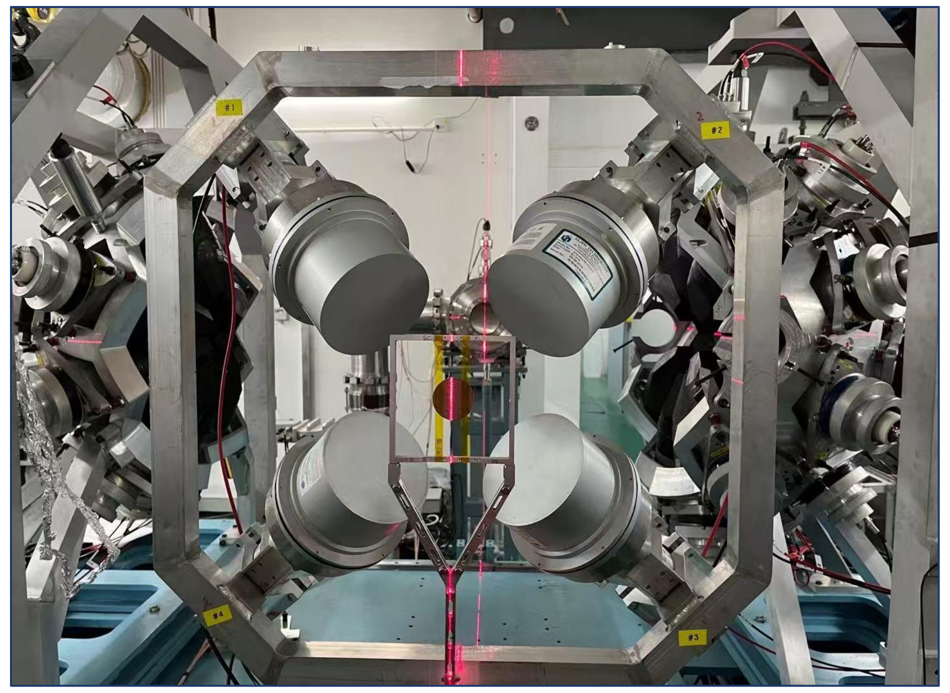
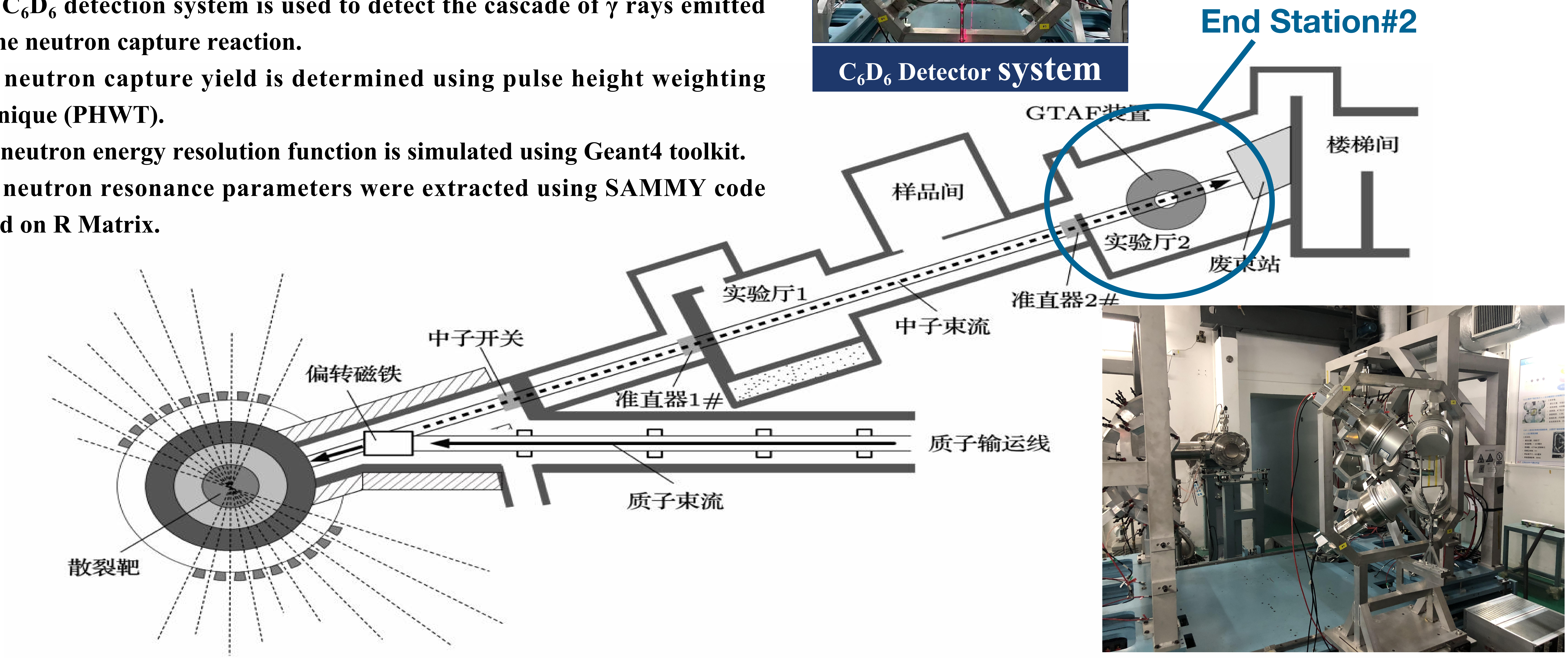
Experimental setup

- 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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Oerview 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)
	^{nat}Sm	50.0	1.0		X.X. Li et al., Nucl. Sci. Tech. (2025) (in press)
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., 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.

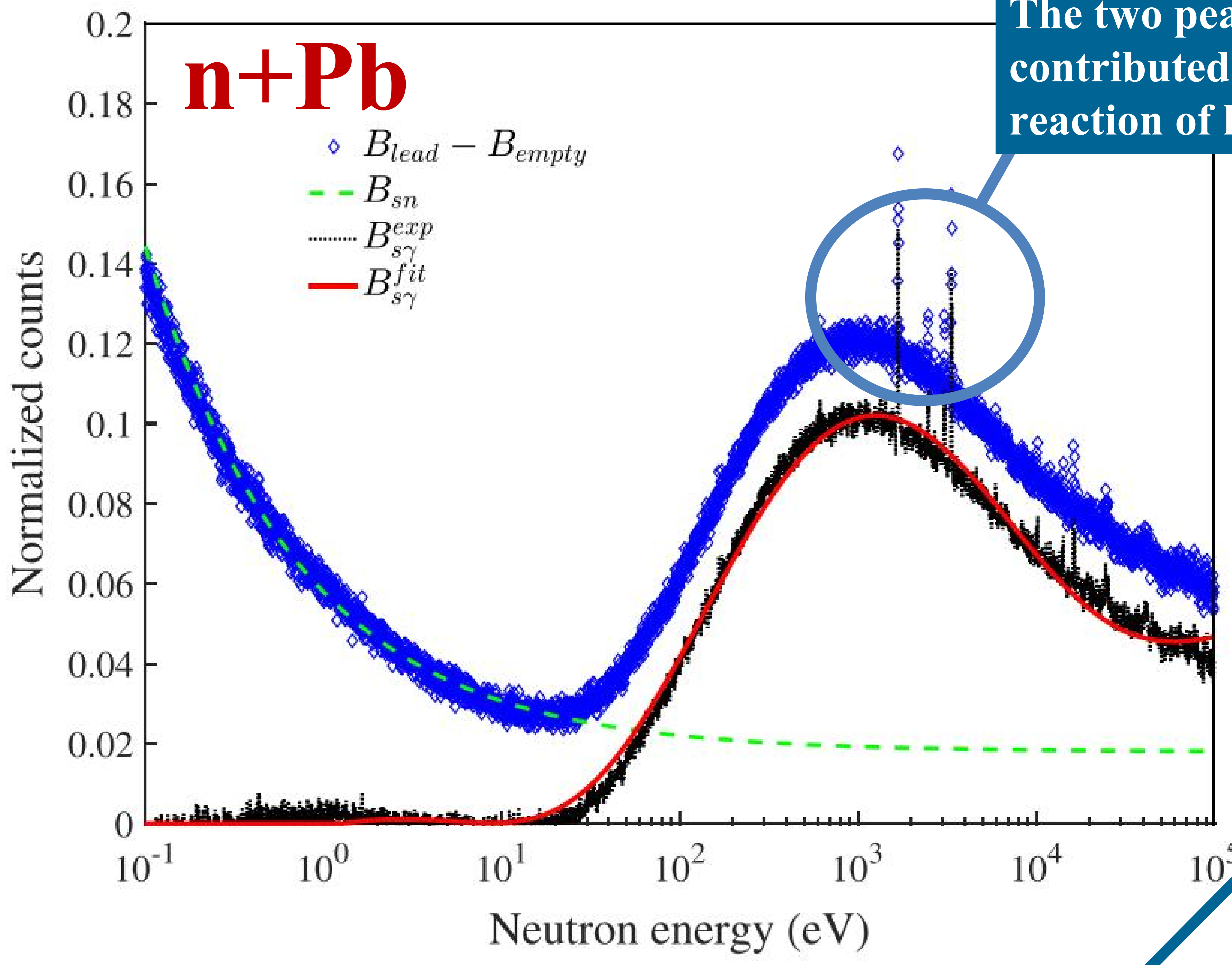
Background composition in the neutron capture cross-section experiment.

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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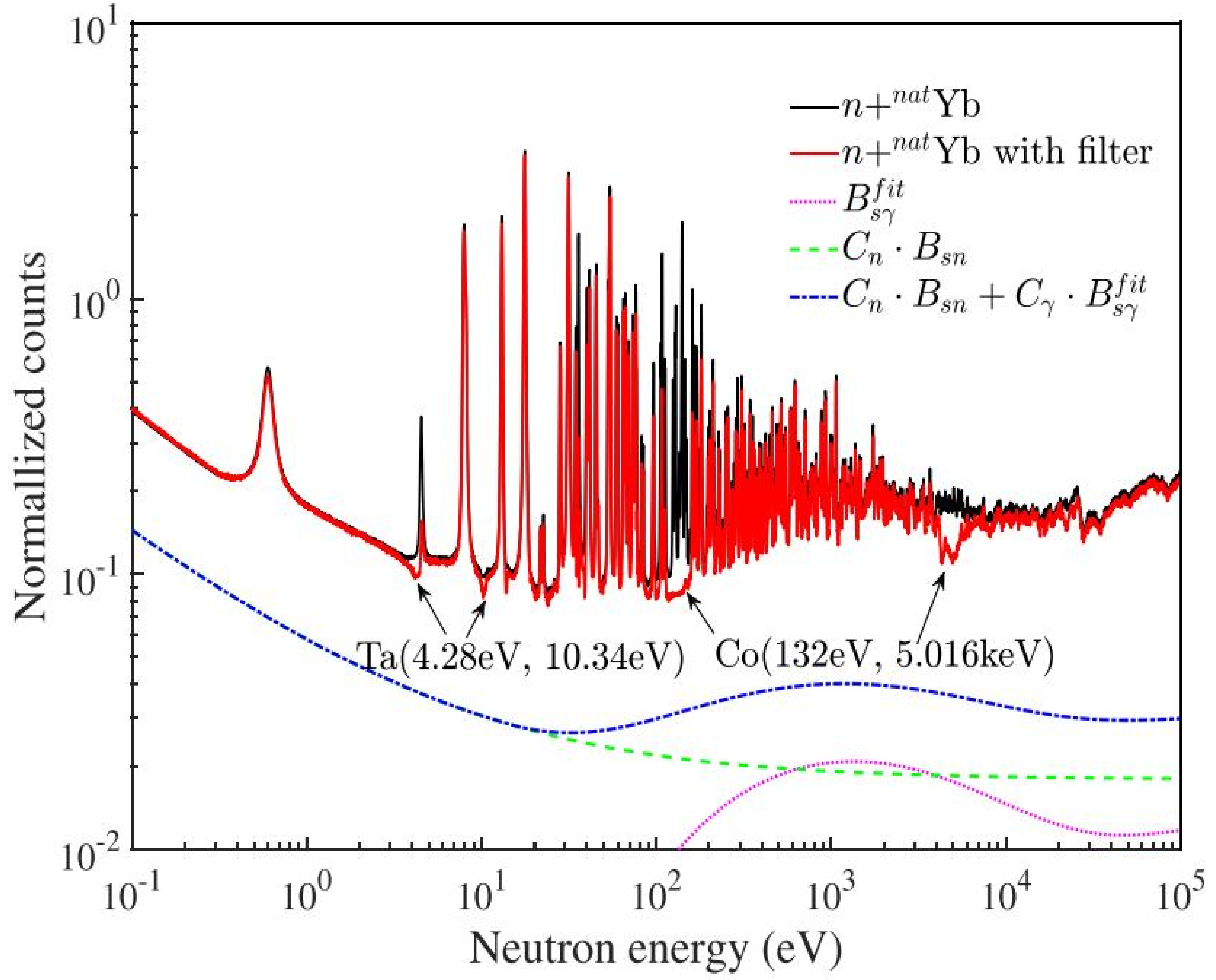
Key Step: Background Determination

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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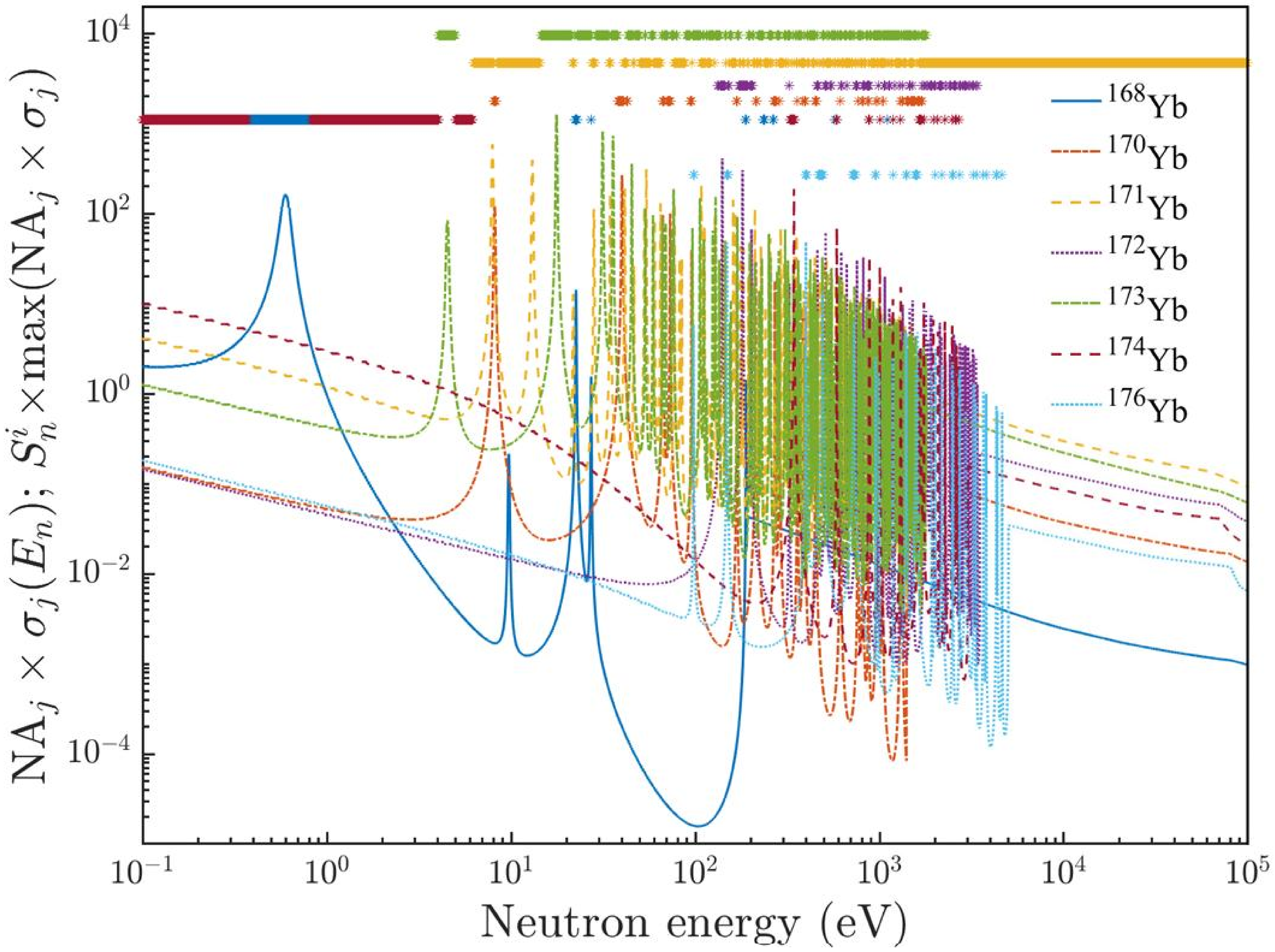
Key Step: S_n for natural target

- 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 resnance energies.
- In this work, the neutron separation energy for natural target is determined by following equation:

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

$A = NA_i * \sigma_i$



Key Step: S_n for natural target

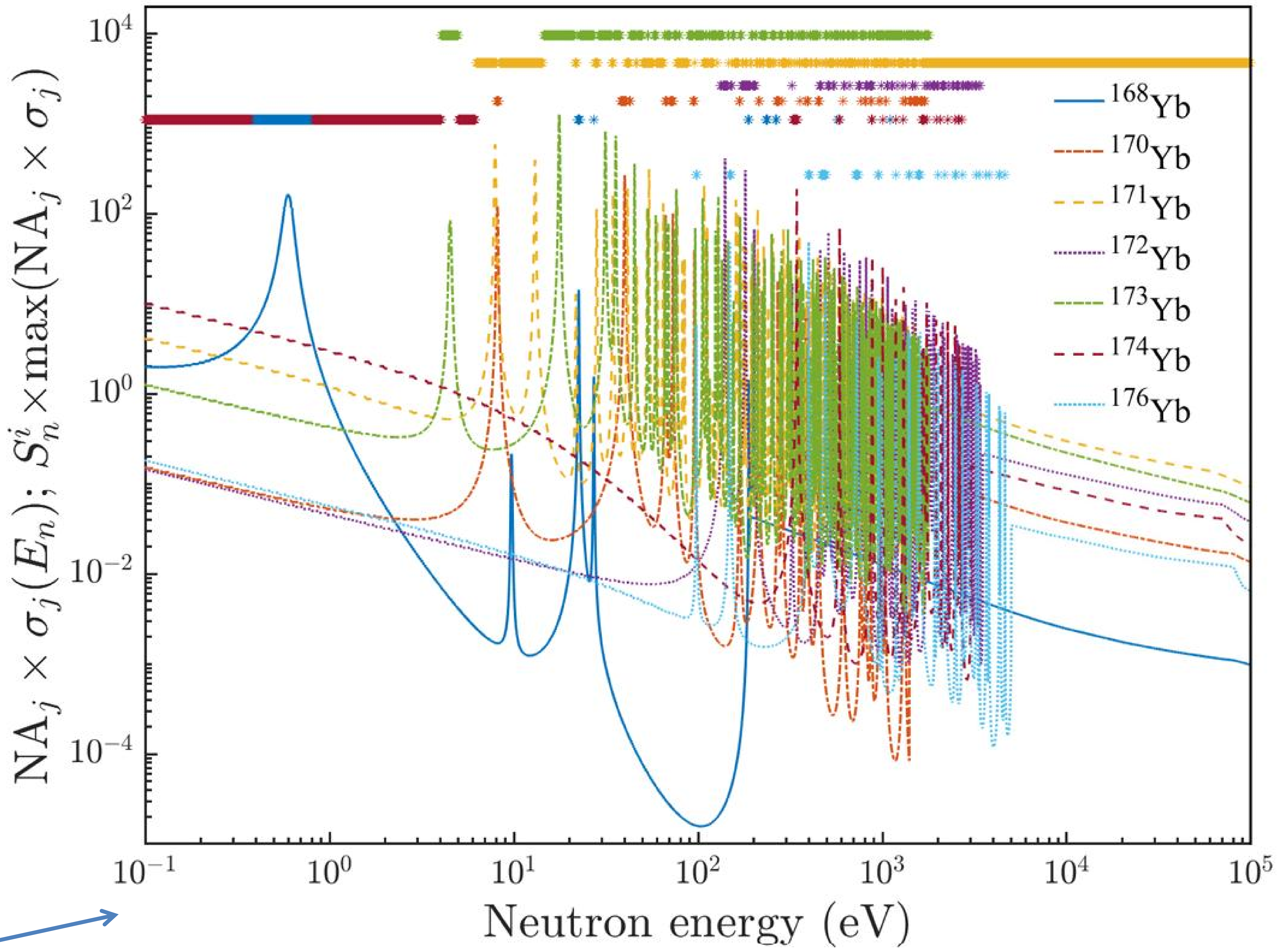
Selection of evauation database

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

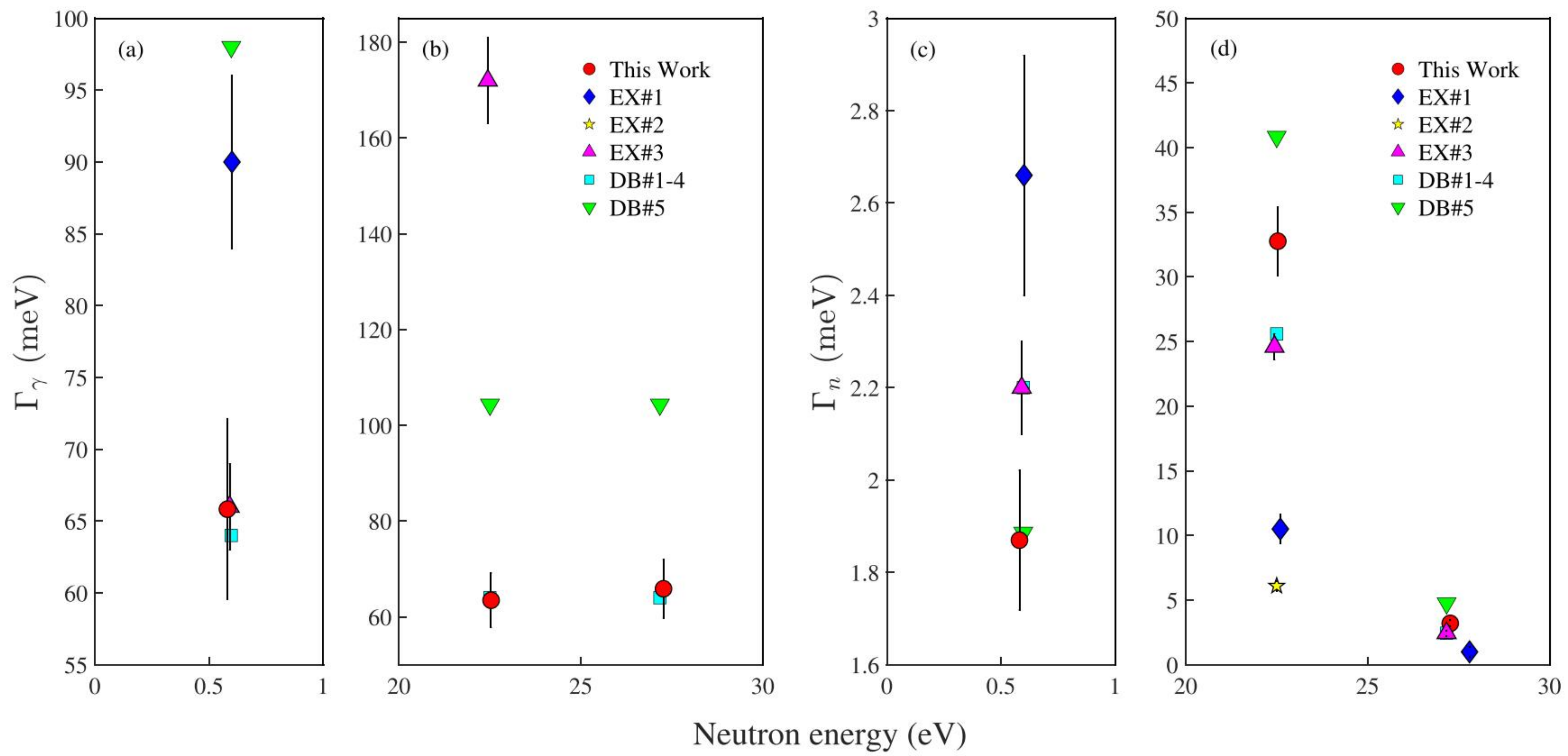

TABLE III: Resonance parameters of ^{168}Yb extracted from the SAMMY code of experimental data.

	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

- the R-Matrix code SAMMY was used to fit experimental yield and extract the nutron parameters;
- The existing experimental data and different evaluation data were used to compare with this work。

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

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

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

EX#3: 1981年 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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Summary

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Summary

- The resonance parameter value of ^{168}Yb at 22.5 eV deserves further experimental verification.
- The measurement and data analysis methods for the neutron capture cross-section of high cross-section targets have matured.
- Experimental techniques and analytical methods of accurate measurement of low cross-section targets and low abundance targets are prerequisites for obtaining high-level physical results.

Collaboration

We appreciate support from all collaborators.
We thank the staff members of the Back-n white neutron 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 support and assistance in data collection and analysis.

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