^{165}Ho(n, γ) 截面测量及其天体物理中的应用研究

Measurement of the ^{165}Ho(n, γ) cross section and implications for stellar nucleosynthesis

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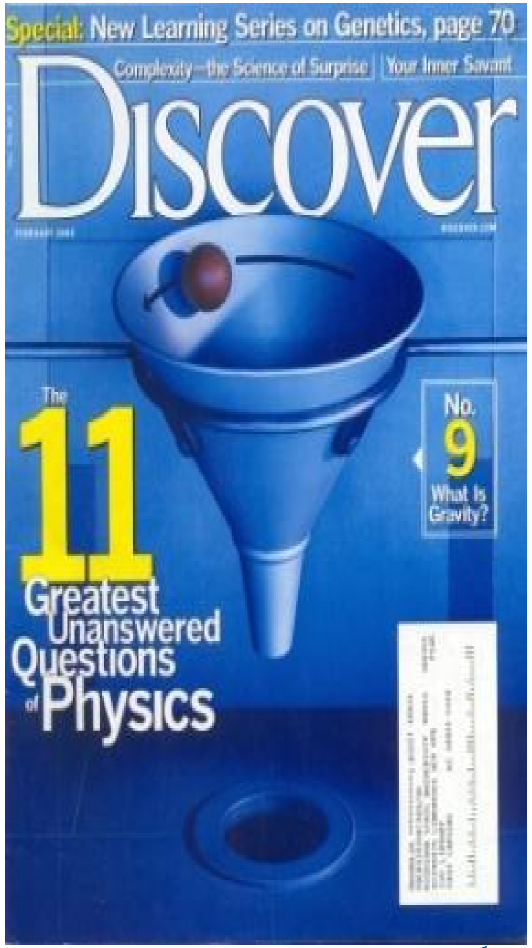
合作单位：散裂中子源、原子能研究院

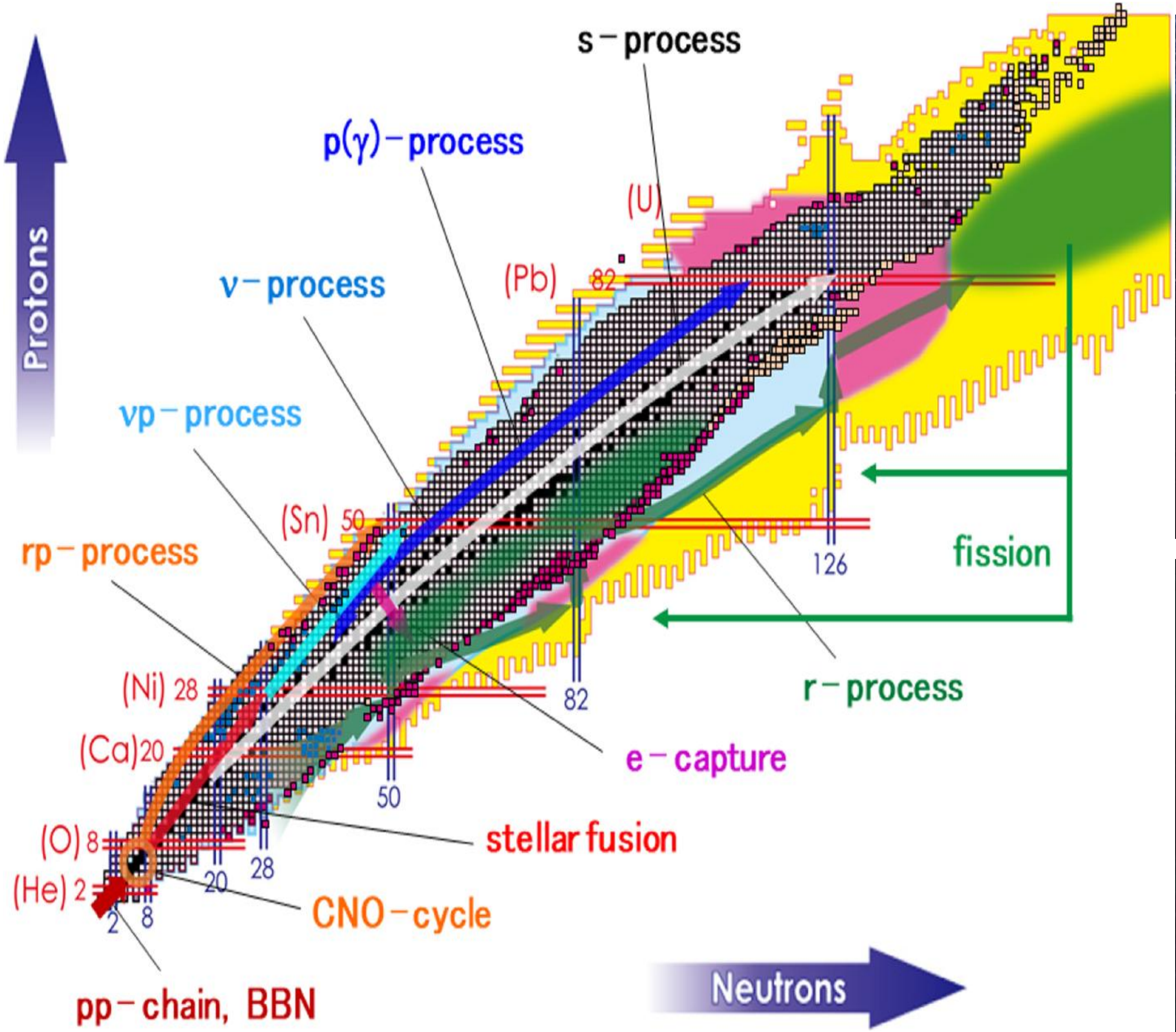
Outline

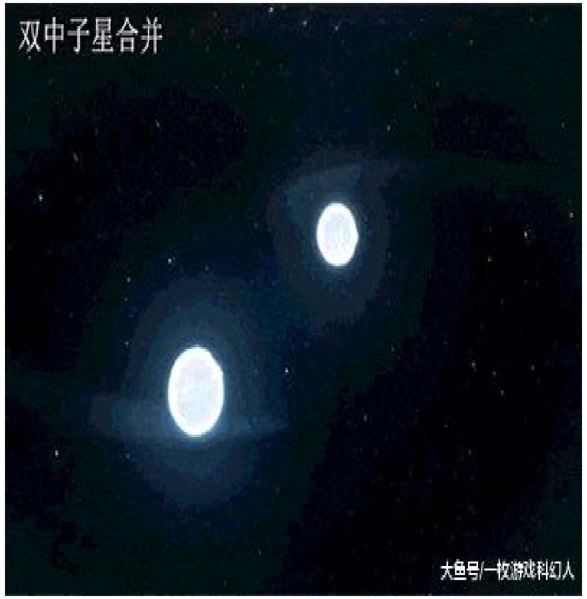
Outline

1.1 Origin of the heavy elements



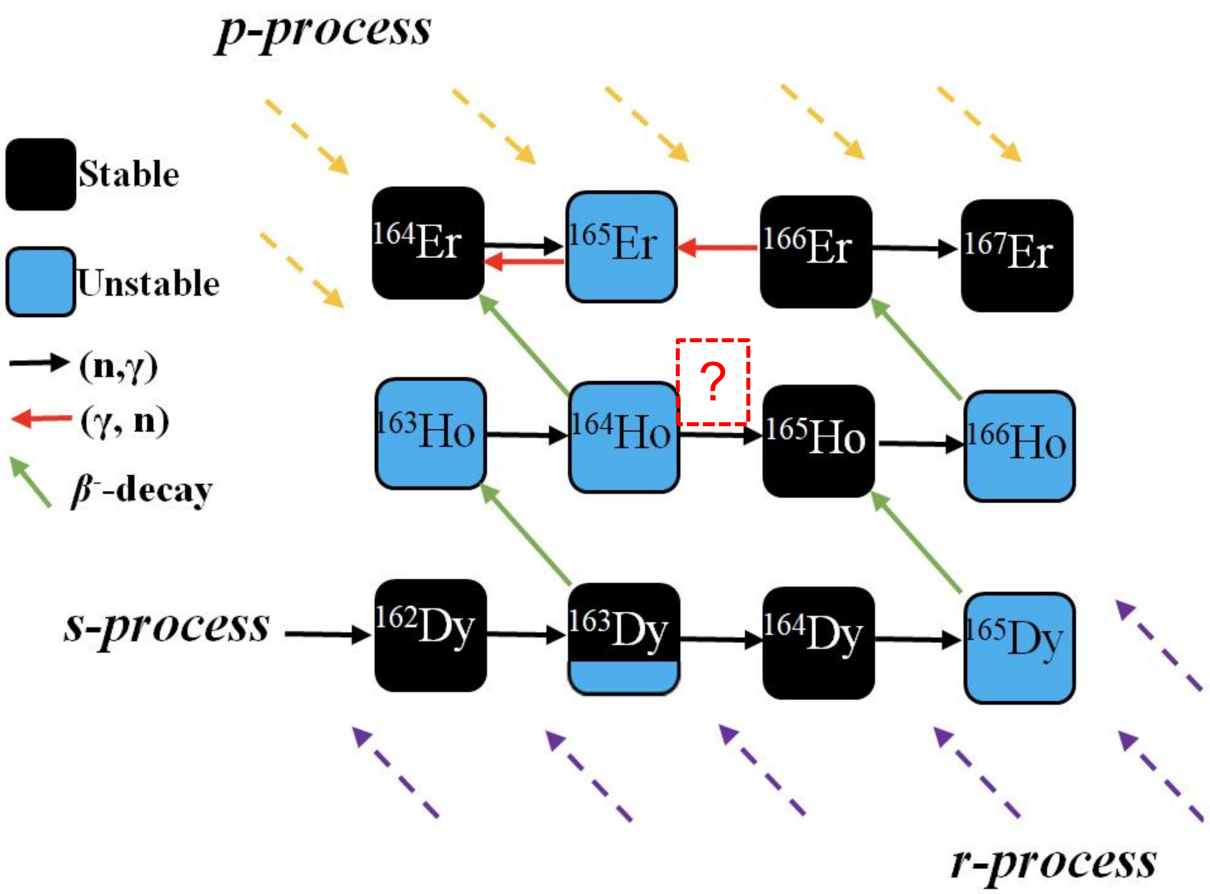
The 11 greatest unanswered questions of physics





Nature 551,64 (2017); AAPPS Bulletin 31,18（2021）

1.2 The s-process path around the Holmium



Nuclear network equations

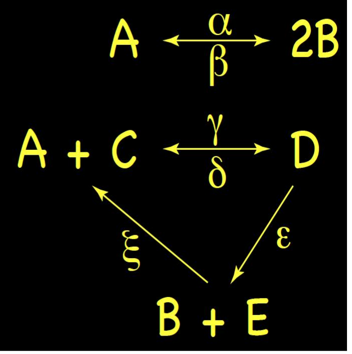
$$\dot{Y}_A = -\alpha Y_A + \beta Y_B^2 - \gamma Y_A Y_C + \delta Y_D + \xi Y_B Y_E$$

$$\dot{Y}_B = 2\alpha Y_A - 2\beta Y_B^2 + \epsilon Y_D - \xi Y_B Y_E$$

$$\dot{Y}_C = -\gamma Y_A Y_C + \delta Y_D + \xi Y_B Y_E$$

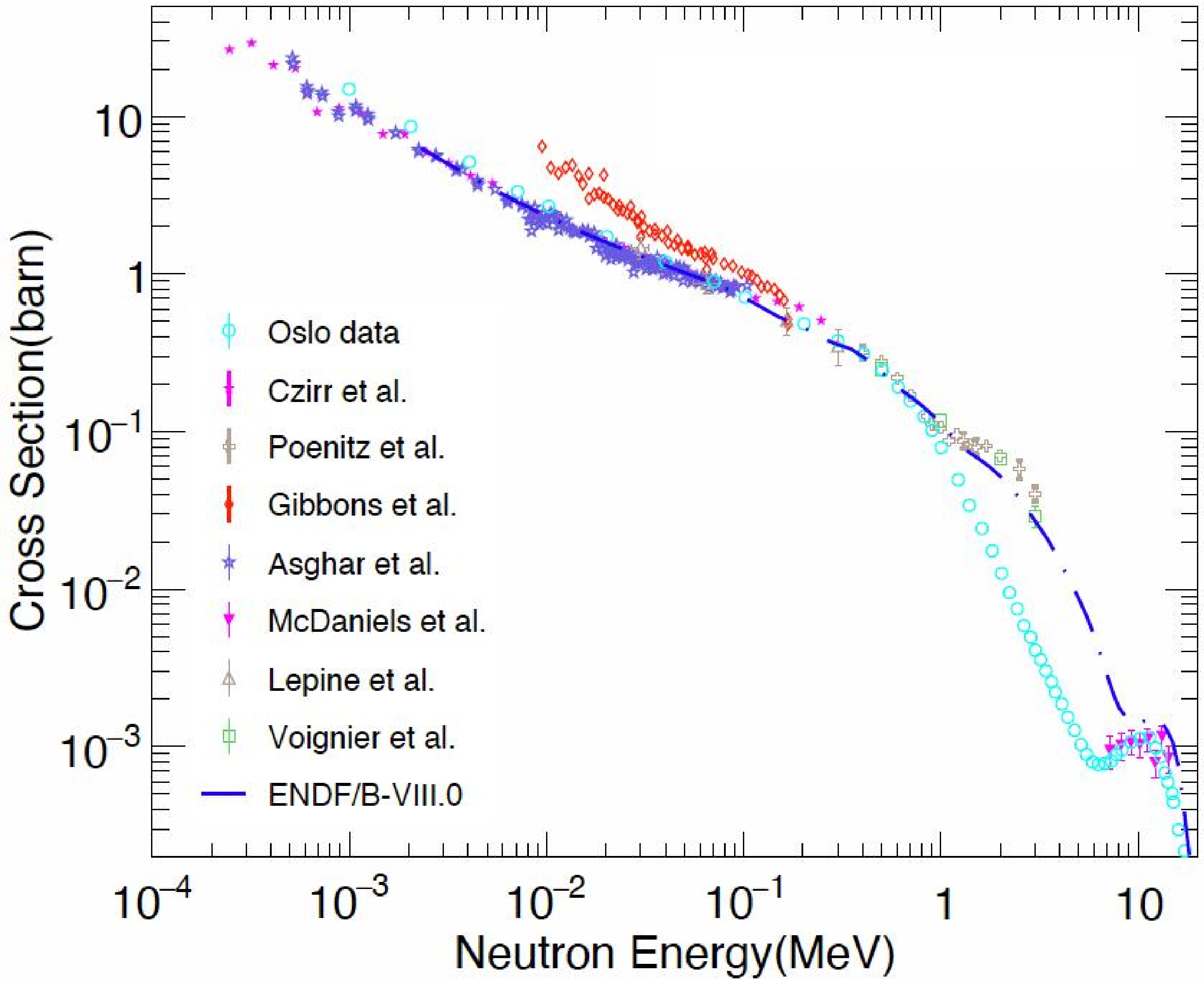
$$\dot{Y}_D = \gamma Y_A Y_C - \delta Y_D - \epsilon Y_D$$

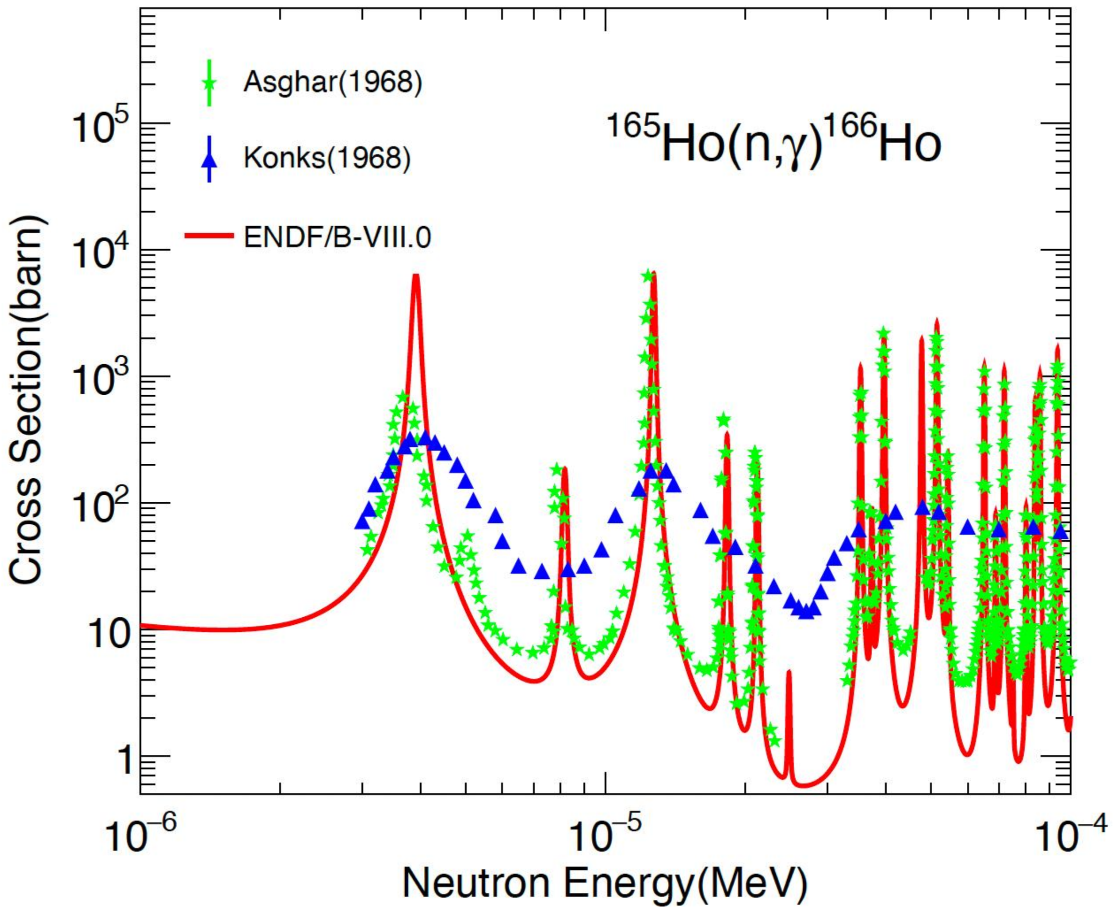
$$\dot{Y}_E = \epsilon Y_D - \xi Y_B Y_E$$



- ^{165}Ho(n, γ) cross section； ^{164}Ho(n, γ) and β^- decay； p-nuclei ^{164}Er problem.

1.3 ^{165}Ho(n, γ) cross section data



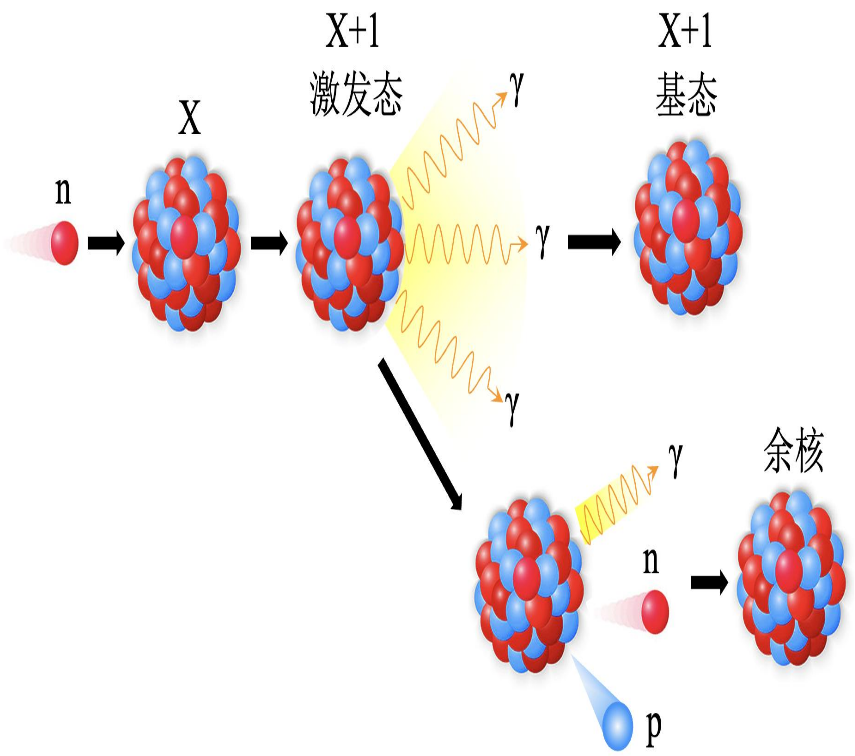


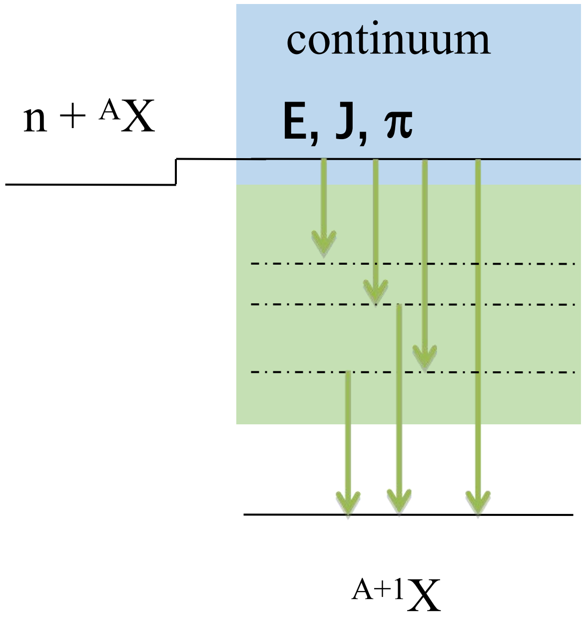
Pogliano(2023)

The reason for this discrepancy in the directly measured cross sections as well as our result is not clear, and it would be desirable to perform new (n,γ) measurements on ^{165}Ho to understand and resolve this issue.

Outline

2.1 Detection principle for (n, γ) reaction





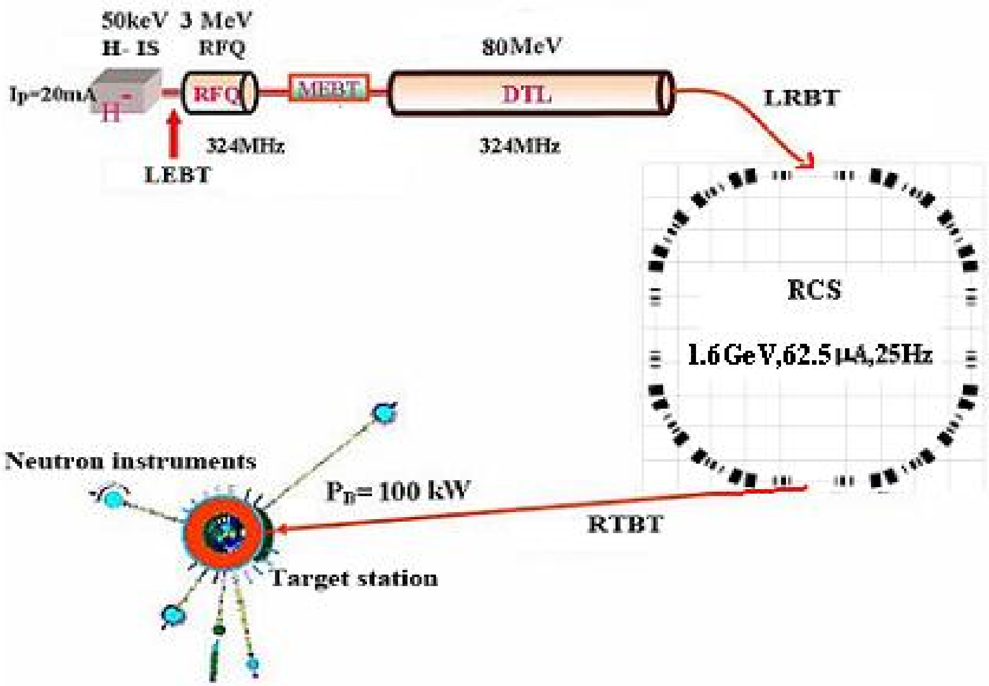
CERN n_TOF, GELINA, Karlsruhe, DANCE, KURRI, CSNS Back-n…

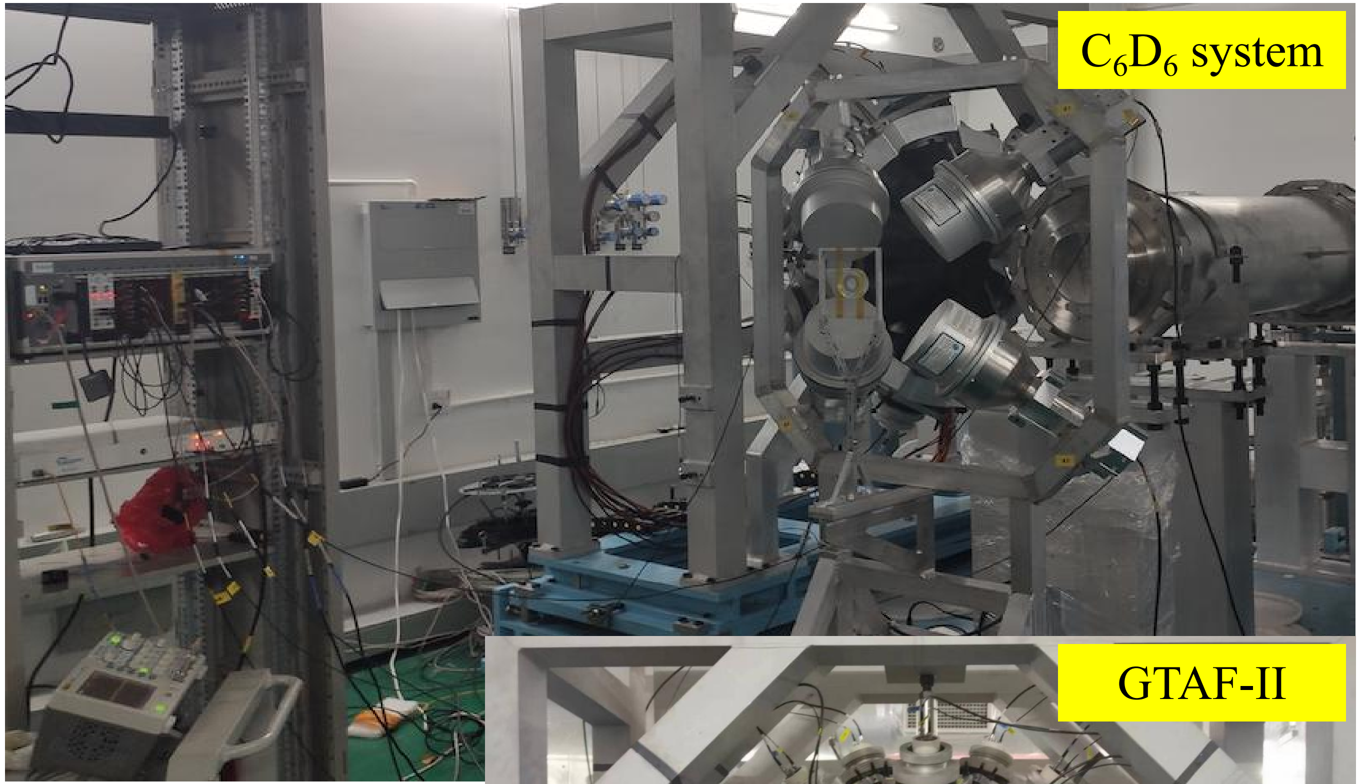
- **High energy resolution**： HPGe, $LaBr_3$, Energy level, Transition
- **Total gamma absorption**： BaF_2, NaI(Tl), BGO, Sum energy
- **Total energy detection**： C_6D_6, Low efficiency, Excitation energy

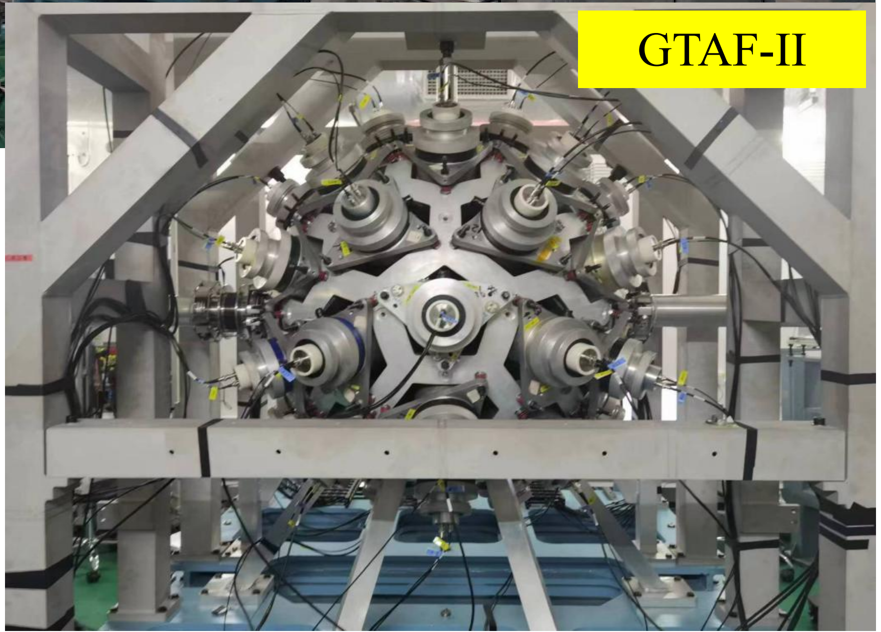
- ☐ Neutron Activation: neutron radiation on sample
- ☐ Prompt-gamma method: TOF method and high energy resolution detectors

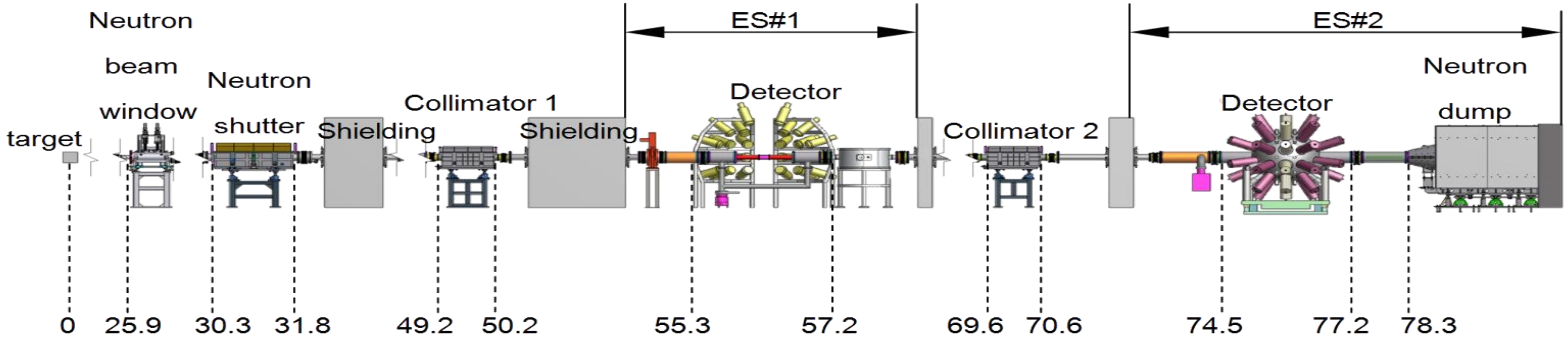
2.2 Experimental setup for (n, γ) reaction

CSNS Back-n facility









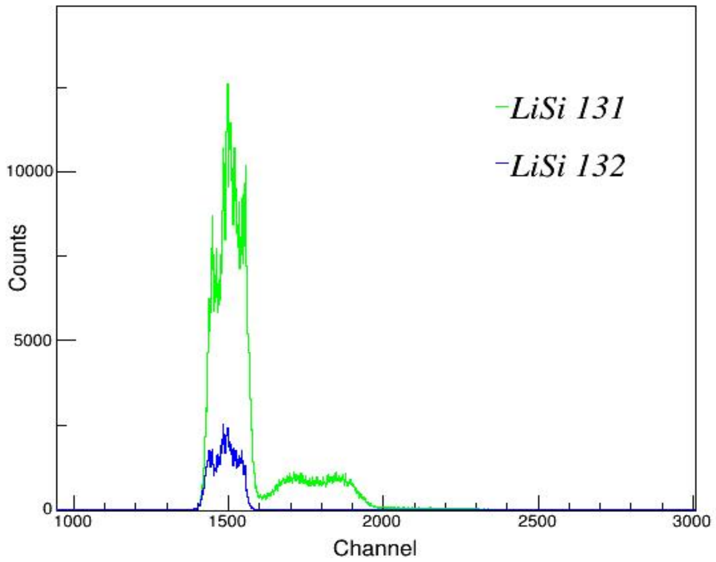
From Fan Rui-Rui et al.

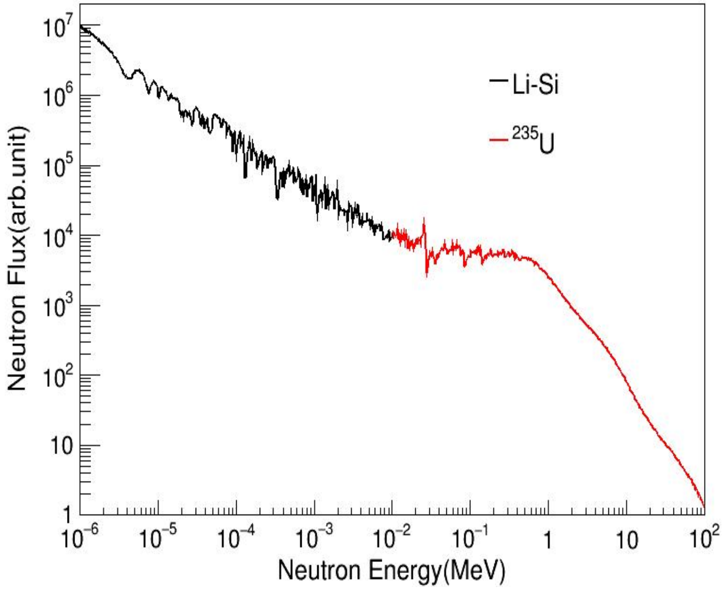
Outline

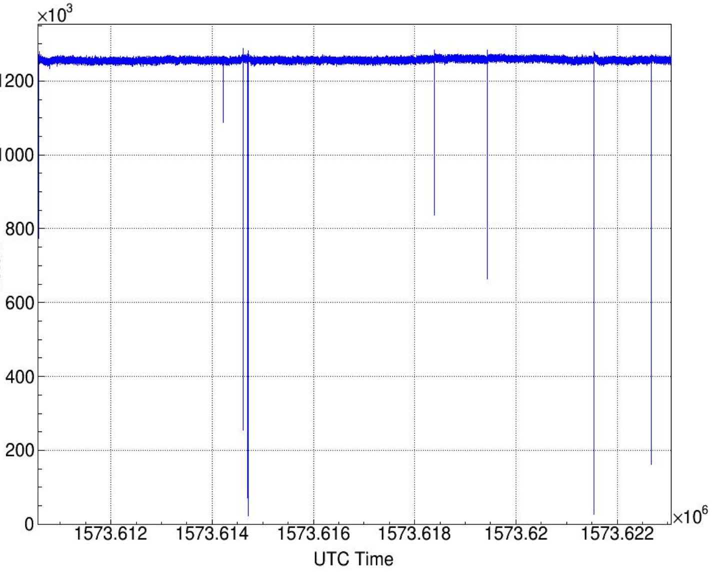
3.1 Measurements

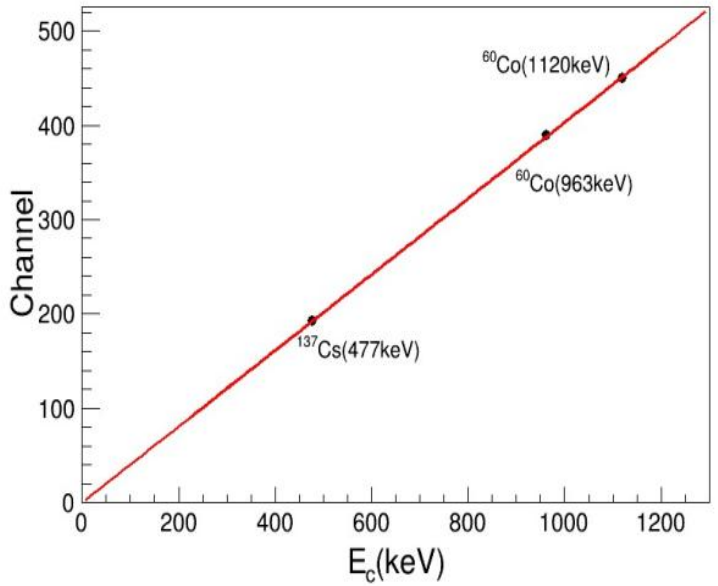
TABLE I: Characteristic parameters of samples

Sample	Thickness (mm)	Diameter (mm)	Mass (mg)	Area desity $(atom \cdot b^{-1})$
^{165}Ho	0.20	30	1243.32	6.42×10^{-4}
^{nat}Lu	0.20	30	1439.84	7.01×10^{-4}
^{nat}Tb	0.20	30	1169.14	6.27×10^{-4}
^{nat}Hf	0.20	30	1881.66	8.97×10^{-4}
^{197}Au	0.10	30	1357.17	5.87×10^{-4}
^{nat}Pb	0.53	30	4249.75	1.75×10^{-3}
Empty holder				









3.2 Analysis method of C_6D_6 detector

- Pulse Height Weighting Technique

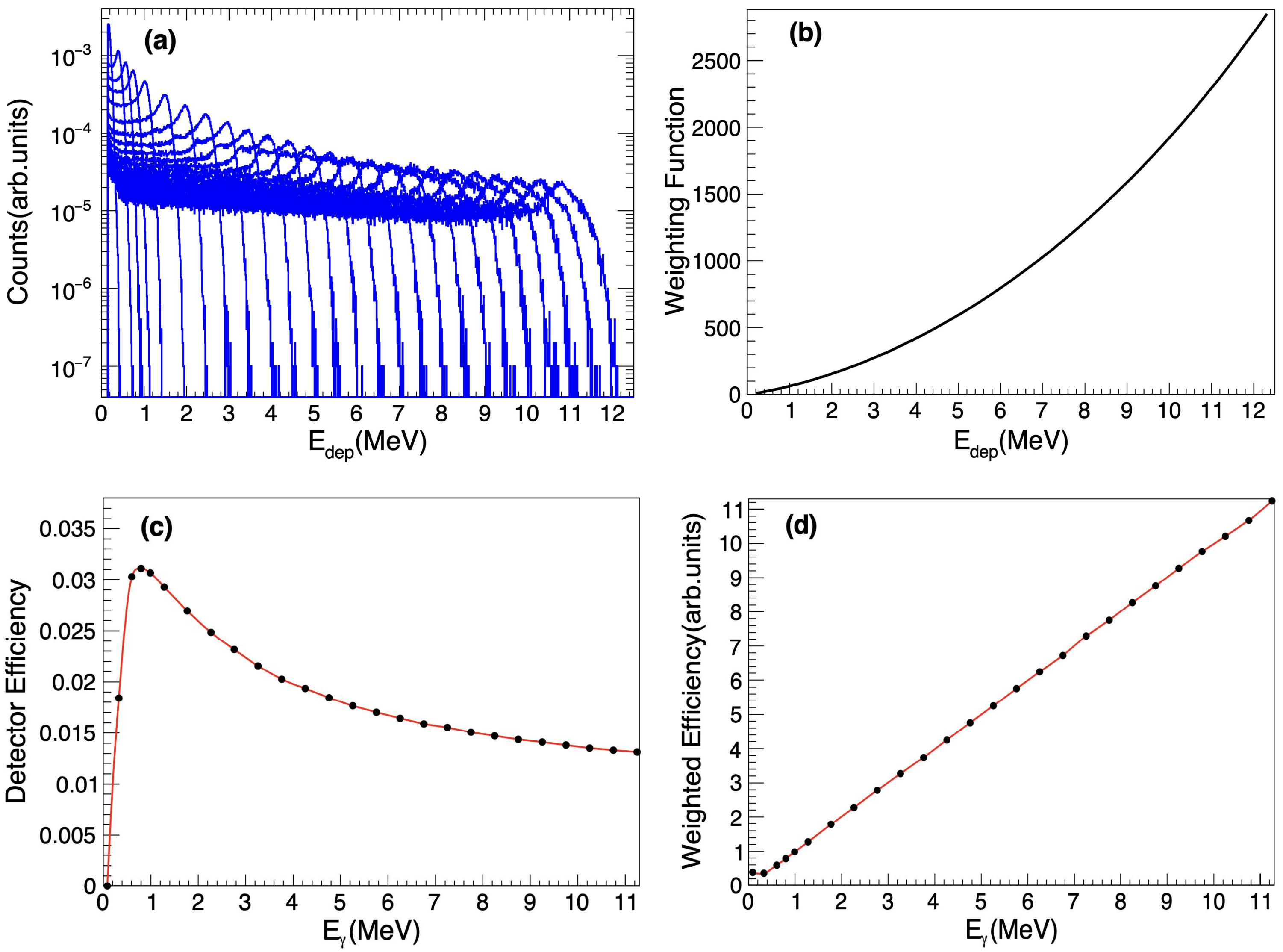
1) $\varepsilon^{\gamma} << 1$

2) $\varepsilon^{\gamma} = \alpha E^{\gamma}$

3) $\sum_{i=1}^{n} W_i R_i^{\gamma} = E^{\gamma}$

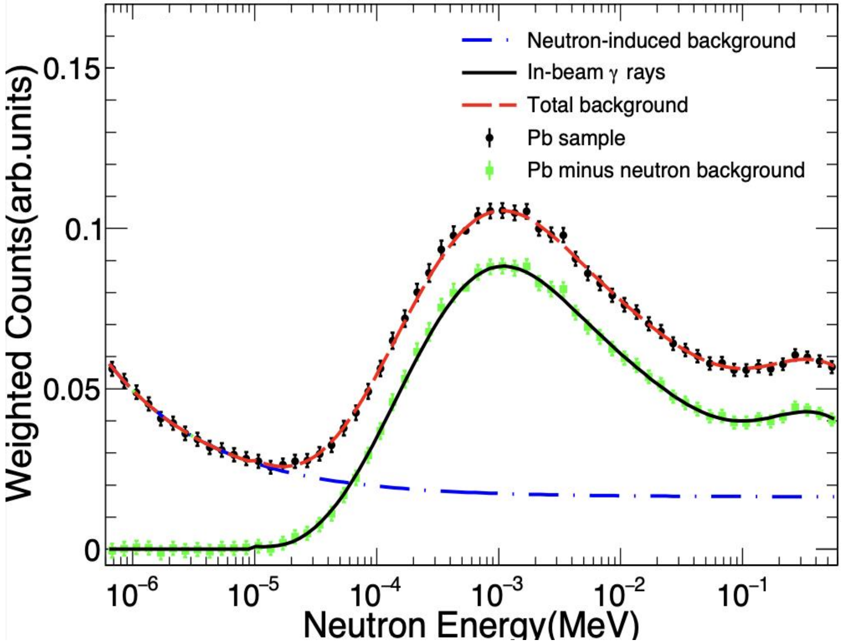
4) $\varepsilon^{c} \approx \sum_{j=1}^{N} \varepsilon_j^{\gamma} = \alpha \sum_{j=1}^{N} E_j^{\gamma} = \alpha E_C$

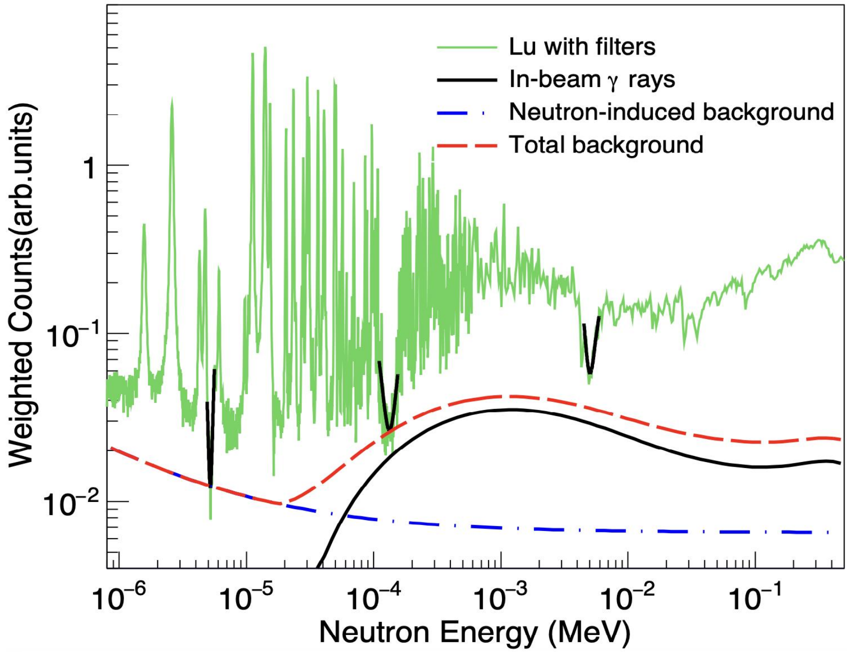
$$Y_{\exp}(E_n) = \frac{1}{f} \frac{C^w(E_n) - B^w(E_n)}{\Phi(E_n) \times E_c}$$

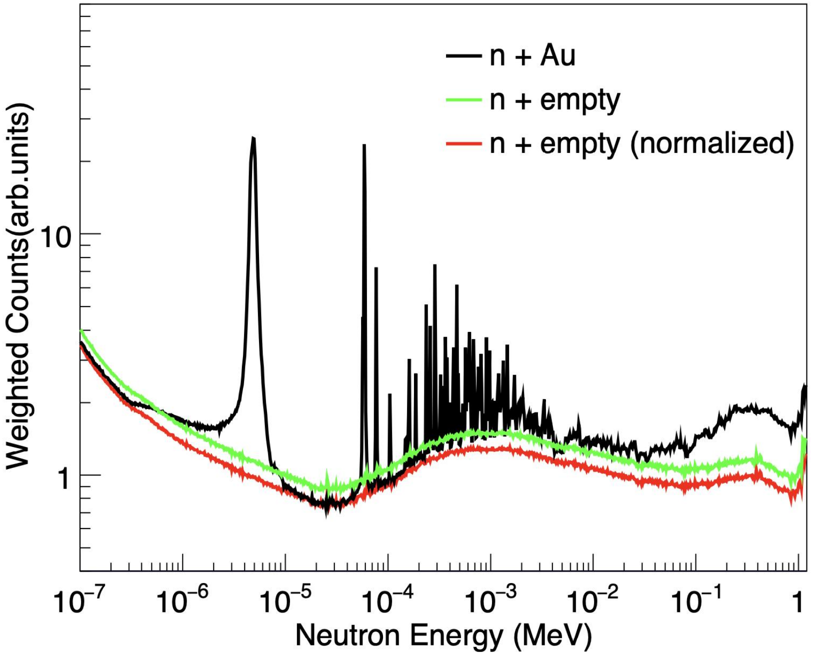


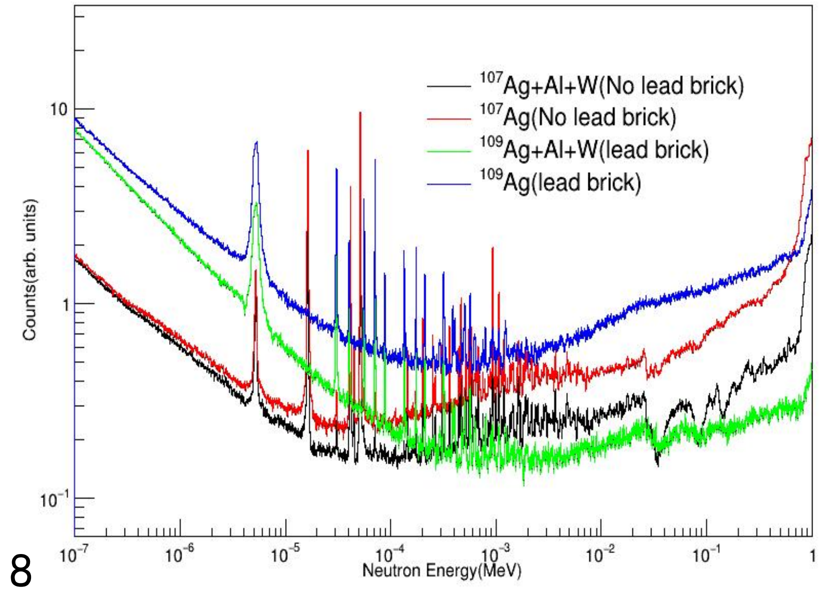
To make the detection efficiency independent of the de-excitation paths, multiplicity, energy of cascade gamma rays.

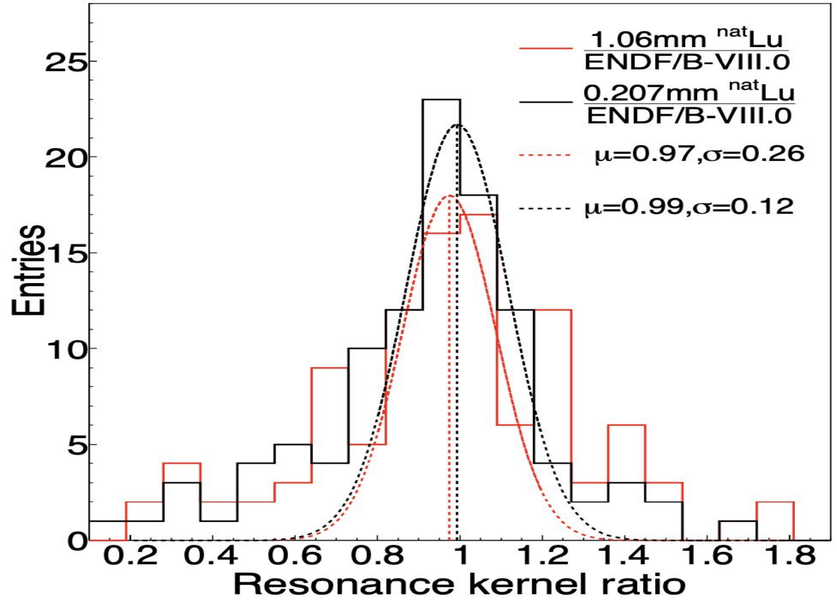
3.3 Background evaluation

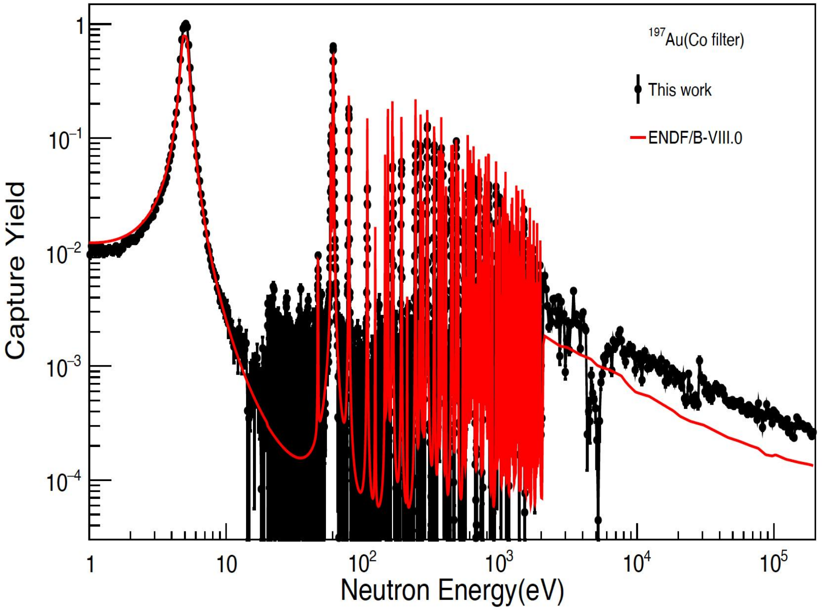






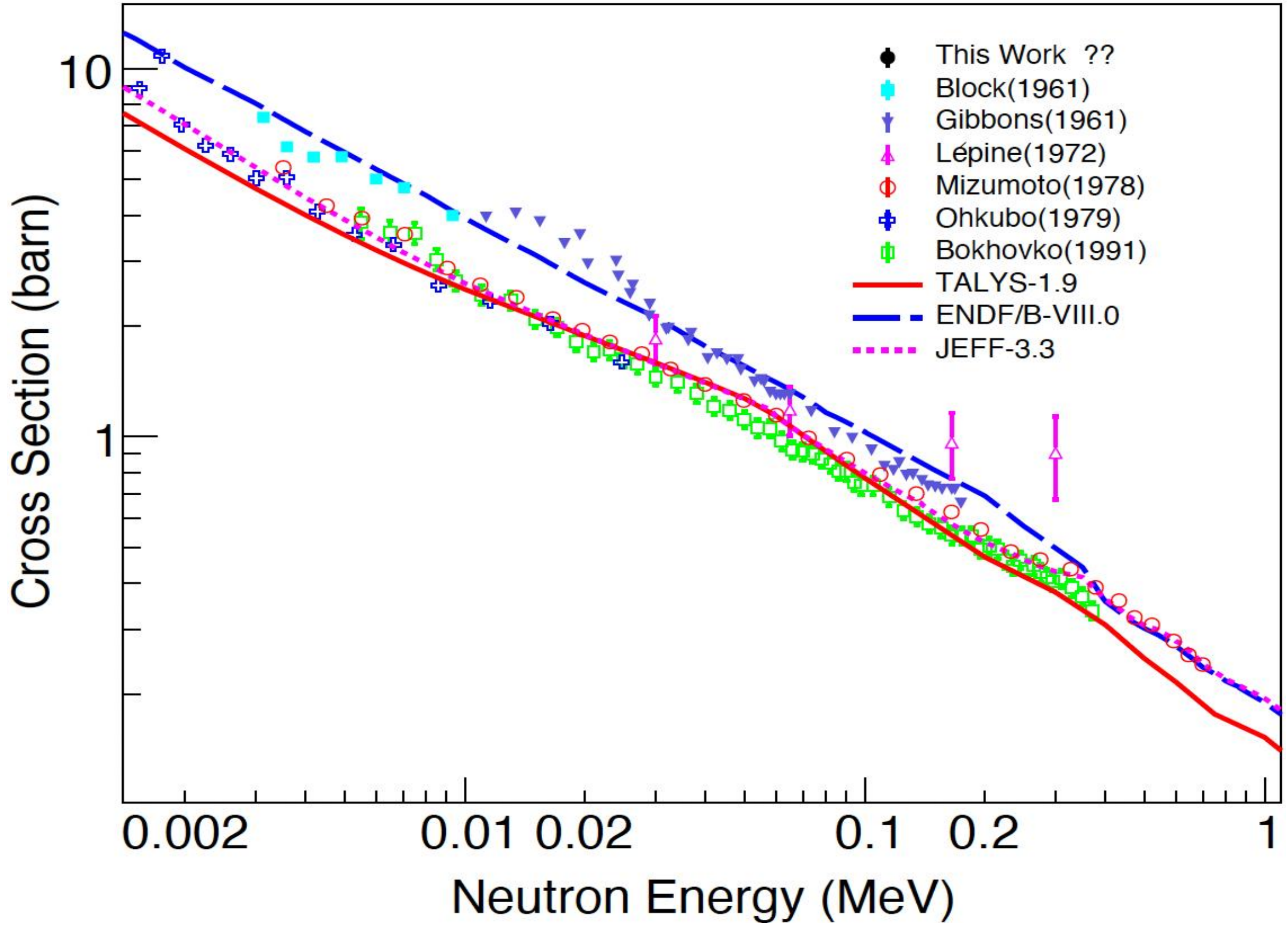


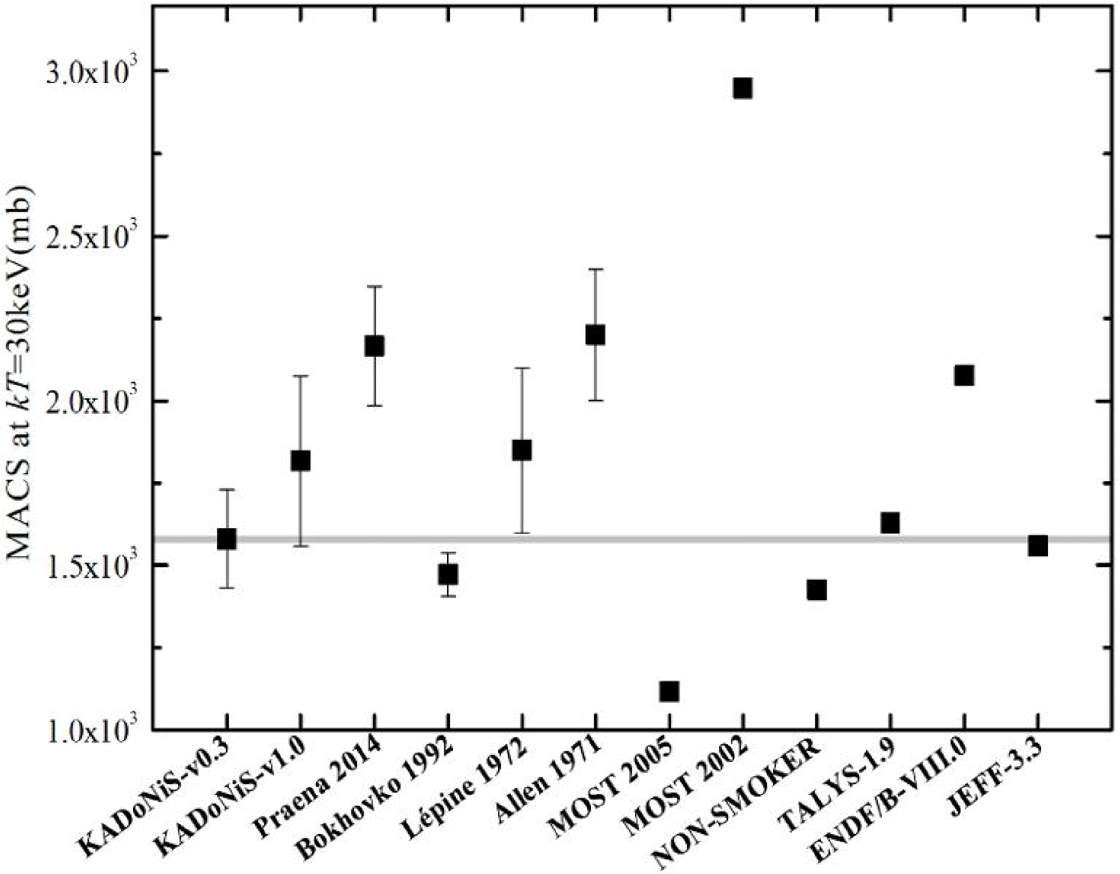




3.4 Test beam case: ^{159}Tb sample

- Terbium is mainly produced by the explosive r process, while about 9% is made by main s process.





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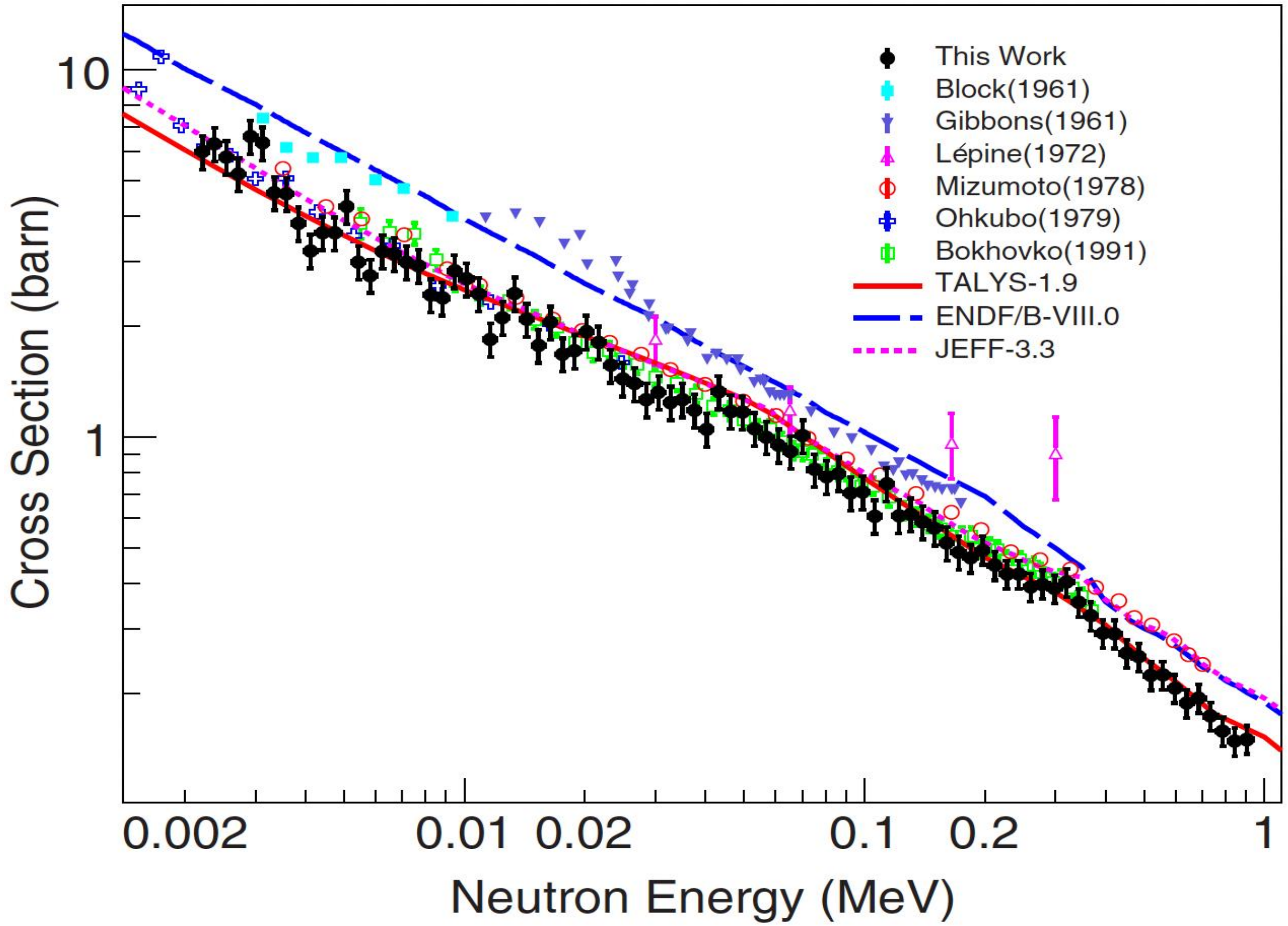
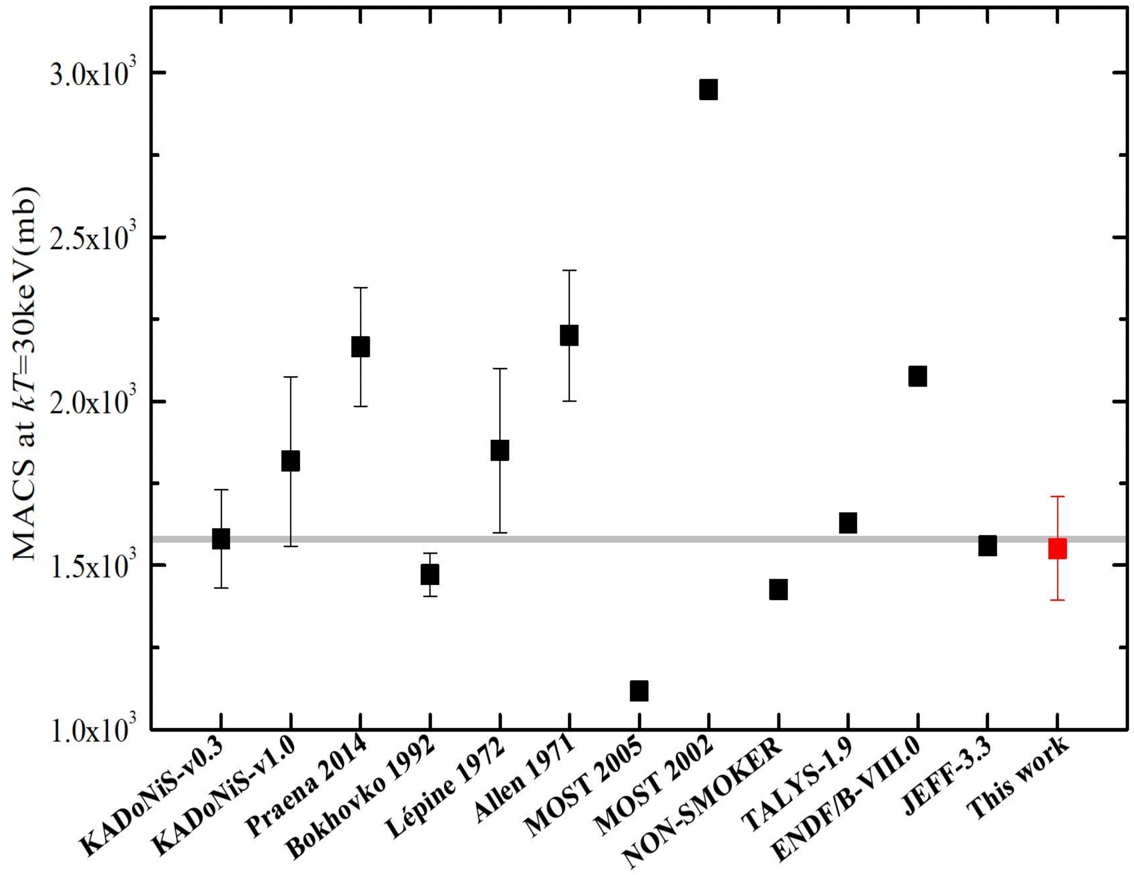
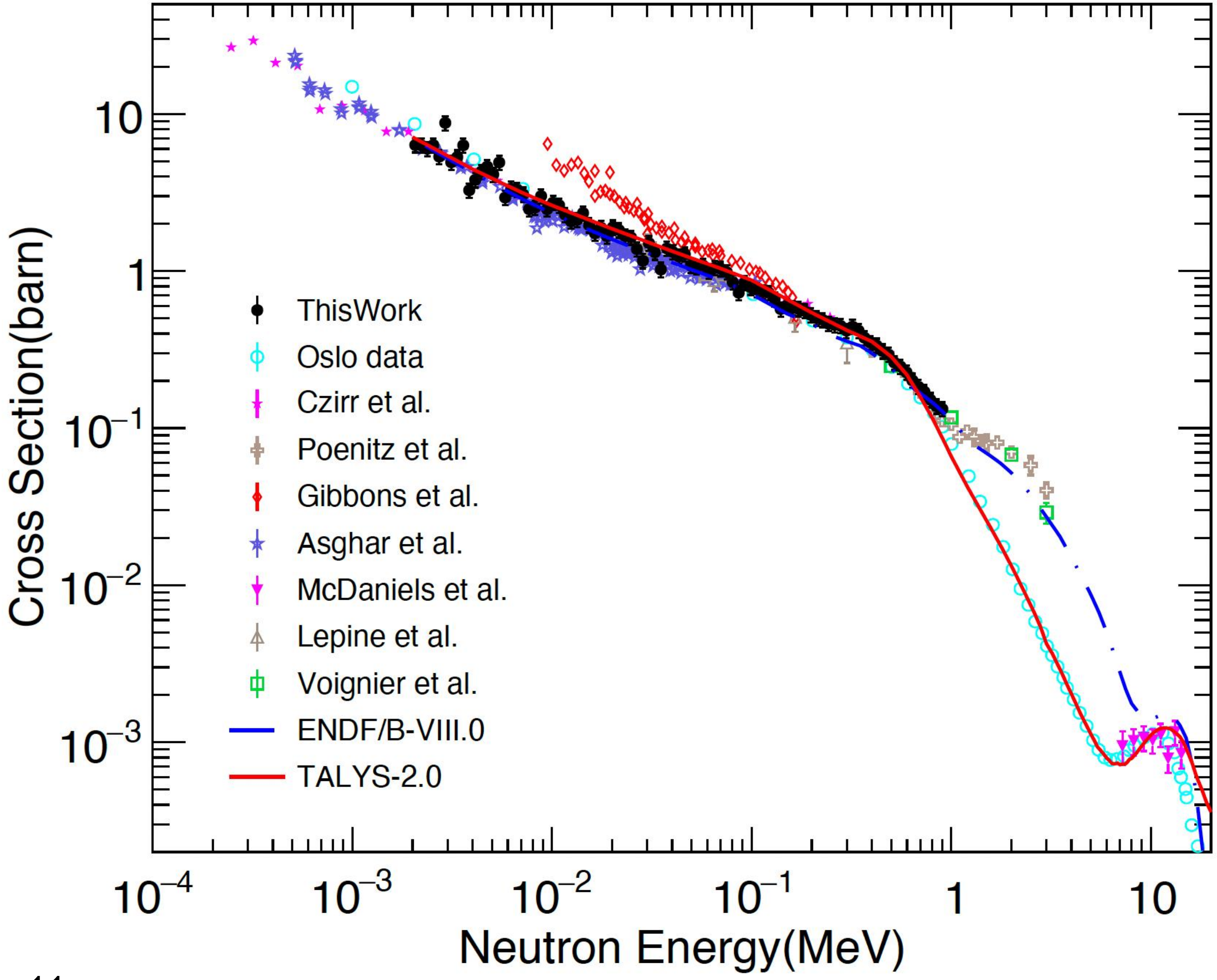
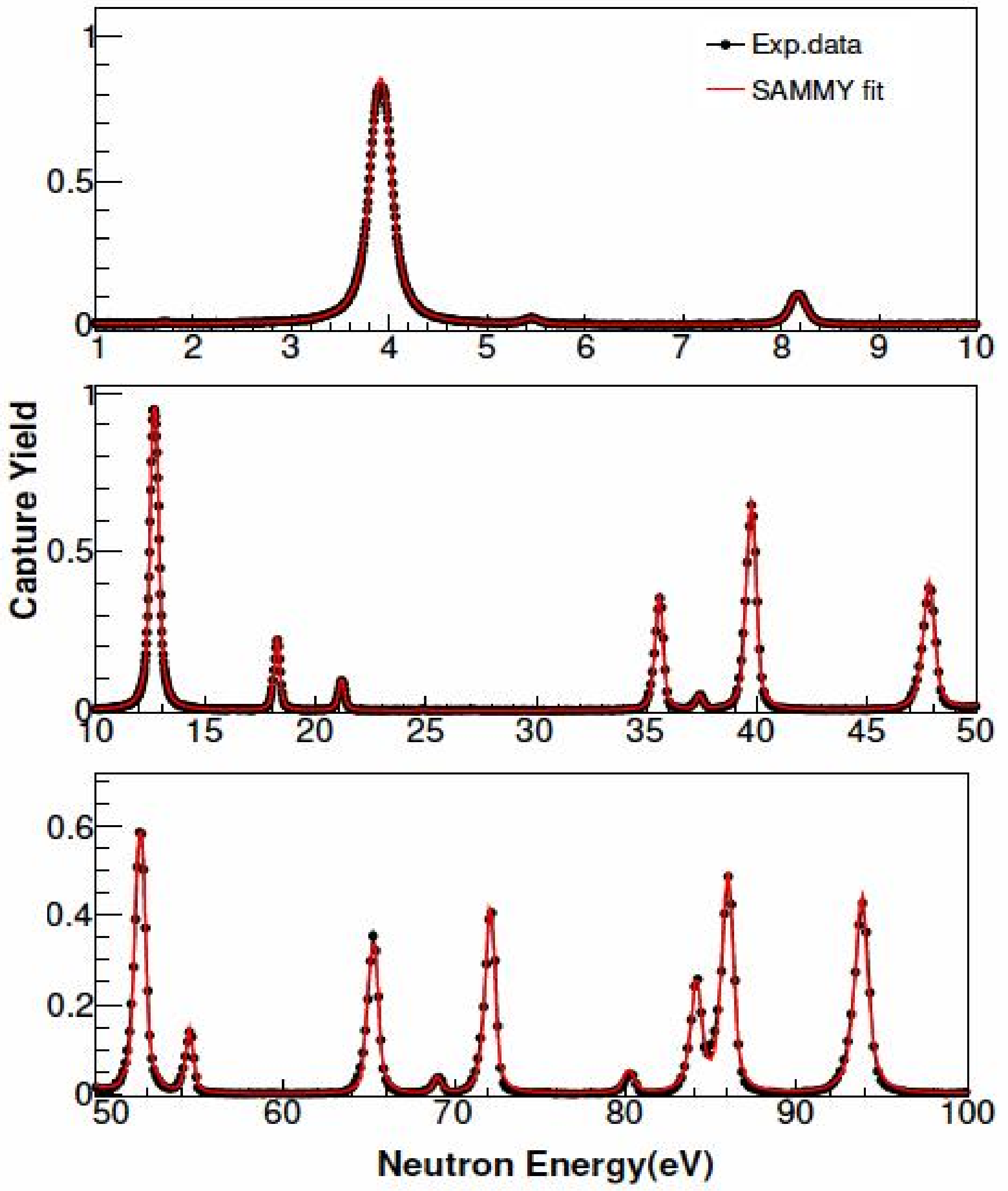




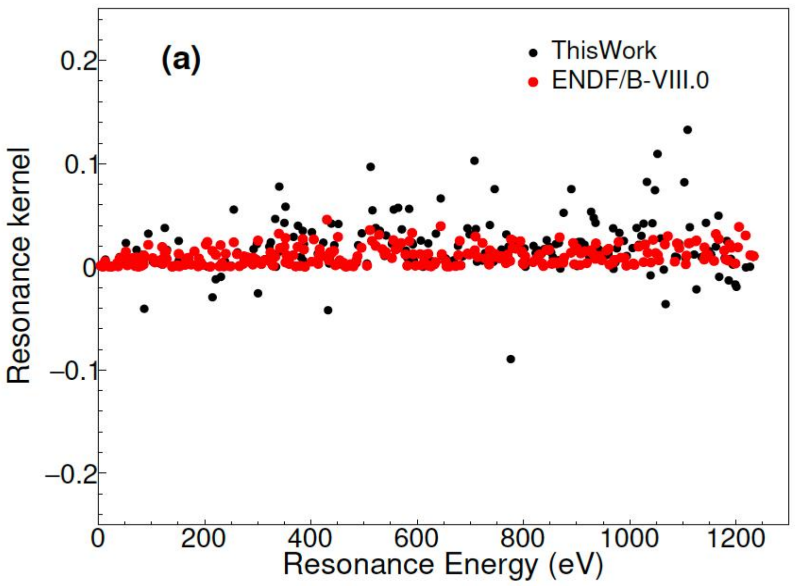
D.X. Wang et al., NST36:43 (2025) ; S. Zhang et al., PRC107: 045809(2023); Acta Phys. Sin. 71(7), 072901(2022)

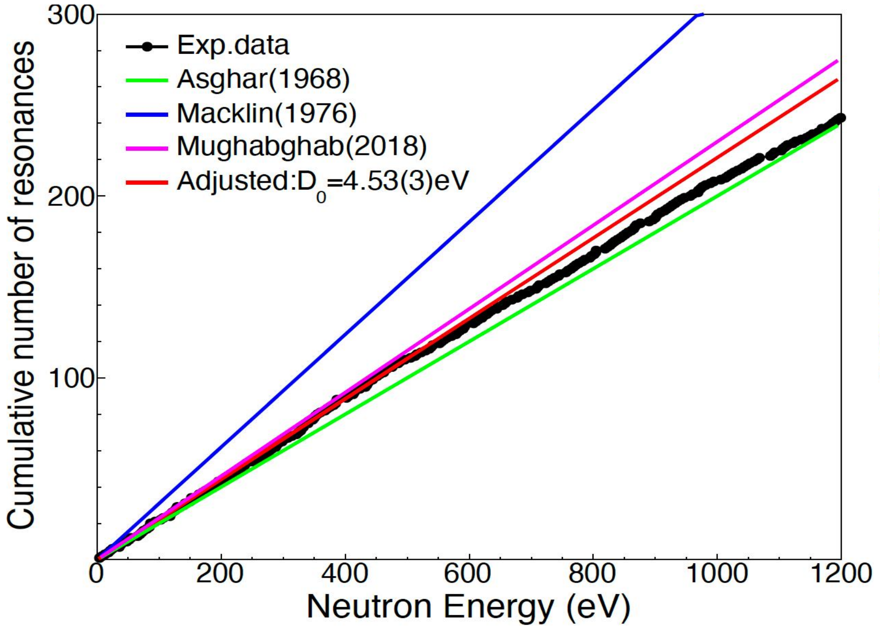
3.5 The ^{165}Ho sample: C_6D_6 results

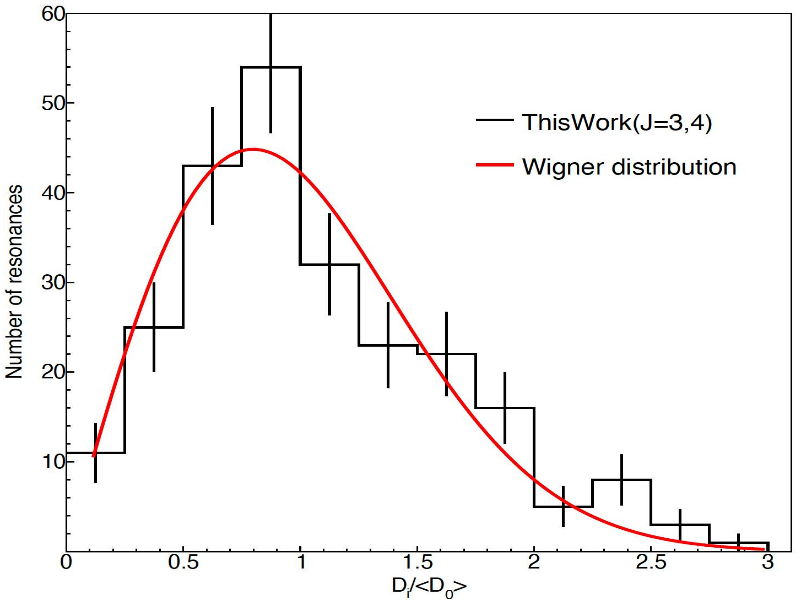


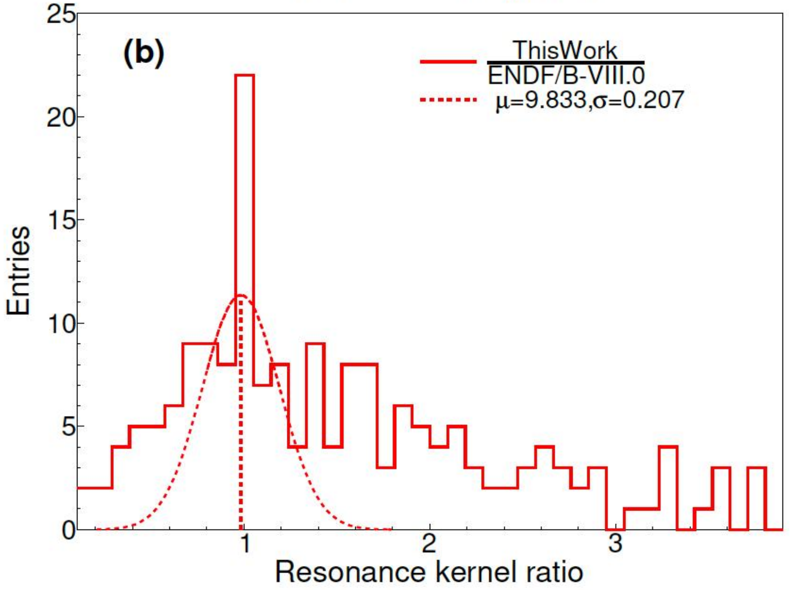


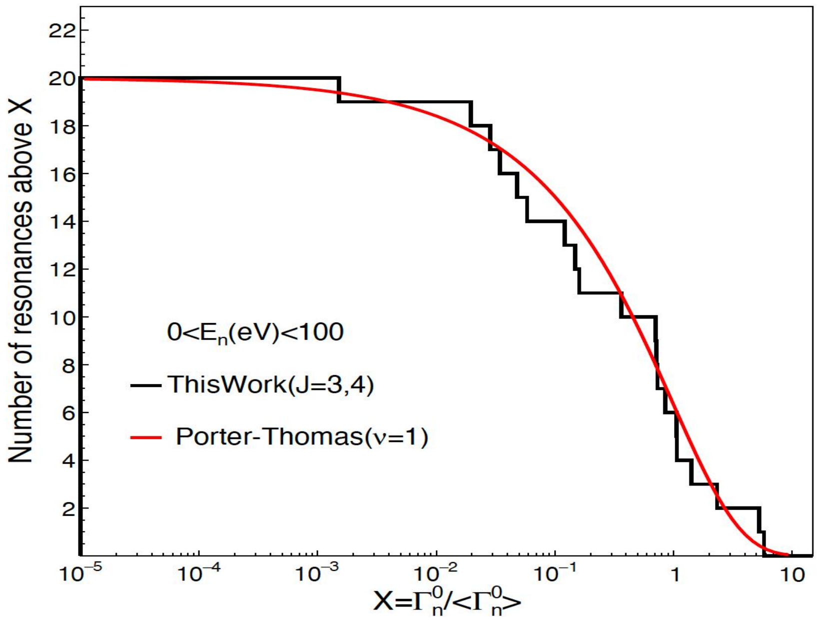
3.6 Resonance analysis

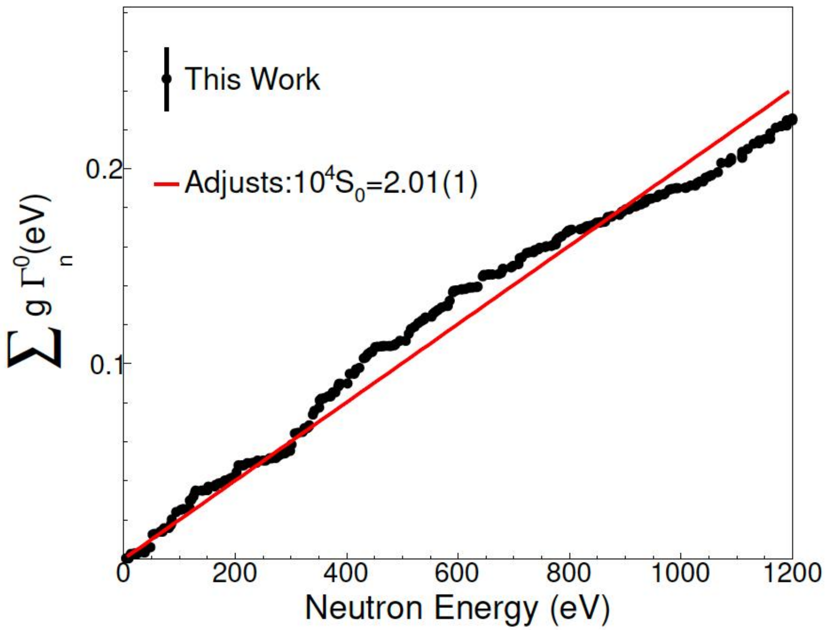












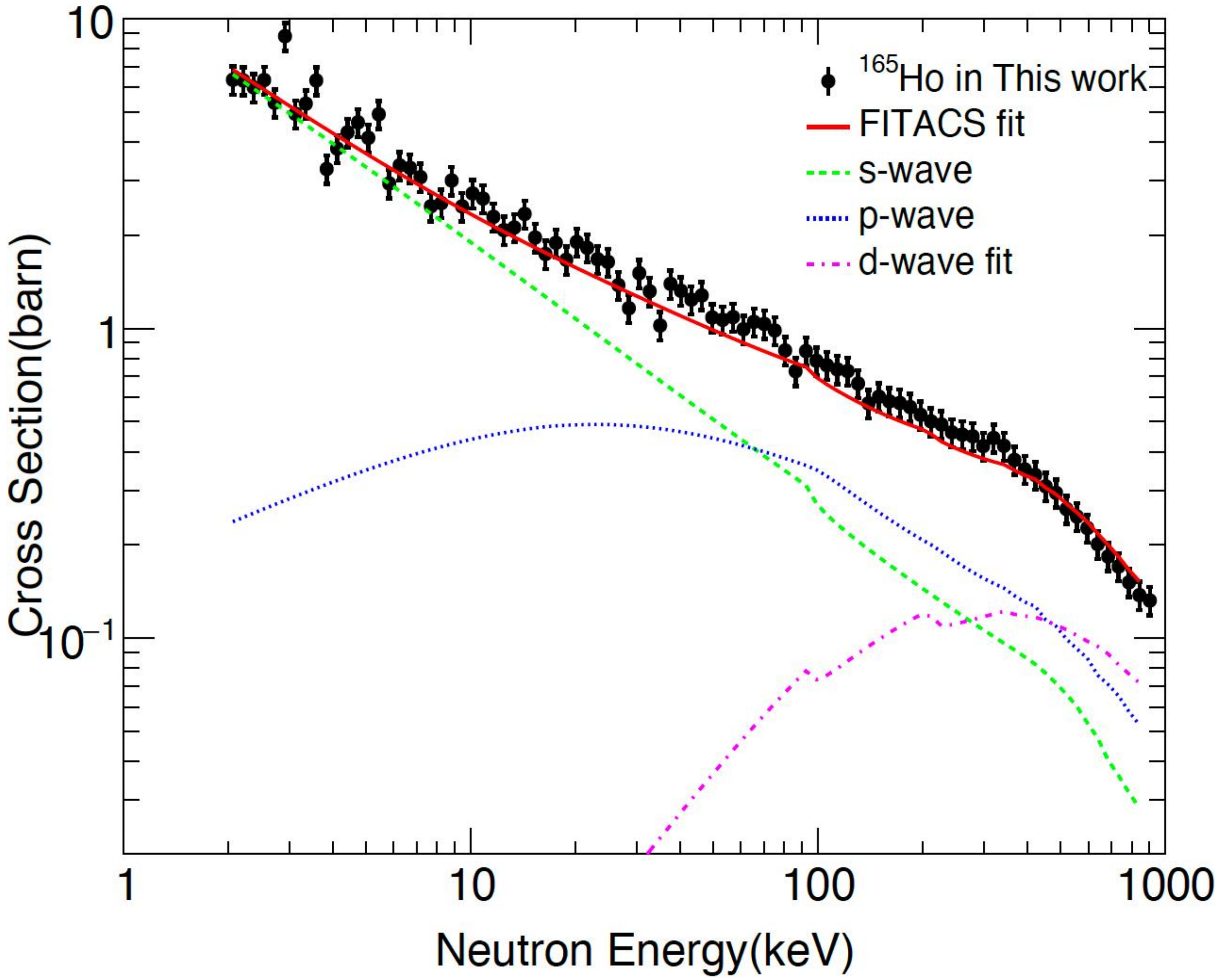
3.7 Statistical properties

Hauser-Feshbach model

$$\sigma_{n\gamma}(E) = \frac{\pi}{k_n^2} \sum_{J,\pi} g_J \frac{T_\gamma(E,J,\pi)\, T_n(E,J,\pi)}{T_{tot}}$$

$^{165}Ho(n,\gamma)$ resonance parameters

	ThisWork	Marklin	S,F.Mughabghab
S_0 ($\times 10^{-4}$)	1.98±0.02	1.33±0.14	1.97±0.19
S_1 ($\times 10^{-4}$)	1.49±0.07	1.36±0.24	1.30±0.07
S_2 ($\times 10^{-4}$)	2.41±0.02	1.19±0.76	2.29±0.22
$<\Gamma_\gamma>_0$ (eV)	0.089±0.001	0.076	0.084±0.005
$<\Gamma_\gamma>_1$ (eV)	0.061±0.005	0.076	0.045±0.002
D_0 (eV)	4.53±0.03	3.23±0.55	4.35±0.15



3.8 Publication

Nuclear Science and Techniques (2025) 36:168
https://doi.org/10.1007/s41365-025-01763-8

DATA ARTICLE

Check for updates

New measurement of ^{165}Ho neutron capture cross sections

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Received: 18 February 2025 / Revised: 9 April 2025 / Accepted: 10 April 2025

Abstract
The neutron capture cross section for ^{165}Ho was measured at the backstreaming white neutron beam line (Back-n) of the China Spallation Neutron Source (CSNS) using total energy detection systems, composed of a set of four C_6D_6 scintillator detectors coupled with pulse height weighting techniques. The resonance parameters were extracted using the multilevel multichannel R-matrix code SAMMY to fit the measured capture yields of the ^{165}Ho(n,γ) reaction in the neutron energy range below 100 eV. Subsequently, the resonance region's capture cross sections were reconstructed based on the obtained parameters. Furthermore, the unresolved resonance average cross section of the ^{165}Ho(n,γ) reaction was determined relative to that of the standard sample ^{197}Au within the neutron energy range of 2 keV to 1 MeV. The experimental data were compared with the recommended nuclear data from the ENDF/B-VIII.0 library, as well as with results of calculations performed using the TALYS−1.9 code. The comparison revealed agreement between the measured ^{165}Ho(n,γ) cross sections and these data. The present results are crucial for evaluating the ^{165}Ho neutron capture cross section and thus enhance the quality of evaluated nuclear data libraries. They provide valuable guidance for nuclear theoretical models and nuclear astrophysical studies.

Keywords Holmium · Neutron capture reaction · Cross section · Total energy detection principle · C_6D_6 scintillator detector · China Spallation Neutron Source

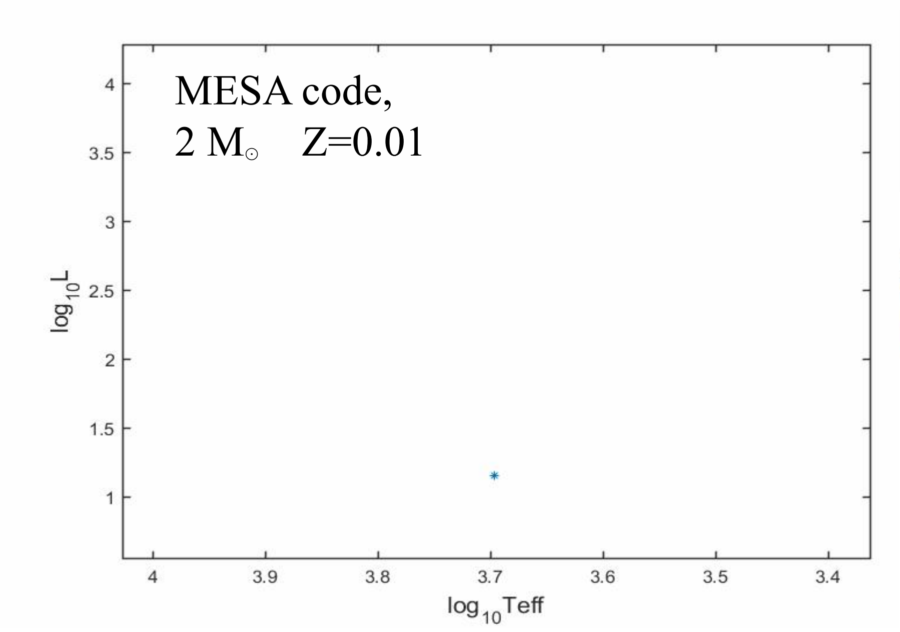
5 Usage notes

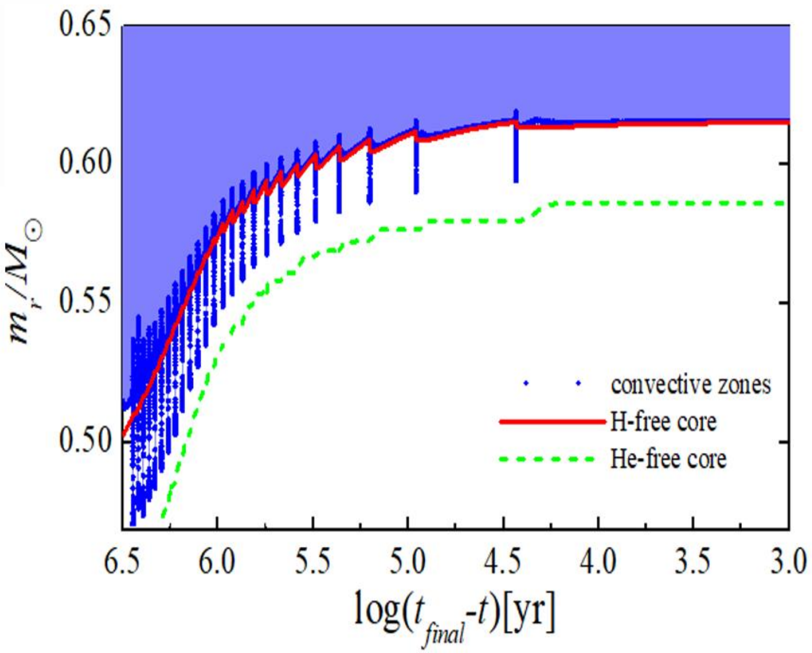
The obtained dataset presents newly measured cross sections for the ^{165}Ho(n, γ)^{166}Ho reaction studied at the CSNS Back-n facility. Our objective is to comprehensively document the data analysis procedures and make the neutron capture data accessible to both the nuclear physics community and researchers working in related fields for future studies. This dataset has numerous applications in nuclear physics, particularly in the following areas:

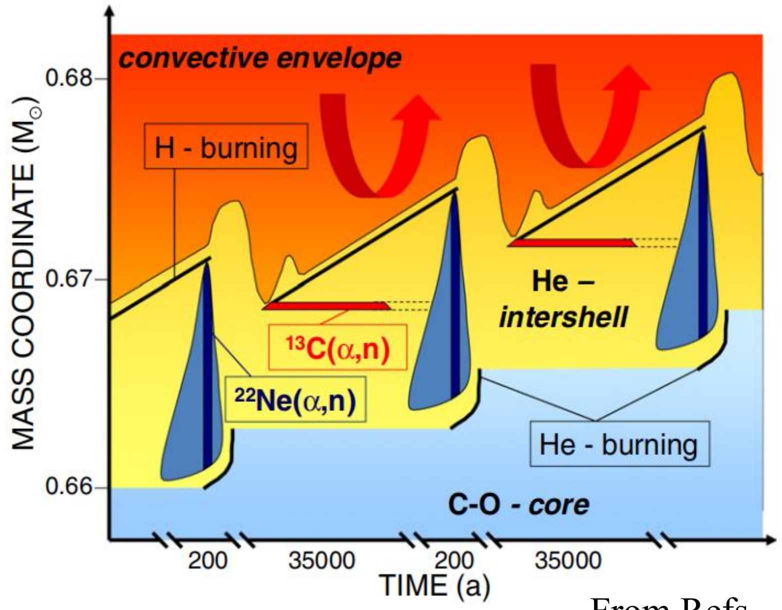
(1) The spectroscopic information of heavy nuclei is challenging to obtain experimentally because of the rapid increase in the nuclear level density (NLD) with increasing excitation energies. To address this, statistical models provide a framework for understanding the internal structure of these nuclei at higher energies, relying on key parameters such as the NLD and γ-ray strength function (γSF). These parameters are essential for a wide array of calculations in nuclear reactions, particularly for determining the neutron capture reaction cross sections. The accuracy of these calculations is vital for evaluating the reliability of the nuclear

Outline

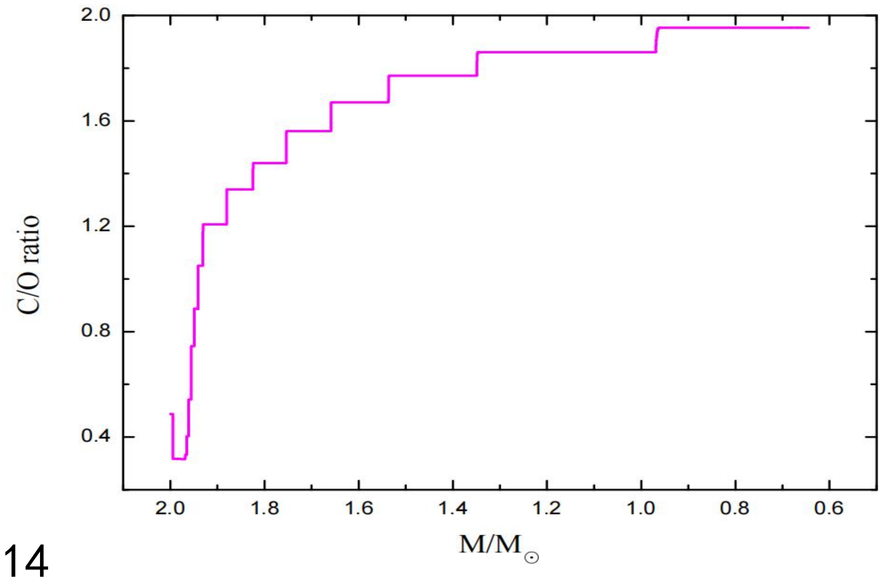
4.1 Simulation of AGB star

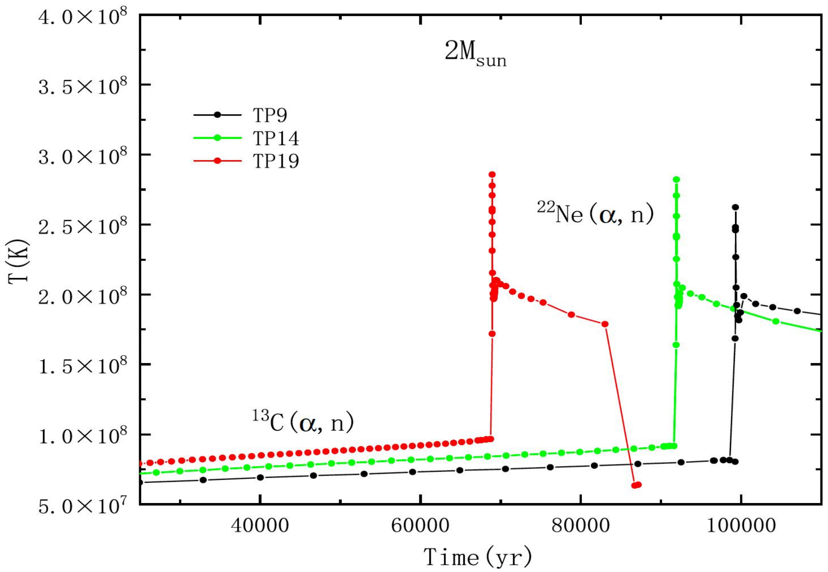


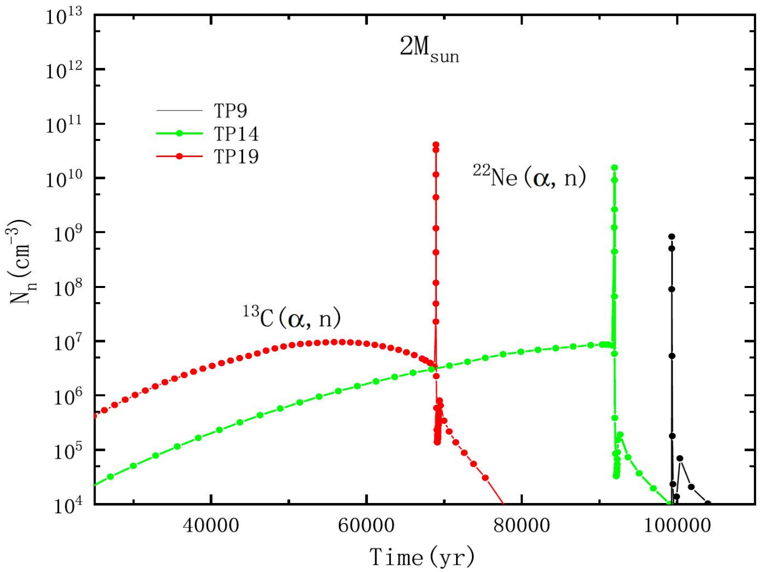




From Refs.

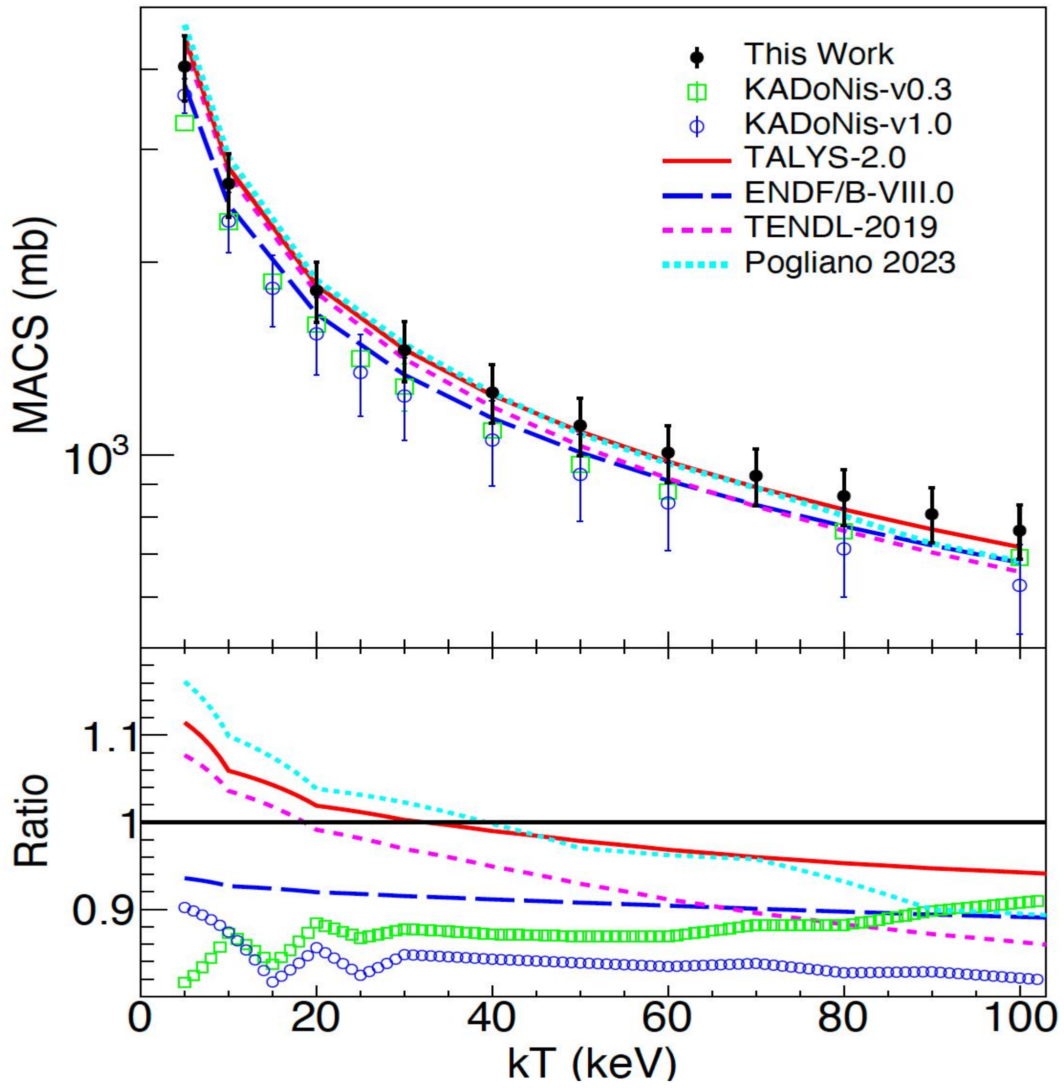




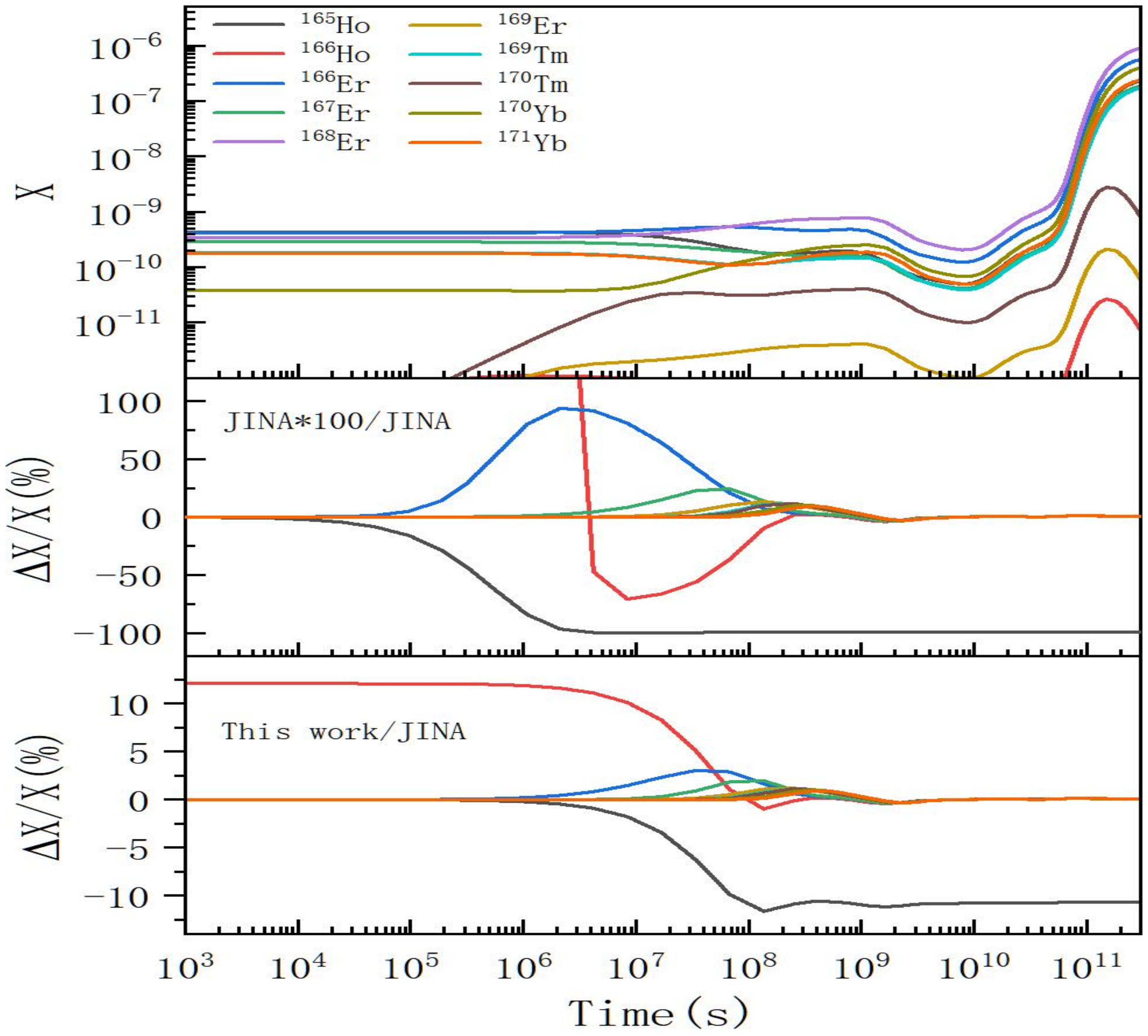


4.2 Sensitivity study of MACS data

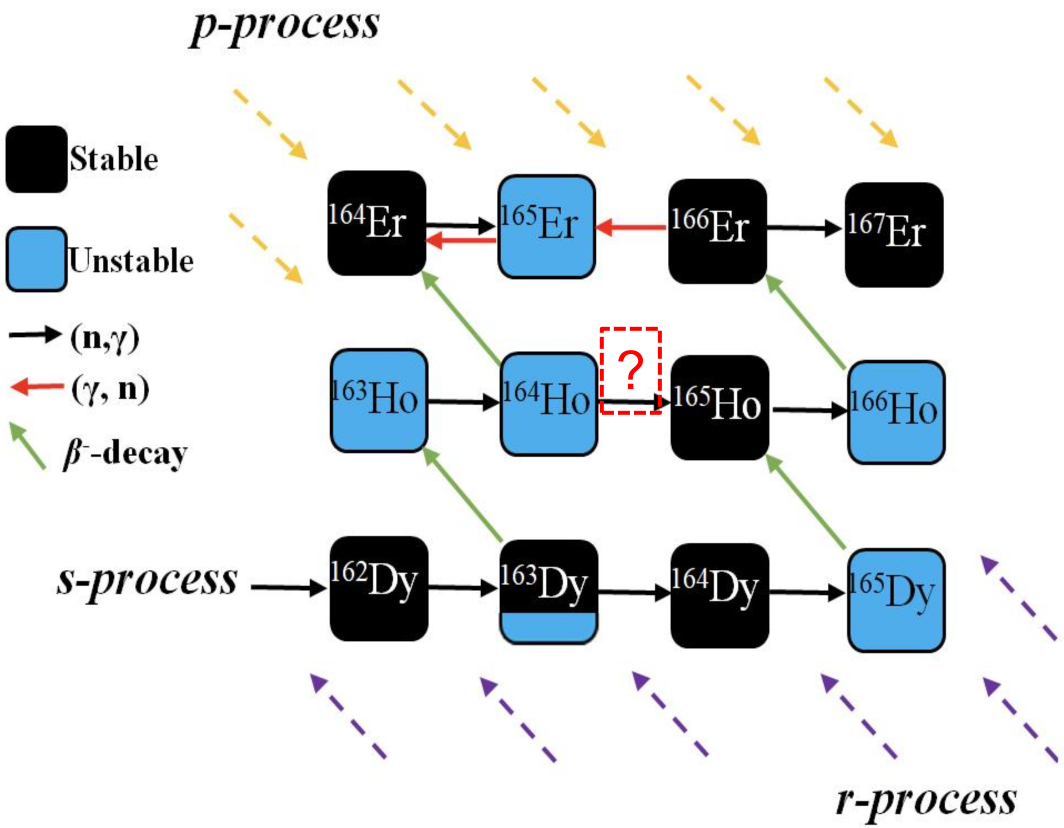
$$\text{MACS} = \frac{2}{\sqrt{\pi}(kT)^2}\int_0^{\infty}\sigma(E)Ee^{-E/kT}dE$$



T=1 × 10^8 K, ρ=9.6 × 10^4 g/cm^3

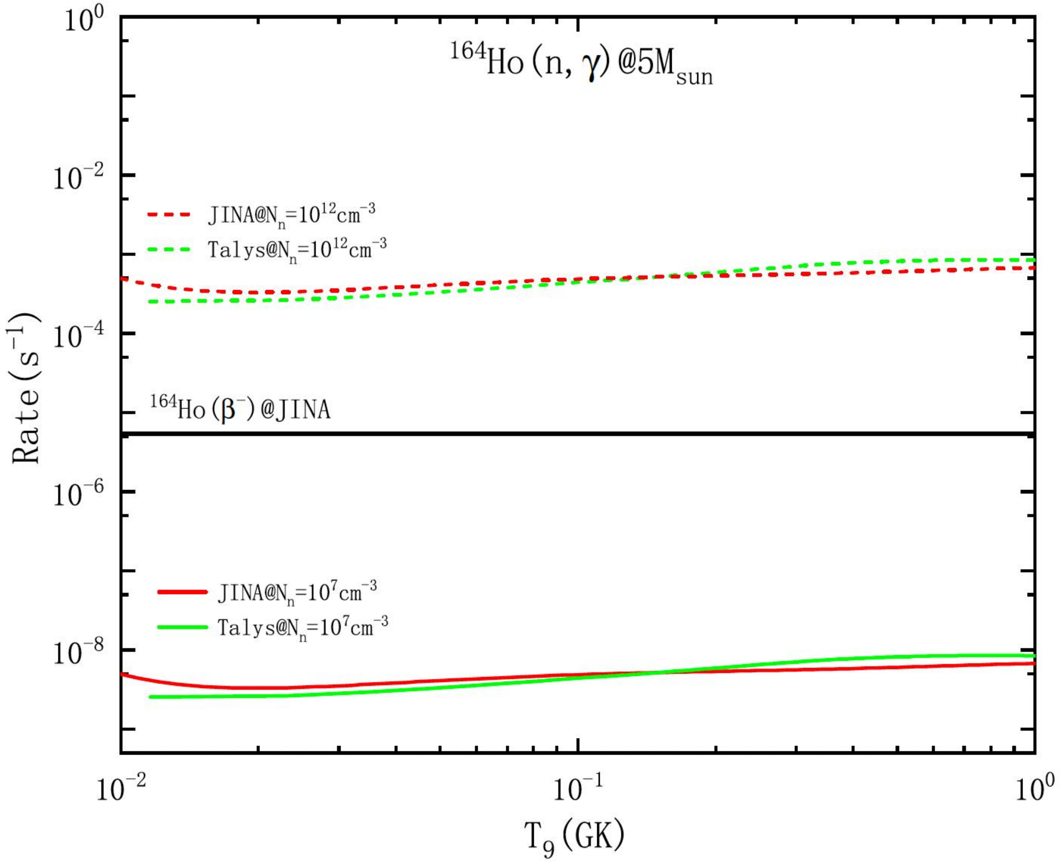


4.3 Implications for ^{164}Er, ^{164}Ho



Takahashi et al.(1983): ^{164}Ho(β⁻)^{164}Er

- ^{164}Ho(n, γ) and β^- decay
- p-nuclei ^{164}Er problem



Outline

5.1 Summary

- Direct measurement techniques of (n, γ) reaction are established based on CSNS Back-n facility, including C_6D_6.
- ^{159}Tb (n, γ) and ^{165}Ho (n, γ) cross section was measured in the energy from 1eV to 1MeV.
- Low-intermediate mass AGB star evolution and nucleosynthesis are studied with MESA code.

5.2 Outlook

- ^{164}Ho (n, γ) cross section will be constrained with the ^{165}Ho (γ, n) measurement at SLEGS.
- New detection system with 10 small size C_6D_6 detectors for (n, γ) reaction are already proposed at IMUN.
- AGB star evolution and i-process nucleosynthesis model will be studied.

Outline

人才队伍

内蒙古唯一的核物理学科点，学校和地方非常重视.

研究方向

核物理基础研究

原子核团簇结构研究

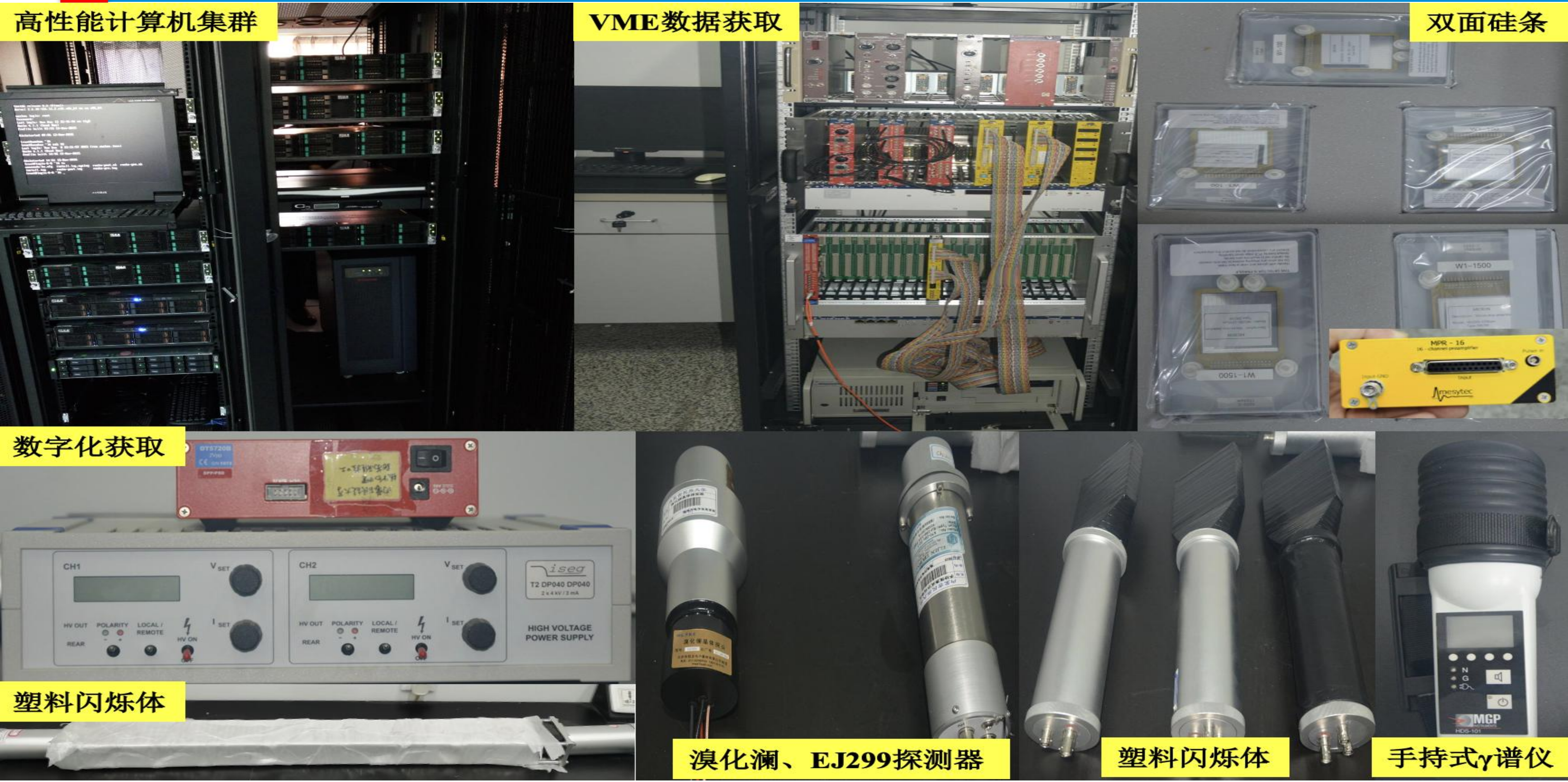
超铁重元素起源之谜

核技术及其应用

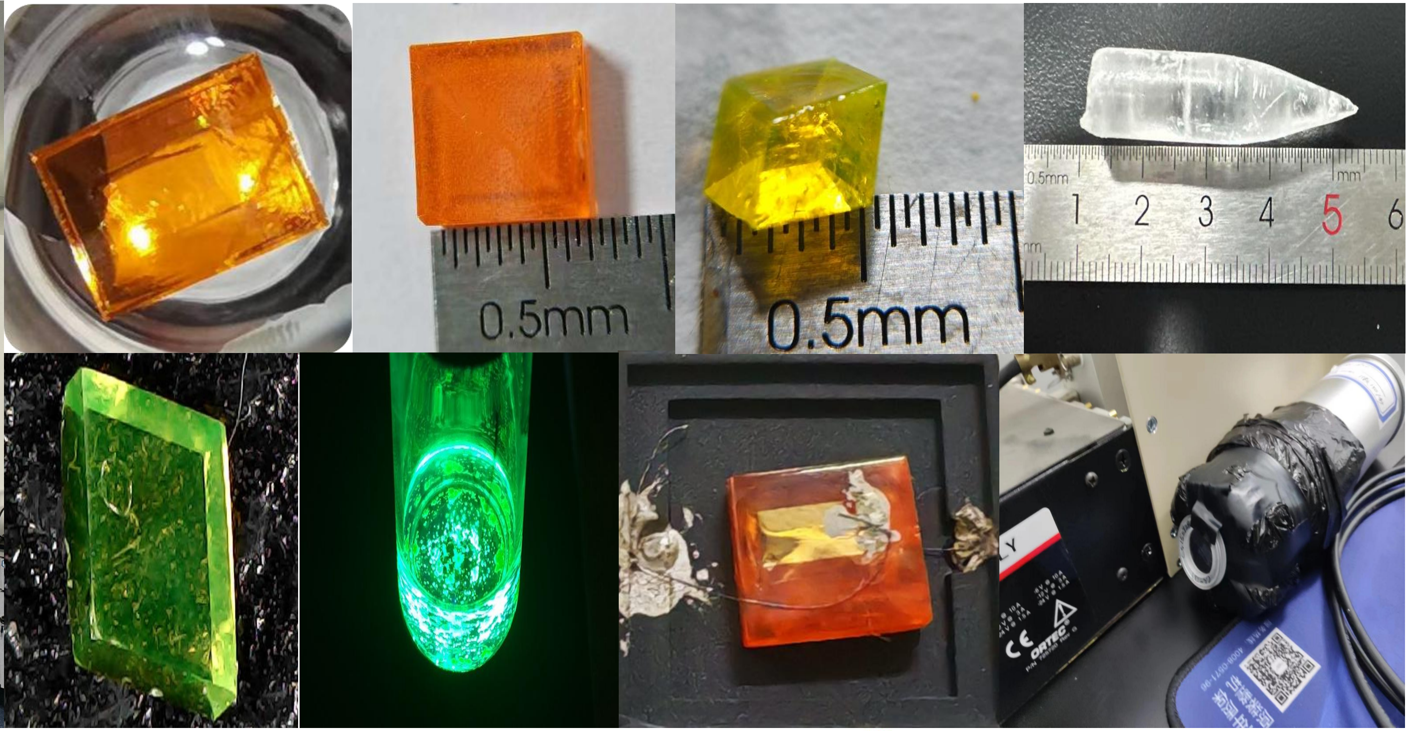
环境与食品辐射探测

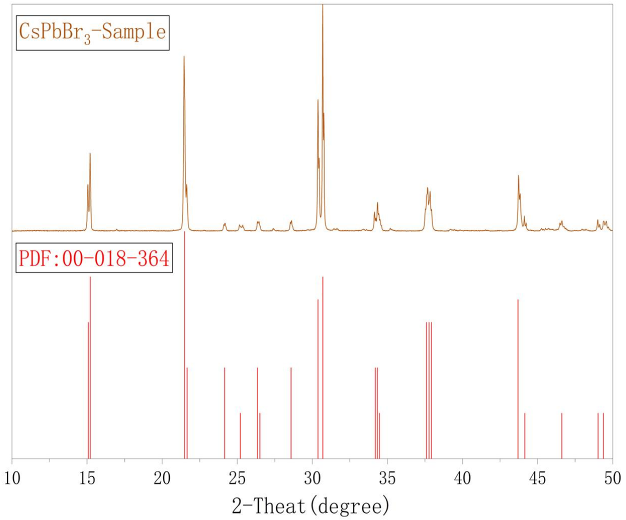
特色蒙药材辐射育种

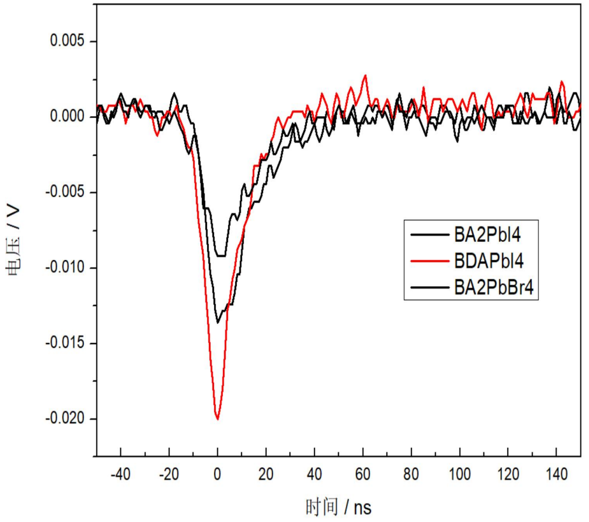
研究平台1：基础研究方面

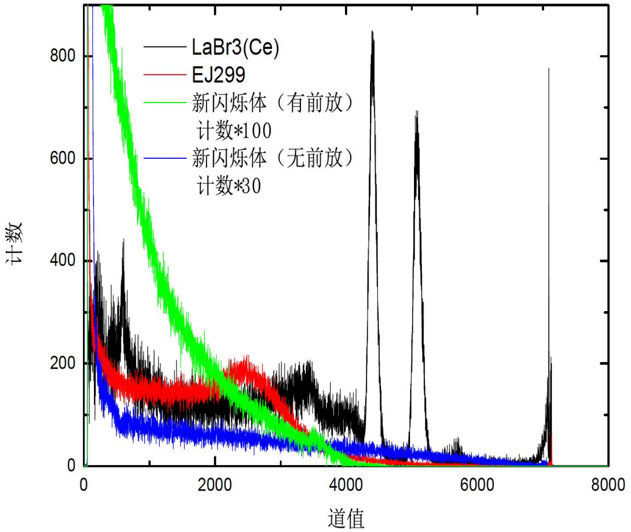


研究平台2：探测技术研发

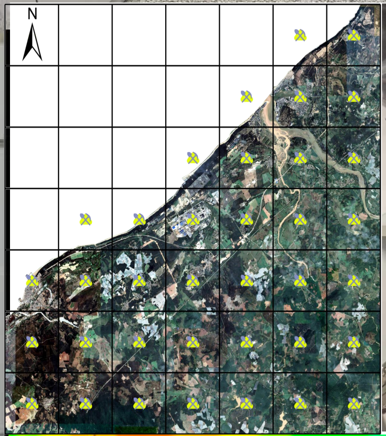


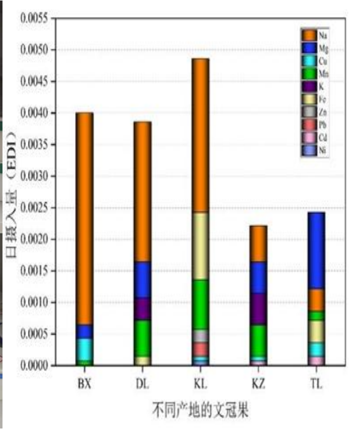


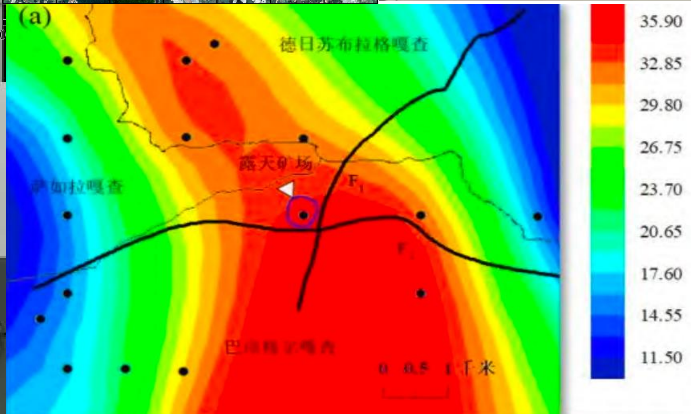




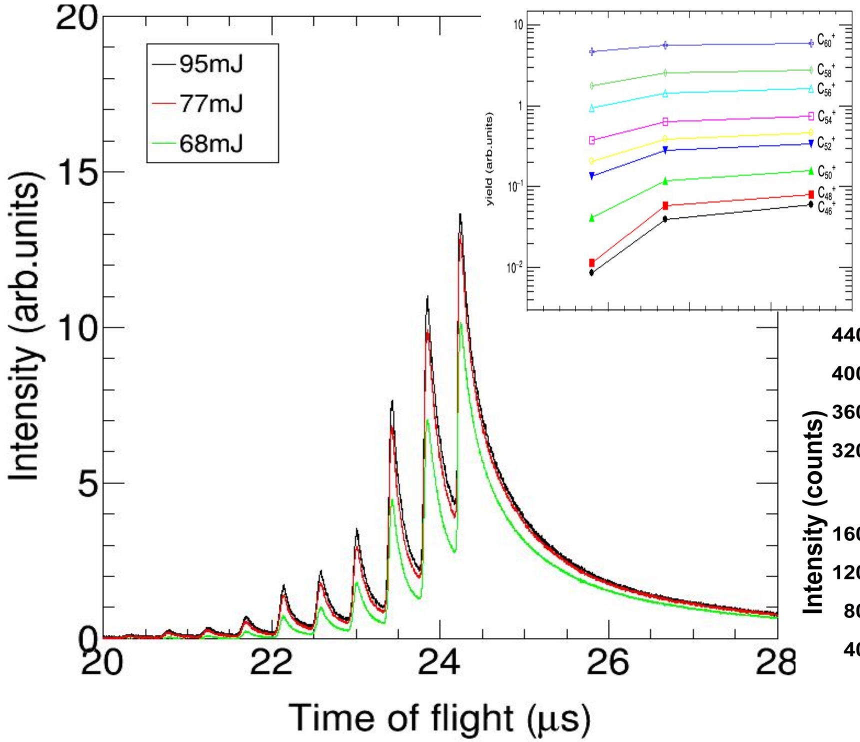
研究平台3：环境与食品辐射测量

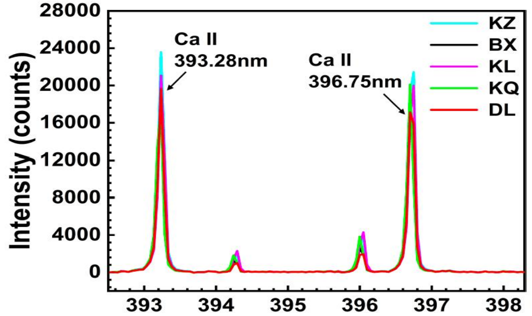


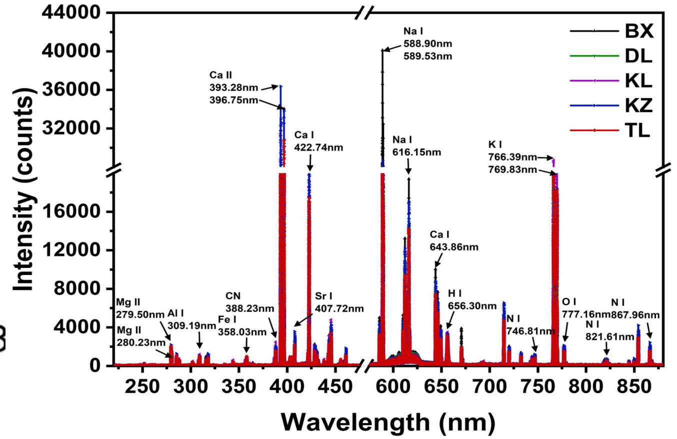


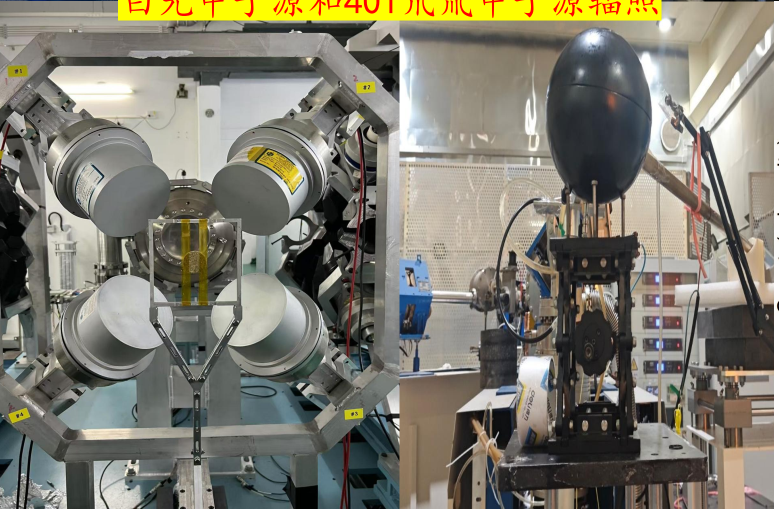


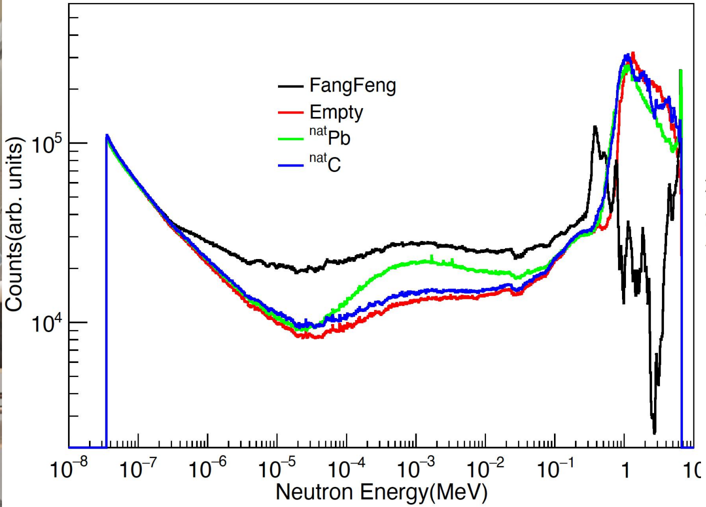
研究平台4：辐射诱变育种机制研究

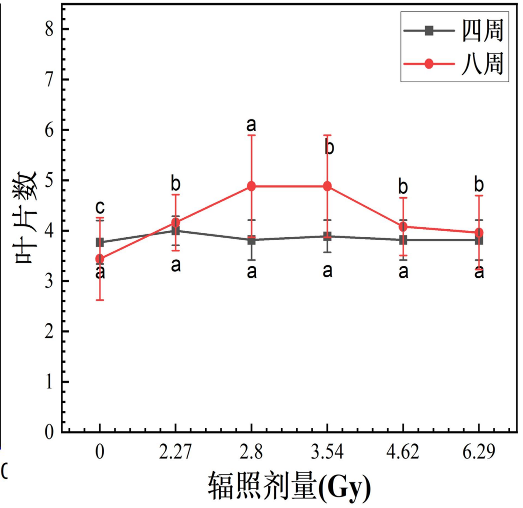










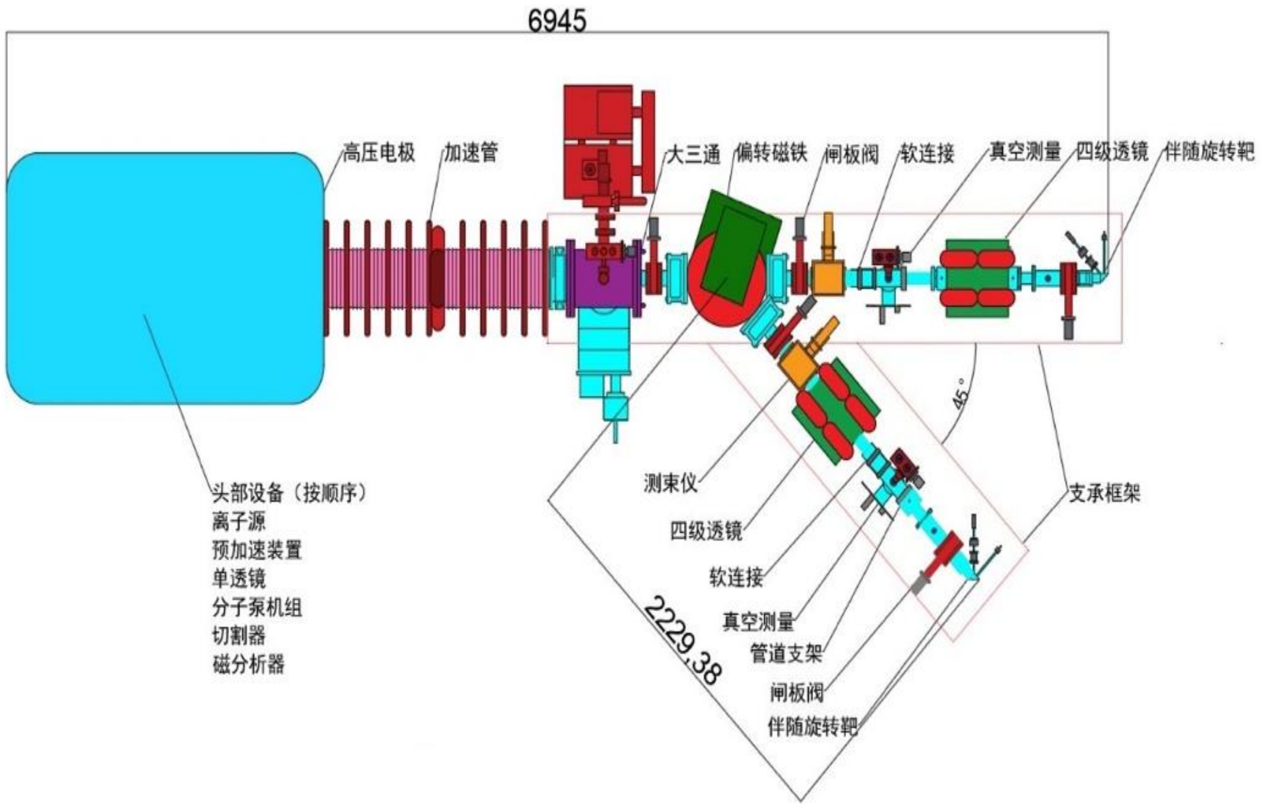


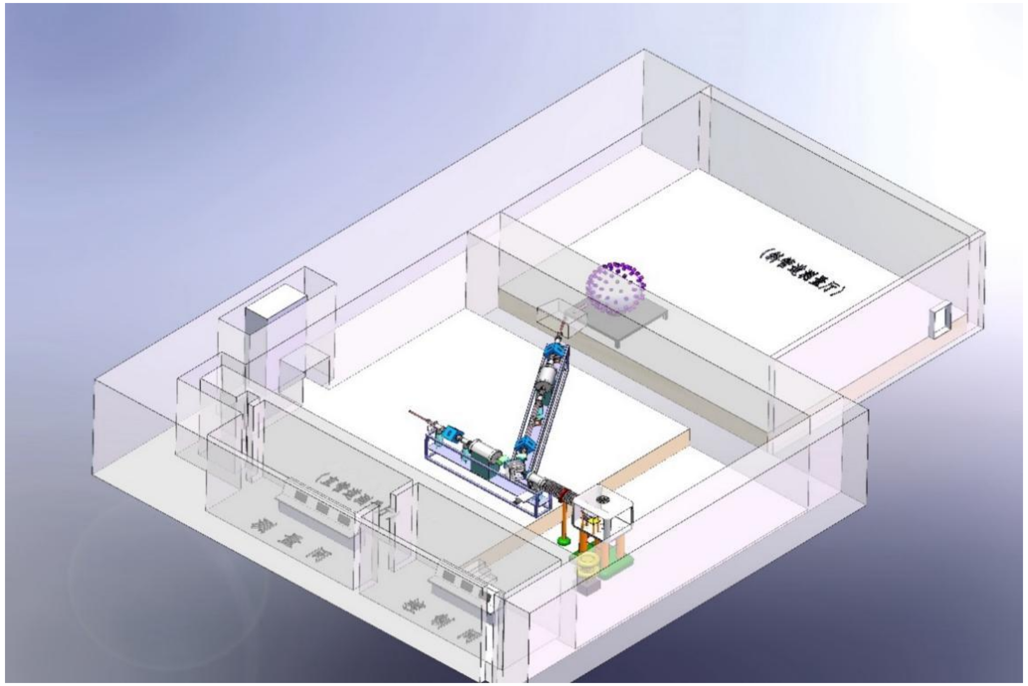
研究平台5：多用途氚氚聚变反应中子源

原子能院陈红涛研究员课题组提供方案

设计指标：

- D$^+$离子能量300keV，流强1mA；
- 2.5MeV中子产额1×10^9/s，14.8MeV中子产额1×10^{11}/s；
- 脉冲束频率1.5MHz，脉冲宽度小于2ns；
- 离靶1cm处约0.5Gy S^{-1}cm^{-2}的14.8MeV中子辐照剂量。





应用领域：

- 特色作物辐照育种
- 中子活化分析
- 低能核物理实验
- 中子辐照材料
- 中子核数据测量
- 中子照相技术

期待“核”你相聚草原

谢 谢 ！