

Measurement of the $\text{Ag}(n, \gamma)$ cross section up to stellar s-process temperatures at the CSNS Back-n

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(Received 1 July 2025; accepted 13 November 2025; published 30 December 2025)

The (n, γ) cross section of silver is crucial for the nucleosynthesis process of nuclear astrophysics, the design of silver-indium-cadmium absorber rod in the nuclear reactors, and neutron resonance capture analysis for determining the elemental and isotopic composition of cultural heritage. The high-precision $\text{Ag}(n, \gamma)$ cross section was measured from 1 eV to 1 MeV at the Back-n facility of the Chinese Spallation Neutron Source using the time-of-flight method and pulse height weighting technique. The resonance parameters were accurately extracted in the resolved resonance region by the multilevel multichannel R -matrix code SAMMY. The TALYS code was used to describe the average cross sections in the unresolved resonance region, and the Maxwellian-averaged cross sections (MACSs) of ^{107}Ag and ^{109}Ag were further given in the 5–100 keV range. The MACS values at $kT = 30$ keV for ^{107}Ag (887 ± 89 mb) and ^{109}Ag (903 ± 90 mb) are slightly higher than the recommended values in the Karlsruhe Astrophysical Database of Stellar Nucleosynthesis.

DOI: [10.1103/1c5x-8d44](https://doi.org/10.1103/1c5x-8d44)

I. INTRODUCTION

Neutron capture reaction is a nuclear reaction in which an atomic nucleus captures a single neutron to form a

heavier nucleus. The electric neutrality of neutrons renders them unaffected by the Coulomb force, thereby facilitating their capture by atomic nuclei. During the formation of the universe, elements heavier than iron were mainly produced by two neutron-capture processes: the slow neutron capture process (s process) [1] and the rapid neutron capture process (r process) [2]. The s process occurs under conditions of relatively low neutron density and moderate temperature. In the s process, the neutron capture rate of atomic nuclei is lower than the β^- decay rate [3]. Stable isotopes capture neutrons, forming isotopes with higher mass numbers. Radioactive isotopes typically undergo β^- decay before capturing additional neutrons, producing elements with higher atomic numbers.

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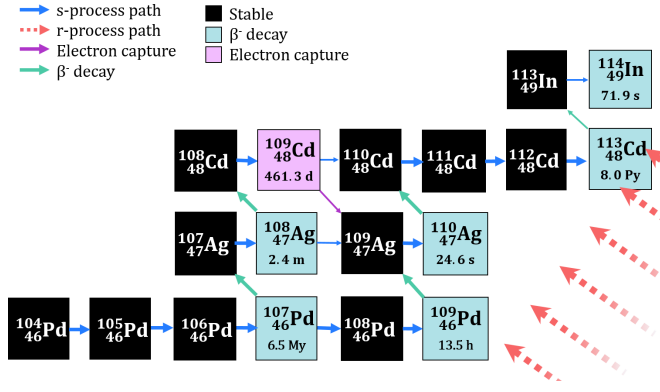


FIG. 1. Synthetic network diagram of nuclei near ^{107}Ag (51.84%) and ^{109}Ag (48.16%) isotopes. The black boxes represent stable isotopes, and the blue boxes represent unstable isotopes. The blue bold lines represent the s-process path, the green bold lines represent the β^- decay process path, the red arrows represent the r-process path, and the purple arrows represent the EC decay process, in which a nucleus captures an inner-shell electron, converting a proton into a neutron with the emission of an electron neutrino.

The s process primarily takes place in the helium shell of the asymptotic giant branch stars and is the main source of most stable elements heavier than iron in the universe [4], such as Sr, Ba, Mo, and W. During the r process, the nucleus captures neutrons at a very high rate, higher than the β^- decay rate, usually starting with seed nuclei from the iron-peak region (such as Fe and Ni), and proceeding through a series of rapid neutron captures to form a neutron-rich heavy element [5]. It primarily occurs in extreme environments with high neutron densities, such as neutron star mergers [6] or certain types of supernova explosions [7].

Natural silver ($^{\text{nat}}\text{Ag}$) consists of two isotopes, ^{107}Ag and ^{109}Ag , both of which lie along the main path of the s process. The evolution of the neutron capture process in their vicinity is illustrated in Fig. 1. In nuclear astrophysics research, the (n, γ) reaction cross sections of these two isotopes and their Maxwellian-average cross sections (MACSs) at $k_B T = 30$ keV are of importance for gaining a deeper understanding of the nuclear reaction pathways of the s process. The MACS is defined as the reaction cross section averaged over a Maxwell Boltzmann distribution of neutron energies characterized by the thermal energy $k_B T$, where k_B is the Boltzmann constant and T is the stellar plasma temperature. $^{\text{nat}}\text{Ag}$ targets (consisting of 51.8% ^{107}Ag and 49.2% ^{109}Ag) are widely used in neutron time-of-flight (TOF) experiments. By employing resonance shape analysis and the R -matrix methods, the contributions from the two isotopes can be effectively separated, as verified in previous studies [8] and in the present work. This allows the extraction of resonance parameters as well as the determination of the (n, γ) cross sections of ^{107}Ag and ^{109}Ag in the unresolved resonance region (URR). Based on these cross-section data, the MACSs of the two isotopes at different plasma temperatures were calculated, providing key input for s-process nucleosynthesis network calculations. Although a $^{\text{nat}}\text{Ag}$ target was used in the experiments, the results still provide valuable constraints for nuclear astrophysics and serve as important references for the improvement of nuclear reaction models.

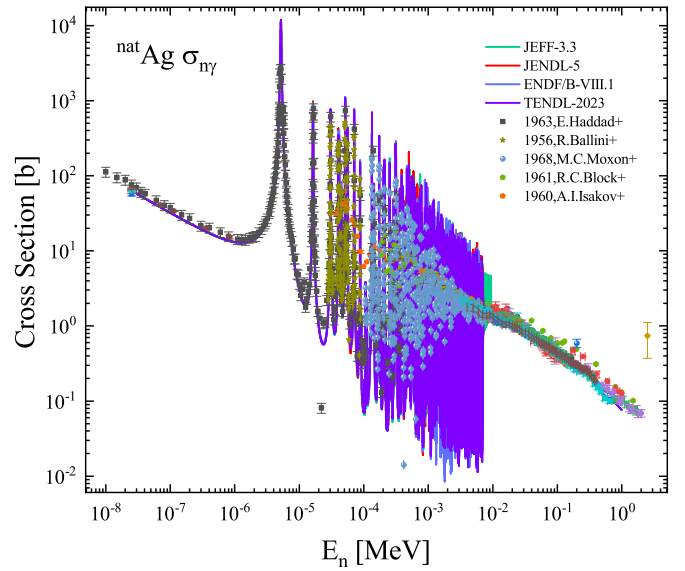


FIG. 2. Existing measurement data on the cross section of $^{\text{nat}}\text{Ag}(n, \gamma)$.

In nuclear reactors, especially pressurized water reactors, the control rod material consists mainly of silver-indium-cadmium (Ag-In-Cd) alloys. Their main functions are to compensate for the residual reactivity of the core, to regulate and maintain the reactor at a specific power, and to ensure that the reactor can be safely shut down in normal or emergency situations [9]. As the control rods are exposed to high flux neutron irradiation for long periods of time, their material is gradually depleted by neutron capture. The accuracy of neutron reaction cross-section data for silver is important for macroscopic cross-section calculations of control rods, which in turn affects reactor design, operation, and maintenance. Two isotopes of $^{\text{nat}}\text{Ag}$, ^{107}Ag , and ^{109}Ag act as neutron poisons in nuclear reactors and can significantly reduce the number of neutrons available for sustaining the chain reaction, thus affecting the reactor's neutron economy. Therefore, improving the accuracy of neutron capture cross-section measurements of Ag is important for optimizing control rod performance and enhancing reactor safety.

The resonance structures of silver in neutron capture reaction cross sections are the basis of neutron resonance capture analysis (NRCA) [10]. NRCA is a powerful nondestructive method for determining the elemental and isotopic composition of archaeological and cultural heritage, such as the elemental analysis through NRCA of antique Coins of the Phanagorian Treasure [11] at the Pulsed Neutron Source Intense Resonance Neutron Source in the Frank Laboratory of Neutron Physics, Joint Institute for Nuclear Research, Celtic silver coins from northern Italy [12], and a metallic ancient flute [13] at the ISIS Pulsed Neutron Source (Rutherford Appleton Laboratory, Chilton-Didcot, UK).

Figure 2 shows the previous measurement results of the $^{\text{nat}}\text{Ag}(n, \gamma)$ cross sections. The resolved resonance region (RRR) corresponds to the energy range where individual neutron resonances can be experimentally distinguished and analyzed, reflecting the underlying nuclear structure of the target nucleus. In contrast, the unresolved resonance region

(URR) corresponds to higher energies where resonances are too closely spaced to be resolved individually, so the cross section is described statistically. Ballini *et al.* [14] reported neutron capture cross-section data for ^{nat}Ag in the RRR, clearly observing several resonance peaks. However, the energy range was limited, and the data were insufficient. Isakov *et al.* [15] provided neutron capture cross-section data for the partial resonance region but did not observe any resonance structures. Block *et al.* [16] conducted neutron radiative capture cross-section measurements for ^{nat}Ag using a large liquid scintillator detector at the Oak Ridge National Laboratory fast neutron chopper. However, only partial cross-section values in the RRR were reported, with relatively few data points. Haddad *et al.* [17] developed a rapid technique suitable for multi-isotope analysis and measured the neutron capture cross section of ^{nat}Ag in the RRR and the URR. The study provided partially resolved resonances in the RRR, but its precision was insufficient to resolve finer resonance structures. Moxon *et al.* [18] employed the Harwell Electron Linac and the TOF method to measure the neutron capture cross section of ^{nat}Ag in the energy range of 100 eV to 50 keV. Previous measurements have mostly focused on the URR, while precise data on the RRR $^{nat}\text{Ag}(n, \gamma)$ cross section remain scarce. Additionally, there are noticeable differences among existing evaluation libraries. Our measurements were performed in the range 1 eV to 1000 keV, which in addition to giving more accurate results in general, clarifies the differences between the different evaluation libraries.

The Chinese Spallation Neutron Source (CSNS) [19] is a large scientific facility based on a high-power proton accelerator, which is mainly used for the research of scattering experiments. The proton beam of the CSNS has a beam energy of 1.6 GeV, a beam power of 140 kW (from October 2022), and a frequency of 25 Hz [20], and impacts a tungsten target to generate neutrons, which are led to the neutron spectrometer through the slower and the conduit for experiments. The Back-n white neutron facility is a branch of CSNS, primarily used for nuclear data measurement. It provides a continuous neutron energy spectrum ranging from 0.1 eV to 400 MeV, with a neutron flux up to $10^7 \text{ cm}^{-2} \text{ s}^{-1}$ [21–24]. The maximum neutron flight distance of the Back-n beamline is approximately 76 m, enabling higher time resolution in detection. There are three different modes of operation for CSNS, and our experiments were performed in double-bunch mode of the proton accelerator. This will be described specifically in the data analysis.

In this work, we measured the cross sections of ^{nat}Ag from 1 eV to 1000 keV with high precision (10% total uncertainty) using high-resolution detectors and advanced data processing. The measurements revealed finer resonance structures than in previous studies and clarified discrepancies among evaluation libraries regarding resonance positions and the existence of certain resonances. The ENDF/B-VIII.1 [25] and TENDL-2023 [26] libraries are most consistent with the experimental data, and our experimental data provide guidance for improving existing evaluation libraries. Resonance parameters in the range 1–1500 eV were extracted and MACS for ^{107}Ag and ^{109}Ag at 5–100 keV were calculated. The experimental methodology and data processing procedures are described below.

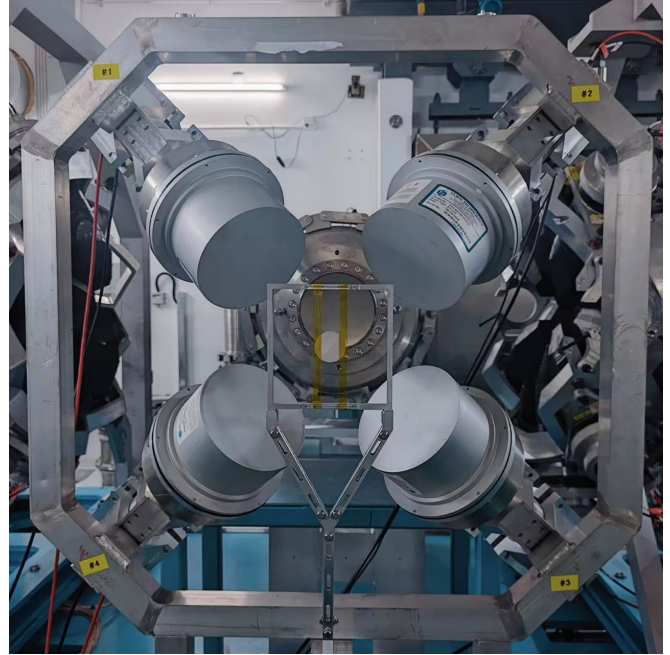


FIG. 3. Photo of the C_6D_6 detector system at Back-n. The position and orientation of the detector and the target holder relative to the neutron beam are the same as in Ref. [24].

II. EXPERIMENTAL METHOD

The measurement relies on the C_6D_6 detection and data acquisition systems. The C_6D_6 detection system consists of four deuterated benzene liquid scintillation detectors, an aluminum detector holder, and an aluminum sample holder [27]. The picture of the C_6D_6 detection system is illustrated in Fig. 3. A neutron capture reaction occurs when a white neutron beam from Back-n strikes the sample target. Four C_6D_6 detectors measure the γ rays emitted from the sample, and digitization full-waveform data are recorded through waveform digitization. Using the TOF [28] method and the pulse height weighting technique (PHWT) [29,30], the neutron capture cross section (σ) for the (n, γ) reaction is derived. The incident neutron energy corresponding to the capture event is obtained using the TOF method. The neutron energy can be derived from the kinetic energy expression:

$$E_n = m_n c^2 \left(\frac{1}{\sqrt{1 - \left(\frac{L}{c \times T}\right)^2}} - 1 \right), \quad (1)$$

where m_n is the neutron mass, c is the speed of light, L is the neutron flight length, and T is the time of neutron flight.

There are three reasons for choosing C_6D_6 to detect prompt γ rays emitted by a composite nucleus [31]: (1) The C_6D_6 detector has a low neutron sensitivity. (2) It demonstrates a relatively fast response time, with its core component, the liquid scintillator EJ315, providing a nanosecond (ns) response to both neutron and gamma signals. (3) The detection efficiency can be weighted by the method of PHWT, so that the detection efficiency is linearly correlated with the energy of the incident γ rays [29]. This feature ensures accurate capture cross section measurements, as detailed in the Sec. III.

TABLE I. Information of experiment targets.

Material	Diameter (mm)	Thickness (mm)	Mass (g)	Purity
^{nat} Ag	40.0	0.5	6.38	>99.9%
^{nat} C	40.0	1.0	2.58	>99.9%
^{nat} Pb	40.0	1.0	13.39	>99.9%
¹⁹⁷ Au	40.0	0.2	4.83	>99.9%
Empty	\	\	\	\

Five targets were measured in this experiment: ^{nat}Ag, ^{nat}C, ^{nat}Pb, ¹⁹⁷Au, and an empty target; the parameters of the samples are shown in Table I. The ^{nat}C samples were chosen because the neutron capture cross section of carbon is much smaller than its scattering cross section, and its γ -ray scattering is very weak, making it suitable for background subtraction of scattered neutrons. The ^{nat}Pb target was used to subtract the in-beam γ background since lead has a high γ -ray scattering cross section but a low neutron scattering cross section. The ¹⁹⁷Au target serves primarily to calibrate the neutron flight distance L ; moreover, it is internationally recognized as a standard due to its precisely known capture cross sections over a wide energy range and its strong, well defined resonances in the eV to keV region, making it suitable for testing the performance of the detection system. Finally, an empty target was used to subtract the background of the environment and the interaction of the in-beam neutrons with the environment.

III. DATA ANALYSIS

A. Pulse height weighting technique

The C₆D₆ detectors are total energy detectors and are used under the ideal condition of assuming that for a cascade emission of neutron capture reactions, only one deexcited γ ray is detected [32,33]. Thus, the detection efficiency ε_c of the capture reaction is approximately equal to the sum of the detection efficiencies $\varepsilon_{\gamma i}$ for the cascade of γ ray [34].

$$\varepsilon_c = 1 - \prod (1 - \varepsilon_{\gamma i}) \approx \sum \varepsilon_{\gamma i}, \quad (2)$$

to ensure a direct relationship between ε_c and the detector output spectrum, the detection efficiency of each γ rays should be proportional to its energy $E_{\gamma i}$ [35]:

$$\varepsilon_{\gamma i} = \alpha E_{\gamma i}, \quad (3)$$

then there is

$$\varepsilon_c \approx \sum \varepsilon_{\gamma i} = \alpha \sum E_{\gamma i} = \alpha E_c, \quad (4)$$

where E_c is the total excitation energy of the compound nucleus. However, due to the complex deexcitation paths of the compound nucleus, the natural response of the detector does not satisfy this condition. Therefore, the pulse height weighting technique is employed. The weighting function $W(E_{\text{dep}})$ is applied to the detector response to ensure that the weighted efficiency is proportional to the γ -ray energy and independent of the deexcitation path. In this way, the cross section can be calculated from the detector output spectrum. $W(E_{\text{dep}})$ is

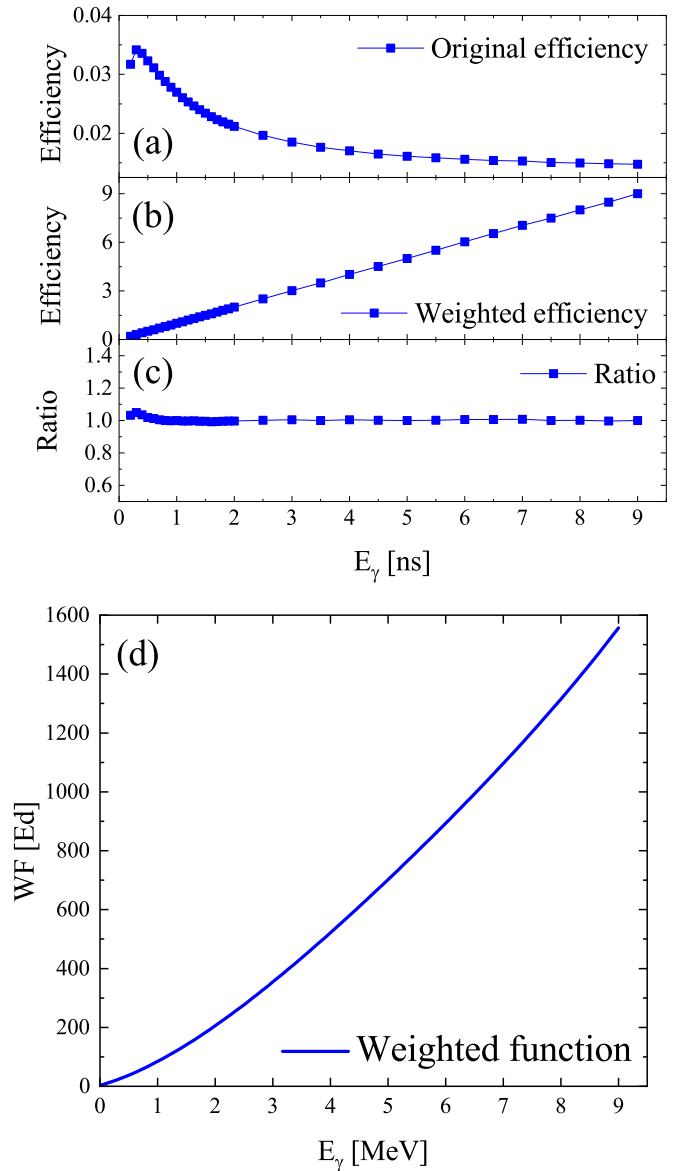


FIG. 4. (a) The C₆D₆ original efficiency. (b) Weighted efficiency. (c) The ratio of weighted efficiency to γ -ray energy. (d) Weight function of C₆D₆ detector.

expanded as a polynomial:

$$W(E_{\text{dep}}) = \sum_{k=0}^4 a_k E_{\text{dep}}^k, \quad (5)$$

and the coefficients a_k are obtained by least-squares fitting:

$$\chi^2 = \sum \left[\alpha E_{\gamma i} - \int_{E_L}^{\infty} R(E_{\text{dep}}, E_{\gamma i}) W(E_{\text{dep}}) dE_{\text{dep}} \right]^2, \quad (6)$$

where E_L is the threshold of the pulse height (PH) spectrum, $R(E_{\text{dep}}, E_{\gamma i})$ is the response function of the C₆D₆ detector to a monoenergetic γ ray with energy $E_{\gamma i}$ [36], and E_{dep} represents the energy deposited by the cascade γ ray in the detector. Usually, α is set to 1. Figure 4 shows the original efficiency, the weighted efficiency, and the ratio of weighted efficiency to γ -ray energy. The results demonstrate that the

weighted efficiency exhibits a strong linear correlation with the incident γ -ray energy, thereby confirming the validity of the PHWT in this measurement. In addition, the PHWT has been experimentally validated in previous studies [27] using the same facility and the same C₆D₆ detection system. Together with the consistency checks performed in this work, these results indicate that the method is reliable for the present measurement.

The neutron capture yield can be calculated from the weighted pulse height count spectrum by Eq. (7).

$$Y_w = \frac{N_w}{I(S_n + E_n)}, \quad (7)$$

where Y_w is the weighted neutron capture yield, N_w is the weighted pulse height weighted counting spectrum, S_n is the neutron binding energy of the compound nucleus, I is the neutron injection rate, and the neutron capture yield is in turn related to the neutron capture cross section by Eq. (8).

$$Y_w(E) = (1 - e^{-N\sigma_t(E)t}) \frac{\sigma_c(E)}{\sigma_t(E)}, \quad (8)$$

where N is the atomic density of the target, σ_t is the ^{nat}Ag total cross section, σ_c is the ^{nat}Ag capture cross section, and t is the thickness of the target; thus, the neutron capture cross section can be calculated from Eq. (15):

$$\sigma_c(E) = Y_w(E) \times \frac{\sigma_t(E)}{(1 - e^{-N\sigma_t(E)t f_c})}, \quad (9)$$

f_c is the target thickness correction coefficient, and it will be described later.

B. Double-bunch unfolding method

CSNS proton accelerator has three modes of operation: double-bunch mode, single-bunch mode, and narrow-bunch mode. At present, the proton accelerator of the CSNS operates in the double-bunch mode, in which the present experiment was also performed. Although the single-bunch mode provides better time resolution, its beam power is considerably lower, which is insufficient for the high-statistics requirements of the present measurement. The double-bunch mode proton accelerator emits proton bunch with a pulse frequency of 25 Hz, and a single pulse contains two proton bunch with a spacing of 410 ns, with a maximum power of more than 140 kW and a time resolution of 0.6%–0.8% at 1 keV to 1 MeV [37]. The neutrons produced by these two proton bunch overlap with each other, resulting in a reduced neutron energy resolution of the TOF measurement, especially in the region of higher neutron energies [23]. This structure has almost no effect on the original counting spectrum below 500 eV, but causes a superposition of the event distribution at neutron energies greater than 500 eV, resulting in the single peaks in some of the counting spectra becoming double peaks. Yi *et al.* [38] have developed an unfolding method based on Bayes' theorem, which is able to revert the double peak structure caused by the bunch pattern to the original single peak structure, effectively improving time and energy resolution.

The spacing between the two beam clusters in the proton beam pulse is a fixed value of 410 ns and the two beam clusters have the same distribution in the time domain, so

the TOF distribution of the double-bunch cluster mode can be regarded as a superposition of two identical but offset 410 ns distributions. Measuring the statistical time count spectrum in the double-bunch cluster mode, the counts of each time bin E_i measured in this mode should theoretically depend on the counts C_i measured in the single-bunch mode [39]. This relationship can be expressed in the form of a matrix:

$$\mathbf{E} = \mathbf{R} \cdot \mathbf{C}, \quad (10)$$

where $\mathbf{C}$ and $\mathbf{E}$ are column vectors, $\mathbf{E} = (E_0, \dots, E_i, \dots, E_n)$, $\mathbf{C} = (C_0, \dots, C_i, \dots, C_n)$, and the transformation matrix $\mathbf{R}$, can be expressed as

$$\mathbf{R} = \begin{bmatrix} R_{11} & & & & \\ \vdots & R_{22} & & & \\ R_{(1+\Delta)1} & \vdots & \ddots & & \\ & R_{(2+\Delta)2} & \vdots & R_{ii} & \\ & & \ddots & \vdots & \ddots \\ & & & R_{(i-\Delta)i} & \cdots & R_{nn} \end{bmatrix}. \quad (11)$$

In matrix $\mathbf{R}$, the elements on the diagonal and subdiagonal are 0.5, while all other elements are 0. The perpendicular distance between the diagonal and subdiagonal is equal to the value of Δ ; Δ is the number of bins corresponding to the offset of the double-bunch interval (410 ns). We need to calculate the count C_i in the single-bunch mode by finding the inverse of the matrix $\mathbf{R}$. Considering statistical fluctuations in actual measurements, this method is not applicable. The iterative algorithm for Bayesian estimation proposed by researchers Yi *et al.* [38] can be applied to practical problems. In the actual unfolding process, C_i is exactly the value we want to estimate, and by modifying the unfolding process into an iterative algorithm, the process of finding the inverse matrix $\mathbf{R}$ can be replaced by an iterative process [38,40]:

$$C_i^{(k+1)} = E_i \frac{C_i^{(k)}}{C_i^{(k)} + C_{i-\Delta}^{(k)}} + E_{i+\Delta} \frac{C_i^{(k)}}{C_{i+\Delta}^{(k)} + C_i^{(k)}}, \quad (12)$$

where C_i^k indicates the result of the k th iteration and the initial C_i^0 is set to the E_i measured in the double-bunch distribution, and after a sufficient number of iterations, the value of C_i^k will converge to the value of C_i corresponding to the single-bunch mode. Some unfolding results for a ^{nat}Ag target are shown in Fig. 5.

C. Background

The backgrounds in this experiment are mainly of two types [41–43]: One is the time-independent background B_0 , which refers to the environmental background and the background brought about by the neutron activation of the sample itself (B_{act}). In the present measurement, B_0 is approximately equal to B_{act} . One class is the time-dependent background [44]. It refers to the background associated with the time structure of the neutron beam flow, which we evaluate in the presence of the beam.

The time-dependent background can be further categorized into the target-dependent background $B_{\text{sample}}(t)$ and the target-independent background $B_{\text{empty}}(t)$. $B_{\text{empty}}(t)$ is the

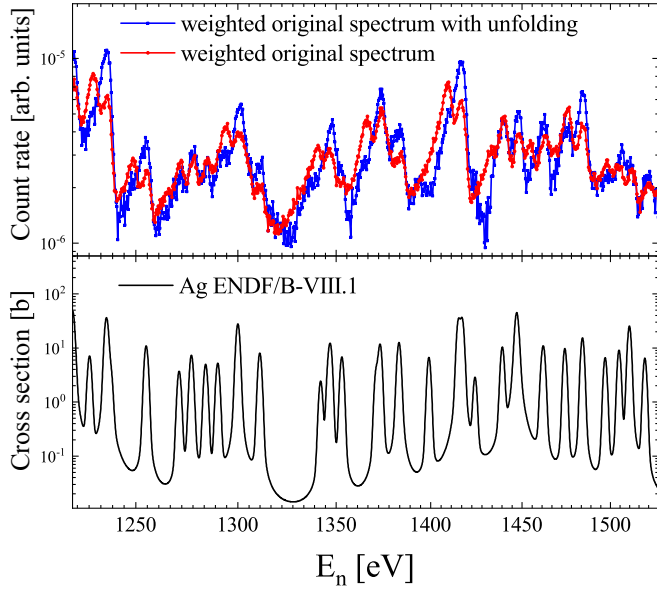


FIG. 5. Comparison between the weighted original spectrum (red curve) and the weighted original spectrum with unfolding (blue curve) with ENDF/B-VIII.1 [25] database (black curve). It shows that the unfolding method could improve the time resolution and eliminate some double peaks caused by double-bunch mode.

background due to scattering of neutrons and γ rays in the neutron beam stream into the ES#2 experimental hall, which is determined by measurements on an empty target in the presence of the neutron beam. $B_{\text{sample}}(t)$ is related to the scattering of neutrons as well as γ in the beam by the sample. So, the total background B_{total} can be expressed in Eq. (13) [44]:

$$B_{\text{total}} = B_{\text{act}} + B_{\text{sample}}(t) + B_{\text{empty}}(t), \quad (13)$$

the background $B_{\text{sample}}(t)$ associated with the target can be expressed as [44]

$$B_{\text{sample}}(t_n) = B_{\text{sn}}(t) + B_{\text{sy}}(t). \quad (14)$$

$B_{\text{sn}}(t)$ denotes the scattered neutron background. It arises when neutrons scattered by the target interact with surrounding materials through neutron capture reactions, releasing deexcited γ rays. $B_{\text{sy}}(t)$ denotes the in-beam γ -ray background. It originates from deexcited γ rays in the CSNS spallation target, which are mixed into the neutron beam and detected after scattering.

$B_{\text{sn}}(t)$ was evaluated using a $^{\text{nat}}\text{C}$ target. In the experiment, a $^{\text{nat}}\text{C}$ target with a thickness of 1 mm and a diameter of 40 mm was placed in the beamline for irradiation. $N_{\text{residual}}^{\text{C}}$ represents the residual spectrum of the $^{\text{nat}}\text{C}$ sample (subtracting the environment background in the beam-on state), and the elastic-scattering yield ratio $Q_{(\text{Ag}, \text{C})}$ [43] was also calculated according to the energy bin. The scattered neutron background to be subtracted equals the product of $Q_{(\text{Ag}, \text{C})}$ and $N_{\text{residual}}^{\text{C}}$, as shown in Eq. (15),

$$B_{\text{sn}}(t) = N_{\text{residual}}^{\text{C}} Q_{(\text{Ag}, \text{C})}. \quad (15)$$

$B_{\text{sy}}(t)$ was evaluated using a $^{\text{nat}}\text{Pb}$ target. Before obtaining the in-beam γ -ray background, the scattered neutron background of $^{\text{nat}}\text{Pb}$ itself must first be subtracted. The final

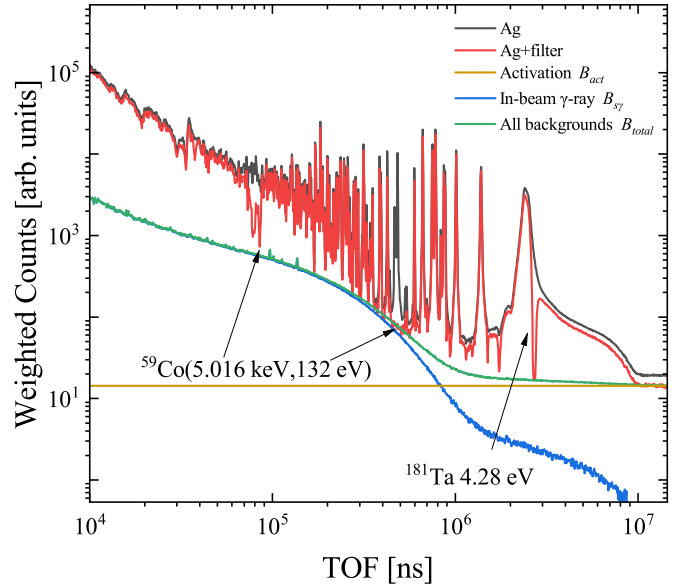


FIG. 6. Residual spectrum with and without filter (red and black line). The in-beam γ -ray background $B_{\text{sy}}(t)$ (blue line); the activation background B_{act} (yellow straight line).

in-beam γ -ray background can then be expressed as

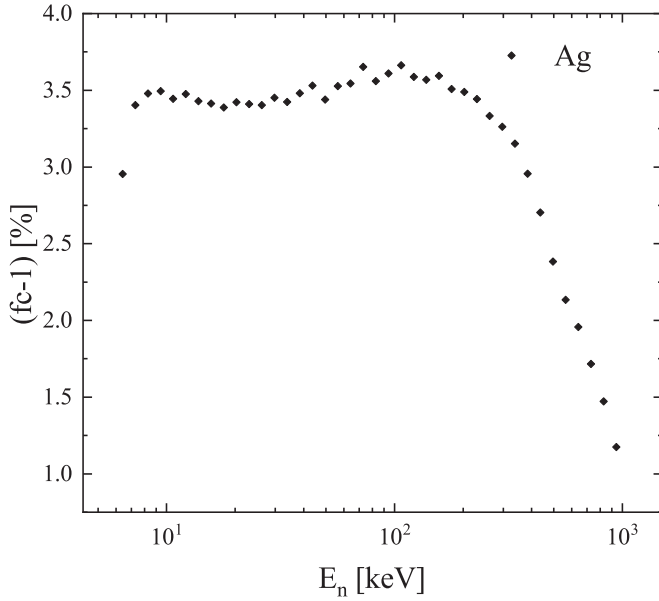
$$B_{\text{sy}}(t) = (N_{\text{residual}}^{\text{Pb}} - Q_{(\text{Pb}, \text{C})} N_{\text{residual}}^{\text{C}}) K, \quad (16)$$

where $Q_{(\text{Pb}, \text{C})}$ denotes the elastic-scattering yield ratio of Pb and C, and K denotes the normalization factor of the true in-beam γ -ray background.

K is obtained using black resonance filtering technique [45,46]. A set of filter (^{59}Co , ^{181}Ta) was placed upstream of the beam. ^{59}Co strongly absorbs neutrons with resonance energies of 5.016 keV and 132 eV, while ^{181}Ta strongly absorbs neutrons with a resonance energy of 4.28 eV. The TOF spectrum count corresponding to these energy positions becomes a deep valley, and the energy level of the valley is the true background energy level of the in-beam γ -ray background. Therefore, the normalization coefficient K of the in-beam γ -ray background can be obtained. Additionally, the activation background of the sample itself was evaluated using the TOF spectrum. A 1-mm-thick Cd plate was placed in front of the first collimator of Back-n for absorbing neutrons with energies below 0.3 eV. 0.3 eV corresponds to a flight time of 10.07 ms, so we consider the counts measured after 10.07 ms as the activation background deduction. The corresponding activation background is deducted in the acquisition of the residual spectrum of each target individually. The background composition of this experiment is shown in Fig. 6. In this figure, the target-independent background $B_{\text{empty}}(t)$ is subtracted from all spectra.

D. Multiple scattering correction

In Eq. (7), f_c represents the multiple scattering correction factor. When neutrons traverse the target material, multiple scattering occurs, causing the actual trajectory to exceed the geometric thickness of the sample and requiring a correction. The f_c factor is obtained through geant4 [47] simulations based on a geometric model of the target, where experimental

FIG. 7. The f_c target thickness correction factor.

conditions such as sample thickness and impurities are fully accounted for. In the simulation, the mean path lengths of neutrons with different energies inside the target are calculated, and the ratio of the mean path length to the target thickness defines the f_c factor [48]. Figure 7 shows the variation of f_c with neutron energy.

E. Discussion of uncertainties

Uncertainty arises mainly from experimental conditions and data processing. The neutron spectrum and its associated uncertainty used in this work are taken from the measurement by Chen *et al.* at Back-n ES#2 with ^{235}U samples [49]. Their study reported uncertainties of 2.30%–4.5% above 0.15 MeV and about 8% below 0.15 MeV. The main contributions arise from the $^{235}\text{U}(n, f)$ cross-section uncertainty (0.6%–3.5%), uncertainties in detection efficiency and sample mass ($\approx 2\%$), and the proton beam intensity ($\approx 1\%$). For neutrons below 0.15 MeV, since the ^{235}U cross section is not a standard and the sample consistency is poorer, an additional 5%–6% uncertainty is introduced, leading to a total of about 8%. The proton beam power was recorded in real time during the beam supply process, with an error of no more than 1.5%. The data processing uncertainties mainly come from the PHWT [27], double-bunch unfolding [50] and normalization. The uncertainty in the PHWT was in the range of 1.1% [27], the uncertainty in the double-bunch unfolding was less than 2%, and the uncertainty introduced by the normalization process is approximately 1.5%. The statistical uncertainty of the samples in the data analysis is less than 5.2%. The final total uncertainty obtained by error propagation is not greater than 10.0%. The uncertainty budget is recorded in Table II.

IV. RESULT AND DISCUSSION

A. Resolved resonance region

For the resolvable resonance region, we used the *R*-matrix program code [51] sammy for resonance fitting of $^{\text{nat}}\text{Ag}$.

TABLE II. The statistic uncertainty and systematic uncertainty of this experiment.

σ	Uncertainty source	Value
Experiment conditions		
$\sigma_{\text{neutron spectrum}}$	Below 0.15 MeV	8.0%
$\sigma_{\text{neutron spectrum}}$	Above 0.15 MeV	4.5%
σ_{sample}	Sample parameters	0.1%
$\sigma_{\text{beam power}}$	Proton beam power	1.5%
Data analysis		
σ_{PHWT}	Uncertainty from PHWT	1.1%
$\sigma_{\text{unfolding}}$	Uncertainty from unfolding	2.0%
$\sigma_{\text{Normalization}}$	Uncertainty from normalization	1.5%
Statistical error		
$\sigma_{\text{Statistic}}$	Statistic uncertainty	5.2%
Error propagation		
σ_{total}	Total uncertainty	10.0%

Resonance parameters such as neutron resonance energies, γ width (Γ_γ), and neutron width (Γ_n) were extracted in the range of 0–1500 eV, and the initial parameters input to the fits were taken from the ENDF/B-VIII.1 evaluation database. The program code takes into account all experimental effects such as multiple scattering effects, self-shielding effects, Doppler broadening, and resolution broadening. The final fit results are shown in Fig. 8, which are good overall, and at 134 eV, we found that the experimental value of the yield is relatively high. After analyzing the results, we believe that it is due to the structure of the neutron energy spectrum. The capture resonance factor k is defined as [52]

$$k = g \frac{\Gamma_n \Gamma_\gamma}{\Gamma_n + \Gamma_\gamma}, \quad (17)$$

where g is given by the following equation:

$$g = \frac{2J + 1}{(2s + 1)(2I + 1)}, \quad (18)$$

where the value of s is 1/2, the spin of the neutron; I is the ground state spin of the compound nucleus; $J = |L + S|$, $S = s + I$, and L is the orbital angular momentum. The experimental k values obtained from the fitting were compared with the k values calculated from the ENDF/B-VIII.1 evaluation database, as shown in Fig. 9. It can be seen that overall the two match well, and some deviations may be due to experimental conditions. The specific data are shown in Table III.

The neutron capture cross section for $^{\text{nat}}\text{Ag}$ was calculated by Eq. (15) on the basis of obtaining the neutron capture yield, and the total neutron cross-section data used for the calculation were obtained from the ENDF/B-VIII.1 evaluation database. For the normalization method, we selected the resonance peaks with strong resonances in the low-energy region and where differences among the evaluation libraries are negligible, and for Ag, we chose the first resonance peak for normalization. The neutron capture cross-section libraries in general shows overall good agreement with the evaluated libraries. Based on the ENDF/B-VIII.1, JENDL 5, JEFF 3.3, and TENDL 2023 evaluation libraries, we conducted a region-by-region analysis of the resonance region based on

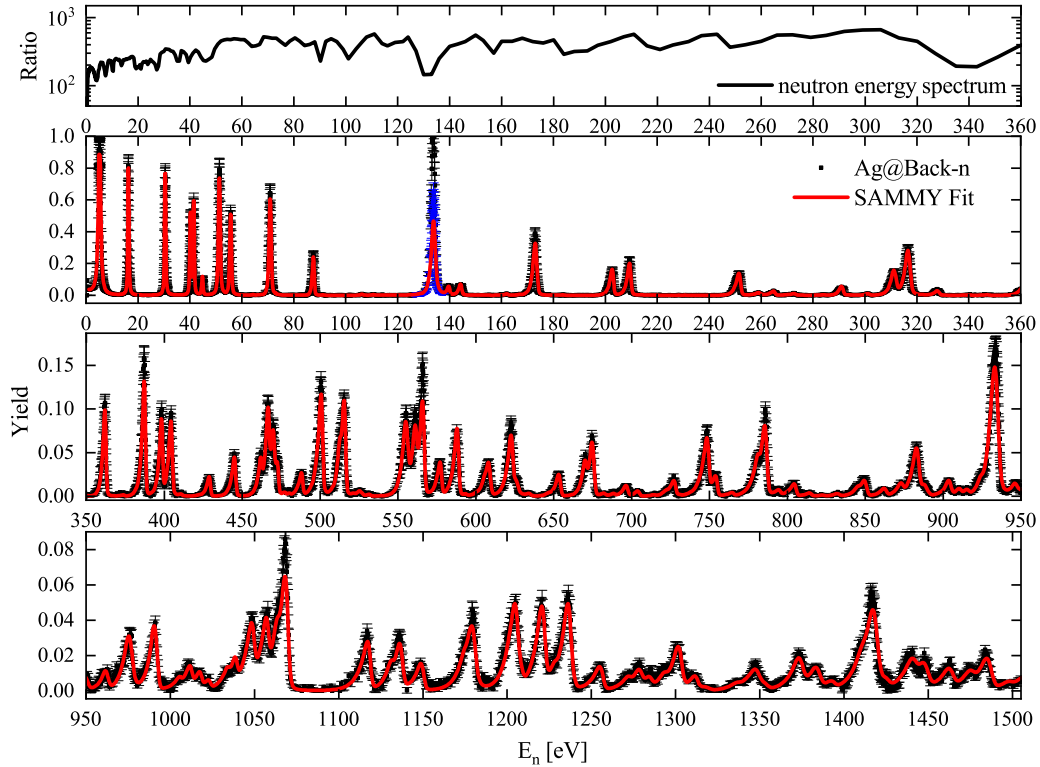


FIG. 8. Experimental capture yields fitted by *R*-matrix code. The blue points represent the experimental data after modifying the spectral structure at 134 eV.

our experimental results as follows. The analysis results for each region correspond to Figs. 10(a)–10(f) and the following six sections (a)–(f).

(a) At 134 eV, the measured capture yield and cross section are higher than those in the evaluated libraries. The fit consistently underestimates the experimental values, which appears inconsistent with the expected low-energy behavior. Further analysis indicates that the incident neutron spectrum exhibits a clear valley near this energy, leading to an overestimation of the yield and cross section (see Fig. 8). To verify this, the yield was recalculated using a smoothed spectrum (blue points in Fig. 8), confirming that the overestimation arises from the spectral structure. Nevertheless, to maintain consistency with the experimental conditions, the final reported yields are still based on the original spectrum. In the 0–300 eV energy range, there are almost no differences among the evaluated libraries, except that JEFF-3.3 lacks resonances at 275.7 and 284.4 eV.

(b) At 387.4 eV, our experimental results do not support JENDL-5 [53]. At 401.7 eV, JENDL-5 gives a resonance, and at 404.2 eV, it does not; our experimental results and the 1968 data of Moxon *et al.* [18] do not support JENDL-5. At 476.5 eV, only TENDL-2023 predicts a resonance, which is confirmed by our measurements. At 487.9 eV, our experimental data support TENDL-2023, while the resonance positions given by the other evaluation libraries show deviations. A double peak structure appears at 512.4 and 515.5 eV, consistent with ENDF/B-VIII.1 and TENDL-2023, whereas JEFF-3.3 shows a single peak and JENDL-5 exhibits shifted peak positions. At 521.5 eV, TENDL-2023 does not predict a resonance, which is also not observed in our experiment. Fi-

nally, at 555.1 eV, our results further support TENDL-2023. In the 300–560 eV energy range, the experimental data generally support ENDF/B-VIII.1 and TENDL-2023.

(c) In the energy range from 577–794.1 eV, our experimental results show the following: Near 577, 587.9, 626.2, 653.2, 674.7, 696.4, and 704 eV, the data support ENDF/B-VIII.1 and TENDL-2023, while the resonance positions in JENDL-5 and JEFF-3.3 [54] deviate. At 630.5 eV, TENDL-2023 predicts a resonance that is not observed experimentally. At 734.1 eV, only ENDF/B-VIII.1 gives a weak resonance, which is supported by our data and may in fact be stronger. At 737.1 eV, all four evaluation libraries predict a resonance, with TENDL-2023 showing a higher peak; however, our experimental data indicate a deep valley, not supporting any library. Experimental data reported by Moxon *et al.* around 737.1 eV support our conclusion. At 763.7 eV, only TENDL-2023 predicts a resonance, which is supported by our data and Moxon *et al.* Finally, at 794.1 eV, resonances are given by TENDL-2023 and ENDF/B-VIII.1, while JENDL-5 and JEFF-3.3 do not show resonances; our results confirm the presence of these peaks. In the 560–800 eV energy range, the experimental results largely confirm ENDF/B-VIII.1 and TENDL-2023, while JENDL-5 and JEFF-3.3 show discrepancies, and the resonance at 737.1 eV is not supported by any library.

(d) At 814.5 eV, the experimental data support TENDL-2023, while the peak positions of the other three evaluation libraries show deviations. At 822.3 eV, neither JEFF-3.3 nor JENDL-5 predicts a resonance, but our data show a pronounced peak, supporting TENDL-2023 and ENDF/B-VIII.1, with ENDF/B-VIII.1 underestimating the peak height. At

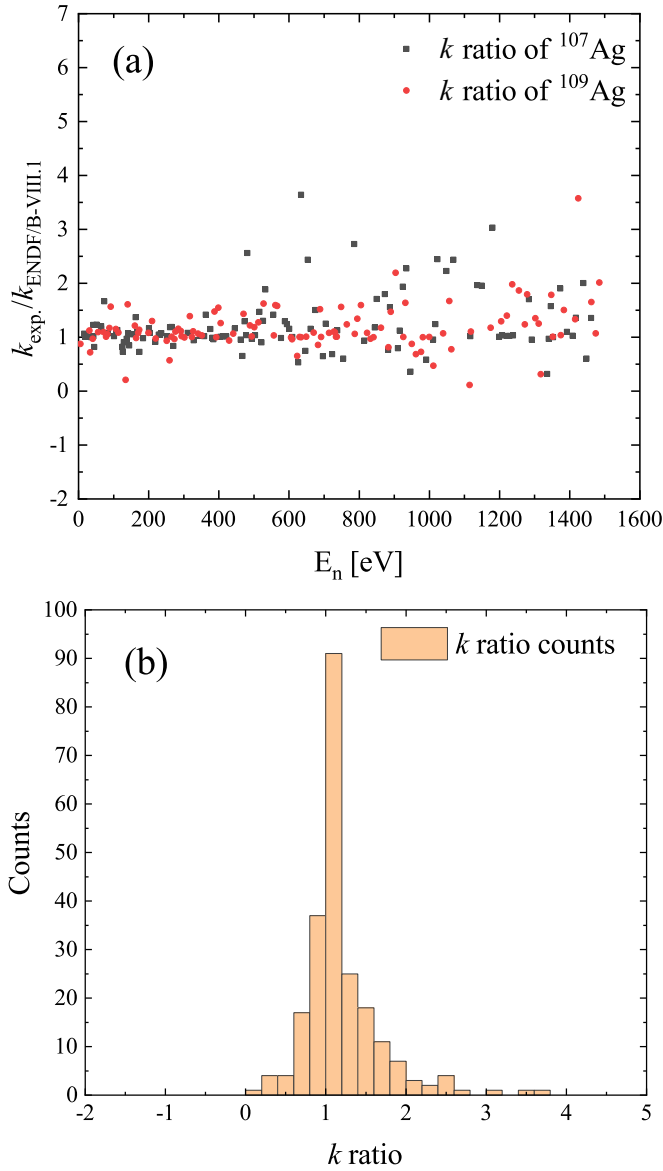


FIG. 9. (a) The capture kernel k ratio $k_{\text{exp}}/k_{\text{ENDF/B-VIII.1}}$ in the 1–1500 eV range and (b) its distribution.

872.6 eV, both our data and those of Moxon *et al.* indicate a resonance, not supported by ENDF/B-VIII.1. Around 931.6 and 934.1 eV, a double peak structure is observed, whereas JEFF-3.3 shows only a single peak. At 946.1 and 990.8 eV,

our data show clear resonances, which are not supported by ENDF/B-VIII.1. In the 800–1000 eV energy range, our experimental results generally support TENDL-2023.

(e) At 1005.7 eV, a resonance peak is observed that differs from all evaluated libraries. Comparison with the raw spectrum suggests that this may be a newly discovered resonance. At 1028.0 eV, all evaluated libraries predict a resonance structure, our experimental data show a deep trough, not supporting any library. However, at 1022.7 and 1033.9 eV, resonances are observed experimentally, suggesting that the evaluated libraries may have inaccuracies or that these may be resonances. At 1068.5 eV, the experimental results indicate that the resonance strength predicted by the ENDF/B-VIII.1 evaluation library is underestimated. At 1077.9 eV, ENDF/B-VIII.1 does not predict a resonance, while the other libraries do, but our data lie in a trough with relatively large statistical fluctuations, preventing accurate conclusions. At 1174.3 eV, a resonance is observed experimentally, which is not supported by JEFF-3.3. In the 1000–1280 eV energy range, our experimental results reveal shifted resonances and indicate that ENDF/B-VIII.1 and JEFF-3.3 show deviations at several points.

(f) At 1317.6 and 1335.5 eV, two clear resonance structures are observed and well fitted, which differ noticeably from the evaluation libraries. ENDF/B-VIII.1 does not predict resonances at these positions, JEFF-3.3 predicts only one resonance, while JENDL-5 and TENDL-2023 predict resonances at 1320.0 and 1330.0 eV. At 1392.0 and 1408.4 eV, the observed resonances are not supported by ENDF/B-VIII.1. At 1430.3 eV, the experimental data show a deep trough, consistent with ENDF/B-VIII.1. In the 1280–1500 eV energy range, the experimental data indicate that ENDF/B-VIII.1 suggests that additional resonance structures may need to be included.

B. Unresolved resonance region

Parameters obtained from the sammy fits, including the mean γ width and mean neutron width for each isotope, were used as input to talys [55] for ^{107}Ag and ^{109}Ag . These calculations provide the talys results for the URR cross sections of the two isotopes. The talys results for ^{107}Ag and ^{109}Ag were then weighted according to their natural abundances to obtain the talys results for $^{\text{nat}}\text{Ag}$. In addition, the talys calculations served as constraints to extract the individual ^{107}Ag and ^{109}Ag cross sections from the $^{\text{nat}}\text{Ag}$ experimental data. The

TABLE III. Resonance energies E_R (eV) and kernels k up to 1.5 keV determined with R -matrix code.

E_R (eV)	k (meV)	E_R (eV)	k (meV)
(a) Kernels k of ^{107}Ag			
16.323 ± 0.004	2.845 ± 0.188	577.298 ± 0.056	16.552 ± 0.680
18.909 ± 0.114	$1.11 (22) \times 10^{-4}$	588.240 ± 0.057	39.767 ± 4.286
20.310 ± 0.116	$1.22 (24) \times 10^{-4}$	593.798 ± 0.322	0.804 ± 0.112
35.843 ± 0.135	$3.40 (68) \times 10^{-4}$	600.493 ± 0.476	0.525 ± 0.085
41.498 ± 0.007	4.770 ± 0.161	609.592 ± 0.172	3.163 ± 0.613
42.827 ± 0.134	0.005 ± 0.001	626.400 ± 0.080	6.735 ± 0.493
44.869 ± 0.008	0.733 ± 0.017	634.332 ± 0.039	0.764 ± 0.144
51.453 ± 0.009	18.925 ± 1.771	646.334 ± 0.264	0.837 ± 0.131

TABLE III. (*Continued.*)

E_R (eV)	k (meV)	E_R (eV)	k (meV)
64.285±0.071	0.022 ± 0.003	653.353 ± 0.053	12.805 ± 0.444
64.735±0.096	0.015 ± 0.002	661.164 ± 0.563	0.173 ± 0.032
73.199±0.069	0.045 ± 0.005	674.860 ± 0.058	36.719 ± 3.399
83.583±0.109	0.016 ± 0.003	696.524 ± 0.077	6.889 ± 0.278
101.223±0.183	0.004 ± 0.001	704.108 ± 0.111	3.567 ± 0.281
107.686±0.154	0.016 ± 0.003	722.891 ± 0.369	1.205 ± 0.195
110.833±0.045	0.091 ± 0.007	737.525 ± 0.769	0.512 ± 0.093
125.176±0.195	0.008 ± 0.002	754.217 ± 0.086	17.480 ± 1.087
126.030±0.189	0.013 ± 0.003	785.800 ± 0.347	18.426 ± 2.118
128.686±0.124	0.082 ± 0.014	814.648 ± 0.166	2.916 ± 0.512
136.716±0.208	0.027 ± 0.006	844.91 ± 0.215	3.513 ± 0.531
141.488±0.212	0.011 ± 0.002	849.603 ± 0.322	10.020 ± 0.976
144.400±0.020	3.182 ± 0.075	872.711 ± 0.109	13.067 ± 2.230
154.907±0.208	0.026 ± 0.005	882.67 ± 0.205	29.411 ± 5.328
162.221±0.045	0.383 ± 0.021	887.806 ± 0.178	10.173 ± 1.094
167.177±0.077	0.207 ± 0.019	910.242 ± 0.149	5.607 ± 0.330
173.817±0.068	3.820 ± 0.776	915.474 ± 0.154	4.551 ± 0.422
183.743±0.164	0.127 ± 0.020	923.900 ± 0.00	8.647 ± 0.888
200.894±0.227	0.314 ± 0.053	934.137 ± 0.085	144.208 ± 14.876
202.813±0.029	13.014 ± 0.508	946.005 ± 0.000	11.229 ± 0.901
218.934±0.292	0.078 ± 0.015	990.784 ± 0.088	14.974 ± 1.032
228.339±0.351	0.042 ± 0.008	1010.170 ± 0.791	0.478 ± 0.097
231.056±0.335	0.054 ± 0.010	1017.25 ± 0.15	10.524 ± 0.866
235.532±0.387	0.031 ± 0.006	1022.650 ± 0.224	6.031 ± 0.599
251.804±0.051	14.158 ± 1.187	1048.540 ± 0.115	49.489 ± 4.903
260.513±0.254	0.296 ± 0.046	1068.490 ± 0.102	95.519 ± 9.516
264.965±0.054	2.910 ± 0.095	1116.610 ± 0.324	9.804 ± 1.887
270.065±0.251	0.167 ± 0.027	1130.420 ± 0.373	9.397 ± 1.893
311.541±0.028	48.626 ± 1.441	1136.410 ± 0.119	41.500 ± 4.472
328.251±0.018	0.564 ± 0.114	1149.060 ± 0.117	22.468 ± 2.133
347.255±0.065	0.409 ± 0.080	1179.580 ± 0.117	80.907 ± 3.479
358.280±0.044	0.265 ± 0.052	1199.080 ± 0.372	3.843 ± 0.759
362.138±0.028	19.983 ± 0.645	1207.690 ± 0.301	13.957 ± 2.522
375.746±0.094	0.217 ± 0.041	1219.950 ± 0.936	2.676 ± 0.528
381.853±0.386	0.286 ± 0.051	1227.780 ± 0.387	8.404 ± 1.238
384.752±0.625	0.096 ± 0.020	1238.330 ± 0.245	3.897 ± 0.764
403.913±0.654	0.302 ± 0.060	1284.000 ± 0.000	10.596 ± 0.982
410.837±0.047	0.364 ± 0.072	1290.950 ± 0.193	6.290 ± 1.235
421.143±0.037	0.181 ± 0.036	1335.530 ± 0.058	8.001 ± 1.591
445.376±0.035	14.338 ± 1.511	1339.870 ± 0.365	3.096 ± 0.617
462.139±0.051	10.012 ± 0.776	1346.000 ± 0.000	6.473 ± 1.310
466.902±0.049	26.897 ± 3.887	1352.62 ± 0.340	2.608 ± 0.519
472.826±0.046	12.585 ± 1.145	1373.000 ± 0.000	30.739 ± 4.713
477.484±0.049	0.497 ± 0.097	1392.000 ± 0.000	10.428 ± 1.091
481.294±0.257	1.163 ± 0.124	1408.400 ± 0.684	25.648 ± 3.926
493.619±0.059	0.466 ± 0.094	1417.390 ± 0.865	69.717 ± 10.417
502.806±0.676	0.279 ± 0.054	1438.65 ± 0.270	31.792 ± 3.656
515.727±0.048	44.363 ± 4.353	1447.780 ± 0.200	51.388 ± 2.981
521.496±0.257	0.615 ± 0.105	1461.200 ± 1.207	6.482 ± 1.046
525.421±0.205	1.311 ± 0.153	1497.000 ± 0.000	7.941 ± 0.850
532.034±0.262	0.705 ± 0.076		
555.206±0.092	38.885 ± 2.568		
(b) Kernels k of ^{109}Ag			
5.195±0.009	7.625 ± 0.763	691.010 ± 0.614	0.010 ± 0.002
30.510±0.005	5.839 ± 0.295	714.030 ± 0.183	0.863 ± 0.159
32.618±0.038	0.009 ± 0.001	727.529 ± 0.098	12.629 ± 1.474
40.265±0.007	3.738 ± 0.113	730.768 ± 0.678	0.870 ± 0.158

TABLE III. (Continued.)

E_R (eV)	k (meV)	E_R (eV)	k (meV)
55.775 $\pm$ 0.009	8.050 $\pm$ 0.681	733.842 $\pm$ 0.878	0.015 $\pm$ 0.003
71.073 $\pm$ 0.011	17.896 $\pm$ 1.487	735.959 $\pm$ 0.881	0.015 $\pm$ 0.003
78.489 $\pm$ 0.183	0.005 $\pm$ 0.001	748.716 $\pm$ 0.086	56.858 $\pm$ 6.081
79.903 $\pm$ 0.182	0.005 $\pm$ 0.001	764.711 $\pm$ 0.089	1.100 $\pm$ 0.187
82.362 $\pm$ 0.105	0.017 $\pm$ 0.003	781.082 $\pm$ 0.182	55.530 $\pm$ 7.981
87.637 $\pm$ 0.011	5.352 $\pm$ 0.137	787.477 $\pm$ 0.819	28.801 $\pm$ 4.981
91.270 $\pm$ 0.106	0.039 $\pm$ 0.005	794.874 $\pm$ 0.164	4.547 $\pm$ 0.563
106.393 $\pm$ 0.034	0.160 $\pm$ 0.010	804.695 $\pm$ 0.121	13.11 $\pm$ 0.758
113.770 $\pm$ 0.179	0.018 $\pm$ 0.003	822.371 $\pm$ 0.606	0.892 $\pm$ 0.159
133.977 $\pm$ 0.022	7.593 $\pm$ 1.702	832.044 $\pm$ 0.058	2.870 $\pm$ 0.575
139.815 $\pm$ 0.021	2.313 $\pm$ 0.075	840.681 $\pm$ 0.692	0.020 $\pm$ 0.004
160.178 $\pm$ 0.194	0.049 $\pm$ 0.008	849.226 $\pm$ 0.200	6.487 $\pm$ 1.009
164.334 $\pm$ 0.235	0.014 $\pm$ 0.003	862.153 $\pm$ 0.130	7.883 $\pm$ 0.410
169.695 $\pm$ 0.170	0.194 $\pm$ 0.031	883.437 $\pm$ 0.264	27.389 $\pm$ 5.149
173.172 $\pm$ 0.029	29.092 $\pm$ 3.134	889.999 $\pm$ 0.291	4.104 $\pm$ 0.613
199.015 $\pm$ 0.262	0.119 $\pm$ 0.021	903.686 $\pm$ 0.105	16.287 $\pm$ 1.265
209.519 $\pm$ 0.030	19.831 $\pm$ 1.635	925.679 $\pm$ 0.900	0.025 $\pm$ 0.005
219.619 $\pm$ 0.345	0.058 $\pm$ 0.011	931.600 $\pm$ 0.000	35.178 $\pm$ 5.580
251.281 $\pm$ 0.133	3.917 $\pm$ 0.765	949.783 $\pm$ 0.218	6.417 $\pm$ 0.807
259.226 $\pm$ 0.060	1.730 $\pm$ 0.098	961.726 $\pm$ 0.160	10.777 $\pm$ 0.692
264.783 $\pm$ 0.435	0.182 $\pm$ 0.036	975.873 $\pm$ 0.095	63.083 $\pm$ 2.230
272.882 $\pm$ 0.061	1.430 $\pm$ 0.069	981.320 $\pm$ 0.796	0.030 $\pm$ 0.006
275.742 $\pm$ 0.434	0.060 $\pm$ 0.011	999.466 $\pm$ 0.810	0.030 $\pm$ 0.006
284.359 $\pm$ 0.134	0.324 $\pm$ 0.036	1005.490 $\pm$ 0.244	4.943 $\pm$ 0.607
291.228 $\pm$ 0.025	7.479 $\pm$ 0.236	1011.350 $\pm$ 0.126	20.760 $\pm$ 3.269
293.872 $\pm$ 0.078	0.305 $\pm$ 0.055	1033.890 $\pm$ 0.148	6.384 $\pm$ 1.109
301.330 $\pm$ 0.031	1.431 $\pm$ 0.220	1038.760 $\pm$ 0.118	14.926 $\pm$ 2.014
316.967 $\pm$ 0.025	82.257 $\pm$ 6.256	1057.000 $\pm$ 0.115	45.054 $\pm$ 4.293
322.993 $\pm$ 0.323	0.111 $\pm$ 0.022	1062.300 $\pm$ 0.249	25.030 $\pm$ 4.620
326.882 $\pm$ 0.078	0.716 $\pm$ 0.135	1114.82 $\pm$ 0.881	0.678 $\pm$ 0.136
340.348 $\pm$ 0.435	0.352 $\pm$ 0.064	1117.960 $\pm$ 0.262	31.796 $\pm$ 4.613
351.348 $\pm$ 0.574	0.057 $\pm$ 0.011	1174.300 $\pm$ 0.455	7.679 $\pm$ 1.170
387.450 $\pm$ 0.028	37.102 $\pm$ 5.426	1204.900 $\pm$ 0.128	78.139 $\pm$ 9.647
392.331 $\pm$ 0.117	0.160 $\pm$ 0.032	1220.930 $\pm$ 0.111	88.489 $\pm$ 9.384
398.481 $\pm$ 0.028	22.076 $\pm$ 1.649	1236.390 $\pm$ 0.105	96.028 $\pm$ 9.445
404.671 $\pm$ 0.036	26.665 $\pm$ 2.972	1255.140 $\pm$ 0.132	26.655 $\pm$ 1.748
429.184 $\pm$ 0.043	7.030 $\pm$ 0.570	1270.930 $\pm$ 0.221	6.097 $\pm$ 0.954
440.887 $\pm$ 0.698	0.101 $\pm$ 0.019	1277.900 $\pm$ 0.226	17.966 $\pm$ 2.046
470.163 $\pm$ 0.059	25.000 $\pm$ 3.085	1301.720 $\pm$ 0.122	53.364 $\pm$ 6.155
488.396 $\pm$ 0.04	10.463 $\pm$ 1.052	1311.540 $\pm$ 0.118	14.009 $\pm$ 2.069
493.709 $\pm$ 0.405	0.455 $\pm$ 0.090	1317.560 $\pm$ 0.055	4.787 $\pm$ 0.953
501.126 $\pm$ 0.042	60.550 $\pm$ 6.257	1347.330 $\pm$ 0.097	27.500 $\pm$ 5.547
512.668 $\pm$ 0.113	11.120 $\pm$ 1.268	1351.950 $\pm$ 0.472	7.120 $\pm$ 1.380
526.971 $\pm$ 0.226	1.133 $\pm$ 0.160	1374.820 $\pm$ 0.433	5.815 $\pm$ 1.138
556.387 $\pm$ 0.220	9.474 $\pm$ 1.801	1383.200 $\pm$ 0.172	30.855 $\pm$ 3.686
561.250 $\pm$ 0.080	35.121 $\pm$ 3.112	1415.400 $\pm$ 0.958	70.082 $\pm$ 10.801
566.082 $\pm$ 0.056	66.586 $\pm$ 10.835	1424.000 $\pm$ 0.000	15.350 $\pm$ 2.024
605.608 $\pm$ 0.314	3.096 $\pm$ 0.431	1461.900 $\pm$ 0.418	25.550 $\pm$ 3.198
608.290 $\pm$ 0.082	17.473 $\pm$ 1.286	1473.910 $\pm$ 0.197	17.283 $\pm$ 2.783
622.852 $\pm$ 0.071	11.592 $\pm$ 0.755	1484.180 $\pm$ 0.120	52.410 $\pm$ 5.313
629.690 $\pm$ 0.570	0.010 $\pm$ 0.002	1505.000 $\pm$ 0.000	10.859 $\pm$ 1.512
633.894 $\pm$ 0.573	0.010 $\pm$ 0.002		
648.915 $\pm$ 0.517	0.504 $\pm$ 0.095		
670.126 $\pm$ 0.098	16.918 $\pm$ 1.174		
682.389 $\pm$ 0.268	1.771 $\pm$ 0.256		
688.689 $\pm$ 0.347	1.555 $\pm$ 0.189		

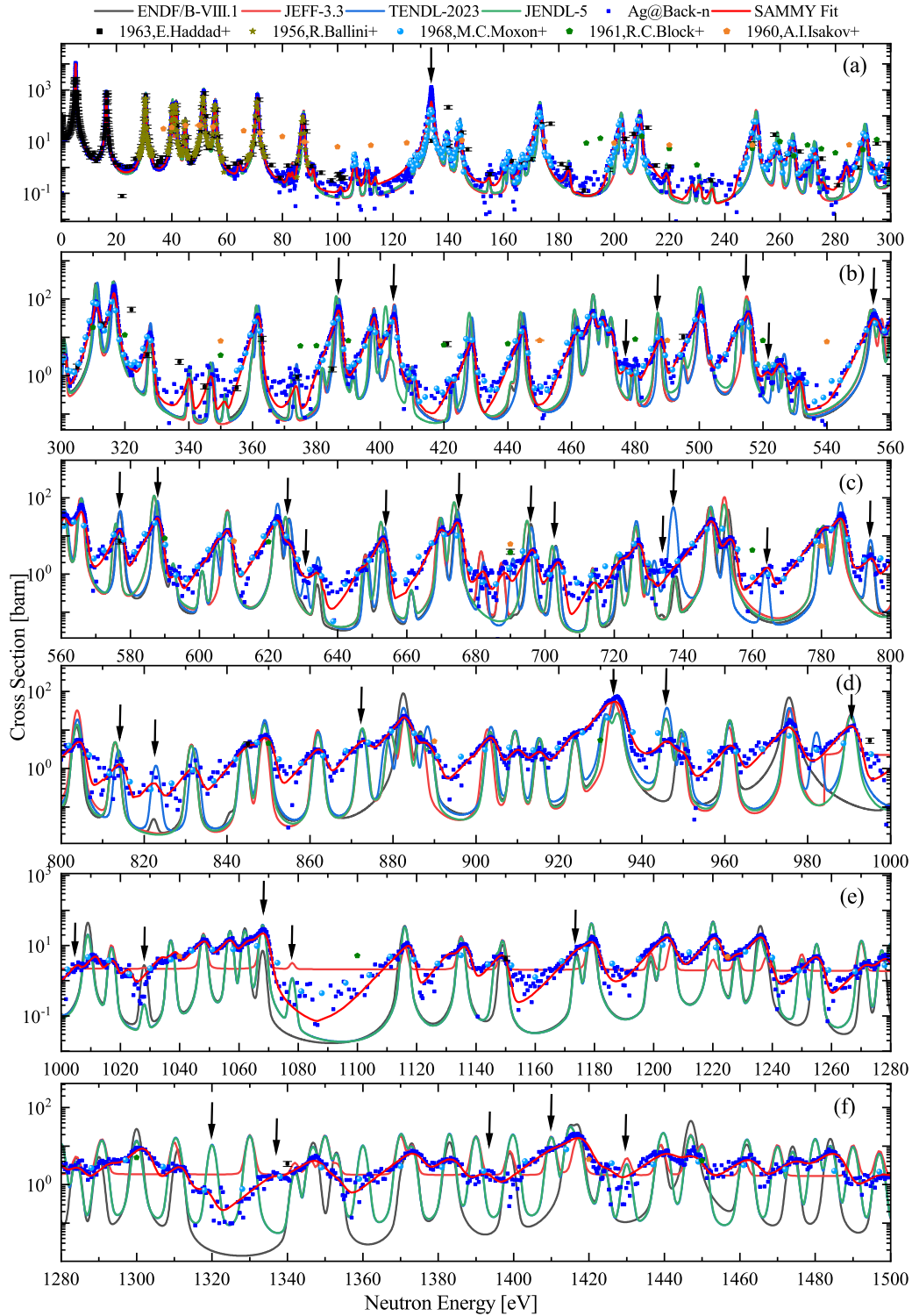


FIG. 10. The neutron capture cross section for $^{\text{nat}}\text{Ag}$ in the range of 1–1500 eV. The blue dots represent our experimental results, while the red curve shows the cross-sections calculated based on the yield fitted by SAMMY.

cross-section data in the URR for $^{\text{nat}}\text{Ag}$, ^{107}Ag , and ^{109}Ag are listed in Table IV. The talys calculations are based on the Hauser-Feshbach statistical emission model [56]. In addition, the global neutron optical model potential of Ref. [57] was used in the calculations and other parameters were chosen using the method reported by Chen *et al.* [58], photon strength function is given by Kopecky and Uhl [59], and level density

a and nuclear temperature T are given by Gilbert Cameron model with adjusted parameters [60]. The calculations are compared with evaluated libraries and previous experimental results in Fig. 11.

For ^{107}Ag , our measurements are slightly higher than JEFF-3.3, TENDL-2023, and part of ENDF/B-VIII.1 and JENDL-5 in the energy region 10–100 keV. In the energy

TABLE IV. The averaged capture cross sections of $^{\text{nat}}\text{Ag}$, ^{107}Ag , and ^{109}Ag in URR.

E_{low} (keV)	E_{up} (keV)	$^{\text{nat}}\text{Ag}$ (mb)	^{107}Ag (mb)	^{109}Ag (mb)	E_{low} (keV)	E_{up} (keV)	$^{\text{nat}}\text{Ag}$ (mb)	^{107}Ag (mb)	^{109}Ag (mb)
10.0	10.5	1803.9 $\pm$ 176.3	1793.6 $\pm$ 175.3	1815.3 $\pm$ 177.5	95.9	104.5	546.6 $\pm$ 50.7	539.7 $\pm$ 50.0	554.2 $\pm$ 51.4
10.5	11.4	1756.8 $\pm$ 164.8	1747.0 $\pm$ 163.9	1767.7 $\pm$ 165.8	104.5	113.8	498.4 $\pm$ 46.1	491.8 $\pm$ 45.5	505.5 $\pm$ 46.7
11.4	12.4	1462.2 $\pm$ 137.4	1454.4 $\pm$ 136.7	1471.0 $\pm$ 138.2	113.8	123.9	462.9 $\pm$ 42.8	456.4 $\pm$ 42.2	469.9 $\pm$ 43.4
12.4	13.5	1538.8 $\pm$ 144.7	1530.9 $\pm$ 143.9	1547.7 $\pm$ 145.5	123.9	134.9	455.6 $\pm$ 42.0	448.9 $\pm$ 41.4	463.0 $\pm$ 42.7
13.5	14.7	1505.6 $\pm$ 141.1	1498.2 $\pm$ 140.5	1513.9 $\pm$ 141.9	134.9	146.9	379.2 $\pm$ 35.0	373.3 $\pm$ 34.5	385.8 $\pm$ 35.6
14.7	16.0	1241.1 $\pm$ 116.6	1235.4 $\pm$ 116.1	1247.6 $\pm$ 117.2	146.9	160.0	417.2 $\pm$ 38.6	410.2 $\pm$ 38.0	424.9 $\pm$ 39.4
16.0	17.4	1292.0 $\pm$ 122.5	1286.3 $\pm$ 122.0	1298.3 $\pm$ 123.1	160.0	174.2	402.7 $\pm$ 26.0	395.5 $\pm$ 25.5	410.6 $\pm$ 26.5
17.4	19.0	1399.9 $\pm$ 131.1	1394.3 $\pm$ 130.6	1406.3 $\pm$ 131.7	174.2	189.8	371.0 $\pm$ 23.8	364.0 $\pm$ 23.4	378.8 $\pm$ 24.3
19.0	20.7	1379.2 $\pm$ 129.2	1374.1 $\pm$ 128.7	1385.0 $\pm$ 129.7	189.8	206.6	340.3 $\pm$ 21.9	333.4 $\pm$ 21.4	347.9 $\pm$ 22.4
20.7	22.5	1300.2 $\pm$ 121.2	1295.6 $\pm$ 120.7	1305.4 $\pm$ 121.7	206.6	225.0	344.4 $\pm$ 22.1	336.9 $\pm$ 21.7	352.5 $\pm$ 22.7
22.5	24.5	1187.7 $\pm$ 110.6	1183.2 $\pm$ 110.1	1192.7 $\pm$ 111.0	225.0	245.1	336.1 $\pm$ 21.6	328.5 $\pm$ 21.1	344.5 $\pm$ 22.1
24.5	26.7	1122.7 $\pm$ 103.8	1118.2 $\pm$ 103.4	1127.8 $\pm$ 104.3	245.1	266.9	325.5 $\pm$ 20.8	317.7 $\pm$ 20.3	334.0 $\pm$ 21.4
26.7	29.1	845.8 $\pm$ 78.8	842.2 $\pm$ 78.5	849.9 $\pm$ 79.2	266.9	290.6	282.9 $\pm$ 18.1	275.7 $\pm$ 17.6	290.7 $\pm$ 18.6
29.1	31.7	1283.9 $\pm$ 121.1	1278.0 $\pm$ 120.6	1290.5 $\pm$ 121.8	290.6	316.5	307.1 $\pm$ 19.7	298.9 $\pm$ 19.1	316.1 $\pm$ 20.2
31.7	34.5	982.0 $\pm$ 92.2	977.2 $\pm$ 91.7	987.4 $\pm$ 92.7	316.5	344.7	278.8 $\pm$ 17.8	271.5 $\pm$ 17.4	286.8 $\pm$ 18.3
34.5	37.5	866.4 $\pm$ 82.3	861.7 $\pm$ 81.8	871.6 $\pm$ 82.8	344.7	375.4	235.7 $\pm$ 15.1	230.0 $\pm$ 14.7	241.9 $\pm$ 15.5
37.5	40.9	923.5 $\pm$ 86.7	918.1 $\pm$ 86.2	929.6 $\pm$ 87.2	375.4	408.8	208.9 $\pm$ 13.4	204.3 $\pm$ 13.1	213.9 $\pm$ 13.7
40.9	44.5	874.8 $\pm$ 81.6	869.2 $\pm$ 81.1	881.0 $\pm$ 82.2	408.8	445.2	195.4 $\pm$ 12.6	191.4 $\pm$ 12.3	199.8 $\pm$ 12.9
44.5	48.5	836.2 $\pm$ 77.7	830.4 $\pm$ 77.1	842.7 $\pm$ 78.3	445.2	484.8	190.0 $\pm$ 12.2	185.9 $\pm$ 12.0	194.5 $\pm$ 12.5
48.5	52.8	717.7 $\pm$ 66.6	712.3 $\pm$ 66.1	723.7 $\pm$ 67.2	484.8	528.0	177.5 $\pm$ 11.4	173.5 $\pm$ 11.2	181.9 $\pm$ 11.7
52.8	57.5	753.3 $\pm$ 70.0	747.1 $\pm$ 69.4	760.1 $\pm$ 70.6	528.0	575.0	169.8 $\pm$ 10.9	165.6 $\pm$ 10.6	174.3 $\pm$ 11.2
57.5	62.6	721.5 $\pm$ 66.8	715.1 $\pm$ 66.3	728.5 $\pm$ 67.5	575.0	626.2	159.9 $\pm$ 10.3	155.6 $\pm$ 10.0	164.6 $\pm$ 10.6
62.6	68.2	635.6 $\pm$ 58.9	629.5 $\pm$ 58.3	642.2 $\pm$ 59.5	626.2	681.9	152.1 $\pm$ 9.8	147.8 $\pm$ 9.5	156.8 $\pm$ 10.1
68.2	74.3	637.0 $\pm$ 58.9	630.4 $\pm$ 58.3	644.1 $\pm$ 59.5	681.9	742.6	146.2 $\pm$ 9.4	142.0 $\pm$ 9.1	150.7 $\pm$ 9.7
74.3	80.9	577.6 $\pm$ 53.5	571.3 $\pm$ 52.9	584.6 $\pm$ 54.1	742.6	808.7	146.5 $\pm$ 9.5	148.6 $\pm$ 9.6	144.2 $\pm$ 9.3
80.9	88.1	521.6 $\pm$ 48.5	515.5 $\pm$ 47.9	528.3 $\pm$ 49.1	808.7	880.7	148.2 $\pm$ 9.6	159.7 $\pm$ 10.3	135.8 $\pm$ 8.8
88.1	95.9	598.5 $\pm$ 55.7	591.1 $\pm$ 55.0	606.6 $\pm$ 56.5	880.7	-	132.7 $\pm$ 8.7	147.7 $\pm$ 9.7	116.6 $\pm$ 7.6

region 60–480 keV, our measurements are consistent with ENDF/B-VIII.1 and JENDL-5, and becomes slightly higher in the energy region above 470–500 keV. Compared with historical experimental data, our measurements are higher than those of Weston *et al.* [72] and Mizumoto *et al.* [73]; lower than Johnsrud *et al.* [74] in the energy region 145–515 keV, and consistent with Johnsrud in the energy region 540–980 keV; higher than Macklin [63] in the energy region 20–70 keV, consistent within uncertainties in the energy region 70–450 keV, and slightly higher in the energy region 550–950 keV;

consistent with Kononov *et al.* [75] in the energy region 29–146 keV; higher than Mizumoto *et al.* in the energy region 4.5–54 keV, and consistent in the energy region 54–390 keV. Overall, our measurements tend to be slightly higher than most evaluated libraries and some historical experimental data in the low-energy region, whereas in the mid- to high-energy region it mostly agrees with evaluated libraries and previous experimental data.

For ^{109}Ag , our measurements are generally higher than ENDF/B-VIII.1, JENDL-5, and TENDL-2023 in the

TABLE V. This experiment is compared with the MACS of KADoNiS (1.0) about $^{107,109}\text{Ag}$ at $kT = 5\text{--}100$ keV.

kT (keV)	^{107}Ag (mb)		^{109}Ag (mb)	
	This work	KADoNiS	This work	KADoNiS
5	1839.8 $\pm$ 184.0	1711 $\pm$ 149	1889.5 $\pm$ 188.9	1771 $\pm$ 173
10	1421.2 $\pm$ 142.1	1309 $\pm$ 99	1446.7 $\pm$ 144.7	1298 $\pm$ 109
15	1205.0 $\pm$ 120.5	1103 $\pm$ 71	1224.0 $\pm$ 122.4	1083 $\pm$ 76
20	1064.9 $\pm$ 106.5	967 $\pm$ 51	1081.5 $\pm$ 108.2	948 $\pm$ 54
25	964.3 $\pm$ 96.4	870 $\pm$ 36	980.0 $\pm$ 98.0	853 $\pm$ 37
30	887.4 $\pm$ 88.7	795 $\pm$ 24	902.7 $\pm$ 90.3	780 $\pm$ 23
40	775.8 $\pm$ 77.6	687 $\pm$ 31	791.0 $\pm$ 79.1	675 $\pm$ 36
50	696.9 $\pm$ 69.7	612 $\pm$ 37	712.3 $\pm$ 71.2	603 $\pm$ 47
60	636.8 $\pm$ 63.7	555 $\pm$ 42	652.3 $\pm$ 65.2	548 $\pm$ 56
80	547.7 $\pm$ 54.8	474 $\pm$ 50	563.2 $\pm$ 56.3	470 $\pm$ 71
100	481.1 $\pm$ 48.1	417 $\pm$ 57	496.1 $\pm$ 49.6	416 $\pm$ 82

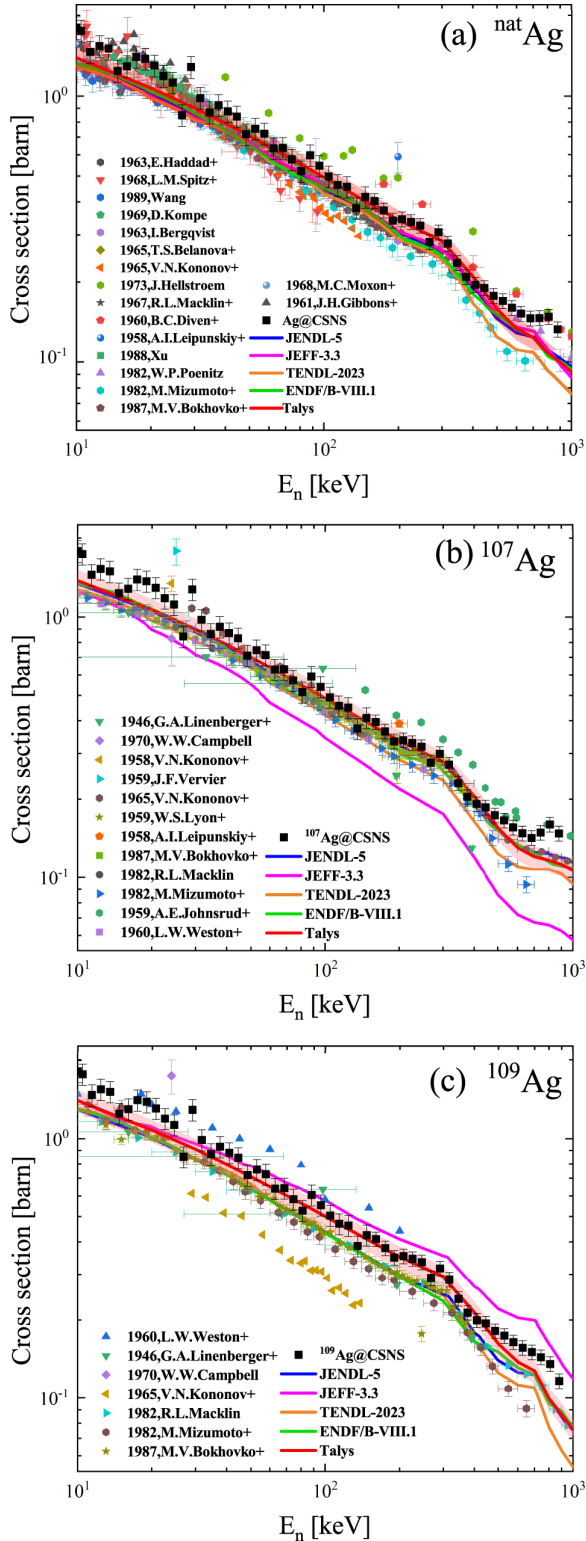


FIG. 11. The experimental data of neutron capture cross section in the URR of $^{\text{nat}}\text{Ag}$ and the talys calculation results and some existing experimental data [panel (a)]. The talys calculation results and some existing experimental data in the URR of ^{107}Ag [panel (b)]. The talys calculation results and some existing experimental data in the URR of ^{109}Ag [panel (c)].

energy region 10–1000 keV. When compared to JEFF-3.3, our measurements are higher in the energy region 10–30 keV,

consistent in the energy region 30–60 keV, and lower in the energy region 60–1000 keV. In the energy region 290–1000 keV, the trend of our measurements aligns with that of all evaluated libraries. Compared with previous experimental data, our measurements are consistent with Weston *et al.* [72] in the energy region 10–35 keV, but lower in the energy region 45–200 keV. Overall, it is higher than Mizumoto *et al.*, Bokhovko *et al.* [76], Kononov *et al.*, and Macklin. In addition, in the energy region approximately 10–27 keV, Bokhovko *et al.*, Weston *et al.*, and our work all show an upward fluctuation, suggesting the possible presence of resonance structures in this region.

For $^{\text{nat}}\text{Ag}$, our measurements are overall slightly higher than the evaluated libraries. In the energy region above 580 keV, all evaluated libraries show a distinct structure, which is also observed in our measurements but has not been reported in previous experiments. In the range of 10–35 keV, both our measurements and those of Gibbons *et al.* [77] and Spitz *et al.* [78] exhibit an upward fluctuation, suggesting the possible existence of a resonance structure in this region, which requires confirmation by future high-precision measurements.

C. Maxwellian-averaged cross sections

MACS are essential for understanding nucleosynthesis processes in stellar interiors, especially when it comes to neutron-capture processes that are key to the production of elements heavier than iron. Experimentally measured (n, γ) cross sections must be convolved with the neutron velocity distribution in the stellar plasma to compute the MACS for astrophysical applications. Calculating the MACS is required to obtain the capture cross section over a wide enough range of neutron energies, ideally from about 100 eV to about 500 keV, to cover the entire scenario of the s process, with a temperature range that includes the highest temperatures attained during the burning of shell carbon in massive stars [79]. According to the MACS definition [80]

$$\sigma_{\text{MACS}}(kT) = \frac{\langle \sigma v \rangle}{v_T} = \frac{2}{\sqrt{\pi}} \frac{\int_0^\infty \sigma(E_n) E_n e^{-\frac{E_n}{kT}} dE_n}{(kT)^2}, \quad (19)$$

where $v_T = (2kT/m)^{1/2}$ is the thermal neutron velocity based on the stellar internal temperature T and $kT = 30$ keV is the focus of astrophysical interest in calculating the s-process branch [81]. We calculated the MACS of ^{107}Ag and ^{109}Ag over $kT = 5 - 100$ keV, and the results are listed in Table V.

Figure 12 shows the comparison of our results with the recommended values of the Karlsruhe Astrophysical Database of Stellar Nucleosynthesis (KADoNiS) [82] and those of different evaluation libraries. Our results of ^{107}Ag and ^{109}Ag are overall slightly higher than the recommended values of KADoNiS. At 5 keV, the MACS value of ^{107}Ag is slightly lower than JENDL-5, and overall slightly higher than JENDL-5, TENDL-2023, ENDF/B-VIII.1, and JEFF-3.3. In the range of 10–100 keV, the MACS result of ^{109}Ag is slightly higher than the values of JENDL-5, TENDL-2023, ENDF/B-VIII.1 and lower than JEFF-3.3.

At $kT = 30$ keV, the MACS values for ^{107}Ag and ^{109}Ag are 887.4 ± 88.7 and 902.7 ± 90.3 mb, respectively. Figure 13 shows a comparison of our results with previously recommended MACS from experimental results, evaluated nuclear

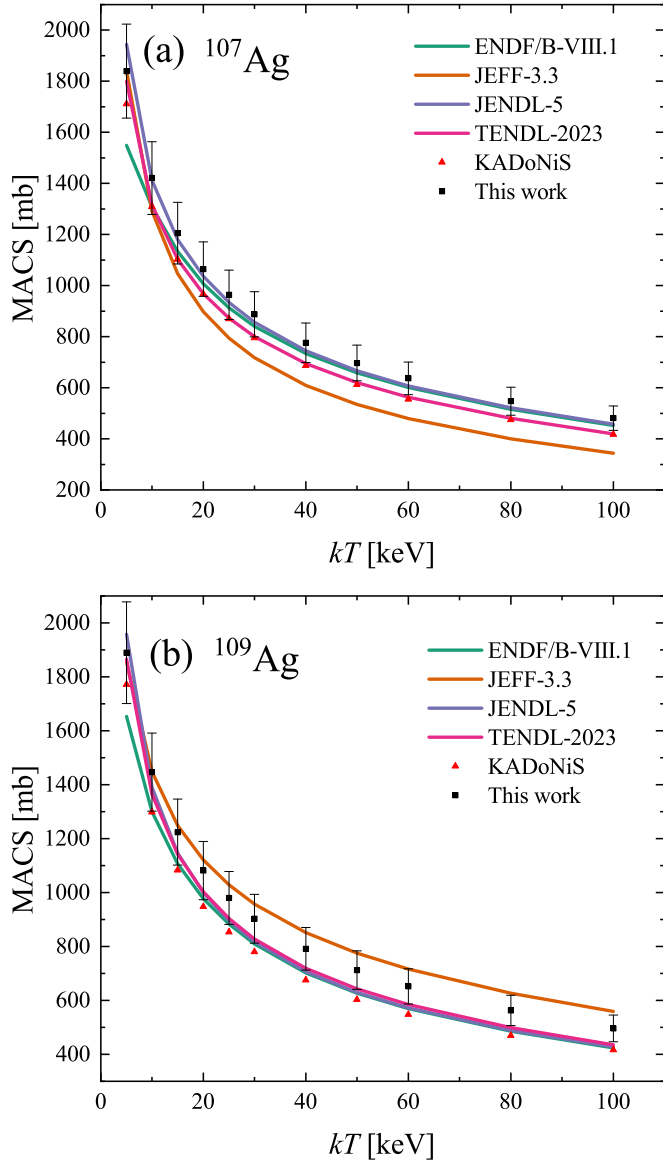


FIG. 12. Comparison of the experimental MACS from $kT = 5$ –100 keV with evaluated data.

data libraries, and theoretical values in nuclear astrophysics related to the thermal energy at $kT = 30$ keV.

V. CONCLUSIONS

In this study, the C_6D_6 detector equipped with the CSNS Back-n was utilized to accurately measure the (n, γ) reaction of $^{\text{nat}}\text{Ag}$, thus obtaining experimental data on the neutron capture cross section. The experimental data were meticulously processed using advanced methods such as the TOF method, PHWT, target thickness correction, black resonance filtering technique, and double-bunch unfolding method, and a variety of interfering factors that could affect the experimental results were successfully eliminated.

In the RRR region, our measurements help to illustrate the differences in resonance positions and strengths among various evaluated libraries. In energy regions where the libraries differ significantly, our experimental data can serve as

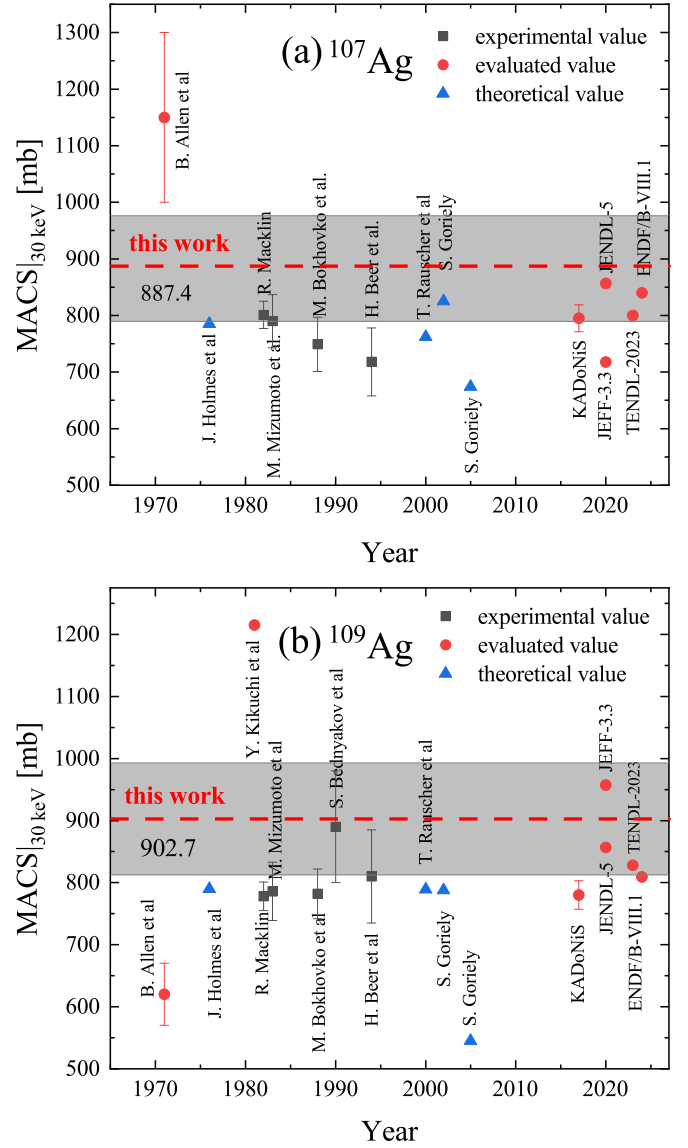


FIG. 13. Experimental MACS at 30 keV of ^{107}Ag and ^{109}Ag (shaded band) compared to previous measurements (black squares) [61–65], theoretical calculations (blue triangle) [66–69], and evaluated data (red circles) [70,71].

a reference to assist in assessing and improving these libraries. Overall, ENDF/B-VIII.1 and TENDL-2023 provide relatively complete resonance data, which can complement each other and be further refined using the results of our study. In addition, we have identified multiple resonances not previously recorded by the evaluation libraries, which adds information to the nuclear database. The yield was precisely fitted using the sammy fitting program, and resonance parameters within the energy range of 0–1500 eV were extracted. These parameters were then used as initial inputs for URR talys calculations, producing the URR results and successfully enabling the extraction of the ^{107}Ag and ^{109}Ag cross sections from the $^{\text{nat}}\text{Ag}$ URR data.

Based on the experimental data, we have also calculated the MACS, which are of interest in the field of nuclear astrophysics, providing data for the MACS of ^{107}Ag and ^{109}Ag in

the energy range of 5–100 keV. At $kT = 30$ keV, the MACS values of ^{107}Ag and ^{109}Ag are 887.4 ± 88.7 and 902.7 ± 90.3 mb, respectively, which are slightly higher than the recommended values in the KADoNiS database.

ACKNOWLEDGMENTS

We thank the staff members of the Back-n white neutron facility [83] at the CSNS [84], for providing technical support and assistance in data collection and analysis. This work

was supported by the National Natural Science Foundation of China (Grants No. 12475152, No. 12035017, No. U1832182, and No. U2032137) and the Natural Science Foundation of Guangdong Province, China (Grant No. 2022A1515011184).

DATA AVAILABILITY

The data that support the findings of this article are openly available [85–87].

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