Measurement of the Neutron Radiative Capture Cross Section and Resonance Parameter Analysis of 93Nb Using White Neutron Source

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Abstract

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Full Text

Preamble

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Abstract

In this study, the neutron radiative capture cross section of 93Nb was measured using the GTAF gamma spectrometer at the Back-n beamline of the China Spallation Neutron Source (CSNS), employing the time-of-flight (TOF) method. A comprehensive data processing approach was implemented, including background subtraction, neutron flux normalization, dead time correction, and yield spectrum calculation. The uncertainties were evaluated from statistical counting, neutron flux, sample thickness, and flight path correction. The excitation function of 93Nb was obtained up to 2 keV. Resonance parameters below 200 eV were analyzed using the SAMMY code. The results show good agreement with evaluated nuclear data libraries such as ENDF/B-VIII.0, JENDL-5, and TENDL-2023 in the main resonance regions, while discrepancies in low cross-section regions were attributed to large statistical uncertainties, possible changes in the RPI function, and impurities such as 181Ta. This work provides valuable experimental data and methodological insight for the cross-section measurement and resonance analysis of 93Nb.

Keywords: Neutron capture reaction cross section, Resonance parameter, White neutron source, Gamma total absorption facility

Introduction

Neutron reaction cross-sections are significant in both nuclear astrophysics and nuclear energy applications. In nuclear astrophysics, most elements heavier than iron are produced by the rapid (r-process) and slow (s-process) neutron capture processes [**?**][**?**]. The timescale of the s-process is on the order of years, and more than half of the elements between Fe and Bi are produced by this process [**?**][**?**]. In contrast, the timescale of the r-process is on the order of milliseconds, and it also plays a crucial role in the synthesis of heavy elements. The neutron radiative capture cross section, as an important parameter in the simulation of these two processes, plays a significant role in the study of cosmic element abundances and the origin of elements [**?**]. In nuclear energy, controlling reactor nuclear reaction rates is essential. Control rods are used to absorb neutrons, regulate neutron flux, and thus control reaction rates. Consequently, the neutron radiative capture cross-sections of reactor control rod and cladding materials are of great interest [**?**].

93Nb, a stable isotope with 100% natural abundance, is used as a structural material or cladding in reactors such as light-water, heavy-water, and fast reactors. In-depth investigation of the neutron radiative capture cross-sections of cladding materials contributes to an accurate assessment of their impact on neutron flux distribution. This facilitates the optimization of neutron moderators and reflectors, thereby enhancing neutron utilization, improving thermal efficiency, and increasing fuel usage, which collectively support the design of advanced nuclear energy systems [?]. During reactor operation, 93Nb in the cladding material gradually transmutes to 94Nb through neutron capture. Therefore, understanding the neutron capture cross section of 93Nb is essential for fuel management, cladding behavior assessment, and post-irradiation processing strategies [?]. As shown in Figure 1 [Figure 1: see original paper], existing experimental data and evaluated nuclear data libraries for the neutron radiative capture cross section of 93Nb exhibit sparse data points and large uncertainties in the resolved resonance region. Furthermore, noticeable discrepancies exist among the resonance peaks in different databases. These issues highlight the necessity for more accurate measurements of the 93Nb neutron capture cross section.

Since the 1960s, the time-of-flight (TOF) method combined with prompt gamma-ray detection has been widely adopted internationally for measuring neutron radiative capture cross sections [?][?][?][?]. Early detection systems, such as large-volume liquid scintillators [?][?] and Moxon-Rae detectors [?], played an important role in advancing the technique; however, their high neutron sensitivity and the interference from cascade gamma rays limited the precision of the measurements. To address these limitations, research institutions such as CERN and ORNL developed detection systems based on C6D6 liquid scintillators [?][?]. These detectors offer low neutron sensitivity and good gamma-ray energy resolution, significantly improving measurement accuracy. Nevertheless, due to their low detection efficiency and limited solid-angle coverage, they are not well-suited for measuring capture cross sections of isotopes with low reaction probabilities, small sample quantities, or strong radioactivity.

In the early 1980s, the discovery of BaF2 scintillators provided a promising solution. With advantages such as low neutron sensitivity, excellent time resolution, and ease of mechanical processing, BaF2 crystals are well-suited for high-precision measurements of neutron capture cross-sections. Today, several major research institutions worldwide have established 4π total absorption detector systems based on BaF2 arrays. Notable examples include the n_{TOF} facility at CERN [?] and the DANCE array at the LANCE beamline of Los Alamos National Laboratory (LANL) [?], both of which have achieved significant results in neutron capture cross-section measurements of various isotopes.

In this study, neutron radiative capture cross-section measurements of 93Nb were conducted using the GTAF facility [?] at the China Institute of Atomic Energy (CIAE) within the neutron energy range up to 2 keV. The SAMMY code was employed to fit the resonance parameters in the resolved resonance region from 1 eV to 200 eV. The experimental results and fitted parameters were compared with existing evaluated nuclear data libraries. This work provides new experimental data for the resonance region of 93Nb, offering valuable reference information for its applications in both nuclear physics research and engineering practices.

Experimental Design, Materials and Methods

2.1 Neutron Source and Beamline

The China Spallation Neutron Source (CSNS) [?], completed in 2018 and located in Dongguan, Guangdong Province, is the first high-power pulsed spallation neutron source in China. It operates at a target power of 140 kW and delivers a 25 Hz pulsed proton beam onto a spallation target, generating neutrons with a broad range of energies and emission angles. Protons are incident on the target at an angle of 15°, and their trajectory is deflected by a magnetic system before hitting the target, allowing for spatial separation between the incident protons and the emitted neutrons. In the 180° direction opposite to the proton beam, the emitted neutrons have a continuous energy spectrum, commonly referred to as "white neutrons" [?]. CSNS has established the Back-n beamline (Figure 2 [Figure 2: see original paper]) in this backward direction [?][?]. The Back-n beamline provides a neutron energy spectrum that spans from thermal energies up to the MeV range, making it particularly suitable for neutron radiative capture cross-section measurements over a wide energy region.

The Back-n beamline is equipped with two experimental end stations: End station 1 with a flight path of 55 m and End station 2 with a flight path of 76 m. To control the neutron beam spot size, the beamline incorporates a neutron shutter, Collimator #1, and Collimator #2 [?]. By adjusting the status of the neutron shutter and the aperture sizes of the collimators, different beam spot sizes can be achieved. The specific configurations and their corresponding spot sizes are summarized in Table 1 .

2.2 Detector System and Measurement Principle

The neutron radiative capture reaction can be described using the compound nucleus model. Upon neutron incidence, the target nucleus forms an excited compound nucleus, which subsequently de-excites via multiple pathways by emitting γ-rays, as illustrated in Figure 2.2. The capture cross section can be calculated using the following expression (Equation 1):

$$\sigma(E_n) = \frac{Y(E_n)}{\Phi(E_n) \cdot A}$$

Here, $\sigma(E_n)$ denotes the neutron radiative capture cross section at neutron energy E_n; $Y(E_n)$ is the total count rate of capture events occurring in the sample; $\Phi(E_n)$ represents the neutron flux passing through the sample (in units of neutrons/cm^2/s/eV); and A is the areal density (atomic thickness) of the sample, expressed in units of atoms per barn. According to the time-of-flight (TOF) method of neutrons, the energy of the incident neutron can be determined, as shown in equation (2) [?][?]:

$$E_n = 72.2977 \cdot \frac{L^2}{(t_\gamma - t_{\gamma-flash})^2}$$

In this equation, t_γ denotes the time at which cascade γ-rays from the neutron capture reaction reach the detector; $t_{\gamma-flash}$ represents the arrival time of the γ-flash at the detector; L is the neutron flight path, approximately 75.9 m; L_γ is the distance traveled by the γ-flash from the spallation target to the detector crystal (also approximately 75.9 m); and c is the speed of light. Accordingly, by measuring the neutron time-of-flight, the count rate of capture events, and the neutron beam intensity provided by the accelerator, the neutron radiative capture cross section can be determined.

To achieve high-precision measurements of neutron radiative capture reactions, the detector must satisfy several critical requirements: excellent time resolution, low neutron sensitivity, and detection efficiency that is independent of γ-ray cascade emission characteristics. BaF2 (barium fluoride) is a solid inorganic scintillator with both high timing resolution and low sensitivity to neutrons. It exhibits two scintillation components: a fast component with a decay time of approximately 0.6 ns, and a slow component with a decay time of about 630 ns [?].

The GTAF detector system (as shown in Figure 3 [Figure 3: see original paper]) is installed at Experimental Hall 2 of the Back-n beamline at CSNS. It consists of 40 BaF2 scintillator crystals—28 hexagonal and 12 pentagonal units—forming a spherical shell with an inner diameter of 10 cm and an outer diameter of 25 cm, covering approximately 95.2% of the solid angle [?]. Each crystal is wrapped with two layers of 2 m Teflon, two layers of 1 m aluminum foil, and one layer of black tape for optical isolation. Optical coupling between the scintillators and photomultiplier tubes (ET9830QB) is achieved using silicone oil to enhance light collection efficiency. According to simulation results, the detector achieves a γ-ray detection efficiency of over 85% for photon energies below 10 MeV [?].

2.3 Samples and Experimental Configuration

Four types of samples were employed in the experiment: 197Au, 93Nb, natural carbon (natC), and an empty sample holder. Each sample served a specific purpose: 197Au was used as a reference for cross-section normalization, 93Nb was the target sample, natC was used to estimate the background contribution, and the empty holder was used to determine the environmental and system background. Detailed sample information is listed in Table 2 .

Due to the difficulty in accurately determining the absolute neutron flux at the Back-n beamline, absolute cross-section measurements would incur significant systematic uncertainties. To reduce experimental errors, the present work employs the relative measurement method for cross-section normalization. 197Au is naturally 100% abundant and possesses a large neutron capture cross section, making it an internationally recognized standard sample. The GTAF setup has previously validated the measurement and data processing procedure for 197Au, including the fitting of its resonance parameters. Based on this, 197Au was selected as the standard sample for relative cross-section normalization in this experiment.

The experiment was conducted under a beam power of 140 kW, with the neutron beam spot diameter set to 30 mm. The samples were mounted inside a vacuum pipeline to minimize background signals caused by scattered neutrons. The Back-n beamline is equipped with several neutron absorbers, including Cd, Ag, and Co. To quantitatively assess background contributions, two absorber configurations were employed during the experiment: a single Cd filter and a combination of Cd, Ag, and Co. The experimental configurations, including absorber arrangements and sample combinations, are summarized in Table 3 .

2.4 Data Acquisition System

The electronics system used in this experiment consists of a 16-channel digital pulse processing module (Pixie-16) developed by XIA LLC [**?**], and a programmable trigger control module based on MicroZed (Trigger I/O). The system operates in conjunction with DAQ firmware developed by Hongyi Wu, which enables real-time data analysis, encoding, and storage [**?**][**?**][**?**]. The data acquisition system comprises four Pixie-16 boards, each with a sampling resolution of 14 bits and a sampling rate of 500 MHz [**?**]. The overall architecture of the GTAF detection system and the XIA-based DAQ system is illustrated in Figure 4 [Figure 4: see original paper]. The system uses the proton beam trigger signal T_0, provided by CSNS, as the time-zero reference. It supports real-time monitoring of key parameters such as pulse shape discrimination (PSD), summed energy spectra, and data throughput during acquisition, significantly enhancing experimental control and data handling capabilities.

Data Analysis

3.1 Pulse Shape Discrimination

The BaF2 scintillator inherently contains radium (Ra), a decay product of naturally occurring barium isotopes, which emits α particles and constitutes an intrinsic background in the experiment. Since γ rays predominantly excite the fast scintillation component of BaF2, while α particles mainly induce the slow component, the background contribution from α decays can be effectively suppressed using the Pulse Shape Discrimination (PSD) technique. The PSD calculation method is given in Equation (3):

$$\mathrm{PSD} = \frac{E_{\mathrm{slow}}}{E_{\mathrm{fast}} + E_{\mathrm{slow}}}$$

Figure 5 [Figure 5: see original paper] shows the two-dimensional PSD vs. total energy spectrum obtained during calibration with a ^{22}Na radioactive source.

The region enclosed by the red contour corresponds to counts induced by α particles. By identifying and subtracting these events, the influence of α-induced background can be effectively eliminated.

3.2 Energy Spectrum and Multiplicity Filtering

By integrating the waveform signals from individual detector units, the summed energy spectrum of events can be obtained. Environmental background, such as X-rays, is typically observed below 2 MeV, while high-energy backgrounds, such as cosmic rays, often appear above 10 MeV. By restricting the summed energy to a region near the Q-value of the (n,γ) reaction, most background contributions can be effectively suppressed. Figure 6 [Figure 6: see original paper] shows the summed energy spectra for 197Au, 93Nb, and the blank sample. Compared with the blank, both 197Au and 93Nb exhibit significant increases in counts in the 4–9 MeV range, while signals from neutron scattering off the C sample are mainly distributed between 8–10 MeV. According to evaluated nuclear data, the Q-values of the (n,γ) reactions for 197Au and 93Nb are 6.51 MeV and 7.22 MeV, respectively. Considering the energy resolution and peak broadening effects, the summed energy range in the data processing of this experiment was limited to 4.5–7.8 MeV, enabling effective preliminary suppression of environmental and scattered neutron background.

In neutron radiative capture reactions, de-excitation typically occurs via the emission of multiple cascade γ-rays, which deposit energy in different scintillation crystals. The number of crystals responding to a single physical event is referred to as crystal multiplicity. Capture events generally produce cascade γ-rays with a multiplicity greater than one, whereas background events from environmental radiation or electronic noise usually trigger only a single crystal, i.e., multiplicity equals one. In this experiment, a 100 ns coincidence window was applied to resolve detector responses originating from the same physical event, and the crystal multiplicity was recorded accordingly. The resulting multiplicity distribution is shown in Figure 7 [Figure 7: see original paper]. By excluding events with a crystal multiplicity of one, accidental coincidences and environmental background can be effectively suppressed.

3.3 Normalization and Dead Time Correction

Due to differences in measurement durations for each sample and fluctuations in the number of neutrons emitted during each cycle, normalization is required for accurate comparison. At the CSNS, the proton beam operates at a repetition rate of 25 Hz, and the number of protons delivered in each cycle is recorded. Since neutron yield is directly proportional to the number of incident protons, the total number of protons accumulated during each sample's measurement period is used as the normalization basis. Taking the total number of protons recorded for the 197Au sample as the reference, correction factors for other samples can be calculated accordingly. The calculation formula is as follows:

$$C_{\text{norm}} = \frac{N_{\text{proton, sample}}}{N_{\text{proton, Au}}}$$

During the experiment, the dead time of the data acquisition system—the interval during which the system is unable to record new events while processing previous ones—can affect the accuracy of the results by reducing the recorded event rate. Therefore, a dead-time correction is necessary. The correction factor for dead time can be calculated using the following formula:

$$C_{\text{dead}} = \frac{1}{1 - R_{\text{sample}} \cdot \tau_{\text{dead}}}$$

where R_{sample} denotes the counting rate of the sample, and τ_{dead} is the system dead time, which is 200 ns in this experiment. The dead time correction factors for the 197Au and 93Nb samples, calculated using the above formula, are shown in Figure 8 [Figure 8: see original paper].

3.4 Background Subtraction

Section 3.3 has described preliminary background screening methods. After this step, two types of background remain in the experimental data: (1) beam-related but sample-independent background, such as gamma rays produced by neutron capture in the sample holder or surrounding structural materials; and (2) environmental background, mainly from the natural decay of long-lived radioactive isotopes and activation caused by scattered neutrons. These two types of background are represented by Equation (6):

$$Y_{\text{total}} = Y_{\text{sample}} + Y_{\text{background}} + Y_{\text{flat}}$$

The following sections provide a detailed discussion and analysis of these two types of background.

Scattered neutrons in the experimental hall react with surrounding materials, emitting gamma rays that contribute to the background. This background can be measured using an empty sample holder. By subtracting the normalized empty holder data from the data of 197Au, 93Nb, and natural carbon (natC) samples, beam-related but sample-independent background can be effectively eliminated.

Long-lived radioactive isotopes present in the experimental environment emit gamma rays, which contribute to a type of background known as flat background. During all data acquisition, a Cd absorber was used, which absorbs all neutrons below 0.3 eV. Therefore, counts below 0.3 eV in the energy spectrum are solely from background and remain stable over time. According to the time-of-flight formula, the flight time is proportional to the square root of the neutron energy. By dividing the counts in each energy bin of the spectrum by the square root of the bin width, the flat background appears as a horizontal line along the x-axis. Taking the average count of this linear segment and then multiplying by the square root of the bin width yields the flat background level for each sample.

Scattered neutrons from the sample activate the surrounding environment, emitting gamma rays. These gamma rays are difficult to distinguish using simple methods such as energy filtering, PSD, or crystal multiplicity, and thus require quantitative analysis with absorbers. Since natural carbon (natC) has a neutron scattering cross section much larger than its neutron capture cross section, measuring natC samples can be used to evaluate the impact of scattered neutron background on the experiment. The background of 197Au and 93Nb are shown in Figure 9 [Figure 9: see original paper].

Both 197Au and 93Nb samples were measured using Cd, Ag, and Co absorbers, with the Ag absorber exhibiting an absorption peak at 5.1 eV. After subtracting the empty holder data and flat background, the natC sample measurement data is aligned at 5.1 eV with the absorption peak of the samples under test, allowing quantitative determination of the scattered neutron background.

3.5 Neutron Flux Normalization and Yield Extraction

The neutron flux in the Back-n beamline varies across different energy regions, which affects the shape of the time-of-flight spectra. The neutron energy distribution can be monitored using a Li-Si detector, as shown in Figure 10 [Figure 10: see original paper]. Dividing the background-subtracted spectrum by the neutron spectrum measured by the Li-Si detector effectively removes the influence of neutron flux variations on the experimental spectrum. The yield spectra are then obtained by normalizing the samples under test using the saturated resonance peak of 197Au, as illustrated in Figure 11 [Figure 11: see original paper].

3.6 Uncertainty Analysis

The experimental uncertainties can be categorized into the following components: statistical uncertainty, neutron flux uncertainty, sample thickness and mass uncertainty, and time-of-flight correction uncertainty. This section provides a detailed analysis of these uncertainties.

Statistical uncertainty can be calculated based on the raw counts of the sample. The calculation method is given by equation (7):

$$\sigma_{\text{stat}} = \frac{\sqrt{N_{\text{total}} + N_{\text{background}}}}{N_{\text{net}}} \times 100\%$$

Here, N_{total} represents the total counts measured, $N_{\text{background}}$ represents the background counts, and N_{net} represents the net counts after background subtraction. These quantities satisfy the following relationship: $N_{\text{net}} = N_{\text{total}} - N_{\text{background}}$. The uncertainty calculated per energy bin from the experimental data shows that the statistical uncertainty is below 10% in the resonance peak region. However, in regions with lower cross section, the statistical uncertainty is significantly higher, reaching up to 600%, primarily due to the small cross section of the 93Nb sample and the limited experimental time.

The neutron energy spectrum in this experiment was measured using a Li-Si detector. The associated uncertainty primarily arises from the statistical uncertainty of the Li-Si detector, and the calculation method is given by equation (9):

$$\sigma_{\text{flux}} = \frac{1}{\sqrt{n}}$$

Here, n represents the counts within each energy bin. Using this method, the neutron flux uncertainty is found to be less than 10% within the energy range from 1 eV to 2 keV.

The mass of the 93Nb sample was measured using a precision balance with a scale division of 0.001 g, resulting in a thickness measurement uncertainty of less than 0.005%. The flight path correction was performed using a linear fit, which exhibited good linearity with a fitting error of less than 0.1%. In summary, based on the error propagation formula, the experimental uncertainties are listed in Table 4 .

Resonance Parameter Analysis

The neutron radiative capture cross section and resonance parameters were obtained using the SAMMY code developed by Oak Ridge National Laboratory [**?**]. SAMMY is based on the R-matrix formalism and is widely used for analyzing neutron-induced reactions. The R-matrix theory is a key component of neutron scattering theory and provides a mathematical description of the physical reaction process. By incorporating models such as Single-Level Breit-Wigner (SLBW), Multi-Level Breit-Wigner (MLBW), and Reich-Moore, the method enables the calculation of resonance parameters for nuclear reactions.

In neutron scattering theory, the reaction cross section can be described using Equation (10):

$$\sigma_{ab} = \frac{\pi}{k_a^2} \sum_J g_J^J \left|\delta_{ab} - U_{ab}^J\right|^2$$

where k_a denotes the wave number of the incident particle in reaction channel a, g_J^J is the spin statistical factor, δ_{ab} is the Coulomb phase shift, and U_{ab}^J is the scattering matrix. Among these parameters, g_J^J can be calculated based on the input spin, orbital angular momentum, and total angular momentum. The formula for g_J^J is as follows:

$$g_J^J = \frac{2J+1}{(2i+1)(2l+1)}$$

In the above expression, J represents the total angular momentum (resonance spin) of the resonance state, i is the spin of the incident particle, and l is the ground-state spin of the target nucleus. The expression for the scattering matrix is as follows:

$$U_{ab}^J = \Omega_a^J \Omega_b^J \left(\delta_{ab} + 2i\sqrt{P_a P_b} R_{ab}^J\right)$$

Here, R_{ab}^J is a term related to the R-matrix and can be calculated by substituting the spin group information of the particles. The resonance parameters can then be determined using the R-matrix method.

For 93Nb, the ground-state spin is $9/2^+$, and the possible orbital angular momenta l are 0 and 1. Therefore, the total spin-parity J^π can take values of 3^-, 4^-, 5^-, and 6^-. The spin group information for 93Nb is shown in Table 5 .

The SAMMY code incorporates various experimental corrections, including Doppler broadening, multiple scattering broadening, and self-shielding effects. These corrections require the use of experimental conditions as input parameters. In this experiment, the temperature is 300 K, and Doppler broadening is treated using the Free Gas Model (FGM). The uncertainty in the neutron source target position is 0.02 m. The reaction radius (a) used for self-shielding correction is referenced from experimental nuclear data libraries. SAMMY also requires the areal density of the sample, which is calculated as follows:

$$\text{Areal Density} = \frac{\rho \cdot N_A}{M} \times 10^{-24} \text{ atoms/barn}$$

where ρ is the density of the sample, M is the molar mass of the sample, and N_A is Avogadro's constant. Based on the above formula, the areal density of the 93Nb sample is calculated to be 0.002885 atoms/barn.

The input information and experimentally obtained yield data were processed using the SAMMY code, with the fitting range set to 0–200 eV. Bayesian fitting was enabled in the program, and the resonance energy, neutron width, and gamma width were sequentially fitted. The fitting results and extracted resonance parameters are shown in Figure 12 [Figure 12: see original paper] and Table 6 . In the figure, the red solid line represents the fit from SAMMY, while the black points correspond to the experimental yield. For comparison, evaluated data from ENDF/B-VIII, JENDL-5, TENDL-2021, and JEFF-3.3 are also included.

Results and Discussion

Analysis of Figure 12 leads to the following observations:

1. Pronounced resonance peaks are observed at the positions indicated by arrows in the figure, which are absent from all major evaluated nuclear data libraries. These peaks are presumed to originate from resonances induced by the 181Ta impurities present in the 93Nb sample [**?**].
2. Minor resonance structures are observed in the spectrum, which are also present in the excitation curve of the 197Au sample. These features are likely caused by inaccuracies in the neutron energy spectrum shape.
3. At around 35 eV and 42 eV, the SAMMY fitting results show good agreement with the evaluated data libraries.
4. At approximately 55 eV, a resonance peak is observed in the experiment, consistent with JENDL-5 and TENDL-2023 data, but deviating from ENDF/B-VIII.0.
5. In the energy range from 60 eV to 90 eV, the SAMMY fit deviates significantly from the database values, likely due to large experimental uncertainties in this region.
6. At 94 eV, 105 eV, and 119 eV, limited statistical counts result in discrepancies between the measured cross section and the evaluated nuclear data.

A comparison with Table 6 reveals that the neutron and gamma resonance widths obtained from experimental fitting deviate from those in the ENDF/B-VIII.0 database. The possible reasons include:

1. The neutron capture cross section of 93Nb is relatively small, and the limited experimental duration results in significant statistical uncertainties.
2. With the ongoing maintenance and upgrades of CSNS, the RPI neutron source function used in SAMMY fitting may have changed, affecting the accuracy of the fitted neutron resonance widths.
3. The 93Nb sample contains impurities of 181Ta, whose neutron capture cross section is much larger than that of 93Nb, thus potentially interfering with the measurement results.
4. The neutron scattering cross section of 93Nb is significantly greater than its capture cross section, so further improvements in the subtraction of scattered neutron background are needed to enhance the data quality.

Based on the above analysis, the following improvements for future measurements can be made:

1. Increase the measurement time to improve the statistical uncertainty of 93Nb at low cross section.

2. Extend the neutron spectrum measurement time to obtain a more accurate neutron spectrum shape, thereby improving the treatment of structures in the neutron spectrum.
3. Improve the method for subtracting experimental background by referring to simulation results.

Conclusion

This study presents the measurement of the neutron radiative capture cross section of 93Nb using the GTAF detection system at the Back-n beamline of the China Spallation Neutron Source (CSNS). A time-of-flight method was applied, supported by a systematic data processing procedure involving multiplicity filtering, time-window coincidence selection, background modeling, and subtraction of beam-related and environmental backgrounds. To ensure the accuracy of the experimental results, neutron flux normalization was carried out using the proton charge information of each beam pulse. Multiple sources of uncertainty, including statistical uncertainty, neutron flux fluctuation, sample thickness measurement, and flight path corrections were carefully evaluated and incorporated into the final results.

The experimental yield of 93Nb in the energy range of 0–200 eV was obtained and fitted using the SAMMY code, which applies the Bayesian R-matrix method. The resulting resonance parameters, including neutron and gamma widths, were compared with evaluated nuclear data libraries such as ENDF/B-VIII.0, JENDL-5, and TENDL-2023. The fit results agree well with the libraries in some regions, while deviations in low-cross-section areas were observed, mainly due to the influence of impurities (e.g., 181Ta), limited measurement statistics, and challenges in background subtraction.

This work demonstrates the capability of the GTAF system in high-precision neutron capture measurements and provides valuable data and methodology for future studies on 93Nb and other isotopes over broader energy ranges. Improvements such as extended measurement time, more refined background handling, and enhanced neutron spectrum accuracy are recommended to further increase data reliability.

Usage Note

This work provides neutron radiative capture cross section data for 93Nb. The data have significant applications across various fields: in nuclear astrophysics, they serve as critical input parameters for the study of the slow (s-process) and rapid (r-process) neutron capture processes; in nuclear energy applications, the cross sections can guide the design and fabrication of reactor fuel rods and cladding materials. Furthermore, this study offers a valuable reference for future high-energy and high-precision measurements using the GTAF facility.

This work presents experimentally obtained resonance parameters, which can be used to reconstruct neutron reaction cross sections via the Breit–Wigner (B-W) formula. These results serve as an important reference for future experimental studies and practical applications.

Code Availability

This study utilized the XIA data acquisition system, generating approximately 20 TB of raw experimental data. The DAQ firmware and data decoding software used in this system have been publicly released; for access information, please contact Wu Hongyi. The data processing code is not currently available; those interested in the data processing methodology are encouraged to contact Luo Haotian for further discussion. Resonance parameters were obtained using the SAMMY code, which is open-source and publicly available on its official website.

Author Contributions Statement

Zhang QW, Luan GY and Wu HY conceived the experiment. Zhang QW, Luan GY, Wu HY, Luo HT and Chen XB conducted the experiment. Luo HT analyzed the results. Ruan XC and Ren J provided advice during analysis. The authors thank 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.

Specifications Table

Table 7 Specifications Table

Subject	Specific subject area	Data format	Type of data	How data were acquired	Parameters for data collection	Description of data collection	Data source location	Data accessibility
Nuclear physics	Neutron capture reaction cross section and resonance parameter	Analyzed	Table and Figure	Measurements were performed using GTAF	Trapezoidal shaping of detector pulses from the detector was performed	Data were collected by saving list-mode detector data during acquisitions.	Institution: China Institute of Atomic Energy Country: China	Repository name: Science Data Bank

Figures & Tables

Figure 13 [Figure 13: see original paper] Comparison of 93Nb (n,γ) cross section with ENDF/B-VIII.0, JENDL-5 and TENDL-2023 (1 eV to 200 eV)

Table 8 Some inputs of SAMMY

Parameter	Value
Experimental temperature	300 K
Flight-path length	75.87 m
Sample thickness	0.002885 atoms/barn
Gauss resolution width of flight-path length	0.1 m

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