A shielding integral experiment with different thickness of slab 9Be samples based on Deuterium-Tritium neutron source

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Abstract

Beryllium (9Be) serves as a crucial neutron multiplier and reflection material, being extensively employed in the nuclear industry. The evaluated nuclear data are utilized in the design of the nuclear devices. Following the interaction between neutrons and 9Be, all neutrons generated stem from the 9Be(n, 2n)8Be reaction channel, except for the elastic scattering reaction channel. Nevertheless, the data of the outgoing neutron double differential cross section of the reaction channel provided by the latest internationally evaluated libraries still exhibit considerable discrepancies. A shielding integral experiment based on slab 9Be samples with measurements of neutron spectra leaked from different angles is an effective approach to verify the double differential cross section data. Hence, in this study, a shielding integral experiment of 9Be samples of different thicknesses was conducted using a nanosecond pulsed deuterium-tritium neutron source established by the China Institute of Atomic Energy. The neutron time-of-flight spectra of three thicknesses (4.4 cm, 8.8 cm, and 13.2 cm) and six angles (47∘, 58∘, 73∘, 107∘, 122∘, and 133∘) were measured by the neutron time-of-flight method, and 18 sets of experimental data were obtained. Additionally, the MCNP-4C program was used to obtain the simulated results of the leakage neutron spectra using the evaluated nuclear data of 9Be from the CENDL-3.2, ENDF/B-VIII.0, JENDL-5, and JEFF-3.3 libraries. The simulated results of the leakage neutron spectra were compared with the experimental results, and the results showed that in the elastic scattering energy region, the simulated results from the CENDL-3.2, ENDF/B-VIII.0, and JENDL-5 libraries were slightly higher at small angles and slightly lower at large angles. In the (n, 2n) energy region, the simulated results from the CENDL-3.2 library were significantly different from the experimental results in terms of spectral shape, and the simulated results from the ENDF/B-VIII.0 and the JENDL-5 libraries were in good agreement with the experimental results at small angles but low at large angles. The simulated results from the JEFF-3.3 library showed serious underestimation at all angles.

Full Text

Shielding Integral Experiment with Beryllium-9 Slabs of Varying Thickness Using a Deuterium-Tritium Neutron Source

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Beryllium-9 (^{9}Be) serves as a crucial neutron multiplier and reflector material extensively employed throughout the nuclear industry. Evaluated nuclear data libraries provide the foundation for nuclear device design, where data precision directly impacts effectiveness, safety, and computational efficiency. Following neutron interaction with ^{9}Be, all secondary neutrons originate exclusively from the ^{9}Be(n, 2n)^{8}Be reaction channel, with the exception of elastic scattering. However, the double-differential cross-section data for this reaction channel provided by current international evaluated libraries exhibit considerable discrepancies. Shielding integral experiments measuring neutron spectra leaked from slab ^{9}Be samples at various angles offer an effective approach for validating these double-differential cross-section data. Consequently, this study conducted a shielding integral experiment using ^{9}Be samples of different thicknesses with a nanosecond-pulsed deuterium-tritium neutron source established at the China Institute of Atomic Energy. Neutron time-of-flight spectra were measured for three thicknesses (4.4 cm, 8.8 cm, and 13.2 cm) at six angles (47°, 58°, 73°, 107°, 122°, and 133°), yielding 18 complete datasets. Additionally, the MCNP-4C program simulated leakage neutron spectra using evaluated ^{9}Be nuclear data from the CENDL-3.2, ENDF/B-VIII.0, JENDL-5, and JEFF-3.3 libraries. Comparison between simulated and experimental results revealed that in the elastic scattering energy region, simulations from CENDL-3.2, ENDF/B-VIII.0, and JENDL-5 were slightly elevated at small angles and marginally suppressed at large angles. In the (n, 2n) energy region, CENDL-3.2 simulations showed significant spectral shape deviations from experimental data, while ENDF/B-VIII.0 and JENDL-5 simulations agreed well with experiments at small angles but underestimated results at large angles. The JEFF-3.3 library exhibited serious underestimation across all angles.

Keywords: Beryllium; Evaluated nuclear data; Shielding integral experiment; Deuterium-tritium neutron source; Neutron time-of-flight spectrum; MCNP-4C program

Introduction

Evaluated nuclear data constitute foundational information for nuclear device design, where precision proves critical for ensuring effectiveness and safety while reducing computational redundancy and improving economic efficiency [1]. Macroscopic examination of nuclear data represents an essential approach for ensuring evaluated data quality and serves as an effective method for data evaluation and refinement. Shielding integral experimental data form the basis for macroscopic examination research [2].

Beryllium-9 plays a critical role in the nuclear industry. In both nuclear power and fusion reactors, ^{9}Be serves widely as a neutron reflector [3]. Moreover, ^{9}Be is integral to space reactors [4], functioning as a neutron reflector, breeding material, and key component for passive reactor startup. Additionally, certain neutron source devices, such as spallation neutron sources, frequently employ ^{9}Be as a reflector and multiplier material to enhance source performance [5]. Consequently, neutron reaction data for ^{9}Be are highly significant in nuclear device design, directly influencing neutron transport processes, particularly regarding the angular distribution of elastic scattering, neutron multiplication factors, and the double-differential energy spectrum of the ^{9}Be(n, 2n)^{8}Be reaction [6].

To test the reliability of ^{9}Be evaluated data, numerous shielding integral experiments have been conducted worldwide, primarily measuring neutron multiplication rates and leakage spectra. Neutron multiplication rate experiments include: (1) Los Alamos National Laboratory's 1993 measurements using the manganese bath method with D-T and ^{252}Cf spontaneous fission neutrons interacting with beryllium spheres of 4.6 cm, 12.1 cm, 15.6 cm, and 19.9 cm thickness [7]; (2) Former Soviet Union measurements in 1987 using total absorption methods with D-T neutrons on beryllium spheres of 1.5 cm, 5 cm, and 8 cm thickness [8]; and (3) China Academy of Engineering Physics measurements in 1991 using total absorption methods with D-T neutrons on beryllium spheres of 4.55 cm, 8.4 cm, 10.45 cm, and 14.85 cm thickness [9].

Neutron leakage spectrum measurements have employed both spherical and slab samples. Spherical sample experiments include: (1) Lawrence Livermore National Laboratory's 1994 series using ^{9}Be spheres of 4.58 cm, 14.3 cm, and 20.0 cm thickness, measuring D-T neutron leakage spectra via time-of-flight (TOF) methods [10]; (2) Chinese Academy of Engineering Physics measurements in 1995 using the reaction proton method to measure leakage neutron energy spectra from an 8.4 cm ^{9}Be sphere irradiated with D-T neutrons [11]; and (3) The Karlsruhe Neutron Transmission Experiment (KANT) conducted in 1995 by Germany's Institute of Neutron Physics and Power Engineering using ^{9}Be spheres of 5 cm, 10 cm, and 17 cm thickness with TOF methods, pulsed D-T neutron sources, and a combination of NE-213 detectors, recoil proton counters, and Bonner spheres to obtain neutron spectra across a wide energy range (thermal to 14 MeV) [12]. KANT results were incorporated into the NEA/SINBAD database in 2006 [13] and have proven instrumental for improving ^{9}Be data in various evaluated libraries [14, 15].

Currently, two principal shielding integral experiments using slab ^{9}Be samples have been conducted. Osaka University performed measurements in 1987 at angles of 0°, 12.2°, 24.9°, 41.8°, and 66.8° using samples of 31.5 cm diameter and 5.08 cm or 15.24 cm thickness [16]. The China Institute of Atomic Energy conducted experiments in 2016 measuring leakage neutron spectra at 61° and 121° using samples of 10 cm × 10 cm surface area and 5 cm or 11 cm thickness [17].

The ^{9}Be(n, 2n)^{8}Be reaction is particularly notable due to its six distinct reaction modes [18]. While most existing integral experiments worldwide utilize spherical samples to evaluate neutron multiplication rates, few experiments focus on assessing double-differential cross-section data. Importantly, only two measurements using slab samples were primarily limited to angles within 90°, with only one measurement extending beyond this range. Consequently, significant discrepancies remain in double-differential cross-section data, particularly at larger angles, as illustrated in Fig. 1 [Figure 1: see original paper].

To satisfy requirements for precise calculations in nuclear device design, improving the double-differential spectrum of the ^{9}Be(n, 2n)^{8}Be reaction is crucial. Measuring neutron leakage spectra at various angles after neutrons traverse slab materials provides an effective approach for validating double-differential cross-sections [19].

This study conducted a shielding integral experiment using ^{9}Be samples of 30 cm diameter and 4.4 cm, 8.8 cm, and 13.2 cm thickness. A pulsed D-T neutron source [20, 21] developed by the China Institute of Atomic Energy was utilized, and neutron time-of-flight spectra were measured at six angles: 47°, 58°, 73°, 107°, 122°, and 133°. Simulations were performed using the MCNP-4C program [22] with nuclear data from the CENDL-3.2 [23], ENDF/B-VIII.0 [24], JENDL-5 [25], and JEFF-3.3 [26] libraries. Simulated and experimental results were compared to evaluate ^{9}Be nuclear data quality, with particular emphasis on the CENDL-3.2 library.

Experimental Device

The shielding integral experiment layout is illustrated in Fig. 2 [Figure 2: see original paper]. The experiment employed a nanosecond-pulsed neutron generator established at CIAE, which has previously supported shielding integral experiments with important nuclides including C [27], Fe [28–30], and ^{238}U [31–33].

A. Neutron Source

The D-T fusion neutron source was used in this experiment. Deuterium ions were accelerated to 300 keV using a high-pressure multiplier, with the accelerator operating at 1.5 MHz pulse frequency and 20 μA beam current. The beam spot measured approximately 5–10 mm. These ions bombarded a T-Ti target with a T/Ti ratio of approximately 1.6 and a reactive layer thickness of 1300 μg/cm^2. Neutrons centered around 14.5 MeV were generated through the T(d, n)^{4}He reaction, with a neutron yield of approximately 1×10^9 neutrons/s.

B. Measurement Platform

The integral experiment platform, illustrated in Fig. 2, comprises a neutron source, sample stage with precise positioning capabilities, sophisticated collimation system, suite of detectors, and digital data acquisition setup. To enhance measurement accuracy and suppress background noise from environmental scattering, the main detector was strategically located in an adjacent hall. This placement, combined with a multi-layer collimation system, ensures that most neutrons reaching the detector originate from the sample, maximizing the signal-to-background ratio.

C. ^{9}Be Sample

In shielding integral experiments, higher sample purity yields better results. The ^{9}Be sample used in this experiment had a purity of 99.24%. Two disc-shaped samples of 30 cm diameter and thicknesses of 4.4 cm and 8.8 cm were custom-fabricated by the Northwest Rare Metal Materials Research Institute. A 13.2 cm thickness was achieved by combining the two samples. Table 1 lists the specific dimensions and parameters of the ^{9}Be samples.

During the experiment, the neutron source and detector positions remained stationary while angle variation was accomplished by moving the sample position, as depicted in Fig. 3 [Figure 3: see original paper]. Keeping the outgoing neutron direction (from sample center to detector) fixed, modifying the sample center position along the quasi-line alters the incoming neutron direction (from source to sample), thereby changing the angle between incident and outgoing neutrons. Leakage neutron spectra were measured at six angles: 47°, 58°, 73°, 107°, 122°, and 133°. The three symmetric angle pairs (47° and 133°, 58° and 122°, 73° and 107°) maintain identical angles between the incident neutron and deuteron beam.

D. Collimation and Shielding System

As shown in Fig. 2, the complex experimental hall structure creates high scattering neutron background. The collimator system effectively reduces scattering background entering the detector. This experiment employed a collimator system consisting of a pre-collimator and wall collimator.

In the pre-collimator system, source neutrons may directly enter the collimator hole, scatter from the inner wall material, and reach the detector, contributing to background. To minimize this background, copper shadow cones were employed in the pre-collimator system to block direct source neutron entry into the collimator.

Four detectors were used: a 2-inch × 2-inch EJ-301 liquid scintillation detector served as the main detector to measure TOF spectra of leaking neutrons at different angles after neutron-^{9}Be interaction; two 0.5-inch × 0.5-inch EJ-301 liquid scintillation detectors functioned as monitors to directly measure source neutron TOF spectra and obtain pulse time distributions; and a Si-C detector acted as an associated particle detector to measure source neutron yield [34, 35].

Additionally, a copper ring in the pipeline before the target generated an induced charge when the D ion beam passed through, creating a pick-up signal that was sent to the acquisition card after fast preamplification to serve as the neutron generation time signal.

Fig. 4 [Figure 4: see original paper] shows TOF spectra from the ^{9}Be sample (4.4 cm thickness) at 47° measured with and without the sample. For most experimental points, the signal-to-background ratio exceeds 10, demonstrating that the collimator system effectively suppresses scattering neutron background.

E. Detector and Data Acquisition System

The leaking neutron spectrum was measured via the TOF method, corresponding to neutrons above 0.8 MeV reaching the detector. The detector and data acquisition system schematic is shown in Fig. 5 [Figure 5: see original paper].

A digital acquisition system was employed, using a Pixie-16 acquisition card manufactured by XIA Corporation (United States) and general acquisition software developed by the Experimental Nuclear Physics Group of Peking University [36]. The acquisition logic is illustrated in Fig. 5. Both the main detector signal and two monitor signals were self-triggered. When any detector signal triggered, a trigger signal was sent to the pick-up signal channel, which collected and recorded the pick-up signal within 700 ns.

For every neutron produced by the T(d, n)^{4}He reaction, an alpha particle is produced in the opposite direction in the center-of-mass system. Therefore, neutron yield can be determined by measuring alpha particle production. This method offers nearly 100% detection efficiency for semiconductor detectors, high measurement accuracy, and enables absolute measurement. Since detector noise is restricted to low-energy regions and the alpha particle-to-noise counting rate ratio exceeds 500 with an amplitude ratio of approximately 3, the plateau effect from scattered neutrons is negligible. Processed counting rates, representing net peak counts after plateau subtraction, ensure accurate neutron yield estimation. The Si-C detector measured alpha particles from the D-T fusion reaction at 135°, enabling normalization coefficient calculation.

The neutron flux per unit solid angle in direction   can be expressed as:

Φ (, E_d) = (dω')_α / (dω')n × $\Delta\Omega\alpha$

where $\Delta\Omega$_α is the solid angle between the Si-C detector and the beam limiting radius (0.16 cm); R is the distance between detector and beam limiting bar (90 cm). To calculate A_α (1.263), the following equation is used, where (dω')_n = 0.943847, determined based on an average deuteron energy (E_d) of 147 keV and alpha particle emission angle of 135°. These foundational values derive from an internal technical document. The T(d, n)^{4}He reaction neutron yield N_n and neutron flux Φ_n can be expressed as:

Φ_n(, E_d) = … [equation continues]

Finally, substituting the relevant equations yields:

A_α R^2 σ_{tot} / (π r^2 σ( )) = 1.263 × 90^2 × 3.984 / (π × 0.15652 × 0.336) = 1.576 × 10^6

Thus, for every alpha particle measured by the Si-C detector, a total of 1.576 × 10^6 neutrons were generated throughout space.

Monte Carlo Simulation

This study obtained the ^{9}Be sample leakage neutron spectrum through simulation calculations using the MCNP-4C program [37]. The simulation process carefully considered energy distribution, angular flux distribution, pulse time distribution, and detector efficiency curves.

A. Source Neutron Energy and Angular Flux Distribution Calculation

Accurate description of the neutron source energy spectrum and angular distribution is necessary for reliable simulation results. Due to the experimental hall's complex environment, eliminating scattering neutron background influence on measurements makes direct experimental determination of the D-T neutron source energy spectrum and angular flux distribution challenging. Therefore, this study adopted Monte Carlo simulation using the TARGET program [38] developed by Germany's PTB Laboratory, incorporating target structure parameters, material data, and incident beam parameters. The calculated results are shown in Fig. 6 [Figure 6: see original paper]. Neutron energy from the T(d, n)^{4}He reaction gradually decreases with increasing angle, while flux decreases as angle increases.

To verify simulation reliability, angular flux was measured at several specific angles. Fig. 7 [Figure 7: see original paper] compares measurement and simulation results, showing good agreement.

Fig. 8 [Figure 8: see original paper] compares NEFF code simulation results with absolute efficiency points calibrated using monoenergetic neutrons.

In D-T neutron sources, deuterium deposition on the target inevitably leads to D-D reactions. SiC detectors measured accompanying particle counting rates from both reactions. Simulations included the D-D reaction neutron energy spectrum in the source term, though its impact remains minimal, contributing only a 1.2% increase to the total flux detected by the main detector. This is primarily because targets are regularly replaced as D-T reaction alpha counting rates decrease, limiting D-D reaction influence.

B. Source Neutron Pulse Time Distribution Calculation

The source neutron pulse time distribution was obtained using the Maximum Likelihood Expectation-Maximization (MLEM) algorithm applied to source neutron TOF spectra measured by two monitors. The detailed process is described in Ref. [39].

C. Detector Efficiency Curve Calculation

The liquid detector efficiency curve was obtained using the NEFF program [40] developed by Germany's PTB laboratory, considering detector crystal geometric parameters, standard light response curves, and energy thresholds. The detector's absolute efficiency was calibrated using 14.1 MeV neutrons from the D-T reaction, with calibration results showing good agreement with theoretical calculations (Fig. 8).

D. ^{9}Be Leakage Neutron Spectrum Simulation

The MCNP-4C input card detailed the obtained neutron energy spectrum distribution, angular flux distribution, pulse time distribution, and liquid scintillator detector efficiency curve to ensure accurate simulation results. The simulation model was simplified by discarding materials with minimal influence on leakage neutron spectra, such as floor and walls, while retaining significant structures including target, sample, shadow cone, pre-collimator, and wall collimator.

As shown in Fig. 9 [Figure 9: see original paper], the entire neutron transport model was simplified into a 1.5 m diameter cylinder, with target structure, collimator, and sample modeled according to actual dimensions. This model simulated leakage neutron TOF spectra at various angles. Background was simulated by changing sample material to air. Evaluated ^{9}Be nuclear data from CENDL-3.2, ENDF/B-VIII.0, JENDL-5, and JEFF-3.3 libraries were adopted, while all other structural material nuclear data were obtained from the ENDF/B-VIII.0 library.

Systematic Inspection Using Standard Sample Method

Comparison between experimental and simulation results for standard samples provides an important benchmark for ensuring experimental system reliability.

Neutron leakage spectra from polyethylene samples (30 cm × 30 cm × 6 cm) were measured at 47°, 61°, and 79° to test system reliability.

A. Pulse Time Distribution Verification

To verify pulse time distribution accuracy obtained via the MLEM algorithm, two rounds of measurements were performed at 47° and 61° for the polyethylene sample. The resulting pulse time distributions are shown in Fig. 10 [Figure 10: see original paper]. The 47°-1 and 61°-1 distributions exhibit obvious left-leaning (higher on left), while 47°-2 and 61°-2 show right-leaning (higher on right). This asymmetry was caused by the 6 MHz focusing signal phase in the accelerator affecting pulse time distributions.

Using these pulse time distributions and evaluated C and H data from CENDL-3.2, ENDF/B-VIII.0, JENDL-5, and JEFF-3.3 databases, simulations were performed. Fig. 11 [Figure 11: see original paper] compares simulation and experimental results, showing good agreement under different pulse time distribution conditions, confirming MLEM algorithm reliability.

B. Low-Energy Detection Efficiency Verification

To verify detection efficiency curve accuracy in the low-energy region (near the 0.8 MeV threshold), polyethylene sample neutron leakage spectra were measured at 79°. At this angle, incident neutrons lose significant energy after n-p scattering, concentrating outgoing neutron energy in the low-energy region. Fig. 12 [Figure 12: see original paper] compares experimental and simulated TOF spectra for the polyethylene sample at 79°, showing good agreement in the low-energy region and confirming detector efficiency curve accuracy.

C. C/E Value Analysis

The n-p scattering neutron peak areas in Figs. 11 and 12 were integrated to obtain experimental and simulated values from different libraries. Table 2 presents C/E values (calculation-to-experiment ratios) after comparing simulated and experimental values. Most C/E values from each library are consistent within 3%, proving the shielding integral system produces highly reliable experimental data.

The C/E values from ENDF/B-VIII.0 and JEFF-3.3 libraries show approximately 5% underestimation at 79°, primarily because the ^{12}C(n, n')3α emitted neutron spectra in these libraries are significantly lower than those in CENDL-3.2 and JENDL-5, as shown in Fig. 13 [Figure 13: see original paper].

Comparison and Analysis of Calculated and Experimental Neutron TOF Spectra from ^{9}Be Samples

A. TOF Spectra Comparison Between Simulation and Experiment

Dividing CENDL-3.2 simulation results by experimental results yields C/E value variations with flight time, shown in Fig. 15 [Figure 15: see original paper]. CENDL-3.2 simulations exceed experimental results in the 180–280 ns range but are lower in the 280–400 ns range. At large angles, simulations are significantly lower than experimental results in the 350–550 ns range.

Dividing ENDF/B-VIII.0 simulation results by experimental results (Fig. 16 [Figure 16: see original paper]) shows C/E values decreasing with increasing flight time (decreasing energy), being higher in the high-energy region and slightly lower in the low-energy region. This phenomenon becomes more pronounced with increasing angle but improves with increasing sample thickness.

Dividing JENDL-5 simulation results by experimental results (Fig. 17 [Figure 17: see original paper]) shows C/E trends generally matching ENDF/B-VIII.0, with simulations higher in the high-energy region and lower in the low-energy region.

Dividing JEFF-3.3 simulation results by experimental results (Fig. 18 [Figure 18: see original paper]) shows simulations generally lower than experimental results across all conditions.

Processed experimental leakage neutron TOF spectra were compared with simulations from different libraries (Fig. 14 [Figure 14: see original paper]). The comparison reveals: (1) CENDL-3.2 simulations exceed experimental results between 200–300 ns at small angles (47°, 58°, 73°); (2) JEFF-3.3 simulations are significantly lower than experimental results at all angles around 250 ns, especially at large angles (>90°); and (3) at large angles (122° and 133°), all library simulations are lower than experimental results between 400–600 ns.

B. C/E Value Variation with Flight Time

[Content continues with detailed analysis of C/E variations…]

C. C/E Value Comparison Across Different Energy Regions

The NDPlot program extracted outgoing neutron spectra for 14.5 MeV neutrons interacting with ^{9}Be samples from the CENDL-3.2 library at different angles (Fig. 19 [Figure 19: see original paper]). The 14.5 MeV neutron energy corresponds to the average forward-angle neutron energy in the D-T reaction, making it representative for cross-section analysis. The outgoing neutrons exhibit only two reaction channels: elastic scattering and (n, 2n) reaction. Due to beryllium's relatively low mass, elastic scattering neutron energy decreases significantly with increasing exit angle.

Secondary neutrons at each angle are divided into elastic scattering and (n, 2n) reaction energy regions based on outgoing neutron energy. Considering the actual pulsed neutron beam width, the elastic scattering peak spans approximately $\pm$10 ns (about 1/10 of the pulse time distribution base width). Additionally, based on the (n, 2n) reaction neutron energy spectrum shape in Fig. 19, the (n, 2n) emitted neutron spectrum is subdivided into: (1) high-energy region, from the elastic scattering peak tail to the 2.8 MeV energy region; and (2) low-energy region, down to the 0.8 MeV energy region.

Integrating experimental and simulated results across these energy ranges yields the C/E values in Table 3 .

D. C/E Value Trends Across Energy Ranges with Angle and Thickness Variation

Figs. 20 and 21 show C/E value trends for different energy ranges as functions of angle and thickness. The observations include: (1) JEFF-3.3 C/E values are significantly lower than other libraries, generally below 1, particularly evident in the (n, 2n) energy region at large angles where C/E values consistently fall below 0.9; (2) In the elastic scattering region, all four libraries show marked C/E decreases with increasing angle, from approximately 1.1 at 47° and 58° to approximately 0.85 at 122° and 133°, with ENDF/B-VIII.0 values slightly higher than others—at small angles (47°, 58°, 73°), C/E values gradually increase with thickness, while at large angles (107°, 122°, 133°), they remain relatively constant with thickness; and (3) For CENDL-3.2, ENDF/B-VIII.0, and JENDL-5, (n, 2n) high-energy region C/E values exceed 1 at small angles and increase with thickness, approaching 1 at large angles with minimal thickness dependence, while low-energy region C/E values are near 1 at small angles but below 1 at large angles, with slight thickness-dependent increases—CENDL-3.2 shows the most pronounced angular variation.

E. Result Analysis

To analyze these large C/E deviations, the NDplot program extracted and compared relevant ^{9}Be data from all four databases. The (n, 2n) reaction cross-section curves (Fig. 22 [Figure 22: see original paper]) show that JEFF-3.3's cross-section (derived by summing 16 reaction channels, MT = 875 to 890) is significantly lower than others around 14.5 MeV. At this energy, cross-section values are 0.4783 b (CENDL-3.2), 0.4783 b (ENDF/B-VIII.0), 0.4760 b (JENDL-5), and 0.4424 b (JEFF-3.3)—JEFF-3.3 being more than 7% lower, likely explaining its significant simulation-experiment deviation.

Elastic scattering angular distributions for 14.5 MeV neutrons on ^{9}Be (Fig. 23 [Figure 23: see original paper]) show that evaluated databases generally overestimate differential cross-sections at small angles (47°, 58°, 73°) and underestimate them at large angles. At small angles, all four databases show relatively small deviations consistently above experimental data. At 107°, ENDF/B-VIII.0 and

JENDL-5 predict larger differential cross-sections than CENDL-3.2 and JEFF-3.3. At 122° and 133°, all four databases are closely aligned but significantly underestimate differential cross-section compared to EXFOR experimental data, particularly at 133°.

Conclusion

This study presents a comprehensive analysis of neutron interactions with beryllium (^{9}Be) through a shielding integral experiment, utilizing neutron time-of-flight spectra measured at various sample thicknesses and angles. Experimental data were compared with simulations from four widely used nuclear data libraries: CENDL-3.2, ENDF/B-VIII.0, JENDL-5, and JEFF-3.3. The results provide valuable insights into library performance and their applicability for neutron transport simulations involving beryllium.

The experimental setup captured high-quality neutron spectra for beryllium samples of 4.4 cm, 8.8 cm, and 13.2 cm thickness at six angles (47°, 58°, 73°, 107°, 122°, and 133°), producing 18 datasets that enabled thorough comparison with simulated results.

Analysis revealed that in the elastic scattering energy region, CENDL-3.2, ENDF/B-VIII.0, and JENDL-5 simulations generally agreed well with experimental data at small angles, though slightly overestimating results. At larger angles, simulations deviated from experimental data. In contrast, JEFF-3.3 consistently underestimated experimental results across all angles, with largest discrepancies at larger angles.

In the (n, 2n) reaction energy region, CENDL-3.2 showed notable spectral shape deviations, while ENDF/B-VIII.0 and JENDL-5 provided good agreement at small angles but underestimated results at larger angles. JEFF-3.3 demonstrated significant underestimation at all angles, with largest discrepancies in the high-energy (n, 2n) region.

Further analysis revealed that ENDF/B-VIII.0 and JENDL-5 performed relatively well at small angles, but none of the libraries achieved full consistency in simulating neutron spectra at large angles, particularly in the (n, 2n) region. CENDL-3.2 showed pronounced variation with angle and thickness, while JEFF-3.3 demonstrated consistent underestimation across all angular ranges.

These discrepancies highlight the need for further refinement of beryllium nuclear data, particularly in the (n, 2n) reaction region where differences were most significant. This study emphasizes the importance of continuous experimental validation for improving nuclear data library accuracy, underscoring the need for more detailed and precise nuclear models to ensure reliable neutron transport simulations critical for nuclear reactor design and radiation shielding applications.

In conclusion, these results underscore the necessity to improve consistency and accuracy of beryllium nuclear data, particularly for high-energy neutron interactions, to enhance precision in both experimental measurements and computational simulations for nuclear applications.

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Note: Figure translations are in progress. See original paper for figures.