Effect of Material Media on Neutron Fluence Rate Perturbation in a Closed Thermal Neutron Field

Authors: Yang Junkai, Wang Ping Quan, Zhang Hui, Chungming Paul Chu, Hu Zhimeng, Li Fan, Zeng Junmei, Xiao Lin, Guo Hongyu, Zhang Jian, Giuseppe Gorini

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Abstract

The neutron radiation field has vital applications in areas such as biomedicine, geology, radiation safety, and many others for neutron detection and neutron metrology. Correcting neutron fluence rate perturbation accurately is an important yet challenging problem. This study proposes a correction method that analyzes three physical processes. This method, which transforms the detection process from point detection to area detection, is based on a novel physical model and has been validated through theoretical analyses, experiments, and simulations. According to the average differences between the calculated and experimental results, the new method (1.67%) demonstrated better accuracy than the traditional simulation (2.17%). In a closed thermal neutron radiation field, the detector or strong neutron absorption material significantly perturbs the neutron fluence rate, whereas its impact on the energy spectrum shape and neutron directionality is relatively minor. Furthermore, based on the calculation results of the perturbation rate formula for medium materials with different compositions and sizes, the larger the volume and capture cross-section of the medium, the higher the perturbation rate generated in the closed radiation field

Full Text

Research on Perturbation of Neutron Fluence Rate in a Closed Thermal Neutron Field Due to Medium Materials

Jun-Kai Yang,[1] Ping-Quan Wang,[2] Zhi-Meng Hu,[3] Fan Li,[2] Jun-Mei Zeng,[1] Lin Xiao,[1] Hong-Yu Guo,[1] Jian Zhang,[2] Giuseppe Gorini,[4] Hui Zhang,[2],† and Chungming Paul Chu[1],‡

[1]College of Engineering and Applied Sciences, Nanjing University, Nanjing 210093, China
[2]National Institute of Metrology, Beijing 100029, China
[3]Department of Nuclear Science and Technology, Nanjing University of Aeronautics and Astronautics, Nanjing 210093, China
[4]Department of Physics, University of Milan-Bicocca, Milan 20126, Italy

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† Corresponding author: zhanghui@nim.ac.cn
‡ Corresponding author: pchu@nju.edu.cn

Abstract

The neutron radiation field plays a vital role in neutron detection and metrology, with critical applications in biomedicine, geology, radiation safety, and numerous other domains. Accurate correction of neutron fluence rate perturbation represents an important yet challenging problem. This study proposes a correction method based on the analysis of three physical processes that transforms the detection paradigm from point detection to area detection. Grounded in a novel physical model, the method has been validated through theoretical analysis, experimental measurements, and Monte Carlo simulations. Based on the average differences between calculated and experimental results, the new method (1.67%) demonstrated superior accuracy compared to traditional simulation approaches (2.17%). In a closed thermal neutron radiation field, the detector or strong neutron-absorbing material significantly perturbs the neutron fluence rate, while its impact on the energy spectrum shape and neutron directionality remains relatively minor. Furthermore, calculations using the perturbation rate formula for medium materials of various compositions and sizes reveal that larger medium volume and capture cross-section produce higher perturbation rates in the closed radiation field.

Keywords: Perturbation rate, Area detection, Three-dimensional neutron energy spectrum, Closed radiation field

Introduction

The neutron fluence rate, defined as the number of neutrons entering a small sphere divided by its maximum cross-sectional area per unit time [1, 2], constitutes one of the most critical physical quantities in neutron metrology due to its close relationship with the neutron energy spectrum and neutron dose equivalent [3–5]. Consequently, it serves as the key comparison quantity for the CCRI(III) (Section III: Neutron Measurement of the Consultative Committee for Ionizing Radiation of the International Committee for Weights and Measures) [6, 7]. For boron neutron capture therapy (BNCT) and binary targeted radiotherapy [8–10], the neutron fluence rate represents a crucial parameter in treatment planning systems (TPS) because of the stringent requirements for accurate dose measurement [11–14].

However, during actual measurement processes, the introduction of medium materials or detectors into the neutron radiation field alters the measurement conditions due to neutron absorption and scattering by materials of various sizes and compositions [15]. This results in changes to the fluence rate, energy spectrum, and neutron direction, creating a distorted neutron irradiation field—a phenomenon referred to as perturbation. Fluence rate perturbation poses an especially challenging problem in closed or semi-closed neutron irradiation fields, such as the neutron emission window of BNCT facilities and certain reference fields with cavity structures. The neutron fluence rate varies when a detector or other material occupies the measurement position [1, 16], making the true value at that position difficult to obtain through direct measurement. This limitation affects the accuracy of critical parameter measurements and instrument calibration. Therefore, correcting perturbations in the neutron fluence rate represents an essential aspect of neutron measurement and metrology.

Over the past century, several theories have been proposed to address this challenge [17, 18]. Williams et al. employed variational methods to calculate neutron reaction rates in plane foils and subsequently published a series of systematic studies on neutron fluence rate perturbation caused by infinite plane absorbers [19–22]. Romesburg utilized diffusion theory and Monte Carlo methods to investigate this problem, demonstrating that Monte Carlo methods yielded more accurate results [23]. However, these studies impose stringent requirements on detector geometries and mathematical representations of neutron fluence rates (e.g., plane detectors and cosine fluence rates), and their mathematical and physical rigor demands substantial expertise from users, thereby limiting their general applicability.

To address neutron irradiation field perturbation, a joint team from the National Institute of Metrology (NIM), China, and Nanjing University has proposed a new, more general physical model. This model, based on systematic physical process analysis, theoretical derivation, and Monte Carlo simulation, yields perturbation correction factors that have been verified against the thermal neutron reference radiation facility at NIM.

II. Theoretical Analysis, Experiment, and Simulation

The correction of neutron flux perturbation encompasses three main components: (1) theoretical analysis of physical processes and establishment of a new physics model, (2) experimental validation, and (3) Monte Carlo simulation and verification of results. Each component is described in detail below.

A. Thermal Neutron Reference Radiation Facility

The thermal neutron reference radiation facility was reconstructed following the decommissioning of the previous facility at NIM in 2020. As shown in [Figure 1: see original paper], the facility employs twelve ^{241}Am–Be neutron sources to provide two radiation fields: an inner field with graphite moderation and an outer field with heavy water (D_2O) moderation. This new facility achieves high thermalization and a large uniformity distribution through its innovative design incorporating a reflector layer, homogenizing lenses, and reflective cavities [24].

The inner-field reflective cavity, constructed from graphite, measures 72 cm × 72 cm × 27 cm. The neutron fluence rate at the reference point is (21433.3 ± 407.2) $\mathrm{cm}^{-2} \cdot \mathrm{s}^{-1}$, determined through gold foil activation—an absolute measurement method—with a thermal fraction of 94.7% [25]. The uniformity within a linear range of 55 cm is 99%. The outer-field reflective cavity, built from polyethylene, measures 90 cm × 90 cm × 65 cm, with a reference point neutron fluence rate of (2046.0 ± 49.1) $\mathrm{cm}^{-2} \cdot \mathrm{s}^{-1}$, also determined by gold foil activation. This field achieves a thermal fraction of 99.96% and uniformity exceeding 99% within a 70 cm × 70 cm area. Moreover, due to the innovative designs mentioned above, the outer radiation field exhibits superior performance in thermal fraction, uniform area, and uniformity compared to similar devices both domestically and internationally [26].

B. Physical Process Analysis and Physics Model Establishment

Because the inner and outer radiation field structures are identical except for their wall materials, this study uses the outer field's reflective cavity as an example for physical process analysis, experimentation, and simulation. To facilitate understanding, we propose the following three physical nomenclatures specific to this research (these terms are used exclusively in this article):

Perturbation of the neutron irradiation field: The phenomenon where placing a material of finite volume in a neutron radiation field of limited space causes changes in neutron momentum, energy spectrum, or other parameters due to capture and scattering effects of the material's nuclei on neutrons.

Perturbation rate ： When irradiation field conditions change, the ratio of the change in a physical quantity at a specific area or point in the field to that quantity with the field unchanged.

Neutron loss rate L: The proportion of neutrons lost per unit time due to decay, absorption, and other processes in a closed neutron radiation field.

1. Neutron Transport Process of the ^{241}Am-Be Neutron Source In the closed neutron radiation field shown in the schematic, neutrons emitted from ^{241}Am–Be sources are moderated by heavy water and reflected by the polyethylene reflector layer. These neutrons are slowed to thermal energies following a Maxwellian distribution and eventually transported to the emission window [27]. The neutrons emitted from this window enter the reflection cavity, where they undergo scattering and capture interactions with nuclei of the cavity wall material, the detector's sensitive region, or other medium materials. These processes ultimately lead to dynamic equilibrium of various physical quantities in the neutron field, with the same physical processes applying to similar fields.

The entire physical process can be decomposed into two steps: (a) neutrons emitted from ^{241}Am–Be sources are moderated in heavy water and transported to the emission window, and (b) neutrons exiting the window enter the reflection cavity and reach equilibrium with the cavity (as well as with the detector or other medium materials). Consequently, if all neutron parameters such as momentum and energy spectrum at the emission window can be fully recorded, the entire physical model can be simplified to include only the emission window and reflection cavity, greatly improving computational efficiency.

2. Physical Process of Neutron Entering the Reflection Cavity To better understand the temporal evolution of the neutron fluence rate in a closed radiation field, we employed a simplified model for physical analysis. As shown in [Figure 2: see original paper], assuming a closed radiation field surrounded by polyethylene, three physical processes occur when a beam of parallel neutrons enters the reflection cavity: (1) neutrons are captured through interactions with cavity wall nuclei, (2) neutrons are scattered by cavity wall nuclei, and (3) fresh neutrons enter the closed radiation field.

Assuming a unit time interval Δt, let the incident neutron count be denoted by ϕ and the neutron loss rate be L ($0 \leq \mathrm{L} \leq 1$). During the nth time interval Δt , a fraction L of the total neutrons present in the reflection cavity from the previous interval Δt $_{1}$ is lost, while fresh neutrons with count ϕ are incident from the emission window. The total number of neutrons in the closed radiation field during each time interval can be derived as follows:

First time interval $\Delta \mathrm{t}_1$: ϕ
Second time interval $\Delta \mathrm{t}_2$: $\phi + \phi(1 - \mathrm{L})$
Third time interval $\Delta \mathrm{t}_3$: $\phi + (\phi + \phi(1 - \mathrm{L}))(1 - \mathrm{L})$
Fourth time interval $\Delta \mathrm{t}_4$: $\phi + (\phi + (\phi + \phi(1 - \mathrm{L}))(1 - \mathrm{L}))(1 - \mathrm{L})$

Therefore, the total number of neutrons in the closed radiation field during the nth time interval Δt is given by (Eq. (1)):

$$\phi[1-(1-L)^n] \quad n = 1, 2, 3, ...$$

When the time is sufficiently long—that is, when n is sufficiently large (compared to nuclear reaction times on the order of 10^{-15} s [28]; durations of several minutes or even tens of seconds are considered sufficiently long)—the neutron fluence rate in the closed radiation field inevitably approaches a stable value of ϕ/L, as shown in Eq. (2):

$$n = \lim \phi[1 - (1 - L)^n]$$

As shown in [Figure 3: see original paper], introducing medium materials such as Cd or detector sensitive region materials into the closed radiation field increases the neutron loss rate to L_1, where $L_1 > L$. The total number of neutrons within the closed radiation field tends toward a stable value after a relatively long time. According to Eq. (2), the total number of neutrons under this condition can be expressed as:

Because $L_1 > L$, the stable total number of neutrons and the neutron fluence rate within the field decrease when a neutron-absorbing medium is introduced, resulting in radiation field perturbation.

3. Physical Process of Neutron Detector Measurement

The physical process of neutron detector measurement is illustrated in the schematic diagram.

4. Neutrons Arriving at the Detector

Neutrons arriving at the detector pass through the detector shell and enter the sensitive region, where they interact with nuclei to produce secondary particles and radiation. Information regarding the neutron fluence can be obtained by detecting the pulse count or current signal from these secondary particles. Neutrons not captured exit the sensitive region, with their quantity related to the capture cross-section of the nuclei in the sensitive region. The neutrons measured by the detector at specific positions in the radiation field per unit time, divided by the detection efficiency, represent the number of neutrons entering the sensitive area from its surface. In other words, the starting point of the neutron detection process is the surface of the sensitive region rather than the geometric center of the detector, and the measurement process represents area detection rather than point detection.

The average surface neutron fluence rate with energy E and direction , measured by the detector, can be obtained by integrating the fluence rate at the surface of the detector's sensitive region and normalizing to the area (Eq. (3)), which represents the detector's displayed value:

$$\phi(E, \theta) = \int \phi(E, \theta) dS$$

Where ϕ(E,) is the normalized neutron fluence rate with energy E and direction , ϕ(E,) is the incident neutron fluence rate with energy E and direction   at the surface of the sensitive region, and S is the surface area of the sensitive detector region.

Therefore, according to the definition above, the perturbation rate (E,) caused by the detector is the ratio of the difference between the normalized fluence rate ϕ_1(E,) without the detector at the measurement position and the normalized fluence rate ϕ_2(E,) with the detector (measurement result) to ϕ_1(E,). This is also equivalent to the rate of change in the number of neutrons incident on the surface of the detector-sensitive region, as given by (Eq. (4)):

$$\eta(E,\theta) = 1 - \frac{\phi_2(E,\theta)}{\phi_1(E,\theta)} = 1 - \frac{\int \phi_2(E,\theta)ds}{\int \phi_1(E,\theta)ds} = 1 - \frac{\int \phi_2(E,\theta)ds/S}{\int \phi_1(E,\theta)ds/S} \quad (0 < \theta < \pi)$$

The actual neutron fluence rate at the measurement position without a detector can be obtained using:

$$\phi_1(E,\theta) = \frac{\phi_2(E,\theta)}{1 - \eta(E,\theta)}$$

To determine the perturbation rate of the neutron fluence rate, counting all neutrons entering the surface of the detector-sensitive region or medium materials is necessary, regardless of their energy or direction. The perturbation rate and the actual neutron fluence rate are given by Eq. (6) and (7), respectively:

$$\int \eta(E,\theta)dEd\theta = 1 - \frac{\int \phi_2(E,\theta)dEd\theta ds}{\int \phi_1(E,\theta)dEd\theta ds} = 1 - \frac{\int \phi_2 ds}{\int \phi_1 ds} \quad (0 < \theta < \pi)$$

$$1 - \eta$$

Where ϕ_1 and ϕ_2 are the fluence rates of incident neutrons with and without the detector at the measurement position, and ϕ_1 and ϕ_2 are the normalized fluence rates of incident neutrons with and without the detector at the measurement position.

C. Experiment

Obtaining the perturbation rate at occupied positions during experiments is challenging, so perturbation rates at selected positions were measured to verify the new physics model in the neutron radiation field. The experiment consisted of two steps. First, a thermal neutron detector measured the neutron fluence rate at a set of positions inside the reflection cavity without any medium present. Second, the same detector measured the neutron fluence rate at the same positions but with the addition of medium material. The change in neutron fluence rate between these two conditions represents the perturbation caused by the introduction of the medium material.

Two principles guided the selection of the detector and material: (a) the detector should be as small as possible relative to the reflection cavity to minimize perturbation from the detector itself and coupling between the medium material and the detector; and (b) the medium material should exert measurable perturbation on the neutron field of the reflection cavity, completely cover the sensitive region of the detector, and allow observation of changes in neutron fluence rate as the distance between detector and material varies.

The thermal neutron detector, SP9, manufactured by Centronic Ltd., UK, has an external diameter of 3.2 cm, a stainless-steel shell 1 mm thick, and nominal pressures of 230 kPa for ^{3}He and 120 kPa for Kr at 20 °C. The influence of SP9 on the neutron radiation field can be neglected because the detector volume is only 3×10^{-5} times that of the reflection cavity. For the medium, Cd was selected with dimensions of 10 cm × 11 cm × 0.1 cm. Cd has an extremely large capture cross-section of 19964.1 barns for thermal neutrons (0.0253 eV) and can be considered a perfect blackbody. Other experimental equipment is summarized in . The measurement time was set to 600 s.

** Experimental devices**

Device	Model
Detector	SP9 (Centronic, UK)
Preamplifier	142PC (Ortec, USA)
Main amplifier	570 (Ortec, USA)
High voltage	556 (Ortec, USA)
Multichannel analyzer	USB-MCA4 CH (TechnoAP, Japan)

The experiment with Cd and its measurement positions is shown schematically in [Figure 5: see original paper] and listed in . The Cd sheet was attached to an aluminum rod with a thermal neutron capture cross-section of 0.233 barns. The geometric center of the Cd sheet was located at the center of the reflection cavity at coordinates (45, 45, 32.5) (45 cm from the bottom, 45 cm from the east wall, and 32.5 cm from the back wall). The geometric center of the SP9 detector was placed 2.5 cm behind the Cd sheet at position 1 (45, 45, 30). The detector measurement at each position lasted 300 s, with movement intervals of 5 cm (toward the east wall). The maximum movement range was 30 cm from the initial position, while other measurement conditions remained unchanged. To further investigate perturbation caused by high-absorption cross-section material in the closed radiation field, the neutron fluence rate at position 8 (45, 45, 35)—mirror-symmetric to position 1 with respect to the Cd sheet—was also measured.

** Measurement positions and their corresponding numbers**

Number	Position (East wall, Bottom, Back wall)
1	(45, 45, 30)
2	(50, 45, 30)
3	(55, 45, 30)
4	(60, 45, 30)
5	(65, 45, 30)
6	(70, 45, 30)
7	(75, 45, 30)
8	(45, 45, 35)

D. Monte Carlo Simulation

Verification of the physical process analysis and perturbation rate physics model from Section II.B was conducted using MCNP X-2.7.0 (Monte Carlo N-Particle) coupled with the ENDF/B-VII library. MCNP is a widely used Monte Carlo transport code system in nuclear physics, particularly well-suited for neutron physics calculations, originally developed at Los Alamos National Laboratory. [Figure 1: see original paper] shows the geometric configuration of the thermal neutron reference radiation facility. The initial energy spectrum of all ^{241}Am–Be neutron sources followed the recommendation of ISO 8529-1:2021 [25], with the final energy spectrum inside the stainless-steel capsule obtained after several iterations of the initial spectrum [29, 30]. Thermal neutron scattering S(α, β) (T = 293 K) was applied to calculations for polyethylene, heavy water, and graphite to account for elastic scattering processes of neutrons with energies below 4 eV.

Based on the analysis in Section II.B.1, the calculation process was divided into two parts to improve overall efficiency: (a) recording all neutron parameters at the emission window, including energy, location, direction, etc., and (b) obtaining parameters at the target location by performing calculations in the reflection cavity with the emission window acting as a new neutron source. MCNP provides surface source write (SSW) and surface source read (SSR) cards to facilitate these calculations. The SSW card writes a surface source file for subsequent MCNP calculations, while the SSR card reads the surface source file created with the SSW card.

First, the initial calculation sets the global importance factor IMP = 1 and uses the SSW card to record neutron parameters for all S1 surfaces, including the emission window surface. Second, we set the importance factor IMP = 0 for the S1 region and IMP = 1 for the remaining regions, using the SSR card to read the neutron parameters of the S1 surface to complete the calculation and verify the new physics model of the perturbation rate. The new method, referred to as area detection based on the analysis in Section II.B.4, is used in the calculation. The F1 card records the total number of neutrons entering the surface. A ^{3}He sphere with the same composition as the SP9 sensitive region, with a diameter of 3.1 cm, is placed in the reflecting cavity. The calculation of cos ranges from -1 to 0 (incident direction: 0 $-\pi$), considering 20 blocks. cos $= -1$ and 0 indicate that incident neutrons are perpendicular and parallel to the tangent plane of the ^{3}He sphere, respectively. To compare results from different methods and experiments, the traditional simulation method—specifically the F5 card (a point detector model for calculating neutron flux at a specific position)—was also employed. Based on the measurement positions listed in and the actual radius of the SP9 sensitive region, the detector's center and radius (1.55 cm) were set. The perturbation rate can be calculated using Eq. (4) and Eq. (6) after obtaining the neutron flux change.

III. Results and Discussion

A. Experimental Results

The experimental measurement results, corrected for dead time, are shown in [Figure 7: see original paper]. As the thermal neutron spectrum follows a Maxwellian distribution in the reflection cavity, the response functions R(E) and R_{average} should be constant. According to Eq. (6), the count rate C is proportional to the fluence rate ϕ. For the condition without the Cd sheet, the count rate varied from (6170 ± 11) counts per second (cps) to (6272 ± 11) cps as the SP9 detector moved from position 1 to position 7, with a count rate of

(6159 ± 11) cps at position 8. The non-uniformity of only 0.64% indicates that neutron fluence rates were essentially identical at all positions in the reflection cavity without Cd.

For the condition with the Cd sheet, the count rate ranged from (4631 ± 8) cps at position 1 to (4631 ± 8) cps at position 7, with a count rate of (4631 ± 8) cps at position 8. The non-uniformity was 15.3% in this case, indicating that introduction of the Cd sheet caused significant perturbation in the neutron radiation field, with the perturbation rate increasing as the detector approached the Cd sheet.

As shown in [Figure 7: see original paper], the perturbation rate of the experimental results varied from (2.5 ± 0.2)% at position 7 to (36.4 ± 0.2)% at position 1 compared to the condition without the Cd sheet. At position 1, where the geometric center of the detector coincided with that of the Cd sheet and the detector body was completely covered by the Cd sheet, the fluence rate perturbation was (36.4 ± 0.2)%, indicating that 63.6% of neutrons originated from scattering by the reflection cavity walls. The fluence perturbation rate at position 8 was (24.8 ± 0.2)%, which is 11.6% smaller than that at position 1. These two positions are mirror-symmetric with respect to the Cd sheet.

B. Results of the New Method and Traditional Simulation

[Figure 8: see original paper] shows the perturbation rate at eight positions from the experiment, the new method, and the traditional simulation. All three results exhibit similar trends: perturbation rates gradually increase as the distance from the Cd sheet decreases. The maximum values for the new and traditional methods were (41.6 ± 0.1)% and (43.2 ± 0.1)% at position 1, and (26.5 ± 0.1)% and (28.2 ± 2.1)% at the mirror-symmetric position 8.

Although differences in perturbation rates between the experiment and the new method, as well as between the experiment and the traditional simulation, were relatively obvious at positions 1, 2, and 8, the absolute values of these differences remained within 10% across all positions, indicating the reliability of results obtained from both calculations. For positions 3, 4, 5, 6, and 7, the differences were consistent and close to zero, showing good agreement with experimental results. The maximum differences—specifically (5.2 ± 0.1)% and (6.8 ± 0.1)%—were observed at position 1, with noticeable deviation at positions 2 and 8 compared to experimental results. This suggests that the complexity of the radiation field and its proximity to the Cd sheet significantly impact calculation accuracy, with greater complexity and closer proximity producing more pronounced effects. However, compared to the average difference of traditional simulation (2.17%), the new method demonstrated a lower average difference of 1.67%. Both the absolute values and average difference were smaller, indicating that calculation results obtained using the new method were more accurate. The two values are quite similar, and the difference between the new method and traditional simulation can be attributed to different mathematical and physical neutron statistical methods used in MCNP.

C. Perturbation of Three-Dimensional Neutron Energy Spectrum

As mentioned above, introducing a medium material—particularly one with strong neutron absorption properties such as Cd—into a closed radiation field perturbs not only the total fluence rate but also influences the neutron energy spectrum and direction. The neutron energy spectrum is a critical parameter describing the neutron irradiation field of a radiation source [31–35], providing information on total fluence and the relationship between fluence and energy. Neutrons also exhibit directionality, which is an important physical characteristic in neutron detection. For certain physical quantities such as the neutron ambient dose equivalent rate and personal dose equivalent rate, the neutron incident direction is a significant parameter alongside the energy spectrum and fluence-dose equivalent conversion coefficients [36].

The neutron fluence at a specific position ϕ is defined as the sum of neutrons of all energies E and incident directions . If only the relationship between neutron fluence and energy, ϕ(E) E, is considered, this represents the conventional neutron energy spectrum. However, including the angle in the conventional neutron spectrum allows construction of a three-dimensional neutron energy spectrum ϕ(E,) E, , providing more detailed information about the neutron radiation field.

[Figure 9: see original paper] and [Figure 10: see original paper] show the three-dimensional neutron energy spectra with and without the Cd sheet at positions 1 and 8. [Figure 11: see original paper] shows the normalized neutron fluence rates for various values of cos . The shapes of these peaks follow standard thermal neutron spectra, adhering to the Maxwellian distribution, with consistent peak positions. The number of neutrons entering the detector increased as cos decreased, with maximum observed for nearly perpendicular incidence (cos ranging from -1 to -0.95), accounting for approximately 10% of the total fluence. Moreover, the normalized neutron fluence rate displayed a linear correlation with cos , with correlation coefficient R^2 exceeding 99.5% in all cases ([Figure 11: see original paper]). Within each cos interval, the change in normalized fluence rate with and without the Cd sheet was relatively minor, indicating that strong neutron-absorbing material had limited influence on neutron direction. While the presence or absence of the Cd sheet had minimal impact on the shape and position of the peak in the reflective cavity, it significantly influenced the neutron fluence rate. Without the sheet, the maximum peak height at position 1 was comparable to that at position 8. Upon introducing the Cd sheet into the reflective cavity, the maximum peak height decreased by $(41.7 \pm 0.1)\%$ at position 1 and $(26.4 \pm 0.1)\%$ at position 8. The difference between these decreases was 15.3%, which closely aligns with the 15.1% difference in perturbation rates between the two positions calculated using the new method. Therefore, perturbation observed in the detector's spectrum within the closed thermal neutron radiation field is mainly associated with changes in neutron fluence rate rather than alterations in neutron direction or spectral shape.

D. Perturbation Rate for Different Materials and Sizes

According to Eq. (6) and the conclusions mentioned above, the perturbation rates of the neutron fluence rate for four common materials—^{3}He gas (same as the SP9 component), Cd, polyethylene (PE), and graphite—were calculated in the reflection cavity. To better observe the relationship between material volume and perturbation rate, these materials were assumed to be spherical with diameters of 1.5 cm (3$×10^{-5}$ times the volume of the reflection cavity) and 15 cm (3$×10^{-2}$ times the volume of the reflection cavity). As shown in [Figure 12: see original paper], the perturbation rate followed the order: _{Cd} > _{He}-3 > _{PE} > _{Graphite} for both sphere sizes. This order matches the neutron capture cross-section order for these materials [37]. The ratio of _{He}-3(r=15 cm) to _{He}-3(r=1.5 cm) was 142.9, significantly higher than for other materials. For a radius of 1.5 cm, the perturbation rate of ^{3}He was only (0.14 ± 0.01)%, indicating that perturbation caused by the SP9 detector was negligible. _{Cd} was 2.26 times greater than _{He}-3 for a radius of 1.5 cm, but only 1.03 times greater for a radius of 15 cm. This discrepancy may be due to the fact that the size of the ^{3}He sphere is much larger than the range of incident neutrons, resulting in capture of most neutrons entering it. Therefore, the perturbation rate of ^{3}He (_{He}-3) is close to that of Cd (_{Cd}). Furthermore, because the neutron range is related to the capture cross-section, large volumes and high capture cross-sections of the medium result in significant perturbation rates in a closed thermal neutron radiation field.

IV. Conclusion

This study conducted systematic and methodological research on perturbation correction of medium materials in a closed thermal neutron radiation field, yielding the following conclusions:

1. A new physics model and associated formulas were developed to address and correct neutron fluence rate perturbations. This approach transforms the detection process from point detection to area detection and was validated through theoretical derivation, experimentation, and Monte Carlo simulation. The perturbation rates obtained using this method were closer to experimental results compared to traditional simulations and can be applied to other detector shapes. This measurement concept is also significant for detecting other radiation sources such as X-rays or γ-rays, correcting geometric effects, and determining effective measurement points in inhomogeneous radiation fields.

2. A three-dimensional neutron energy spectrum was constructed by incorporating neutron directionality, providing more comprehensive information about the radiation field. Analysis of this spectrum revealed that perturbation primarily affects the neutron fluence rate rather than neutron

direction or spectral shape in a closed thermal neutron radiation field.

3. Perturbation rates of different materials and sizes were analyzed. Results indicated that the perturbation rate is influenced by the capture cross-section and size of the medium; larger volumes and higher capture cross-sections lead to high perturbation rates in the closed radiation field.

This study plays a crucial role in improving the accuracy of instrument calibration and material performance evaluations. Moreover, it addresses a key physics problem in closed radiation field research and enhances understanding of radiation field distribution characteristics. Future work will focus on detailed investigation of perturbation rates with different materials and neutron fields.

Author Contributions

All authors contributed to the conception and design of this study. Material preparation, data collection, simulation, and analysis were performed by Jun-Kai Yang, Ping-Quan Wang, Zhi-Meng Hu, Fan Li, Jun-Mei Zeng, Hui Zhang, Chungming Paul Chu, and Giuseppe Gorini. The first draft of the manuscript was written by Jun-Kai Yang, Ping-Quan Wang, Hui Zhang, and Chungming Paul Chu, and all authors commented on previous versions of the manuscript. All authors have read and approved the final version of the manuscript.

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