

Article

High-Efficiency Thermal Neutron Detector Based on Boron-Lined Multi-Wire Proportional Chamber

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Abstract

The global shortage of ^3He resources has created an urgent need for alternative neutron detection technologies in applications such as national security, neutron scattering, and nuclear energy. This study designed and developed a zero-dimensional planar high-efficiency thermal neutron detector based on a boron-lined multi-wire proportional chamber (MWPC) employing two distinct efficiency-enhancement approaches: a multilayer structure and grazing-incidence geometry. For ease of use, a sealed detector has been developed, eliminating the need for gas cylinders. Geant4 simulations were utilized to optimize the B_4C thickness of conversion layer and evaluate γ -ray sensitivity. Prototype detectors were fabricated and experimentally validated at the 20th beamline (BL20) of China Spallation Neutron Source (CSNS). Simulation results indicate that the optimal B_4C thickness varies with layer count and neutron wavelength, measuring approximately $2.0\text{ }\mu\text{m}$ at $1.8\text{ }\text{\AA}$ and $1.5\text{ }\mu\text{m}$ at $4\text{ }\text{\AA}$ for a 10-layer structure, with γ -ray sensitivity below 5×10^{-6} . Experimental measurements demonstrate that a five-layer detector achieved neutron detection efficiencies of $28.0 \pm 1.5\%$ at $4.78\text{ }\text{\AA}$ and $17.8 \pm 1.8\%$ at $2.87\text{ }\text{\AA}$, while a two-layer detector at 11.5° incidence attained 19.2% and 11.7% . This research lays the groundwork for developing large-area, high-efficiency, position-sensitive neutron detectors

Keywords: neutron detector; multi-wire proportional chamber; Geant4; γ -ray sensitivity



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1. Introduction

Neutron detection technology is essential for nuclear physics research, reactor monitoring, neutron scattering science, and homeland security applications [1]. Traditional neutron detectors often utilize the ^3He gas as conversion medium, favored for its high thermal neutron absorption cross-section and extremely low γ -ray sensitivity [2,3]. However, the increasingly limited supply and high cost of ^3He gas in recent years have significantly constrained the development of neutron detection technology, particularly for applications requiring large-area detector arrays [4–6]. Therefore, identifying alternative detection technologies to replace ^3He has become an urgent research priority.

The main alternative technical routes include the scintillator ^6Li , the proportional counters BF_3 , and gas detectors incorporating thin films rich in ^{10}B [7,8]. Among these, gas

detectors based on boron-rich films are considered one of the most promising alternatives to ^3He detectors. Compared to ^3He , the B_4C material enriched with ^{10}B offers the advantages of wide availability and lower cost and can be fabricated into uniform films by magnetron sputtering and other processes [9–17]. For single ^{10}B layer, the maximum thermal neutron detection efficiency is only a few percent [18–20]. To improve the efficiency, most boron-lined neutron detectors adopt multilayer structure. Currently, various detector designs based on B_4C have been developed internationally, including boron-coated straws [21–23], honeycombs [15,24], GEMs [25–29], Micromegas [30], and multi-grid [31,32] etc.

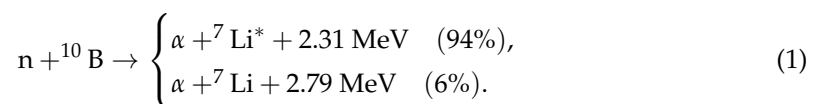
Another effective method to improve efficiency is to use a grazing-incidence geometry. By directing neutrons to strike the boron-coated surface at a shallow angle, the effective path length within the conversion layer is increased, thereby boosting the interaction probability without increasing the physical thickness of the boron layer. Detectors with macrostructured cathode [33–35], Jalousie detector [36,37], multi-blade detector [38–40], and other types of detectors [41–44] were studied.

The γ -ray sensitivity of a neutron detector is one of the key performance indicators [45–47]. In neutron scattering experiments, the neutron signal scattered from the sample is often orders of magnitude weaker than the γ -ray background, requiring detectors to have extremely low γ -ray sensitivity. Especially in reactor monitoring and homeland security applications, detectors must maintain stable neutron detection performance in environments with strong γ -ray backgrounds. For detectors with multilayer or grazing-incidence structures, which typically have larger volumes of active material, the issue of γ -ray sensitivity requires particular attention.

In this paper, boron-lined MWPCs with multilayer and grazing-incidence structures were studied. Unlike the detectors reported in the referenced literatures, the detectors developed in this work are of a closed type with a vacuum degree reaching 10^{-5} Pa. Specifically, the multilayer structure adopts double-sided coating, which not only improves the neutron detection efficiency but also reduces the space occupation ratio. The neutron detection efficiency and the γ -ray sensitivity were simulated with the Geant4 (v11.1.1) [48–50] program; the simulation results regarding γ -ray sensitivity verified that the detector still possesses a certain detection capability under high radiation background. Subsequently, detector prototypes were fabricated and tested at BL20 of CSNS.

2. Basic Principles

Neutron detection relies on nuclear reactions to generate detectable secondary charged particles. This work utilizes the $^{10}\text{B}(\text{n}, \alpha)$ reaction:



A thin layer of 96% ^{10}B -enriched B_4C (neutron conversion layer) is employed as a neutron converter. The reaction products (α and ${}^7\text{Li}$ ions) escape into the detector's gas volume, inducing ionization, and generating an electrical signal.

The overall detection efficiency η , for a single-layer, is governed by two sequential physical processes: the probability of neutron absorption within the layer and the probability that at least one of the charged particles resulting escapes the layer and enters the active gas volume. A simplified yet physically grounded model is presented below to elucidate the key design principles [51].

2.1. Probability Functions

2.1.1. Neutron Absorption Probability $P_1(x)$

For a neutron beam with normal incidence, the probability of absorption at a depth x within the material is given by

$$P_1(x) = \mu_1 e^{-\mu_1 x}, \quad (2)$$

where $\mu_1 = N_{10B} \cdot \sigma_{10B}$ is the macroscopic neutron absorption cross-section, N_{10B} is the atomic number density of ^{10}B in B_4C , and σ_{10B} is the neutron absorption cross-section, which is proportional to the neutron wavelength λ .

2.1.2. Charged Particle Emission Probability $P_2(x)$

Upon neutron absorption, an α particle and a ^7Li ion are emitted in opposite directions. Two emission modes are possible (see Figure 1):

Backward Emission (BE): particles emitted toward the incident neutron surface;

Forward Emission (FE): particles emitted away from the incident neutron surface.

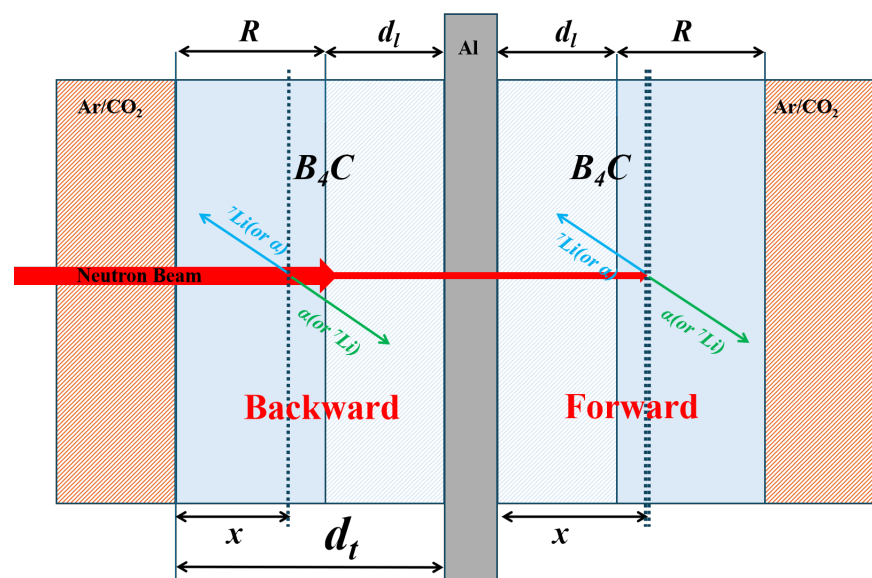


Figure 1. Schematic of Backward and Forward Emission.

When the thickness of the conversion layer $d_t > R$ (the maximum range of the particle in the material), a thickness depletion layer $d_l = d_t - R$ is defined, where the generated particles cannot escape and be detected. The probability function for particle emission at depth x is

BE

$$P_2^{(b)}(x) = \begin{cases} \frac{1}{2} - \frac{x}{2R} & x \leq R, \\ 0 & x > R, \end{cases} \quad (3)$$

FE:

$$P_2^{(f)}(x) = \begin{cases} 0 & x \leq d_l, \\ \frac{1}{2} - \frac{d_t - x}{2R} & x \geq d_l. \end{cases} \quad (4)$$

2.2. Total Detection Efficiency η

The total detection efficiency is the integral of $P_1(x)$ and $P_2(x)$ over the thickness of the entire layer d_t .

2.2.1. BE Efficiency $\eta_{\max}^{(b)}$

When $d_t > R$, the upper integration limit can be set to R since contributions beyond are zero:

$$\eta_{\max}^{(b)} = \int_0^R \left(\frac{1}{2} - \frac{x}{2R} \right) \cdot \mu_1 e^{-\mu_1 x} dx. \quad (5)$$

At this point, the efficiency enters a plateau region and no longer increases with thickness.

2.2.2. FE Efficiency $\eta_{\max}^{(f)}$

When $d_t = R$ (i.e., $d_l = 0$), the efficiency reaches its maximum:

$$\eta_{\max}^{(f)} = \int_{d_l}^{d_t} \left(\frac{1}{2} - \frac{d_t - x}{2R} \right) \cdot \mu_1 e^{-\mu_1 x} dx = \int_0^R \frac{x}{2R} \cdot \mu_1 e^{-\mu_1 x} dx. \quad (6)$$

When $d_t > R$, the lower integration limit d_l increases, causing the efficiency to decrease.

2.3. Optimal Thickness and Efficiency Plateau Region

For a single particle type, the optimal thickness of the layer D (defined as the thickness at which the neutron detection efficiency first reaches saturation) is equal to its range R . However, the actual reaction simultaneously produces α particles (range R_α) and ${}^7\text{Li}$ ions (range $R_{\text{Li}} < R_\alpha$). Therefore (for FE): In the range $R_{\text{Li}} < D < R_\alpha$, the efficiency for ${}^7\text{Li}$ begins to decline, while that for α particles continues to rise. The combined total efficiency remains stable over a certain thickness range, forming an efficiency plateau region. When $d_t > R_\alpha$, the total efficiency begins to decrease.

2.4. Implications for High-Efficiency Detector Design

To improve detection efficiency, the effective neutron path should be increased, while avoiding or reducing the formation of depletion layers. This leads to two detector structure designs:

2.4.1. Multilayer Structure

In a multilayer configuration, the total efficiency is the sum of efficiencies from each layer over different integration intervals:

$$\eta(N) = \sum_{n=1}^N \int_{(n-1)D}^{nD} P_1 P_2^{(k)} dx, \quad (7)$$

where $k = f$ when n is odd and $k = b$ when n is even. In such a structure, neutrons transmitted through the upper layer (with thickness $< R$) can participate in reactions in subsequent layers. As the number of layers increases, each layer must be significantly thinner to prevent neutrons from being fully absorbed by the preceding layers prematurely, ensuring effective participation of subsequent layers in detection.

2.4.2. Grazing-Incidence Geometry

The conversion layer is tilted so that neutrons strike at an incident angle θ_t , increasing the effective path length (for P_1) to

$$x \rightarrow \frac{x}{\sin \theta_t}. \quad (8)$$

This improves the probability P_1 while the probability of particle emission P_2 remains unchanged, thus increasing the total detection efficiency. This mechanism can be incorporated into the theoretical model by adjusting the path length.

3. Detector Simulation

This study used the Geant4 toolkit for Monte Carlo simulations, with the model structure shown in Figure 2. A layer of ^{10}B -enriched B_4C (96% enrichment, purity $\geq 99.9\%$, total density set to 2.382 g/cm^3 in simulations) was coated on a 0.5 mm thick aluminum substrate. The thickness of the gas layer is 8 mm , sufficient for $>99\%$ of the charged particles (α and ^7Li) to deposit their total energy in the working gas volume [52]. For the detector simulation, the FTFP_BERT_HP physics list in Geant4 was adopted. The HP and BERT modules in this physics list are suitable for simulating neutron nuclear reactions with energies below 20 MeV , enabling accurate description of neutron processes such as elastic scattering, inelastic scattering, capture, and fission, while the EM module can simulate γ -ray interactions including the photoelectric effect, Compton scattering, and pair production. The simulation focused on the effects of the B_4C conversion layer thickness, the number of detector layers, and the neutron incident angle on the detection efficiency, and also analyzed the detector's γ -ray sensitivity. Anode wires ($20\text{ }\mu\text{m}$ diameter gold-plated tungsten) were not included in the model due to their negligible volume fraction ($<0.1\%$ of the total detector volume) and their minimal impact on neutron conversion efficiency and γ -ray sensitivity.

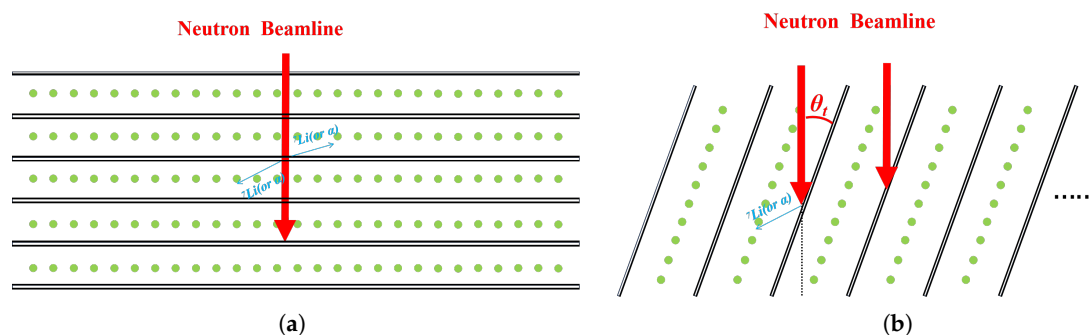


Figure 2. (a) High-efficiency detection with multilayer conversion layers. (b) High-efficiency detection with neutron-inclined incident geometry.

3.1. Neutron Detection Efficiency Simulation

The detection efficiency is defined as the ratio of the number of ^7Li or α particles entering the working gas with deposited energy greater than 100 keV to the number of incident neutrons. Based on the efficiency model in Section 2.3, this section focuses on the influence of the number of layers and the incident angle on the efficiency, to find the optimal conversion thickness of B_4C corresponding to the maximum efficiency.

3.1.1. Multilayer Structure Simulation

The multilayer simulation structure is shown in Figure 2a. For structures consisting of 1, 2, 5, and 10 B_4C conversion layers, the detection efficiency of the detector for neutrons with wavelengths of $1.8\text{ }\text{\AA}$, $2.5\text{ }\text{\AA}$, $2.8\text{ }\text{\AA}$ and $4\text{ }\text{\AA}$ was simulated.

As shown in Figure 3a, for $1.8\text{ }\text{\AA}$ neutrons, the maximum detection efficiency increases from 3.8% for a single layer to 25.8% for 10 layers. With the double-sided coating design, the efficiency is improved approximately 7 times while the total detector volume is only increased by about 5 times. In addition, the optimal thickness D of the $^{10}\text{B}_4\text{C}$ conversion layer for the 10-layer structure is reduced from $3.5\text{ }\mu\text{m}$ (rounded for practical fabrication) for a single layer to $2.0\text{ }\mu\text{m}$. A distinct “efficiency plateau” appears in the first layer (FE mode).

Within this thickness range ($<R_\alpha$), the decrease in $P_2(^7\text{Li})$ and the increase in $P_2(\alpha)$ offset each other, resulting in stable total efficiency. As the number of layers n increases, due to the cascading effect, the number of neutrons entering the next layer decreases with increasing upper layer thickness under the condition that the efficiency of the upper layer remains unchanged, thus leading to a decrease in D corresponding to the maximum efficiency. Moreover, the increase in the number of layers leads to an increase in the proportion of BE layers in the total efficiency, thus significantly narrowing the thickness window where the efficiency remains near its peak (e.g., $>95\% \eta_{\max}$), i.e., the width of the plateau is shortened.

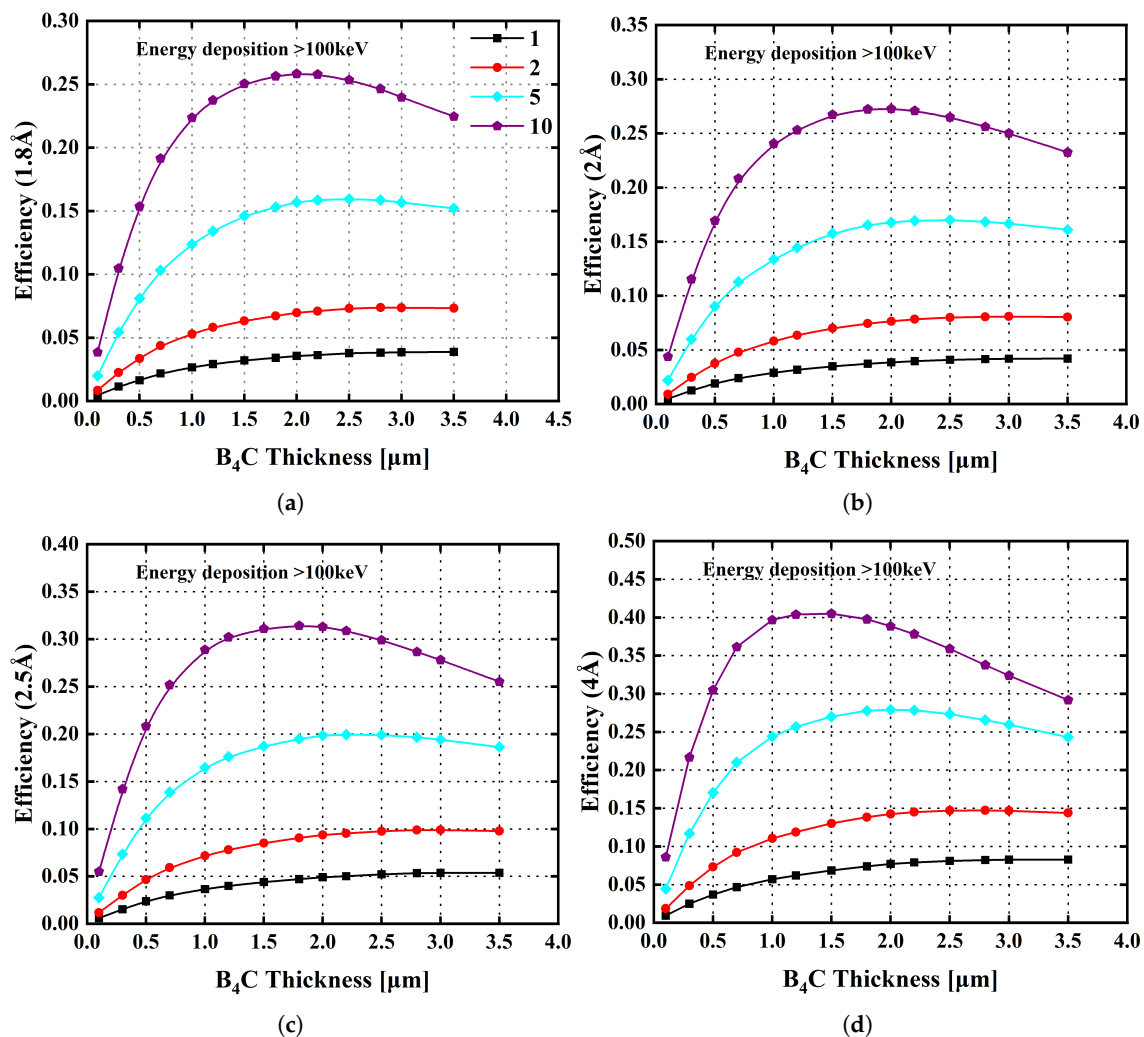


Figure 3. Efficiency changes of multilayer detectors with different B_4C conversion layer thicknesses at neutron wavelengths of (a) $1.8 \text{ \AA}$, (b) $2.5 \text{ \AA}$, (c) $2.8 \text{ \AA}$, (d) $4 \text{ \AA}$.

Comparing Figure 3a,d, when the neutron wavelength increases from $1.8 \text{ \AA}$ to $4 \text{ \AA}$, D decreases from $2.0 \mu\text{m}$ to $1.5 \mu\text{m}$ for the 10-layer structure, and from $2.8 \mu\text{m}$ to $1.5 \mu\text{m}$ for the two-layer structure. This is because the macroscopic cross-section μ_1 increases (since $\mu_1 \propto \lambda$), resulting in a faster saturation of total efficiency with thickness at the same thickness.

In engineering practice, when using magnetron sputtering for coating, a lower optimal thickness facilitates the attainment of B_4C films with high density, high uniformity, and low stress, thus enhancing device performance and reliability.

3.1.2. Grazing-Incidence Simulation

For a single-layer structure, the effects of different boron coating thicknesses and various incident angles on neutron detection efficiency were simulated.

As shown in Figure 4a, the detection efficiency increases significantly at small incident angles compared to normal incidence. For example, for a 3.5 μm conversion layer, the efficiency is 4% at normal incidence but reaches 32.8% at a 5° incident angle. As the coating thickness increases, the rate of improvement in efficiency slows down. At an incident angle of 5°, the efficiency increases from 17.6% to 25.8% when the thickness increases from 0.5 μm to 1.0 μm ; however, it increases by only 0.3% when the thickness increases from 2.5 μm to 3.0 μm , showing a clear marginal diminishing effect. Therefore, for a small-angle incidence, a thickness of around 2.5 μm is sufficient to meet the requirements for high-efficiency detection. Figure 4b simulates the variation in efficiency with angle for different neutron wavelengths for a 2.5 μm boron layer. The detection efficiency increases monotonically with wavelength. At an incident angle of 5°, the efficiency increases from 32.5% at 1.8 Å to 58.9% at 5 Å. Similarly, as the wavelength increases, the rate of efficiency increase also shows a slowing trend. The slowing growth of efficiency with increasing angle and wavelength is derived from the characteristics of the exponential term in the formula of P_1 .

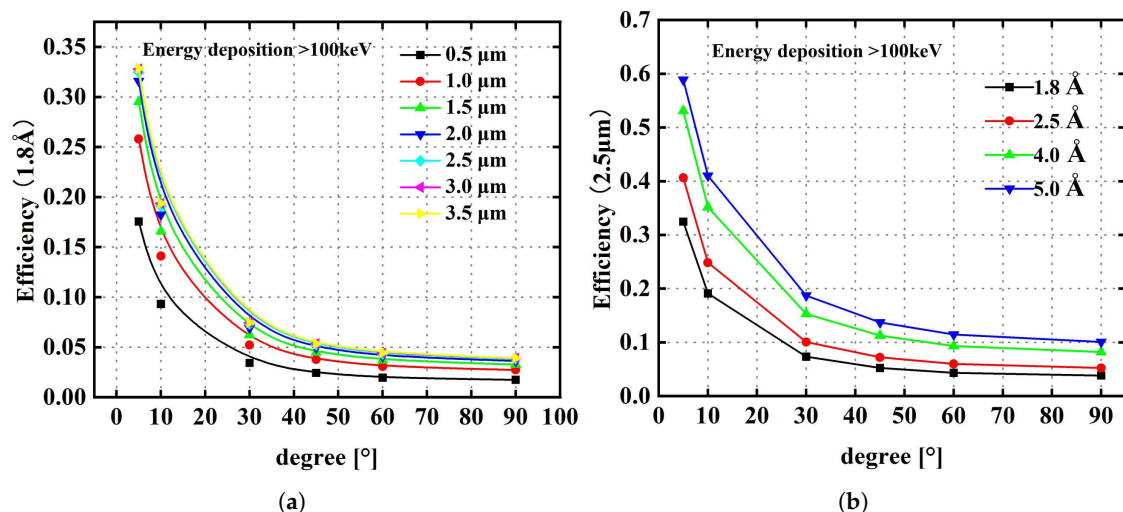


Figure 4. (a): Detection efficiency vs. incident angle for different B₄C conversion layer thicknesses ($\lambda = 1.8 \text{ \AA}$). (b): Detection efficiency vs. incident angle for different wavelengths (B₄C conversion layer thickness = 2.5 μm).

3.2. γ -Ray Sensitivity Simulation

As the number of detector layers increases or a grazing-incidence structure is adopted, the volume of active material in the detector increases, potentially leading to a higher probability of γ -ray energy deposition, which could affect the effective discrimination of neutron signals. Following the efficiency analysis above, this section simulates the detector response to four typical γ -ray energies, with the structure the same as the conditions specified in Section 3.1.

Figure 5 shows the energy deposition spectra of γ -ray in the 10-layer detector. The thickness of the single gas volume is approximately 8 mm, which is almost the same as that of the grazing-incident structure. For 59 keV γ -ray, the 2.96 keV Ar K α characteristic X-ray emission and the 59 keV photopeak were observed. For higher-energy γ -ray (662 keV, 1173 keV, 1332 keV), Compton scattering is the dominant interaction mechanism, but the probability of producing electrons with energy deposition exceeding 100 keV remains low.

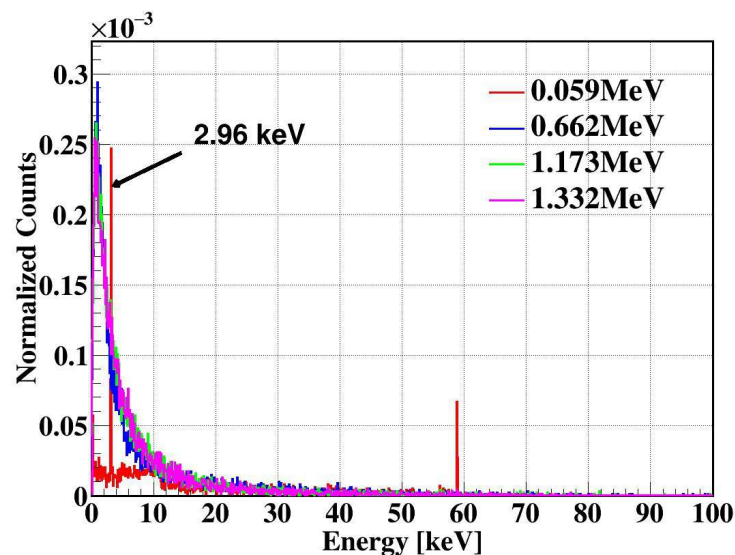


Figure 5. Energy deposition spectra of γ -ray in the 10-layer detector.

The simulated γ -ray sensitivity for detectors with different layer numbers is summarized in Table 1 in a range of γ -ray energies, where γ -ray sensitivity is defined as the ratio of γ -induced events depositing > 100 keV to the total number of incident γ -ray. For all detector configurations, the sensitivity remains below 1×10^{-6} at energies up to 662 keV. While a slight increase is observed for higher-energy γ -ray (1173 keV and 1332 keV) as the number of layers increases, it remains below 5×10^{-6} even for the 10-layer structure. Furthermore, in a detector with a geometry of 10° grazing-incidence, the simulated sensitivity to all four γ -ray energies was also below 1×10^{-6} . This level of γ -ray suppression is comparable to that of ^3He detectors, meeting the requirements for applications in high γ -background environments.

Table 1. γ -ray sensitivity of detectors with different numbers of layers for various γ -ray energies.

γ -Ray Energy (MeV)	2-Layer	5-Layer	10-Layer
0.059	$<1 \times 10^{-6}$	$<1 \times 10^{-6}$	$<1 \times 10^{-6}$
0.662	$<1 \times 10^{-6}$	$<1 \times 10^{-6}$	$\approx 1 \times 10^{-6}$
1.173	$<1 \times 10^{-6}$	$\approx 1 \times 10^{-6}$	$\approx 3 \times 10^{-6}$
1.332	$<1 \times 10^{-6}$	$<1 \times 10^{-6}$	$\approx 1 \times 10^{-6}$

4. Detector Fabrication

Based on the simulation results, prototype multilayer detectors were fabricated. The detector housing was constructed from aluminum alloy to minimize neutron scattering and features a central 0.8 mm thick aluminum window. The anode plane comprises a printed circuit board (PCB) (Figure 6a) with 24 gold-plated tungsten wires (20 μm in diameter, 4 mm pitch) soldered onto it. To stabilize the distribution of the electric field under high voltage, additional gold-plated tungsten wires (50 μm diameter) are soldered along both edges. All wires were collected together for reading. The cathode consists of a 0.5 mm thick aluminum substrate coated with a 1.6 μm thick B_4C conversion layer. The middle-layer cathodes implement a double-sided coating configuration. A fully assembled detection unit has a total thickness of approximately 8 mm.

The specific assembly is as follows: the boron-coated plate of the upper unit is separated from the anode wire frame by spacers at the four corners, with a distance of 4 mm; the boron-coated plate of the lower unit is in close contact with the anode wire frame, and the

distance from the wires soldered on the frame is also 4 mm. The size of the boron-coated plate is 150 mm × 150 mm, providing an effective detection area of 100 mm × 100 mm.

To ensure the vacuum integrity of the chamber, critical components on the detector side were assembled using vacuum welding techniques. Specifically, the gas inlets were connected to vacuum valves to facilitate gas filling, while the high-voltage feedthroughs were dedicated to signal readout. Additionally, A sealed cavity capable of reaching a vacuum of 10^{-5} Pa was fabricated, with the anode-wire planes and boron-lined electrodes mounted inside. The cavity consists of upper and lower aluminum-alloy cover plates and a square side frame. The sealing grooves are machined on the surface of the frame, allowing the O-rings to create a seal between the frame and the cover plates.

During long-term operation, the working gas can be replaced via the vacuum valves, thereby extending the detector's lifespan. Compared to the ^3He detectors, the Ar/CO₂ (9:1, volume ratio) mixture used in this study is low-cost and does not require high-pressure filling, significantly reducing the overall cost of the system.

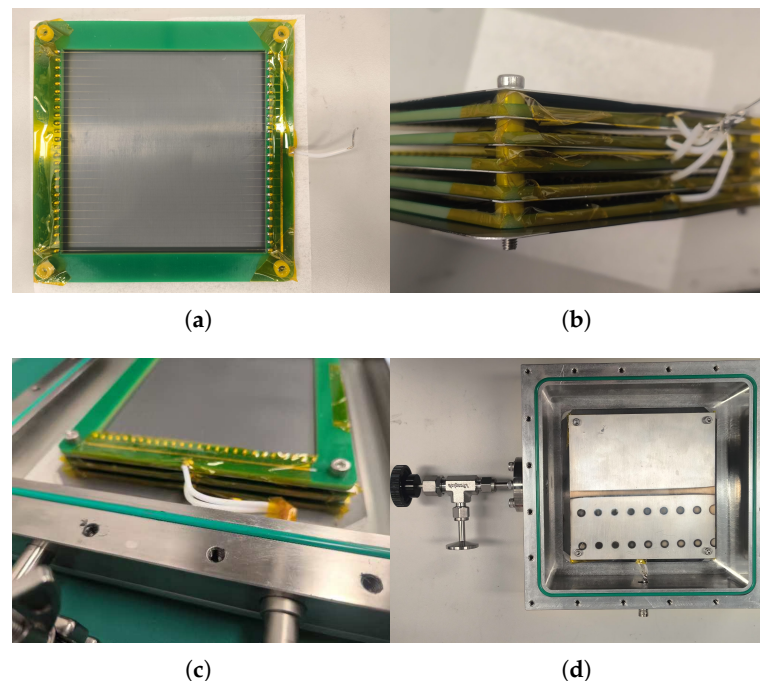


Figure 6. (a) Wire frame and boron-coated substrate unit. (b) Physical image of the multi-unit structure. (c) Schematic of the five-layer effective coating structure. (d) Cavity for the multilayer effective coating structure.

Based on this, we have further designed a grazing-incidence structure detector capable of position resolution, with independent readout for multiple anode wires. Related testing is currently underway.

5. Detection Performance Test

To evaluate the actual performance of the detectors, experimental tests were conducted on the BL20 at the CSNS. BL20 provides a neutron beam with wavelengths from 1–6 Å via a chopper system, effectively eliminating interference from fast neutrons and γ -ray background. The detector was operated at a voltage of 800 V. The tests utilized the CSNS self-developed electronics system: front-end ASIC chips are responsible for amplifying, shaping, and discriminating the detector signals, and communicate with an FPGA via LVDS interfaces; a digital electronics module processes the signals from the FPGA and sends the data to a host computer for further analysis via Gigabit Ethernet [52].

A specific wavelength of monochromatic neutrons was selected from the incident white beam using a mica monochromator via Bragg diffraction to precisely evaluate detector performance. The wavelength λ_n of the selected neutrons is calculated using the Bragg diffraction formula:

$$\lambda_n = \frac{2d_n \sin \theta_n}{n_n}, \quad (9)$$

where d_n is the lattice spacing of the mica monochromator (10.137 Å), θ_n is the diffraction angle, and n_n is the diffraction order. The angle between the monochromator and the incident neutron beam was fixed at 45° in the experiment, causing the outgoing monochromatic neutron beam to be perpendicular to the incident beam, which facilitated optical alignment.

The testing first involved measuring a standard ^3He tube, using its count rate as a benchmark to calibrate the absolute efficiency of the subsequent detectors under test. The standard ^3He tube has a diameter of 1 inch and is filled with ^3He gas at a pressure of 20 atm; its detection efficiency was assumed to be 100% for the neutron wavelengths under measurement. Figure 7a shows the actual optical path diagram of the experimental setup. The standard ^3He tube was housed in a 10 cm-thick cadmium metal shield with a pinhole of 1 mm in diameter. To minimize the influence of stray neutrons, we shielded the periphery of the detector with boron-containing polyethylene following beamline optimization. The shielding assembly consisted of 5 cm thick boron-containing polyethylene bricks and 3 mm thick flexible boron-containing polyethylene sheets, which were wrapped around the exterior of both the detector and the cadmium shield, as illustrated in Figure 7b.

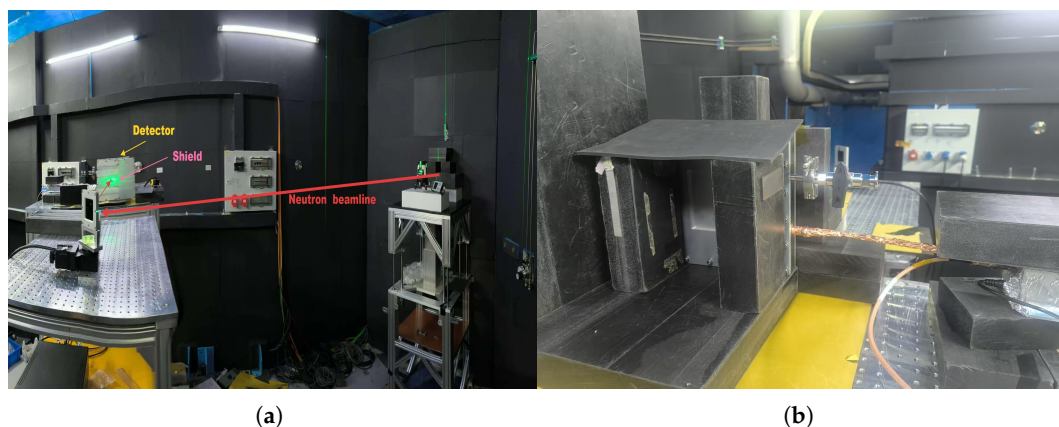


Figure 7. On-site detector test setup. (a) shows the actual light path diagram of the setup. (b) shows the external shielding setup.

After completion of the calibration measurements with the ^3He tube, the standard detector was replaced with the multilayer detector under test, while the test setup was kept unchanged. The detection efficiency of the detector for neutrons of wavelength λ_n is calculated by the following formula:

$$\eta_{\lambda_n} = \frac{(N_{det} - N_b(t_1))/N_p(t_1)}{(N_{^3\text{He}} - N_b(t_2))/N_p(t_2)}. \quad (10)$$

Here, N_{det} is the detector count under test, $N_{^3\text{He}}$ is the standard ^3He tube count, N_b is the background count during the respective measurement time, and N_p is the proton beam current count at the corresponding time. Under constant beamline optical conditions, the neutron flux entering the detector is proportional to the proton beam current. This method allows for the precise determination of the detector's absolute detection efficiency for neutrons of a specific wavelength.

Fitting and analysis of the detector efficiency curves indicate that a certain level of background counts exists in the detector. These background counts are mainly derived from the full-wavelength spectrum of BL20 and the inherent noise of the detector [52]. Despite the application of Bragg diffraction, the wavelength spectrum of BL20 still contributes to background interference. In the data processing procedure, the total counts were obtained by subtracting the average baseline value at the peak bottom from the peak signal, thus yielding comparative results of the net count rates. Figure 8b shows the measured pulse height spectrum of the boron-lined detector. As observed from the spectrum, for the enriched conversion layer material of this thickness, the energy peaks of charged particles exhibit significant broadening, with relatively high noise counts in the low-energy region.

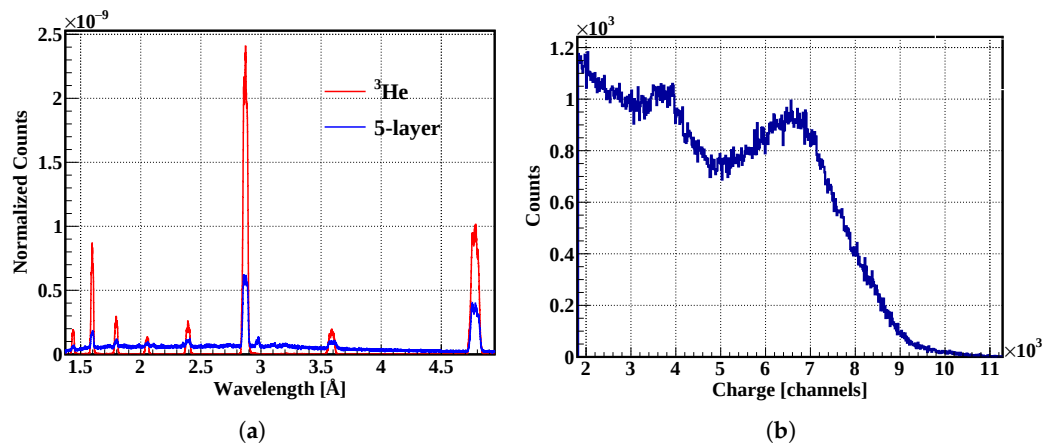


Figure 8. (a) Normalized efficiency comparison. (b) Detector pulse height spectrum.

After background subtraction and analysis of the test data for the five-layer detector, the results show that the detector achieves neutron detection efficiencies of $17.8 \pm 1.8\%$ at 2.87 Å and $28.0 \pm 1.5\%$ at 4.78 Å , with corresponding simulated predictions of 20.4% and 29.4%, respectively (Figure 9). It can be observed that the experimental values are lower than the simulated values (deviations of approximately $12.7 \pm 1.8\%$ at 2.87 Å and $4.8 \pm 1.5\%$ at 4.78 Å), but the agreement improves with increasing wavelength.

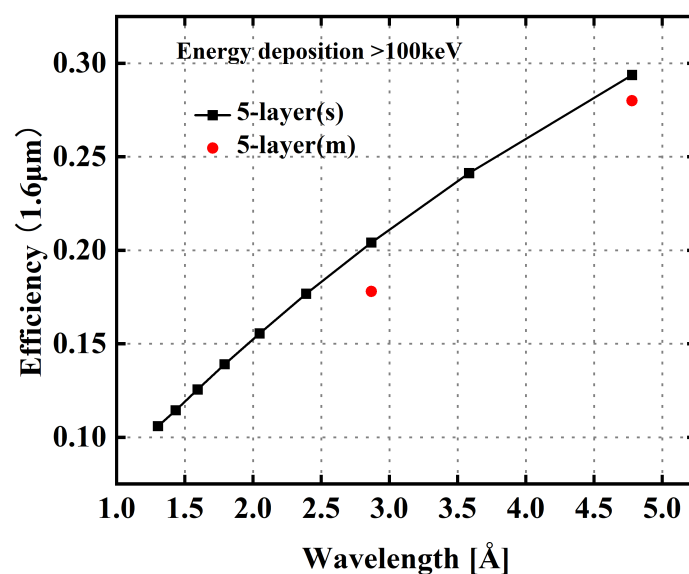


Figure 9. Comparison of simulated (s) and experimentally measured (m) neutron detection efficiencies for the 5-layer detector at different wavelengths.

The discrepancy between experimental values and simulated predictions, where the former are lower than the latter, can be attributed to two primary factors. First, simulations adopt an idealized homogeneous conversion layer model, whereas practically fabricated coatings inevitably contain material impurities and exhibit local density inhomogeneities. This directly alters the macroscopic neutron cross-section and the escape probability of nuclear reaction products (${}^7\text{Li}$ and α particles). Second, as evidenced by the pulse height spectra in Figure 8b, background noise subtraction and signal discrimination in experiments inevitably result in the loss of valid neutron counts. During this process, neutron events that overlap with the electronic noise spectrum or fall below the discrimination threshold are inadvertently removed, leading to a measured detection efficiency that is lower than the theoretical limit and thus causing the discrepancy between experimental and simulated values.

In addition, the detection efficiency of a $1.6\text{ }\mu\text{m}$ two-layer detector was evaluated at three distinct incident angles (11.5° , 30° , and 90°). As shown in Figure 10, the detector achieved efficiencies of 11.7% and 19.2% for $2.87\text{ }\text{\AA}$ and $4.78\text{ }\text{\AA}$ neutrons at an incident angle of 11.5° , which is generally consistent with the overall trend predicted by simulations. However, the measured efficiency is lower than the simulated values, primarily due to the higher energy discrimination threshold (about 300 keV) used in the experiment and the discrepancy between the idealized parallel beam model in simulations and the actual beam divergence encountered experimentally. Despite these discrepancies, the fundamental characteristic revealed by both experiments and simulations remains consistent: the smaller the incident angle, the higher the detection efficiency. These findings provide a critical basis for optimizing grazing-incidence geometries in future studies to achieve more reliable and high-efficiency detector performance.

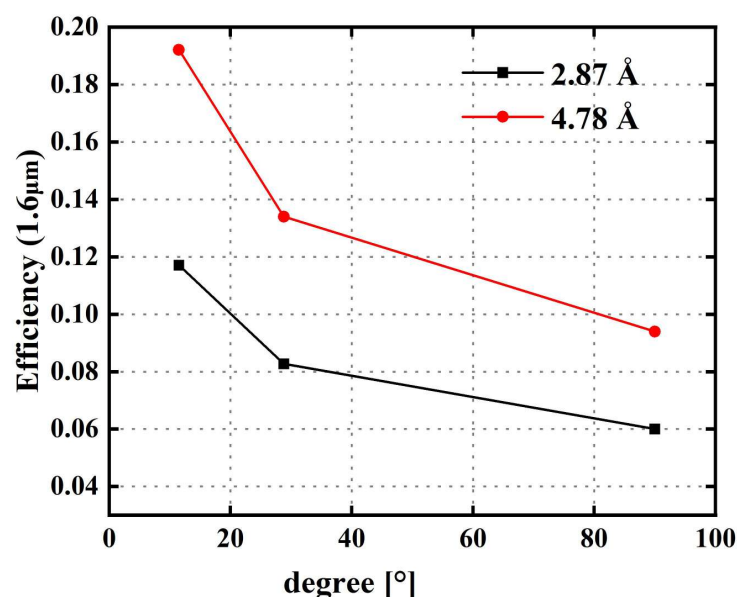


Figure 10. Detection efficiency of $1.6\text{ }\mu\text{m}$ 2-layer detector at different incident angles.

6. Conclusions

This study successfully designed and optimized a high-efficiency neutron detector based on a boron-lined multi-wire proportional chamber through a combination of theoretical analysis, simulation, and experimental validation, focusing on two enhancement schemes: multilayer structure and grazing-incidence.

The key findings are summarized below.

1. **Efficiency Enhancement Mechanisms:** A five-layer detector with a conversion layer of $1.6\ \mu\text{m}$ B_4C (96% ^{10}B enrichment) achieved neutron detection efficiencies of $28.0 \pm 1.5\%$ at $4.78\ \text{\AA}$ and $17.8 \pm 1.8\%$ at $2.87\ \text{\AA}$, validating the effectiveness of the double-sided coated multilayer design that improves detection efficiency per unit volume compared with conventional single-sided coating configurations. For a $1.6\ \mu\text{m}$ two-layer detector with 11.5° incidence, efficiencies reached 19.2% ($4.78\ \text{\AA}$) and 11.7% ($2.87\ \text{\AA}$), demonstrating the potential of the grazing-incidence geometry to extend the effective path length of neutrons in the conversion layer, thus boosting interaction probability without increasing the physical thickness of B_4C films.
2. **Structural Optimization:** Geant4 simulations revealed that the optimal thickness of the B_4C conversion layer depends on the number of layers and neutron wavelength. For a 10-layer structure, the optimal thickness is $2.0\ \mu\text{m}$ at $1.8\ \text{\AA}$ and $1.5\ \mu\text{m}$ at $4\ \text{\AA}$. The “efficiency plateau” narrows with increasing layer count and neutron wavelength.
3. **γ -Ray Suppression Performance:** The detector exhibits excellent γ -ray sensitivity ($<5 \times 10^{-6}$ for γ -ray energies up to $1.332\ \text{MeV}$), comparable to ^3He detectors and suitable for high γ -background environments.

Furthermore, the developed detector features a sealed vacuum structure (with a vacuum degree of $10^{-5}\ \text{Pa}$), eliminating the need for continuous gas supply. Compared with high-pressure ^3He -based systems, the use of low-cost Ar/CO_2 working gas significantly cuts down the overall fabrication and operational costs. In summary, the multilayer boron-lined neutron detector developed in this study demonstrates favorable performance in terms of detection efficiency, γ -ray sensitivity, and cost-effectiveness, providing a scalable and practical alternative to ^3He detectors and showing broad application prospects in fields such as reactor monitoring, neutron scattering instrumentation, and homeland security.

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