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Investigation of neutron detection using the Digital Video Disc (DVD) and converter layers

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HIGHLIGHTS

- Calculate the neutron tracks in DVD using practical and simulation methods.
- Using of a converter layer on DVD to convert neutrons to alpha particles.
- Determination of the neutron spectrum reached to the DVD layer.
- Calculation of the number of tracks as a function of the boron concentration in converter layer.

ABSTRACT

The neutron source at the Shahid Bahonar University of Kerman employs an Americium-Beryllium (Am-Be) source with an activity of 5 Ci. This study aimed to calculate neutron tracks from this source using experimental and simulation approaches. The PTRAC command of the MCNPX code was utilized to determine the neutron spectrum incident on the Digital Video Disc (DVD) converter layer. Advances in neutron detection methods have introduced significant innovations, including the use of converter layers combined with DVD layer as nuclear track detector. In this technique, a boron oxide layer with a thickness of 0.1 millimeters was put on the DVD surface to convert neutrons into alpha particles, allowing for nuclear track recording. Empirical results demonstrated that the number of tracks depended on the boron concentration in the converter layer. The angular spectrum of the DVD converter layer indicates that the highest particle collision angle occurred near 60°. Simulation result confirmed the feasibility of this method for neutron detection.

KEYWORDS
DVD
Am-Be neutron source
Boron
MCNPX code
Detection
Alpha Track

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1 Introduction

Americium-Beryllium (Am-Be) is widely used as a neutron-emitting source in multiple research fields, including chemistry, physics, geology, and archaeology, due to its high stability and consistent neutron flux over time (Clark, 1989). Am-Be sources produce stable neutron flux, making them suitable for diverse applications. Historically, neutron detection has relied on techniques such as foil activation, scintillation detectors, and semiconductor detectors, each with specific advantages and limitations. Foil activation is highly accurate but costly, lacking real-time measurement capabilities (Murata et al., 2007). Scintillation detectors provide high sensitivity but are costly and require complex calibration, limiting their practicality in specific settings. Semiconductor detectors offer high precision but are expensive and demand rigorous handling, especially in complex experimental setups (Šagátová-Perdochová et al., 2007). These limitations have increased interest in alternative neutron detection materials that are more cost-effective, straightforward, and widely accessible. Boron-based conversion layers, such as boron-doped Ga_2O_3, show promise in enhancing neutron detection efficiency while maintaining reasonable costs (Blevins and Yang, 2020). Digital Video Disc (DVD) to better understand neutron activity associated based layers coated with boron oxide (B_2O_3) have recently gained attention for their simplicity, low cost, and potential to enable neutron detection through alpha particle generation. However, challenges remain, particularly regarding the sensitivity of these materials, which is affected by the purity of boron in the converter layer. Addressing these limitations could make the DVD and converter layer method a viable alternative for neutron detection,

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Figure 1: Polycarbonate layer extracted from DVDs.

especially in field-based or cost-sensitive applications. Recent studies further underscore the feasibility of novel neutron detection materials. Thoms et al. demonstrated that imaging plates could provide high-resolution neutron imaging at a higher operational cost (Thoms et al., 1999). Arnaldi et al. explored the use of resistive plate chambers for thermal neutron detection, revealing high accuracy but with increased setup complexity (Arnaldi et al., 2004). These studies highlight the trade-offs between sensitivity, accuracy, and cost, reinforcing the need for alternative methods that balance these factors. The DVD and converter layer approach, with its accessibility and ease of use, holds promise as a complementary or supplementary detection technique to address these gaps (Solberg et al., 2001). This study aims to evaluate the DVD layer as nuclear track detector paired with an alpha-related converter layer to analyze the Am-Be neutron spectrum and angular distribution. The MCNPX code code can simulate the particle interactions and predicts track data on the DVD converter layer. Additionally, chemical etching reveals particle tracks, providing a straightforward method for neutron detection that complements existing technologies by balancing cost-effectiveness and performance (Riahi and Rezaie Rayeni Nejad, 2023). How to do this research will be explained in the next sections.

2 Materials and Methods

2.1 Simulation Method

To better understand neutron activity associated with the neutron source at Shahid Bahonar University and to establish accurate code inputs, simulations were done using the MCNP software package. Custom code was developed, and outputs were extracted via the PTRAC file. The simulation media employed a simplified geometry to validate fundamental physical processes, focusing on neutron interactions within the converter layer and quantifying the neutron production spectrum from a 5 Ci Am-Be neutron source. The simulation geometry included four key components: A) First, neutron collisions with the B_2O_3 converter layer were modeled, where neutrons interacted with a B_2O_3 layer, generating alpha particles through neutron capture reactions. These alpha particles were subsequently tracked as they entered the DVD layer. B) Second, the B_2O_3 converter layer was modeled with a thickness of 0.5 cm, based on prior studies indicating optimal alpha particle production within this range. A 1×1 cm^2 transition area and a $10 \times 10 \times 10$ cm^3 surrounding air volume were used to ensure ideal particle tracking conditions. C)Third, the neutron source was represented as a spherical region with a 0.15 cm radius at the beamline center. This radius was selected to confine all neutrons within the sphere, allowing precise measurement of path thickness. The PTRAC method was employed to calculate energy loss rates along particle trajectories, determining the average stopping power per unit path thickness and angular spectrum. D) Lastly, alpha particle angles ranging from 0 to 180 were analyzed using the Tally F8 random measurement function. A modified version of the MCNPX software was employed to generate detailed particle interaction data, including event counts, particle types (neutrons, photons, or electrons), interaction types, target nuclei, deposited energy, time, position, number of collisions, and collision energies.

The PTRAC card tracked particle spectra as they traversed the B_2O_3 converter layer and entered the DVD layer. Interdependencies among source variables, such as energy as a function of angle, were managed using distribution functions within MCNP for source variable modeling.To ensure the reliability of simulation results, uncertainties for critical variables, such as neutron flux and collision energy, were calculated based on multiple simulation runs. Averaging values and computing standard deviations provided a robust assessment of measurement precision.

2.2 Practical Test

As shown in Fig. 1, the DVD layer was used as the primary detection material due to its high resolution and sensitivity. Polycarbonate DVDs with a chemically extracted conversion layer were utilized, as polycarbonate facilitates effective ionization and particle detection, particularly when etched with NaOH and KOH solutions.

2.3 Experimental Setup

The experimental process was done at the radiation and activity position of the Am-Be neutron source facility . The radiation facility included the Am-Be neutron source at Shahid Bahonar University, a target set, a primary separation shield, and a protective enclosure. The target set, located at the end of the beamline in a vacuum-sealed aluminum box with a beryllium target, ensured consistent neutron generation. The primary separation shield, composed of 30% polyethylene blocks and a lead as shield, was designed to minimize gamma and neutron radiation exposure to the surrounding environment.

An image of the source setup is shown in Fig. 2, which includes beam-transfer tubes positioned approximately 2 cm downstream from the beryllium target. These tubes facilitate reproducible placement of specimens within the test chamber, ensuring consistent irradiation conditions. Samples were then transferred to the activity measurement site.

The first set of tests aimed to determine the optimal number and placement of transducer layers that could be included in a single radiation sample. Various sheets were positioned at regular intervals across the back surface of a glass plate secured with tape to function as transducers. These tests were conducted at an ambient temperature of 25 °C, with chemical etching at 70 °C. The transducer sheets were placed at different radial distances on the leading layer.

Since B-10 is rare in nature, with only six atoms of Boron-10 extracted per 30 grams of natural boron, the boron used in this experiment was prepared in the form of B_2O_3, produced in the laboratory. Samples were irradiated using blank DVDs and DVD converter layer sheets placed at designated locations.

The results of this process, including the spatial configuration and performance of the materials, are presented in Fig. 3.

The B_2O_3 thickness in the converter layer ranged from 1 mm to 13 mm, as measured with a micrometer, based on prior studies indicating that thicker boron layers improve neutron capture efficiency (Šagátová-Perdochová et al., 2007). Thicknesses within this range optimally balanced particle conversion and signal detectability. While greater thickness increased sensitivity, it also introduced potential reductions in resolution due to alpha particle scattering. A final thickness of 0.5 cm was selected for the primary test as a compromise between maximizing particle generation and preserving resolution in track detection.The transducer sheets were placed at various diameters on the main layer, with each thickness subjected to neutron irradiation for approximately ten minutes. Following irradiation, samples were transferred to the measurement system for particle track analysis. Each layer was examined under a microscope to count particle tracks. To improve reliability, each thickness was irradiated three times, and the resulting measurements were averaged to minimize errors caused by environmental factors. Figure 4 illustrates the different thicknesses of B_2O_3 layers applied to the DVD converter layers, along with the spatial configuration of the irradiated materials. By utilizing multiple thicknesses and analyzing each result, this study aimed to optimize sensitivity in neutron detection while balancing reliability and practicality.

Figure 2: A view of the neutron source at Shahid Bahonar University of Kerman.

Figure 3: DVD Lay on The B_2O_3 converter layer.

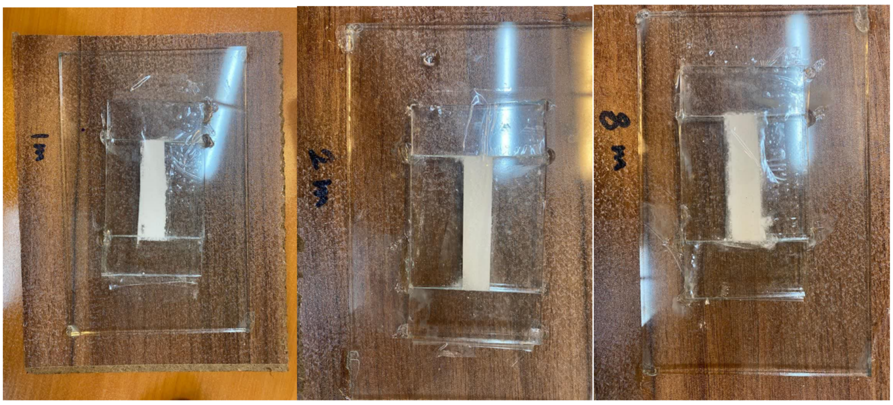
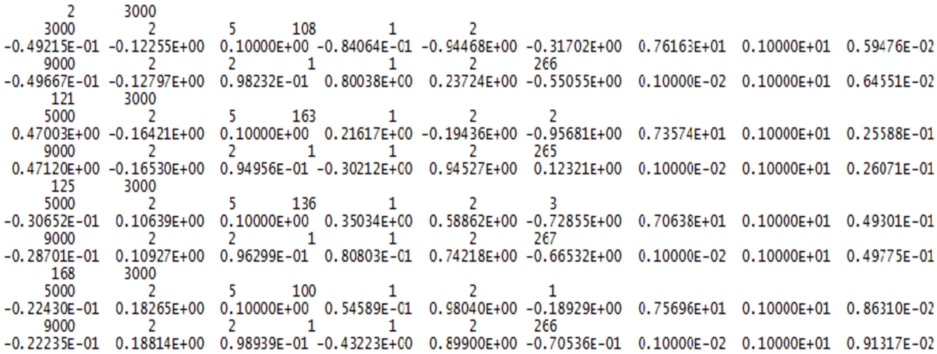


Figure 4: The converter layers, with different thickness.



```
          2      3000
       3000         2         5       108         1         2
-0.49215E-01 -0.12255E+00 0.10000E+00 -0.84064E-01 -0.94468E+00 -0.31702E+00  0.76163E+01  0.10000E+01  0.59476E-02
       9000         2         2         1         1         2       266
-0.49667E-01 -0.12797E+00 0.98232E-01  0.80038E+00  0.23724E+00 -0.55055E+00  0.10000E-02  0.10000E+01  0.64551E-02
        121      3000
       5000         2         5       163         1         2         2
 0.47003E+00 -0.16421E+00 0.10000E+00  0.21617E+00 -0.19436E+00 -0.95681E+00  0.73574E+01  0.10000E+01  0.25588E-01
       9000         2         2         1         1         2       265
 0.47120E+00 -0.16530E+00 0.94956E-01 -0.30212E+00  0.94527E+00  0.12321E+00  0.10000E-02  0.10000E+01  0.26071E-01
        125      3000
       5000         2         5       136         1         2         3
-0.30652E-01  0.10639E+00 0.10000E+00  0.35034E+00  0.58862E+00 -0.72855E+00  0.70638E+01  0.10000E+01  0.49301E-01
       9000         2         2         1         1         2       267
-0.28701E-01  0.10927E+00 0.96299E-01  0.80803E-01  0.74218E+00 -0.66532E+00  0.10000E-02  0.10000E+01  0.49775E-01
        168      3000
       5000         2         5       100         1         2         1
-0.22430E-01  0.18265E+00 0.10000E+00  0.54589E-01  0.98040E+00 -0.18929E+00  0.75696E+01  0.10000E+01  0.86310E-02
       9000         2         2         1         1         2       266
-0.22235E-01  0.18814E+00 0.98939E-01 -0.43223E+00  0.89900E+00 -0.70536E-01  0.10000E-02  0.10000E+01  0.91317E-02
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Figure 5: A segment of the PTRAC output data showing alpha particles incident on the DVD layer, produced through neutron interactions with the converter layer.

3 Results

The MCNPX simulation provided data on the energy spectrum angular spectrum and tracked particle interactions in the PTRAC output for neutron detection using the DVD converter layer. The output file generated by the PTRAC provides a detailed report on the interactions between primary and secondary particles within the system. Key parameters in the dataset include Cartesian coordinates, cosine values of effects, and the energy and time of particle collisions with the detector surface. Each event line in PTRAC describes a particles energy and trajectory along a designated path, recorded over two consecutive lines. Figure 5 presents sample PTRAC output data illustrating neutron interaction parameters in the DVD converter layer.

The PTRAC output categorizes particle interactions into five distinct groups. The first variable, "2," indicates the number of new particles generated during the Particle Tracking process within the simulation. A value of 3000 indicates a surface confluence, representing the specific surface traversed by the particle, while a value of 5000 marks the termination event, indicating the final recorded point in the particles path. The numeric value of 9000 corresponds to the last line of the data block. Similarly, the numeric undervalue 3000 specifies the point at which the particle enters the geometric structure.Further parameters in the output describe particle behavior. Numeric values 5 and 1 indicate that the particles have crossed from cell 5 into cell 1. The number 2 refers to the number of material objects encountered, while the value 108 denotes the angular measurement between the particle's path and the perpendicular to surface number 5. The first six digits in the third line specify the Cartesian coordinates and cosine values of the entering particle. The remaining values on the same line represent the particles energy, weight, and travel time. In the fourth line, the numerical value of 9000 signifies the ejection of the particle from the specified geometries.

This structured output allows for detailed tracking of particle interactions, enabling the quantification of behaviors such as blockages, termination events, and entry and exit points within the geometric framework. The angular spectrum represents the distribution of particle intensities based on emission angles. This analysis focuses on the spatial entry of particles at specific angles with energy levels exceeding the threshold determined by the etching condition.

Using the PTRAC output from the MCNPX simulation, data were processed and plotted using OriginPro software. Figure 6 shows the alpha energy spectrum following interaction with the converter layer. The spectrum indicates a peak in alpha particle generation at an energy of 4 MeV, with fewer particles observed at higher neutron energies. This trend suggests alpha particle conversion efficiency decreases as neutron energy increases, likely due to energy losses in the converter layer, which reduces track density.

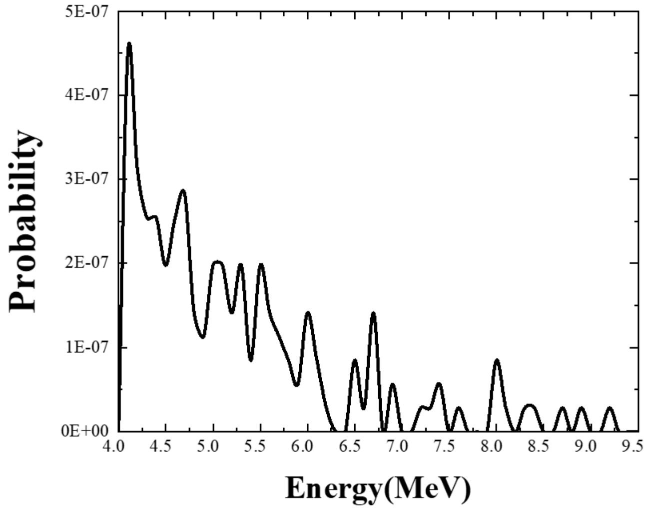

Figure 6: Alpha energy spectrum after the converter layer.

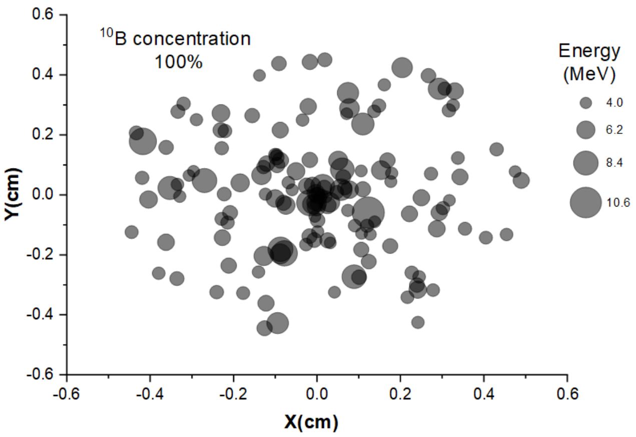

Figure 7: Spatial density of tracks on the DVD converter layer.

The spatial density of tracks on the DVD converter layers was mapped using the PTRAC file. Figure 7 illustrates the particles impacting the DVD at different (x, y) positions with different energy.

A chemical etching process exposed only the deeper particles that successfully penetrated the surface, improving data clarity. This method minimized superficial particle scatter and focused on primary impacts, yielding higher precision in measurements. The angular spectrum of the DVD converter layer, shown in Fig. 8, indicates that the highest particle collision angle occurred near 60°. The number of detected particles peaked at this angle, highlighting a maximum neutron interaction efficiency with the converter layer material.

At 90°, approximately 40 particles penetrated the DVD layer. The angular spectrum suggests that collision activity is highest around 80°, although particle density decreases at this angle.

These findings are consistent with previous studies, demonstrating that intermediate angles are optimal for converting neutron particles to detectable particles (Šagátová-Perdochová et al., 2007). This directional behavior is critical for optimizing detector alignment in practical applications.

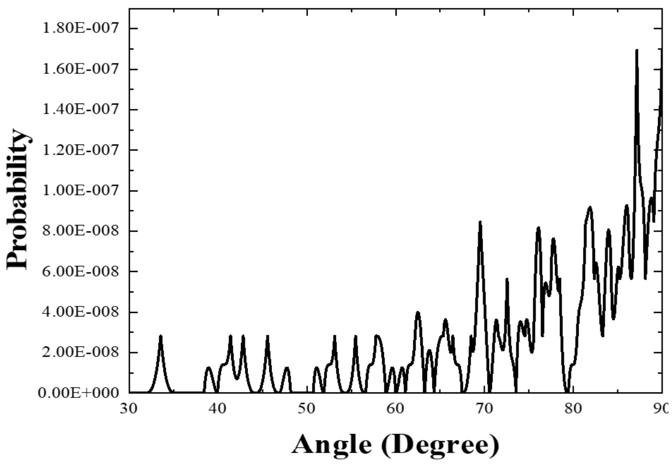

Figure 8: Angular spectrum of alpha on DVD surface calculated by PTRAC Output File Analysis.

3.1 Spatial Density and Boron Concentration Effects

Figure 7 shows the spatial density of particle tracks on the DVD converter layer, showing the highest density at the central region where particles strike at direct angles. This density distribution correlates with the initial neutron intensity, highlighting a high track density near the central impact zone. Table 1 shows a strong positive correlation between boron concentration in the converter layer and the number of tracks. Higher boron concentrations increase the likelihood of neutron capture and alpha particle generation, thereby increasing the track density. Optimal results were observed at a boron concentration of 100%, where the highest detection rates were obtained.

These results imply that increasing boron purity enhances sensitivity, which could be critical for effectively detecting low-energy neutrons. Table 2 demonstrates that as boron concentration increases, the number of tracks also rises, with a 100% boron concentration yielding the maximum number of tracks, indicating higher detection efficiency at 100% boron purity.

Table 1: The number of tracks generated by the converter layer.

Thickness of converter layer	B-10 (%)	Neutron Count (per sec)
1 cm	25%	165116.1
1 cm	20%	39104.58
1 cm	5%	22485.44

Table 2: Relationship between boron concentration, Neutron Flux, and Number of tracks.

Boron Concentration	Neutron Flux (per sec)	Number of Tracks
1.0 (100%)	35300000	151
0.25	30600000	31
0.2	35500000	35
0.05	20600000	12

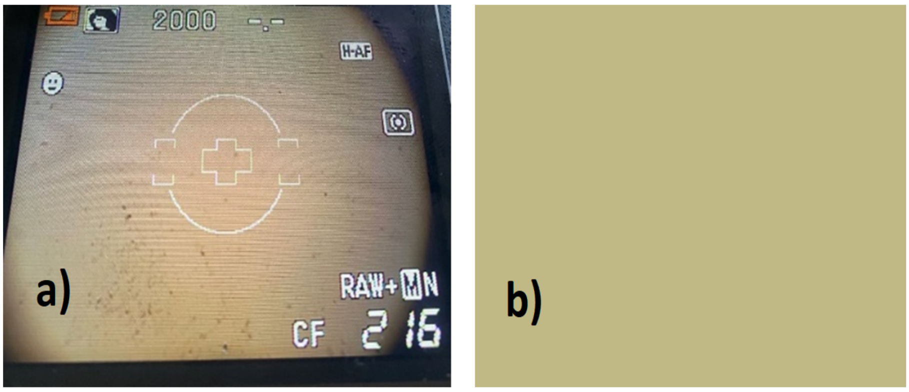

Figure 9: a) Tracks observed on the DVD converter layer after neutron irradiation. b) DVD converter layer before neutron irradiation.

3.2 *Practical results*

Initially, the polymer DVD conversion layer was divided into unit areas (1 cm^2) through a washing process to remove residual materials that could obstruct particles or cause defects on the polymer surface. The polymers were then coated with a B_2O_3 converter material. Each polymer was exposed to the neutron source for a specified duration in the next phase. Following neutron irradiation, chemical etching was performed at 70 to 80 °C. After the reaction was complete, the polymers underwent a drying process. Once dried, the polymers were examined under an optical microscope equipped with a camera to capture images of the tracks formed on their surfaces, as shown in Fig. 9-a.

Analysis of the images obtained from the polymers in the DVD conversion layer revealed that some fractures displayed conical or oblique shapes. These slopes were attributed to the impact of alpha particles. The primary objective was to minimize particle dispersion on the polymer surface. Figure 9-b shows the configuration of a chemically etched DVD conversion layer before radiation exposure, demonstrating the absence of visible marks on the surface.

While most results followed expected trends, some deviations were observed. For example, the neutron flux density in regions with lower boron concentrations was slightly higher than anticipated. This may have been caused by background radiation interference or incomplete neutron capture by the B_2O_3 layer. Additionally, a minor reduction in track density at higher energy levels was noted, likely due to energy loss within the layer caused by scattering effects and limited sensitivity at elevated neutron energies. The results demonstrate that the sensitivity of the DVD converter layer method is closely linked to boron purity. Higher boron concentrations enhance neutron-to-alpha particle conversion, leading to an increase in track density. Spatial density analysis further supports this finding, as regions with higher boron content exhibit denser neutron interaction patterns. This relationship underscores the potential for optimizing detection sensitivity by increasing boron purity in the converter layer, particularly for applications requiring accurate neutron detection at low-energy levels.These results suggest that optimizing boron concentration can significantly improve detection efficiency. Understanding tracks' angular distribution and spatial density could also help refine neutron detectors' alignment and material composition. The observed trends confirm the potential of the DVD converter layer as a cost-effective alternative for neutron detection, offering particular promise in applications where traditional high-cost detection technologies are impractical.

4 Discussion

The DVD with converter layer method for neutron detection presents advantages and limitations compared to conventional neutron detection technologies. This approach utilizes affordable and readily available materials, making it accessible for resource-limited settings. However, challenges related to sensitivity and boron purity limit its efficiency.A key advantage of the DVD/converter layer method is its cost-effectiveness. Unlike more complex and expensive detection systems, such as semiconductor or scintillation detectors, which require high-cost materials and specialized manufacturing, this method uses accessible components like DVDs and B_2O_3. This makes it especially suitable for low-resource environments where high-cost detectors are impractical (Paul et al., 2014). Furthermore, the simplicity and portability of this method enhance its applicability for field studies and remote research, where ease of handling and setup are critical (Clark, 1989).

Another significant benefit is its ability to analyze neutron tracks visually. Neutrons are converted into alpha particles within the boron converter layer, which creates visible tracks on the DVD surface. These tracks allow direct observation and analysis of particle paths, supporting a better understanding of neutron energy distribution and directional behavior. This feature represents a unique capability not typically achievable with conventional methods and aligns with findings in fast neutron detection (Šagátová-Perdochová et al., 2007).

Despite these advantages, the method has several limitations. One major drawback is its dependence on the purity of boron in the converter layer. Lower boron purity reduces the number of detectable particle tracks, thereby decreasing the method's sensitivity. Similar issues have been reported in other boron-based detection techniques, where material purity directly influences efficiency (Blevins and Yang, 2020). Additionally, the sensitivity of this method is lower than that of advanced detectors like semiconductor detectors and resistive plate chambers. These systems offer greater accuracy and efficiency, especially in low-flux environments, but are significantly more expensive (Arnaldi et al., 2004). Semiconductor detectors, in particular, provide superior sensitivity and energy resolution, making them ideal for applications requiring high precision. However, their high cost limits their accessibility for routine or field use (Solberg et al., 2001).

Another limitation is the need for post-processing, such as chemical etching, to reveal tracks. This step can be time-consuming and may introduce inconsistencies if not carefully controlled. Consequently, the method is less practical for real-time detection or rapid data collection (Thoms et al., 1999). Compared to conventional neutron detection methods, such as foil activation and scintillation detectors, the DVD/converter layer method is affordable and straightforward. Foil activation is accurate but lacks real-time measurement capabilities and can be expensive. Scintillation detectors are sensitive and capable of real-time measurements but require extensive calibration and specialized handling, which increases operational costs. Semiconductor detectors remain the most precise option but are prohibitively expensive for routine or field applications (Murata et al., 2007; Solberg et al., 2001).

To address these limitations, several modifications could be considered. Enhancing boron purity in the converter layer could significantly improve sensitivity, as demonstrated in other boron-based detection systems (Blevins and Yang, 2020). Alternative materials like multi-layered composite boron nitride may offer higher neutron conversion efficiency while maintaining cost-effectiveness (Roth et al., 2015, 2014). Refining the post-processing technique, such as developing faster or automated etching methods, could reduce processing time and improve consistency. This would make the method more suitable for environments requiring quick turnaround times. The DVD/converter layer method offers notable advantages, including affordability, ease of use, and portability. These features make it an appealing option for neutron detection in scenarios where high sensitivity and real-time measurement are not critical. The method's performance and applicability could be significantly enhanced by improving boron purity, exploring alternative materials, and optimizing post-processing. With these refinements, the DVD/converter layer approach holds potential as a practical and cost-effective solution for neutron detection, particularly in resource-constrained and field-based applications.

5 Conclusions

This study used a DVD/converter layer approach for neutron detection with a 5 Ci Am-Be neutron source at Shahid Bahonar University.The MCNPX simulations and practical result experiments evaluated the energy spectrum and angular distribution of neutrons impacting the DVD layer, which served as a nuclear track detector. Practical results showed low boron purity in the converter layer reduced detectable particle tracks. However, simulation results demonstrated the method's potential to capture energy distribution and angular data from neutron interactions.

An alpha spectrum was generated through neutron collisions with the boron-enriched converter layer. The produced alpha particles interacted with the DVD layer to create visible particle tracks. These tracks provide an innovative method for analyzing neutron energy. Angular distribution analysis revealed that the highest particle interaction occurred at a collision angle of about 60 degrees. At 85 degrees, around 40 particles penetrated the polymer layer. Results suggested that increasing boron purity, especially nearly 100%, significantly enhances detection efficiency and the relationship between neutron counts and particle tracks.

Traditional neutron detection methods often rely on electronic detectors, such as He-3 detectors, which use electronic circuits to identify secondary particles. In contrast, this study used secondary alpha particle tracks from neutron interactions with nuclear track detectors and DVDs.

The DVD/converter layer approach offers several advantages. It is cost-effective, easy to use, and portable, making it ideal for field-based studies and budget-limited research. This method can visualize neutron tracks directly without requiring advanced calibration or specialized equipment, which enhances its utility in educational research and remote applications.

Future studies should focus on increasing boron purity in the converter layer to address sensitivity limitations. Higher purity levels can improve detection efficiency. Additionally, exploring alternative materials or composite layers could further enhance neutron-to-alpha conversion. Optimizing post-processing techniques, such as automated etching, could also improve consistency and reduce processing time, making the method suitable for real-time applications.

In conclusion, the DVD/converter layer approach demonstrates promise as a novel and practical neutron detection method. Its low cost and simplicity make it particularly useful for resource-limited and field-based applications. With further refinements, this technique could become widely adopted in neutron spectroscopy and other areas where traditional detection systems are not feasible.

Conflict of Interest

The authors declare no potential conflict of interest regarding the publication of this work.

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