Nuclear Engineering and Technology 50 (2018) 439–445

Contents lists available at ScienceDirect

Nuclear Engineering and Technology

journal homepage: www.elsevier.com/locate/net

Original Article

Experimental and theoretical study of BF_3 detector response for thermal neutrons in reflecting materials

Rubina Nasir [a], Faiza Aziz [b], Sikander M. Mirza [c], Nasir M. Mirza [c, *]

[a] *Department of Physics, Air University, PAF Complex, E-9, Islamabad, 44000, Pakistan*
[b] *Department of Nuclear Engineering, Pakistan Institute of Engineering & Applied Sciences, Nilore, Islamabad 45650, Pakistan*
[c] *Department of Physics & Applied Mathematics, Pakistan Institute of Engineering & Applied Sciences, Nilore, Islamabad 45650, Pakistan*

ARTICLE INFO

Article history:
Received 28 July 2017
Received in revised form
6 December 2017
Accepted 28 December 2017
Available online 31 January 2018

Keywords:
Albedo
BF_3 Detectors
Monte Carlo Simulation
Response

ABSTRACT

Experimental measurements of the response of BF_3 detector to a 3 Ci Am–Be neutron source for three different reflecting materials, i.e., aluminum, wood, and Perspex of varying thicknesses have been carried out. The varying contribution of wall effect to the response due to change in active volume of the detector has also been determined experimentally. Then, a Monte Carlo code has been developed for the calculation of the neutron response function of the BF_3 detector using source biasing and importance sampling. This code simulates the BF_3 detector response exposed to the neutron field in a three-dimensional source, detector, and reflecting medium configurations. The results of simulation have been compared with the corresponding experimental measurements and are found to be in good agreement. The experimental neutron albedo measurements for various values of Perspex thickness show saturating behavior, and results agree very well with the data obtained by Monte Carlo simulation.

1. Introduction

Owing to their use in quantification of nuclear materials and shielding, neutron detectors have been studied extensively. The response of these detectors has been of concern, and various attempts have been made to study it both theoretically and experimentally [1,2]. The Monte Carlo method has been proven as one of the most accurate techniques for neutral and charged particle transport simulation. The method is applied to two main classes of nuclear problems: (a) fixed sources and (b) eigenvalue/criticality problems. Fixed source problems in general have transport of radiation through a medium that may cause absorption and isotropic/anisotropic scattering. These reactions produce changes in energy and direction of radiation. The Monte Carlo method has also been used for theoretical estimation of the response of neutron detectors. The characteristics of proportional counter were studied with experiments and conventional Monte Carlo simulations. Lippold et al. carried out Monte Carlo simulation of neutron moisture gauge [3], and Lees et al. (1980) performed similar calculations for the BF_3 detector assembly [4] while Dhairyawan et al. (1980) carried out these studies for spherically moderated neutron detectors [5]. In addition, a spherical neutron counter for spectrometry and dosimetry has been developed having polyethylene moderator and three slender ^{3}He position–sensitive proportional counters were inserted into the moderator [6]. Dunn and Shultis (2009) also carried out a detailed review of the use of conventional Monte Carlo methods for the design and analysis of radiation detectors [7].

Then, Saegusa et al. (in 2004) obtained the energy responses of three types of Japanese neutron dose-equivalent meters by basic Monte Carlo simulations and experimental measurements [8]. The energy responses were evaluated for thermal neutrons, monoenergetic neutrons with energies up to 15.2 MeV, and also for neutrons from radionuclide sources such as ^{252}Cf and ^{241}Am–Be.

Recently, hybrid Monte Carlo methods have emerged as fast converging techniques to simulate stochastic response of detectors by combining basic Monte Carlo method with empirical relations in the particle history within the detector [9]. These methods have high efficiency and fast convergences as compared with conventional Monte Carlo procedures.

The purpose of this study is to analyze the response function of the BF_3 detector using various reflector materials. First, the response of the BF_3 detector has been studied experimentally, and the dependence of the BF_3 detector response on detector size and on thickness of the reflector was studied. Then, a Monte Carlo–based computer code was developed to simulate the response

---

* *Corresponding author.*
E-mail address: nmm@pieas.edu.pk (N.M. Mirza).

https://doi.org/10.1016/j.net.2017.12.014

of the BF_3 detector by considering the neutron histories in the BF_3 detector using importance sampling in the conventional Monte Carlo method. This simulation program has been developed using MATLAB, version 6. This simulation software has been developed by MathWorks Inc., of USA. The details of the experimental setup and method used in this work are described in section 2. Then, the mathematical details of model including the governing differential equations along with particulars of computer implementations are given in section 3. In section 4, comparisons of the results obtained by using this methodology with experimental results are discussed. The conclusions of this study are presented in section 5.

2. Materials & Experimental method

The BF_3 proportional detectors have cylindrical outer cathode and small diameter central wire anode. Aluminum is used as cathodes due to its low neutron interaction cross section. Typical gas multiplication at operating voltage is of the order of 100–500. These systems are limited to temperatures up to about 100°C as pulse height resolution decreases beyond room temperatures.

2.1. Setup and measurements

A 3 Curie cylindrical Am–Be neutron source was used with neutron emission rate of 7.2×10^6 neutrons/second. The source was enclosed in a cylinder filled with paraffin wax at a depth of 11 cm from the top level. The geometrical arrangement of the neutron source, moderator (paraffin wax), and BF_3 detector is shown in Fig. 1 [10]. For the thermalization of neutrons emitted from the neutron source, paraffin wax was used. A slab, about 7 cm in thickness, was placed over the cylinder containing the source. For the placement of the detector on the slab, a channel on the surface of paraffin was available.

The block diagram of experimental setup is shown in Fig. 1, and the nuclear electronics used was built in standard nuclear instrumentation module (NIM) system. Here SCA is single channel analyzer, Large values of electric fields are needed for high gas multiplication, and applied voltage was about 1500 V using extra-high tension supply, with anode radius of 0.1 mm and cathode inner radius of 2.5 cm. The resulting electric field at the anode surface was about 2.7×10^6 V/m.

The electronic pulses from the BF_3 detector, on passing through the amplifier, were amplified and interfaced to the pulse-processing electronics. The signal from the preamplifier was further amplified by the amplifier, and the bipolar output from the amplifier was fed to the Timing Single Channel Analyzer (TSCA) operated in crossover timing mode. The discriminator level was fixed to a position such that the electronic noise was eliminated. The output logic pulses from the TSCA were routed to the counter. The bipolar pulses from the amplifier were also sent to the cathode-ray oscilloscope and the personal computer–based multichannel analyzer (MCA). The APTEC multichannel analyzer system was used in the experiment.

Five different reflecting materials, Perspex, aluminum, iron, copper, and wood, of different thicknesses were used. These are based on some typical materials used as neutron reflectors and in neutron shields [11]. The BF_3 detector was placed over the paraffin wax, and for various thicknesses of all the reflectors, counts from the TSCA were noted, and the corresponding spectrum was collected on the MCA. The gamma-ray emission from neutron sources is typically large, but energy deposition due to their interactions inside the BF_3 detector is small. Consequently, the resulting pulses heights are mostly below lower wall effect edge. For gamma pulse rejection, suitable cutoff was used in the MCA. The detector was then covered with semi-cylindrical cadmium cover and was placed such that in the first set of observations, the cadmium cover faced the neutron source, and in the second set, it was opposite to the source. Counts were again noted from the TSCA, and corresponding spectra were collected on the MCA for varying thicknesses of the reflecting materials for both of the cases. Albedo was measured for various thicknesses of the reflecting materials.

To see the effect of change in active volume on the response of the detector, three different locally designed detectors, designated as BF3-1, BF3-2 and BF3-3, were used. Parameters of these three detectors are shown in Table 1. Using the method adopted by Yamashita et al. [12], relative sensitivity of moderated BF_3 detectors for isotropic fluxes was measured, and it remained in the range of 0.45–0.83 for energy domain of 0.01–0.5 eV for these three detectors. The self-shielding factor for thermal energies in Cd shields was in the range of 0.895–0.991.

All other parameters such as the collection time, reflecting material, thickness of the reflecting material, time constant of the amplifier, and discriminator level were kept constant. Same

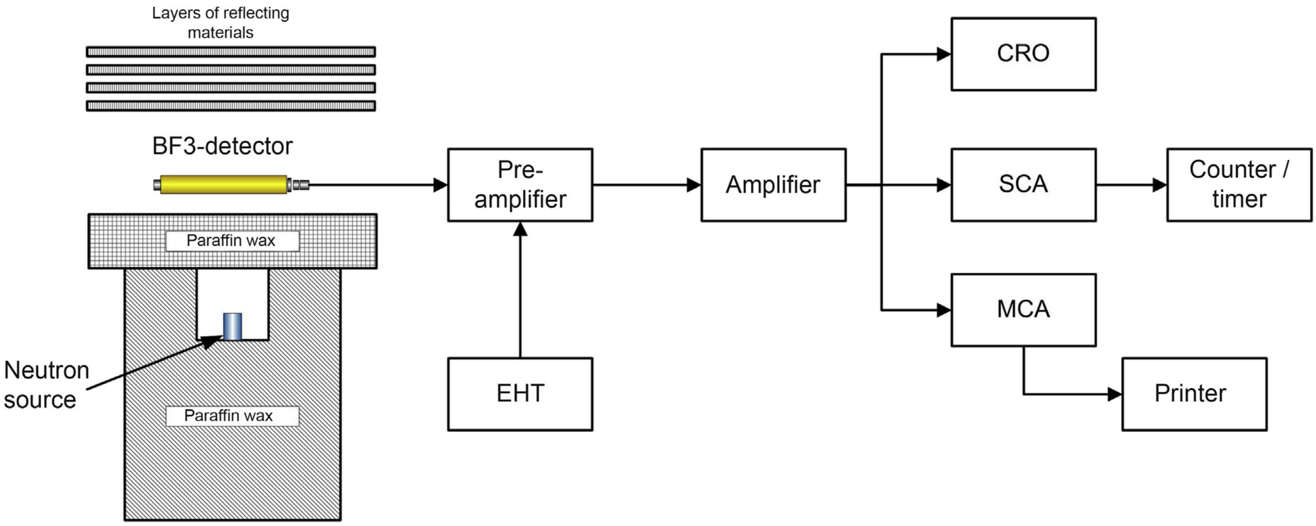

Fig. 1. Block diagram of the experimental setup for neutron detection using a typical BF_3 detector.
CRO, cathode-ray oscilloscope; EHT, extra-high tension; MCA, multichannel analyzer.

Table 1
The design parameters of various BF_3 detectors used in this work.

Detector label	Active length (cm)	Diameter (cm)	Sensitive volume (cm^3)	Operating voltage (V)
BF3-1	20	2.54	101.34	2000
BF3-2	15	2.50	73.63	1700
BF3-3	21	2.55	107.24	2000

observations were made for all the three detectors for the same three cases; without cadmium cover, with cadmium cover facing the source, and with cadmium cover opposite to the source. The cadmium, a thermal neutron absorber, as a detector cover, allows the detection of neutrons with energies higher than the cadmium cutoff value $\sim 0.5\,eV$. The reflection coefficient was calculated from the data taken from the TSCA, and albedo was plotted as a function of thickness of each of the neutron reflectors.

3. Simulation procedure

In this work, a typical cylindrical BF_3 detector has been considered. The design specifications of three different detectors used are listed in Table 1. For calculating the response of the BF_3 detector, neutron tracking from source to detector has been used for a cylindrical Am–Be source. Sampling of position of emission of neutrons, their direction of emission, and the free flight distance have been carried out as described by Kalos and Whitlock [13].

The flow chart representing the transport of neutrons from source up to the BF_3 detector is shown in Fig. 2. When the interaction of neutron takes place inside the detector, $n(^{10}B,^{7}Li)^{4}He$ reaction takes place.

$$n + {}^{10}B \rightarrow \begin{cases} {}^{7}Li + \alpha + 2.79MeV(6.1\%) \\ {}^{7}Li^{*} + \alpha + 2.31MeV(93.9\%) \end{cases} \tag{1}$$

The reaction products ^{4}He and ^{7}Li are assumed to be emitted in an isotropic manner, and their range in the detector can be computed by using Bethe's formula for a nonrelativistic form [12]:

$$\frac{dE}{dx} = -\frac{4\pi n z^2}{m_e v^2}\left(\frac{e^2}{4\pi\varepsilon_o}\right)^2 \ln\left(\frac{2m_e v^2}{I}\right) \tag{2}$$

The energy E_d deposited inside the detector is approximated by assuming linear energy deposition rate. In the first part, the range was assumed as an input to the Monte Carlo program, and empirical adjustments were made to conform to the response. This procedure makes the Monte Carlo scheme a hybrid one. The range

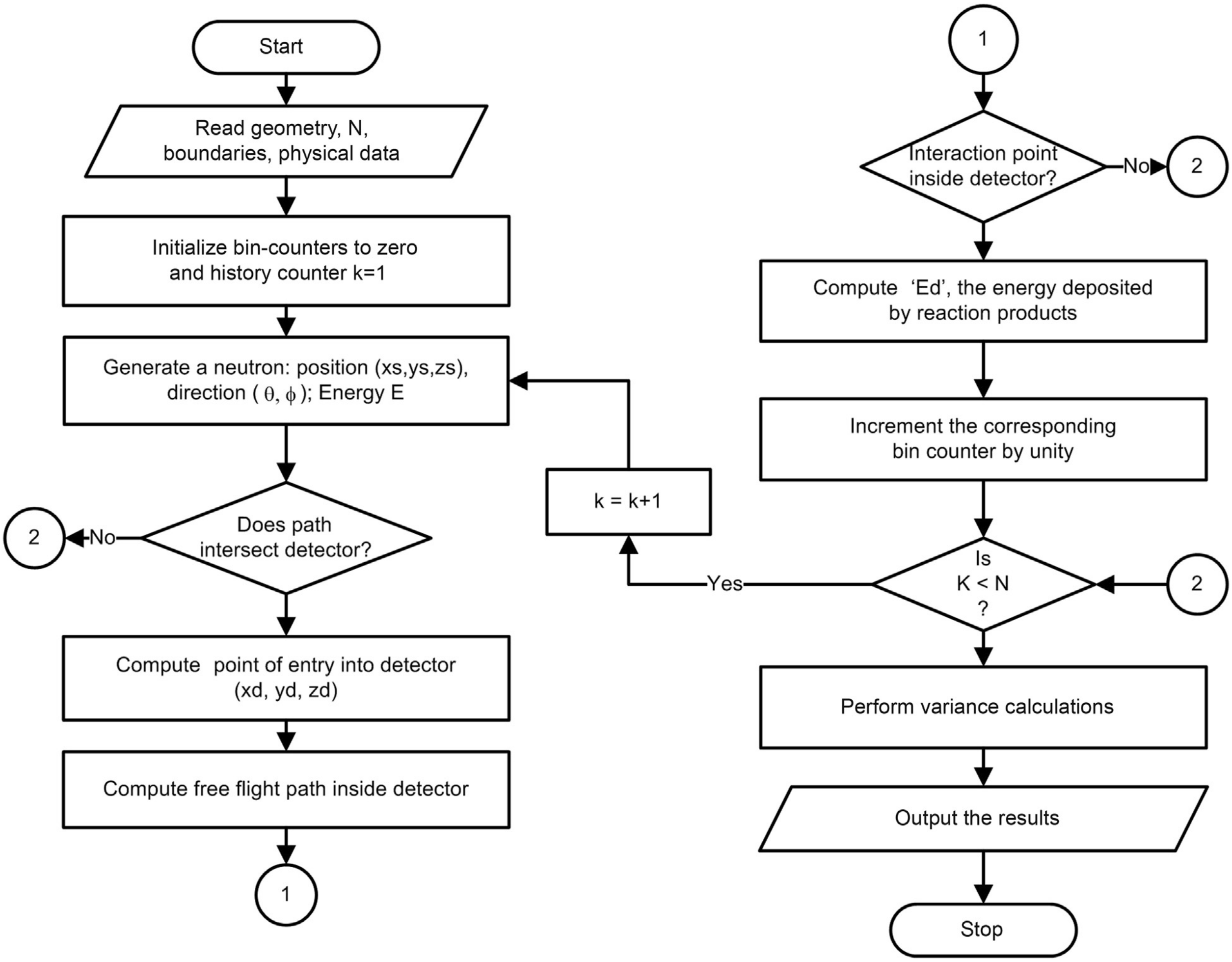

Fig. 2. Computational steps in hybrid Monte Carlo methodology developed in this work.

of the reaction products was calculated by Bethe's formula at a pressure of 600 mbars. However, the range does not have a constant value and is a function of energy and gas pressure; therefore, a weighting factor was included. The calculated range of the reaction products was then multiplied by the weighting factor. The range remains a nonlinear function of energy because the number of collisions undergone by each of the reaction products on their way with the atoms of the fill gas is different. Therefore, the energy deposited by the reaction product within the active volume of the detector does not depend linearly on the range. We have included a nonlinear term into the calculations of energy deposited by the reaction products. The deposited energy as a function of range of reaction product (R) has been modeled as following:

$$\text{Energy deposited} = a \times E \times (R/R_H) + b \times E^2 \times (R/R_H)^2 \qquad (3)$$

where, E is the energy of the reaction products; R is the range of the reaction product; R_H is the distance covered by the reaction product within the active volume. The first term models the linear trend, and the second term represents the nonlinear behavior of the energy deposited by the reaction products.

The excited state reaction has high Q value and results in large mean free paths. In case of large mean free path, the energy deposited within the detector becomes small. Consequently, the wall effect dominates in the detector. Hence, more energy is deposited in the walls of the detector than energy deposition in the active volume. The wall effect associated with the full energy peak of the ground state interaction does not allow the full peak to be equal to the energy of 2.79 MeV; therefore, by taking the proper energy to be deposited within the active volume, the response of the detector is modeled adequately.

In Monte Carlo method, the particle counts remain low when large numbers of bins are made in the energy range and each bin size has very small energy size. Therefore, large numbers of histories are needed to achieve statistically reliable results. Variety of methods has been developed to reduce variance in natural sampling procedure based on physical laws of particle transport [12]. In this work, we have used importance sampling for each energy bin with source biasing. Source biasing is widely used to reduce the amount of computer time spent on simulating source particles in regions that do not contribute to the objective. We have also focused our computational efforts on the simulation of “important” particles. The importance of each bin is estimated as suggested by Haghighat and Wagner [9]. To compensate for this modification and to conserve particles, each particle is given a statistical weight that is adjusted based on the following equality,

$$w(\mathit{biased})\mathrm{pdf}(\mathit{biased}) = w(\mathit{unbiased})\mathrm{pdf}(\mathit{unbiased}) \qquad (4)$$

where, “pdf” refers to the probability distribution of the physical process being sampled and “w” refers to the particle weight. The main difficulty associated with using such variance reduction techniques is the determination of the problem-dependent variance reduction parameters present in the biased terms. In this regard, the source biasing technique is very popular and has been used in this work. In this technique, the simulation of more source particles, with appropriately reduced weights was done, in the more important regions of each variable (that is space, energy, and angle). We have done the sampling of the source from a biased probability distribution rather than from the true probability distribution and then correcting the weight of the source particles by the ratio of the actual probability divided by the biased probability according to Eq. (4). Therefore, the total weight of particles in any given interval is conserved, and an unbiased estimate is preserved.

Furthermore, owing to inadequate sampling, poor estimates of the importance function can happen. In this regard, an iterative procedure was used to keep appropriate variance reduction for the calculations of response.

4. Results and discussion

4.1. Detector size dependencies

The response of the BF_3 detector depends on the sensitive volume of the detector. In this study, three BF_3 detectors with different values of detector length, diameter, and sensitive volumes have been considered, and their design specifications are given in Table 1. The BF3-1 and BF3-3 are somewhat similar in the values of various parameters, whereas the BF3-2 is of smaller dimensions. The corresponding experimentally measured response of these detectors is shown in Fig. 3. It is clear from this figure that a detector having larger value of sensitive volumes and higher relative sensitivity has higher value of counts recorded in the main peak, whereas the opposite is true for a detector with smaller value of sensitive volume. The response of smaller sized detector becomes low because the sensitive volume of the detector allows lower interaction rate, and consequently, the main peak height becomes smaller, and also, the small-sized detector has low solid angle values. The experimental results are consistent with the expected behavior.

4.2. Effect of reflector thickness

By increasing the thickness of the reflecting material, more neutrons are reflected back toward the BF_3 detector. The behavior of the BF_3 detector response for aluminum, wood, and Perspex, as a function of reflector thickness, is shown as Fig. 4. Furthermore, the BF_3 detector response for various thickness values of Cu and Fe reflectors is given in Fig. 5. It is observed that there is a rising trend in the BF_3 response with an increase in the reflector thickness which agrees with the expected behavior. For equal increments in the reflector thickness, the amount of uplift is higher initially, and for larger thickness values, it becomes saturated. As reflector thickness is increased, the scattered neutron current rises sharply and subsequently approaches the maximum value which corresponds to the infinite thickness of the reflecting medium.

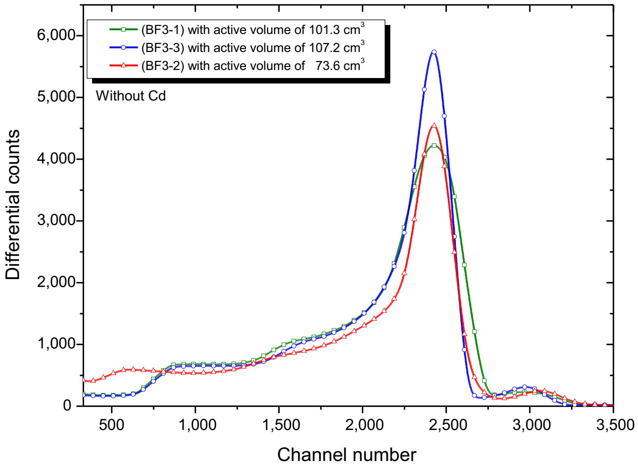

Fig. 3. Experimental response of three different BF_3 detectors with cadmium cover facing the source for same amplification factors.

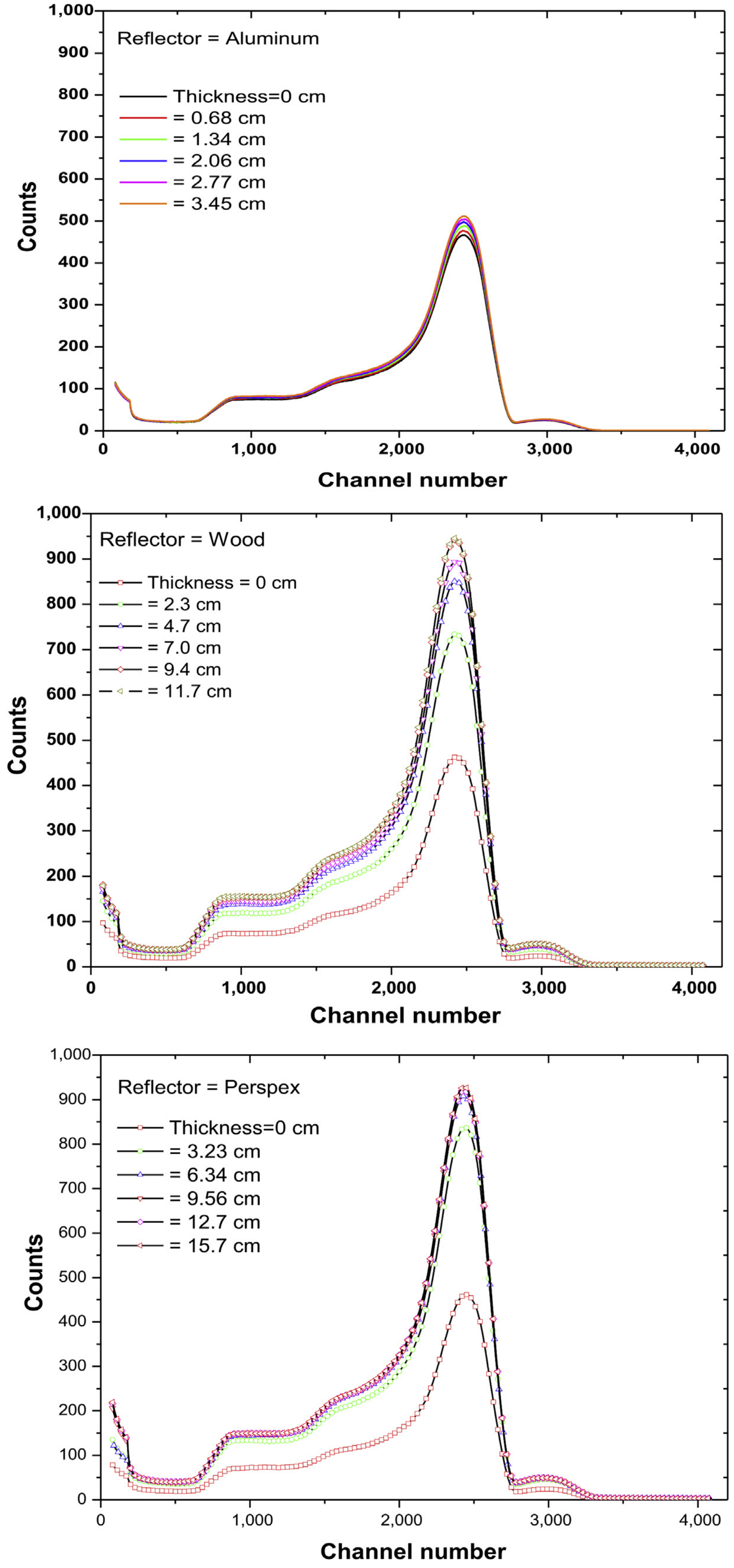

Fig. 4. Experimental response of the BF_3 detector without cadmium cover as a function of thickness of reflecting materials (aluminum, wood, and Perspex).

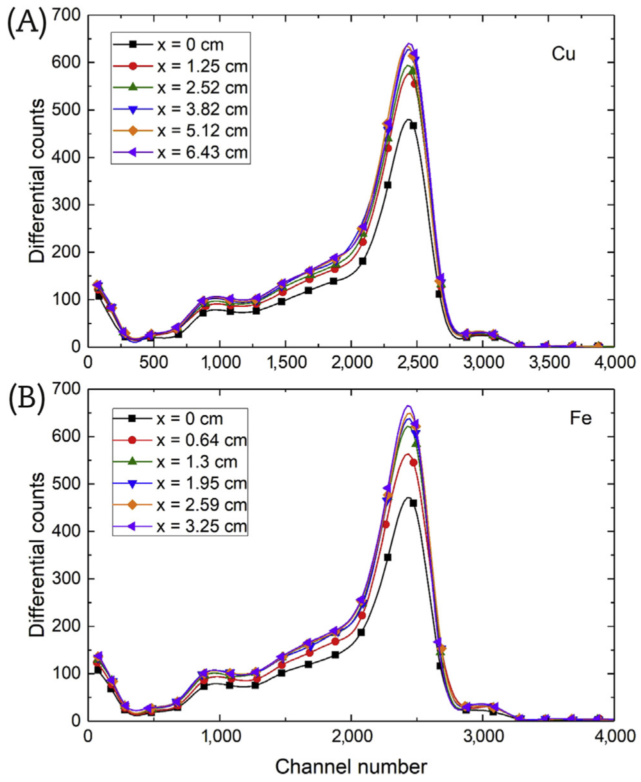

Fig. 5. Experimental response of the BF_3 detector without cadmium cover as a function of thickness. (A) Copper as reflecting material. (B) Iron as reflecting material.

4.3. Comparison of simulated response with experiments

By using the hybrid Monte Carlo–based code, simulations for the response of the BF_3 detector have been carried out. To improve statistics, neutron histories in excess of a million have been tracked in these simulations. The variance in the simulated results is quite small, and the corresponding size of error bars is smaller than the symbols shown in the figures. The importance sampling was employed along with deterministic variance reduction method which included source biasing technique. It was found that by iterative process, better variance reduction parameters can be fixed and even with small bin size, faster convergence was achieved. Even with these improvements, the program still requires substantial computational time.

The deposited energy as a function of range of reaction product (R) was expressed as Eq. (7), and the values of weighting factors a and b were found by parametric studies. These results are shown in Fig. 6. The optimum values of the factors a and b for ^{4}He are 0.9 and 0.45, respectively, and for ^{7}Li, they are found as 0.5 and 0.5, respectively. As depicted in Eq. (3), the energy deposition depends on linear and nonlinear terms. The first term having factor a is depicting a linear trend, and the second term with b represents the nonlinear behavior of the energy deposited by the reaction products. These factors (a and b) were different for He-4 and Li-7 due to the strong linear dependence of range on energy deposited and the respective mass of reaction products.

Once the parameters were fixed for a typical detector, the complete comparison was done. Both the theoretical and experimental results for such a case are shown in Fig. 7. It shows a good agreement between the theoretical and experimental model for the full peak energy of the ground state ^{10}B (n, α) Li^7 reaction. It is also clear from the figure that the hybrid Monte Carlo–based simulations predict both the peaks and the first wall effects correctly. However, there are small differences in the spread of the full peak energy of the excited state at 2.31 MeV for ^{10}B (n, α) Li^7 interaction because there is a wall effect associated with the full energy peak of 2.792 MeV which adds up to the full peak of 2.31 MeV.

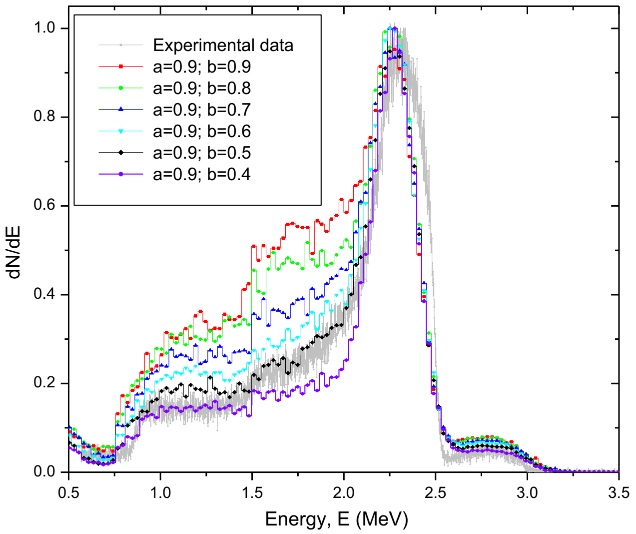

Fig. 6. Theoretical response of the BF_3 detector using hybrid Monte Carlo method for various values of a & b weighting factors and experimental results.

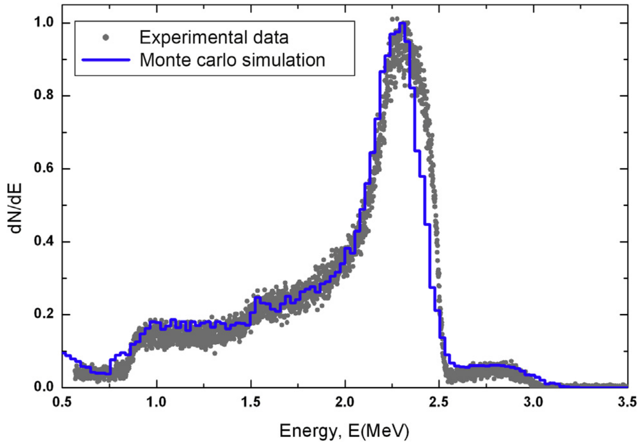

Fig. 7. Comparison of experimental response for a typical BF_3 detector with results from hybrid Monte Carlo method.

The first step of the wall continuum, due to the full energy peak of 2.31 MeV, was uplifted. A good agreement of hybrid Monte Carlo method and experiments was found for the second step of the wall effect due to excited state of ^{10}B (n, α) Li^7 interaction. This is due to the nonlinearity introduced into the range of the reaction products. The nonlinearity becomes important when detectors have small dimensions. The low energy part of the response shows small discrepancies between theoretical predictions and the corresponding experimental values.

The ratio of reflected-to-incident neutron current, called “albedo,” depends on the value of reflector thickness, and it was measured for Perspex using the BF_3 detector and cadmium covers. The measured neutron albedo for various values of thickness of Perspex is shown in Fig. 8. We have also determined the neutron currents and their ratios using Monte Carlo method, and it matches

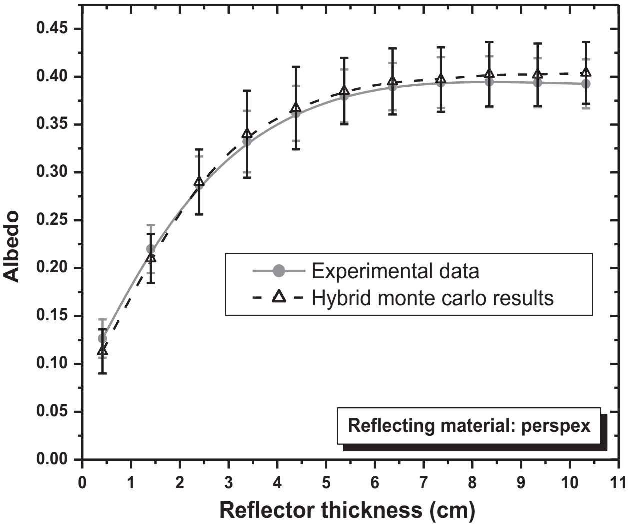

Fig. 8. Comparison of experimental neutron albedo as a function of thickness for Perspex reflector with results from hybrid Monte Carlo method.

fairly well with the experimental results. However, Monte Carlo simulations show large variance as compared with experiments for about million histories and require only six iterations to converge at predetermined accuracy. The variance could further be reduced if iterations are increased or total number of histories in iteration is increased.

5. Conclusions

Experimental measurements of the response of the BF_3 detector to a 3 Ci Am–Be neutron source for five different reflecting materials, i.e., Perspex, aluminum, iron, copper, and wood, of varying thicknesses have been carried out. Then, a hybrid Monte Carlo code was developed for the calculation of the neutron response function of the BF_3 detector using source biasing and importance sampling. This code simulates the behavior of the BF_3 detector exposed to the neutron field in a three-dimensional configuration for desired accuracy in an iterative manner.

The ranges of the reaction products ^{4}He and ^{7}Li are nonlinear function of energy because the number of collisions undergone by each of the reaction product on its way with the atoms of the fill gas is different. Therefore, the energy deposited by the reaction product within the active volume of the detector does not depend linearly on the range. A nonlinear term was included in calculations of energy deposited by the reaction products. The simulated response has been found in good agreement with the corresponding experimental measurements.

The experimental response of the detector shows strong dependence on the physical dimensions including the length and diameter of the detector. The response indicates higher values of main peaks for detectors having larger values of detector-sensitive volumes. By increasing the thickness of reflecting materials, the measured response shows an increase. This rising trend becomes saturated beyond certain thickness of the reflector. This behavior is consistent with the corresponding results from Monte Carlo method. The experimental neutron albedo measurements as a function of thickness for Perspex show saturating behavior, and results agree very well with the hybrid Monte Carlo simulation.

Conflicts of interest

The references quoted are based on simple and direct Monte Carlo methods and we have employed hybrid Monte Carlo method which is very different from simple Monte carlo methods and requires experimental inputs and iterative procedures beyond simple Monte Carlo procedures.

References

[1] D.M. Crawford, B.W. Thomas, K. Bottcher, et al., Experimental verification of the flatness of response of a multi-BF_3 counter neutron detection system, Nucl. Instrum. Methods 106 (1973) 311–315.
[2] R.F. Barrett, J.R. Birkelund, H.H. Thies, Investigation of the flatness of response of a multi BF_3-counter neutron detection system, Nucl. Instrum. Methods 68 (1969) 277–283.
[3] W.J. Lippold, A. Carnesale, R.P. Gardner, A Monte Carlo simulation of the surface-type neutron moisture gauge, Nucl. Eng. Des. 10 (1969) 373–380.
[4] E.W. Lees, B.H. Patrick, E.M. Bowey, A high efficiency BF_3 detector assembly for photofission and photoneutron studies, Nucl Instrum. Methods 171 (1980) 29–41.
[5] M.P. Dhairyawan, P.S. Nagarajan, G. Venkataraman, Response functions of spherically moderated neutron detectors, Nucl. Instrum. Methods 169 (1980) 115–120.
[6] H. Toyokawa, A. Uritani, C. Mori, et al., Neutron spectrometer with position-sensitive proportional counters, Nucl. Instrum. Methods Phys. Res. Sec. A 381 (1996) 481–487.
[7] W.L. Dunn, J.K. Shultis, Monte Carlo methods for design and analysis of radiation detectors, Radiat. Phys. Chem. 78 (2009) 852–858.
[8] J. Saegusa, M. Yoshizawa, Y. Tanimura, et al., Evaluation of energy responses for neutron dose-equivalent meters made in Japan, Nucl. Instrum. Methods Phys. Res. Sec. A: Accelerators, Spectrometers, Detectors and Associated Equip. 516 (2004) 193–202.
[9] A. Haghighat, J.C. Wagner, Monte Carlo variance reduction with deterministic importance functions, Prog. Nucl. Energy 42 (2003) 25–53.
[10] S.M. Mirza, M. Tufail, M. Rizwan Liaqat, Thermal neutron albedo and diffusion parameter measurements for monolithic and geometric voided reflectors, Radiat. Measurements 41 (2006) 89–94.
[11] G.W. Neeley, D.L. Newell, S.L. Larson, et al., Reactivity Effects of Moderator and Reflector Materials on a Finite Plutonium System, SAIC, 2004, pp. 1322–1324, 2001 Rev. I, US NRC-Public Documents.
[12] M. Yamashita, L.D. Stephens, A.R. Smith, H.W. Patterson, Detector efficiency of bare and moderate BF3-gas-filled proportional counters for isotropic neutron fluxes, J. Nucl. Sci. Technol. 3 (8) (1966) 343–353.
[13] M.H. Kalos, P.A. Whitlock, Monte Carlo Methods, vol. 1, WILEY-VCH Verlag GmbH & Co., 1986.