NUCL SCI TECH (2017) 28:61
DOI 10.1007/s41365-017-0213-z

Optimization of moderator assembly for neutron flux measurement: experimental and theoretical approaches

Abdul Waheed[1] · Nawab Ali[2] · Muzahir A. Baloch[3] · Aziz A. Qureshi[1] · Eid A. Munem[4] · Muhammad Usman Rajput[2] · Tauseef Jamal[5] · Wazir Muhammad[6]

Received: 24 June 2016 / Revised: 2 September 2016 / Accepted: 24 September 2016 / Published online: 28 March 2017

Abstract A moderator of paraffin wax assembly has been demonstrated where its thickness can be optimized to thermalize fast neutrons. The assembly is used for measuring fast neutron flux of a neutron probe at different neutron energies, using BF_3 ($\Phi1''$ and $2''$) and ^{3}He($\Phi0.5''$) neutron detectors. The paraffin wax thickness was optimized at 6 cm for the neutron probe which contains an Am–Be neutron source. The experimental data are compared with Monte Carlo simulation results using MCNP5 version 1.4. Neutron flux comparison and neutron activation techniques are used for measuring neutron flux of the neutron probe to validate the optimum paraffin moderator thickness in the assembly. The neutron fluxes are measured at $(1.17 \pm 0.09) \times 10^5$ and $(1.19 \pm 0.1) \times 10^5$ n/s, being in agreement with the simulated values. The moderator assembly can easily be utilized for essential requirements of neutron flux measurements.

Keywords Am–Be and ^{252}Cf neutron sources · BF_3 & ^{3}He detectors · Paraffin wax · Neutron flux · Monte Carlo simulation

✉ Wazir Muhammad
wazirm@hotmail.com

1 Radiation Physics Laboratory, Physics Department, COMSATS Institute of Information Technology (CIIT), Islamabad, Pakistan

2 Physics Division, Pakistan Institute of Nuclear Science and Technology (PINSTECH), Islamabad 45650, Pakistan

3 Department of Physics, College of Science, Majmaah University, Al-Zulfi, Saudi Arabia

4 School of Physics, University Science Malaysia, 11800 Gelugor, Penang, Malaysia

5 DCIS, Pakistan Institute Engineering and Applied Sciences (PIEAS), Islamabad 45650, Pakistan

6 Health Physics Division (HPD), Pakistan Institute of Nuclear Science and Technology (PINSTECH), Islamabad 45650, Pakistan

1 Introduction

The Am–Be and ^{252}Cf neutron sources are widely used in neutron dosimetry laboratories. The important features of Am–Be source are its long half-life and emission of fast neutrons with rather wide energy spectra, while ^{252}Cf yields a highly concentrated and reliable neutron spectrum from a small assembly. The last feature of both sources is helpful in covering the energy domain of interest for many applications in ambient and personal dosimetry. Nevertheless, the neutron energy spectrum depends on materials and dimension of the capsule and on amount and physiochemical properties of active material, thus affecting relevant quantities such as spectrum-averaged fluence-to-dose equivalent conversion coefficient [1–6]. It is important to know the neutron flux accurately so as to measure different quantities related to a neutron source [7].

Neutron detection has a key role in the development of nuclear technology and its applications [8, 9]. High-sensitive neutron detectors are required. However, most of the neutron detectors are also sensitive to gamma rays. Therefore, an effective technique is required to eliminate the gamma background for accurate neutron measurements. Generally, methods used to recognize neutron interactions within a detector rely on second-order effects. Two neutron interactions used for a variety of thermal neutron detectors are the $^{10}B(n,\alpha)^{7}Li$ [9, 10] and $^{6}Li(n,\alpha)^{3}H$ reactions [11, 12]. The α particles can be easily detected.

Low atomic number materials, such as high-density polyethylene (HDPE), which has a high concentration of hydrogen, tend to have relatively high elastic scattering cross sections for fast neutrons, and often (n, p) reactions from fast neutrons interacting in hydrogen-filled materials are manipulated for fast neutron detection. For detection of thermal or low-energy neutrons, polymers-based SSNTDs, i.e. solid-state nuclear track detectors (such as CR-39), can be used only in combination with a neutron reactive film which converts neutrons into other detectable radiations, recoil nuclei [13, 14]. Use of a BF_3 or ^{3}He neutron detector, one can measure the optimum thickness of the moderator accurately, which is essential to avoid excessive thermal neutron absorption in the moderator. The neutron activation analysis can determine accurately the major and trace elements in different samples [10–12, 15]. In practice, aromatic hydrocarbons are considered as the most radiation-resistant hydrogenous substances and have properties to moderate slow neutrons more effectively [16].

A paraffin wax moderator assembly has been developed to find out optimum thickness of paraffin wax. It can be utilized for fast neutrons from various neutron-producing reactions on an accelerator or for measurement of neutron yield from a Mather-type plasma focus device [17–20]. The assembly has been utilized to find out neutron flux of a neutron probe which contains Am–Be as a neutron source [21]. Neutron flux comparison and neutron activation are used to the measure neutron flux [22]. A 50-mCi Am–Be neutron probe is used as a neutron source for the measurement of moisture in soils [21].

The moderating materials should be of large scattering cross section, small absorption cross section and large energy loss per collision [23], and paraffin wax is just a desired moderator. Its optimum thickness was calculated for 3 MeV neutrons [22] and was experimentally determined at 7 and 2.5–4.5 cm for Am–Be and ^{252}Cf neutron sources, respectively [24, 25]. The results were based on the maximum gamma ray yield due to neutron activation. The optimum thickness of HDPE moderator was measured at 4–6 cm for 2.8 MeV neutrons. For theoretical calculations, different codes such as MNCP, MNCPX and SRIM are used [26, 27]. The present paper is designed to determine the optimum moderator thickness that is required to be wrapped around a BF_3 detector used in monitoring fissile material. The experimental results are compared with MC simulations for Am–Be neutron source using MCNP5 code version 1.40 [28].

2 Materials and methods

2.1 Theoretical calculations

The work of Goshal [22] is referred for theoretical calculations. The slowing down process involves elastic scattering by light nuclei like hydrogen and carbon in paraffin wax ($\rho = 0.93$ g/cm^3) [5]. The average logarithmic decrease in neutron energy per collision is calculated. The average number of collisions needed to thermalize fast neutrons is also calculated. The transport, thermal neutron mean free paths are calculated for paraffin wax, and finally, the optimum moderator thickness is calculated at 6 cm for 3 MeV neutrons.

2.2 Experimental approach

The paraffin wax moderator assembly consists of two parts as shown in Fig. 1. The first part consists of a removable paraffin wax discs, neutron detector and a neutron source (i.e. Am–Be/^{252}Cf neutron sources). The second part is a mounting frame with two parallel spring-loaded Φ12 mm steel rods, each fixed at one end with the frame. The other two ends are fixed to a movable plastic ring around a 1.4-cm-thick paraffin wax disc. The purpose of the plastic ring is to give strength to the paraffin wax discs. A number of paraffin wax discs are used. Sized at Φ27 cm × 0.6–1.4 cm, each disc is mounted in a 6-mm-thick plastic ring. The paraffin wax discs can be assembled easily on the mounting frame, between two semi-cylindrical fixed pipes with the assembly at the same axes, one for the neutron detector and the other for the neutron source. The two parallel rods act as a guide for the paraffin wax discs and keep the discs in close contact with each other. The Φ27 cm discs keep the axis same with respect to the axes of the neutron detector and the neutron source. Paraffin wax discs can be added or removed for measurement of optimum thickness of paraffin wax, where the

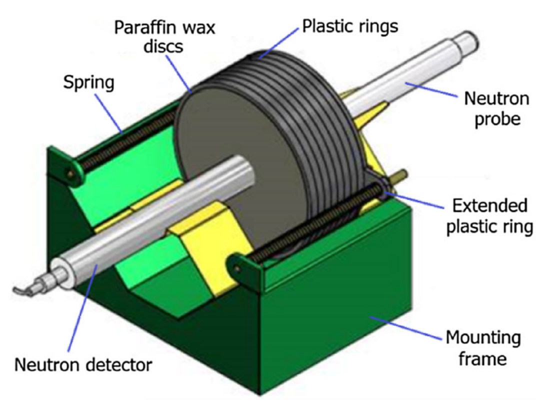

Fig. 1 Sketch of the paraffin wax moderator assembly

neutron detector counts is the maximum. Two BF_3 ($\Phi 1''$ and $2''$) and one ^{3}He ($\Phi 0.5''$) neutron detectors are used for measuring the optimum thickness with Am–Be or ^{252}Cf neutron sources. The associated electronics with detector assembly consisted of pre-amplifier, amplifier, single-channel analyser and counter/timer manufactured by the ORTEC.

The background counts per second were measured without the neutron sources, and they were subtracted from the actual neutron count rates emitted from neutron sources. For different paraffin wax thicknesses, counts emitted from either Am–Be or ^{252}Cf neutron sources were taken for 100 s by using the BF_3 and one ^{3}He neutron detectors. For both the Am–Be and ^{252}Cf neutron sources, the paraffin wax thicknesses were increased to find the maximum counts, and on further increase in thickness, the counts started decreasing. Here, the maximum counts represent optimum paraffin wax thickness that is required to thermalize fast neutron (of course, the process is the trade-off between absorption and moderation). To minimize scattering from the walls, the heavy shielding was placed about 4 m away from the source. The scattering contribution at the detector position was checked with and without the shielding, with the source at its position. The difference was negligible, and hence, an evidence of no scattering contribution from shielding walls was seen. Furthermore, BF_3 or ^{3}He detectors can detect only slow or thermal neutrons and the gases have very low interaction cross section for fast or scattering neutrons.

The moderator assembly (Fig. 1) was also used for the measurement of neutron flux emitted from the Am–Be and ^{252}Cf neutron sources to check the validity of the optimum thickness of the paraffin wax moderator, using the neutron flux comparison method and the neutron activation analysis method [29].

2.2.1 *Neutron flux comparison method*

The comparison of counting rates was carried out, between the standard Am–Be neutron source of known flux (F_1) and that from the neutron probe of unknown flux (F_2) under conditions insensitive to the energy of neutrons. Let C_1 be the average counts per sec for F_1 recorded by a BF_3 ($\Phi 1''$) neutron detector in contact with the 6-cm-thick paraffin wax moderator and C_2 be the average neutron counts per sec, with their background subtracted, from the neutron probe under the same condition. The neutron flux F_2 from the neutron probe is given by $F_2 = F_1\ C_2/C_1$.

2.2.2 *Neutron activation analysis method*

The paraffin wax moderator assembly was used to measure the neutron flux of the neutron probe through activation analysis technique by using silver foil, and the 6 cm optimum thickness of the paraffin wax moderator was validated.

Thermal neutron activation analysis is the absolute method to determine the neutron flux of a neutron probe. The silver isotopes of ^{108}Ag ($T_{1/2} = 0.39$ min) and ^{110}Ag ($T_{1/2} = 24.6$ s) are produced through nuclear reactions of ^{107}Ag(n, γ) ^{108}Ag and ^{109}Ag(n, γ) ^{110}Ag with thermal neutron. After a few half-lives of ^{110}Ag, most of the radioactivity in silver foil is due to ^{108}Ag [30]. A G.M counter with Mylar end window is used for the neutron activation analysis. The silver foil is placed at the Mylar window. Both the neutron probe and the end window of G.M detector are placed at the same axis in opposite and in contact with the paraffin wax moderator (Fig. 2).

The optimum paraffin wax thickness of 6 cm was used in the moderator assembly. At the termination of activation, the flux φ of the neutron probe (in n/cm^2/s) is given by $\varphi = [A_0 w(1 - e^{-\lambda t})/(\sigma A_{av} \alpha m)]\ \varepsilon\ (4\pi/\Omega)$ [22], where A_0 is the activity of ^{108}Ag at $t = 0$, w is the atomic weight of silver, λ is the decay constant, t is the irradiation time, σ = 37.6 barns (taken from the ENDF library [31]) is the thermal neutron capture cross section of ^{107}Ag, A_{av} is the Avogadro's number, α is the natural isotopic abundance of ^{107}Ag, m is the mass in grams of ^{107}Ag, ε is the intrinsic efficiency of the detector, and Ω is the solid angle subtended by the G.M detector at the neutron source (Am–Be) of the probe.

The intrinsic efficiency of the G.M detector was determined from a ^{137}Cs γ-ray source of known activity. The silver foil was activated for 5 min. Although both ^{108}Ag and ^{110}Ag are produced, most of the activity is due to ^{108}Ag at the time of counting. The neutron probe was taken far away from the moderator assembly as quickly as possible, so the G.M detector background count was made almost negligible at the time of counting. The activated silver foil was counted immediately and was repeated several times for better results. The background of the G.M detector was measured in advance.

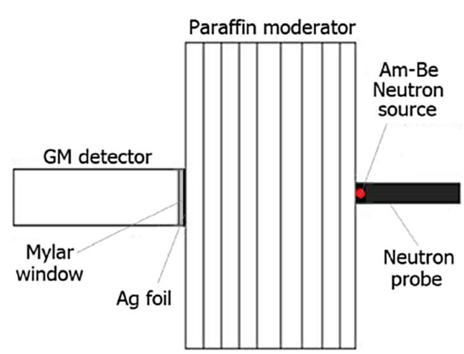

Fig. 2 The G.M detector with the end Mylar window, Ag foil, the paraffin wax moderator and the neutron probe

2.3 Monte Carlo simulation

MCNP is an advanced Monte Carlo code for simulation of the neutron transport [28, 32]. It has the ability to model complex geometry of designed experiment and contains all necessary cross-section data for neutron, photon and electron transport calculations [32]. For a neutron detection process, the history of each starting neutron is followed between collisions, and its energy deposition is recorded, throughout its life to its death, until its energy is low enough to be neglected. In the present study, the experimental set-up was simulated in the School of Physics, University Science Malaysia, Penang, Malaysia, using the MCNP5 code version 1.40 [28, 32]. The experimental set-up as described in Fig. 1 was modelled. According to this model, the neutron source was located at one side of the paraffin wax moderator, while the neutron detector was simulated facing the source at the other side of the moderator. The experimental set-up was simulated on wooden table top. To calculate the detector neutron flux, F_2 tally calculates the flux averaged over a surface [28] was used. Surface segmentation was utilized to calculate the flux at a surface segment facing the neutron source.

3 Results and discussion

The measured counts per 100 s for different wax thicknesses by using the three neutron detectors for the Am–Be and ^{252}Cf neutron sources plotted against wax thickness are shown in Fig. 3. The maximum counts for each neutron detector and source represent the optimum paraffin wax thickness that is required to thermalize fast neutrons. From Fig. 3, the optimum paraffin wax thicknesses were 6 and 5.5 cm for Am–Be and ^{252}Cf neutron sources, respectively. The yield of thermal neutrons increases with the thickness of paraffin wax from 1.6 to 6 cm, due to fact that the fast neutrons lose their energy through elastic collision with hydrogen atoms of paraffin wax. The yield of thermal neutrons at these thicknesses is found to be maximum, as a large number of fast neutrons lose their maximum energy through elastic collisions. However, on further increase in thickness of the paraffin wax from 6.5 to 12 cm, the yields of thermal neutron decrease due to elastic and inelastic scattering reactions. The neutrons lose their energy through the interactions until they are captured by paraffin wax (shielding material) [23]. Normally, the neutron capture cross section is larger only for thermal neutron energies, that is why the neutrons slowing down by scattering are important before capture [23].

To validate the optimum thickness of paraffin wax, the neutron flux was calculated. By the neutron flux comparison method, the average neutron counts per second, C_1, was 141.3 ± 0.66 with the known neutron flux of $F_1 = (8.3 \pm 0.66) \times 10^4$ n/s. With $C_2 = 199.1 \pm 0.79$ of the neutron probe, the F_2 was $(1.17 \pm 0.09) \times 10^5$ n/s. On the other hand, the neutron flux deduced by the activation method was $(1.19 \pm 0.1) \times 10^5$ n/s. The two results are virtually the same, considering the measurement errors. The neutrons emerging out of paraffin wax are of both thermal and epithermal in energy. The fluence of epithermal neutrons was estimated from Ref. [30]. The ratio of epithermal to the total neutrons at a distance of 18.9 cm in air from the neutron source is 5.56% where the total fluence is maximum as calculated from Ref. [33]. Therefore, this ratio is the same for the paraffin moderator at 6 cm in thickness.

By using MCNP5, the energy spectra of Am–Be neutron source at 3, 5 and 8 MeV were produced with the relative probabilities of 1.000, 0.986 and 0.551, respectively. The simulation results for the Am–Be source are shown in Fig. 4, and the counts are maximized at 6 cm thickness of the paraffin wax moderator, agreeing well with the experimental results.

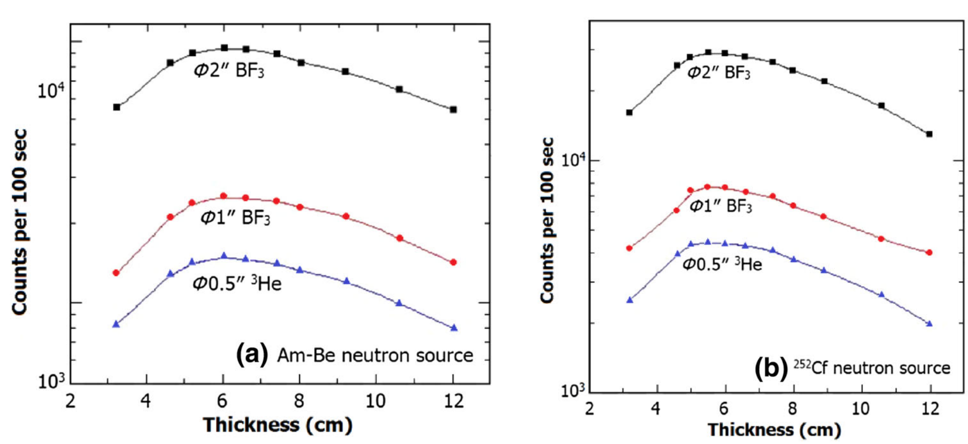

Fig. 3 The paraffin wax thickness versus neutron counts, with different neutron detectors for Am–Be **a** and **b** ^{252}Cf neutron probes

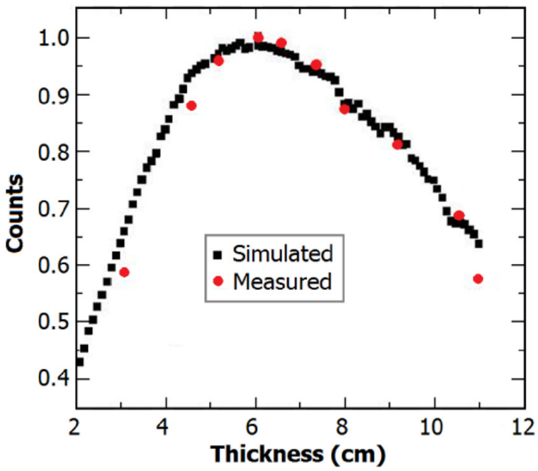

Fig. 4 The Monte Carlo simulation for the Am–Be neutron probe versus the paraffin wax moderator thickness

4 Conclusion

The paraffin wax moderator assembly can be used easily to thermalize fast neutrons of various energies produced from neutron-producing reactions on an accelerator. Neutron flux comparison and neutron activation techniques are used for accurate determination of neutron flux of the neutron probe to validate the optimum thickness of the paraffin wax moderator in the assembly. The neutron flux of $(1.17 \pm 0.09) \times 10^5$ n/s by the neutron flux comparison method agrees well with the flux of $(1.19 \pm 0.1) \times 10^5$ n/s by neutron activation analysis method. The techniques can be utilized for the measurement of neutron yield from Mather-type plasma focus device. The optimum thickness of the paraffin wax moderator is 6 cm for Am–Be and 5.5 cm for ^{252}Cf neutron sources.

Acknowledgements The authors gratefully acknowledge services provided by Mr. Usman Ali, RPL, CIIT, in the fabrication of mechanical assembly and safe handling of neutron sources.

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