GAMBE: Thermal Neutron Detector for Directional Measurement of Neutron Flux*

A. Ahmed[1,2], S. Burdin[1], G. Casse[1], H. van Zalinge[2], S. Powel[1], J. Rees[1], A. Smith[1] and I. Tsurin[1]

***Abstract*—A novel approach for the determination of the direction of a neutron flux is presented. This approach based on the combination of a solid-state neutron capture detector with neutron moderators and reflectors such as high-density polyethylene (HDPE) and lead respectively. This detector has a sandwich configuration of two silicon sensors of 1 cm^2 active area and a layer of ^{6}LiF (1.5$\pm$0.6) mg/cm^2 thick. It has been fixed at the center of an aluminium enclosure (inner dimension 60 mm $\times$ 50 mm $\times$ 30 mm) for eliminating photoelectric noise. HDPE sheets encircle the entire detector from all directions except one, which faces a 1 Ci Am-Be neutron source where lead blocks 5 cm thick have been used for suppression of gamma-ray background. Thermal neutron detection efficiency has been estimated according to different setups where the whole system is rotated by an angle of 90° in front of Am-Be neutron source. The variation of thermal neutron detection efficiency due to the rotation process provides an evaluation about the location of the utilised neutron source. This location is identified by the maximum thermal neutron detection efficiency, which is achieved and the lowest count rate of gamma-rays where the lead window faces the neutron source. Theoretical investigation using MCNP-4C code approved the variation of thermal neutron flux through ^{6}LiF film according to the rotational angle.**

I. Introduction

The past decades have seen rapid development of neutron detectors since the discovery of neutrons in 1932 by James Chadwick [1]. These detectors have been used either as a counter for the the number of neutron and/or measured the neutron energy. Since the neutrons have no charge, they are detected indirectly through either scattering or neutron capture mechanism. Detecting the direction of neutron flux and locating the source of neutrons is mainly depend on detection of fast neutrons through scattering interaction, which based on the knock on proton mechanism where a thin polyethylene sheet is placed in front of silicon detector. The protons knocked on by the incident neutrons are detected through interaction with this silicon detector [2]. Hence, scattering detectors have the ability to provide directional information, which relies on the direction of detected protons. There are several directional neutron detectors, which have been investigated depending on different techniques with different scattering neutron detectors such as ^{3}He detectors and plastic scintillating fibres [2]–[6].

Typical neutron detectors employed today are thermal neutron capture detectors because of their high intrinsic efficiency. In contrast to fast neutron detectors, thermal neutron capture detectors do not have the capability of inferring the direction of neutron flux or the location of the emitting neutron source. Since, thermal neutrons have low kinetic energy due to the multiple scattering involved in moderating reactions with the surroundings until they are in thermal equilibrium with them. The capture reaction products are emitted in random directions without any effect of the thermal neutron kinetic energy. Consequently, the direction of the original neutron emission cannot be determined [7]. However, it has been discussed that an array of large area silicon detectors was used as a neutron captured detector with the capability of detecting thermal neutron and determine the direction of the neutron emitting source for the purpose of nuclear monitoring [8].

In the present work, neutron detection system, (GAMBE) Gamma Blind Neutron Efficient Detector, which is based on two silicon sensors and a layer of neutron sensitive material in sandwich configuration [9], has been motivated to provide information about the location of neutron source. The goal of this research is to construct a portable neutron detection system which is based on both scattering and capture mechanism to increase the detection efficiency. Moreover, making the detector able to determine the direction of neutron flux according to the variation of detection efficiency at different angles in-front of neutron source. In this manner, the developed thermal neutron detector, GAMBE, could be used to find and locate the direction of neutron source in different application such as nuclear fuel safety, imaging and detection of special nuclear material (SNM) and in nuclear science.

II. Device Performance Modeling Approach

A. GAMBE Configuration

The thermal neutron detector, GAMBE, has a sandwich configuration, which was modeled by geant4 [10], [11]. The detector consists of two 10 $\times$ 10 mm^2 silicon diodes with a thickness of 300 μm, on either side of a sensitive ^{6}LiF film with an adjustable thickness. In addition, a 100 nm Al contact covering the active region of both Si diodes. The examined design is depicted in Fig. 1, which shows the concept of neutron detection mechanism based on identifying a neutron by each of silicon sensors or by both in case of coincidence event. The efficiency was defined as a total and coincidence detection efficiency. Total detection efficiency represented all detected neutrons by both single and coincidence events, while coincidence detection efficiency identified a true neutron hit based on the simultaneous signal recorded by the two sensors facing the conversion film. These coincidences provide a very good method for rejecting the spurious hits coming from gamma-ray, which are usually present in the neutron field under measurement. The GAMBE system yields a rejection

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[1]A. Ahmed (m.o.ahmed@liv.ac.uk) and all other authors except those listed below are with Faculty of Science and Engineering, Physics Department, University of Liverpool, UK, L69 7ZE.

[2]van Zalinge is with the Department of Electrical Engineering and Electronics, Faculty of Science and Engineering, University of Liverpool, UK, L69 3GJ.

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factor at the level of 10^8 allowing very pure neutron detection in high gamma-ray background conditions.

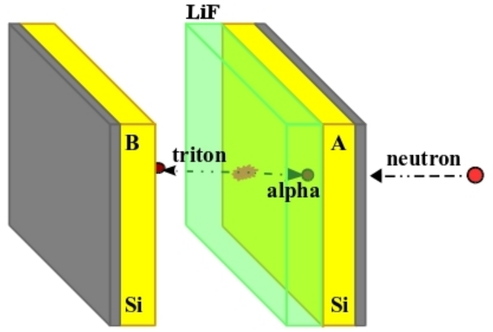


Fig. 1. Principle of thermal neutron detection system, GAMBE. As shown the thermal neutron detection mechanism on ^{6}LiF film (not to scale).

B. Monte Carlo Simulation of Neutron Flux

MCNP simulations were performed to have a full depiction about the neutron flux through the 1 cm^2 area of ^{6}LiF film corresponding to experimental measurements. In these simulations, an ^{241}Am-^{9}Be neutron source generating 1.5×10^9 particles with energies up to 11 MeV is assumed. The source is in a water tank. The detector is in axis with the source, 75 cm away from the source including 25 cm in water. Neutron moderators (2 cm thick HDPE sheets) and reflectors (5 cm thick lead blocks) in various arrangements as presented in Fig. 2 have been studied to determine the total and thermalised neutron flux. These thermal neutrons are slow neutrons, which are in thermal equilibrium with a surrounding medium, and they have a kinetic energy below 0.5 eV.

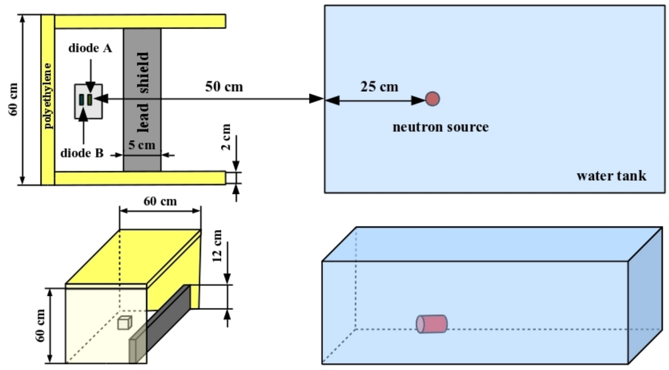


Fig. 2. Schematic description of the experiment geometry.

It has been expected that this layout would result in the highest total and thermal neutron flux of 13.0±0.2 and 7.9±0.2 n/cm^2/s respectively, through the sensitive film. Approximately 60% of fast neutrons are thermalised by the HDPE sheets. Moreover, lead blocks reflect the thermal neutron back towards the detector and increase the percentage of thermal neutron flux through the ^{6}LiF film in the detector by 35%. Different positions of the reflector (lead blocks) have been studied to determine the effect on thermal neutron detection efficiency of the detector and its capability to indicate the direction of incoming neutron flux. The whole setup, which includes the detector and HDPE box with a lead window was rotated corresponding to the original position by a solid angle $\theta = 90°$ in-front of the neutron source as displayed in Fig. 3. The original position is where the lead window faced the neutron source and the neutron flux is perpendicular to the surface area of the sandwich detector configuration.

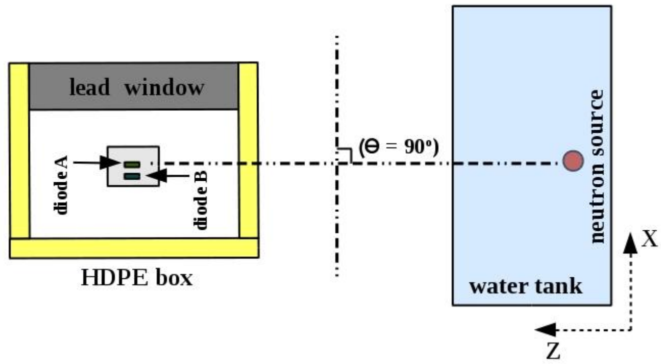


Fig. 3. MCNP layout, which presents the rotational movement of the whole setup in front of the neutron source.

Neutron flux through the sensitive part of the detector (^{6}LiF film) was affected by this rotational movement by means of changing the angle between flux direction and surface area of the detector. The predicted total and thermal neutron fluxes from this study are summarised in Table I.

TABLE I
SIMULATED THERMAL AND TOTAL NEUTRON FLUX THROUGH THE AREA OF ^{6}LIF FILM AS A FUNCTION OF NEUTRON FLUX DIRECTION.

Direction of flux (Solid angle)	Thermal neutron flux $\Phi_{th,sim}$ ($n/cm^2/s$)	Total neutron flux $\Phi_{t,sim}$ ($n/cm^2/s$)	% of thermal neutron (Normalised to total)
Front (0^o)	3.6±0.1	7.9±0.1	≃ 45%
Right (90^o)	1.7±0.1	6.5±0.4	≃ 26%
Back (180^o)	2.1±0.1	7.9±0.2	≃ 27%
Left (270^o)	1.6±0.1	6.6±0.3	≃ 25%

Furthermore, Fig. 4 illustrates the predicted energy spectrum of neutron flux as a function of neutrons energy and rotational angle (θ). It can be seen that the highest thermal neutron flux is achieved when the lead window faced the neutron source (i.e. $\theta = 0°$). This is because light material like HDPE will work as a neutron moderator, which will reduce the energy of fast neutrons and scatters them back into the detector, therefore, the neutrons will not be lost.

On the other hand, heavy material like lead will have less effect on neutron kinetic energy, therefore, lead is quite ineffective in blocking the incoming neutrons from the source. However, lead will work on shielding the detector against gamma-rays and reflects the thermal neutrons towards the detector which were scattered back from HDPE sheets (neutron vs. heavy nucleus just like ping pong ball against a bowling ball).

It is apparent from this theoretical investigation that there is a possibility to locate a neutron source based on the increment of thermal neutron flux in a specific direction. According to this direction the probability of a thermal neutron to be captured increases, and as a result the thermal detection efficiency of the detector increases. Therefore, using neutron capture detector inside a box of HDPE with a lead window will have the ability to predict the location and direction of neutron source.

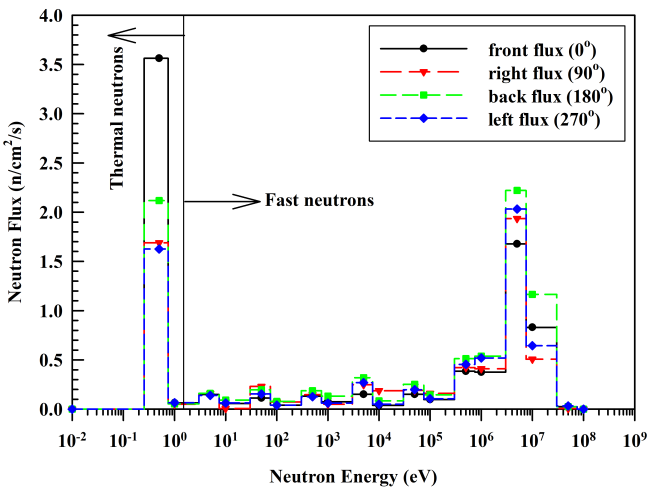


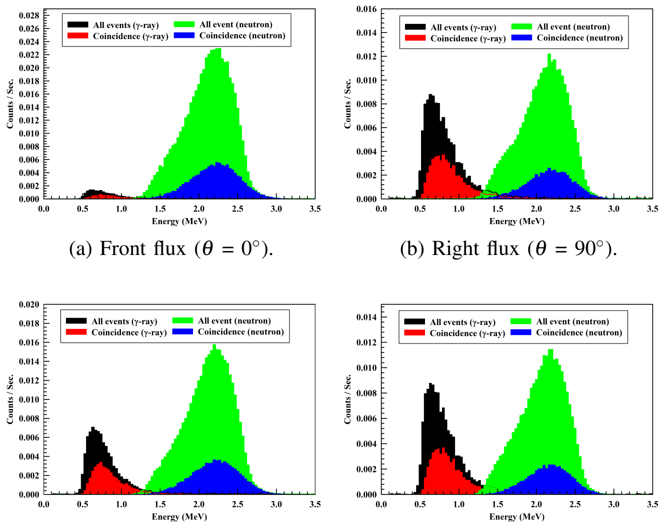
Fig. 4. The estimated neutron flux as a function of the neutrons energy and different flux direction.

III. Experimental Validation and Discussion

Experimental measurements have been carried out using ^{6}LiF film 1.5±0.6 mg/cm^{2} thick in a sandwich configuration. The detector has been placed in a particular position in front of 1 Ci ^{241}Am-^{9}Be neutron source where neutrons emitted as a part of the reaction Be(α,n)C*. Thermal neutron flux has been measured using the ^{3}He detector tube. The tube is 50 cm away from the end of the neutron tank, and the 1 Ci ^{241}Am-^{9}Be neutron source is 25 cm inside the water tank. Another detector such as the NMS017NG3 neutron survey monitor has been used to characterise the variation in the neutron flux along the length of the ^{3}He detector tube. This detector demonstrates that the neutron flux at the center of the ^{3}He detector tube is 1.40 times greater than over the entire length of the detector.

HDPE sheets work on fast neutron thermalisation via elastic collisions between neutrons and hydrogen atoms. Furthermore, these sheets result in scattering thermal neutrons back and enriched the filed around GAMBE with them. As a result, the thermal neutron flux through the area of ^{6}LiF film of 1 cm^{2} increased. Hence, the probability of thermal neutrons to be captured inside the volume of sensitive ^{6}LiF layer will increase and the detection efficiency improves. The measured count rates of neutrons and gamma-rays events for all configurations are presented in Fig. 5. The highest neutron count rate is achieved when the lead window is facing the neutron source. On the other hand, gamma-ray count rate is the lowest as a result of shielding using lead in the direction of neutron and gamma-ray fluxes as shown in Fig. 5a.

Total and coincidence detection capabilities of the detector in all configurations have also been determined, and presented in Table II. These results show that the highest total and coincidence detection efficiency are possible where the lead window of the detector is perpendicular on the direction of neutron flux and facing the neutron source. The detection efficiency varies with the rotational movement of the detector in front of neutron source where the lowest detection efficiency of the detector is obtained when the lead window is parallel to the direction of neutron flux. In the case of the back-flux, however the neutron flux is perpendicular on the detector surface, the detector has a lower neutron detection efficiency than that in the case of front neutron flux. This is because of a HDPE sheet, which is in the direction of neutron flux where thermal neutrons from the source are scattered back away from the detector.



(a) Front flux (θ = 0°). (b) Right flux (θ = 90°).

(c) Back flux (θ = 180°). (d) Left flux (θ = 270°).

Fig. 5. Measured neutron and gamma-ray energy spectrum as a function of the solid angle between the detector and neutron flux.

TABLE II
THE EXPERIMENTAL VALUES OF TOTAL AND COINCIDENCE DETECTION EFFICIENCY AS A FUNCTION OF NEUTRON FLUX DIRECTION.

Direction of flux (Solid angle)	Total detection efficiency $\varepsilon_{t,exp}$ (%)	Coincidence detection efficiency $\varepsilon_{c,exp}$ (%)
Front (0^{o})	11.53±0.04	2.54±0.02
Right (90^{o})	5.96±0.03	1.17±0.01
Back (180^{o})	7.6±0.03	1.65±0.01
Left (270^{o})	5.71±0.02	1.1±0.01

These experimental results, which describe the behaviour of the detector are in agreement with those obtained by the theoretical investigation using MCNP-4C simulations as it can be seen in Fig. 6. This figure shows the variation of normalised values of simulated thermal neutron flux and detection efficiency corresponding to front configuration. This variation suggests that the combination between the thermal neutron detector, GAMBE, and neutron moderators and reflectors can be used to locate and prove the presence of neutron source. Moreover, the direction of neutron flux is identified based on the thermal neutron detection efficiency of the detector and the measured energy spectrum of both neutrons and gamma-rays corresponding to the solid angle between the detector and neutron source.

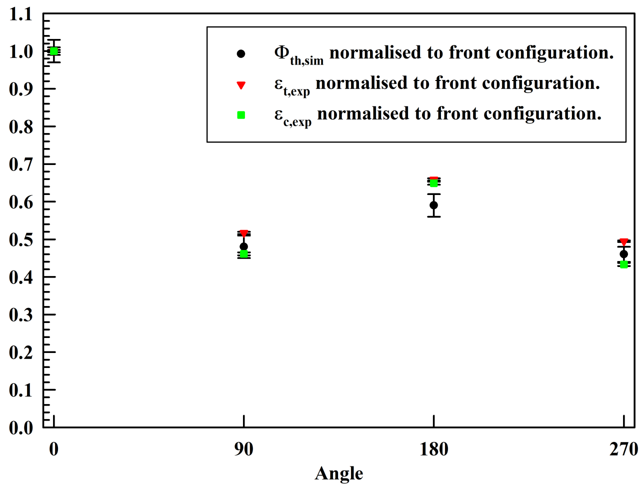


Fig. 6. Variation of simulated thermal neutron flux and both detection efficiencies as a function of neutron flux direction with respect to the surface area of sensitive ^{6}LiF film.

IV. Conclusion

This paper has argued that the neutron detection system, GAMBE, based on thermal neutron capture detector in a sandwich configuration, which is coupled with neutron moderators and reflectors can be used as a directional detector. The thermal neutron detection efficiency and the measured neutron and gamma-ray count rate of of this detection system surrounded by scattering material rotating with respect to the direction of the neutron flux are varied depending on the angle between the detector and neutron source. Experimental results are in agreement with MCNP simulations of the thermal neutron flux. This result suggests that a compact system made of neutron capture detector inside a HDPE box with an open window can have the ability to determine the intensity and location of a neutron source.

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