Experimental and Simulation Study of the Response of a Boron-Loaded Plastic Scintillator to Neutrons and Gamma-rays

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Abstract

A boron-loaded plastic scintillator has been investigated for possible use in neutron spectrometry. The sensor composition of hydrogen and carbon leads to multiple scattering collisions that are useful for fast neutron spectroscopy, while its boron component can serve as a thermal neutron detector. The response function of this detector has been simulated using MCNPX code for gamma-rays and neutrons. The sensor has been mounted on a photomultiplier tube connected to a data acquisition system. The system has been tested in different gamma-ray and neutron fields at the UOIT Neutron Facility. The simulation and experimental results have been compared and analyzed.

1. Introduction

Radiation monitoring instrumentation has applications in many nuclear facilities. These include but are not exclusive to the nuclear power industry, nuclear research laboratories, radionuclide neutron sources, and nuclear waste management [1]. These fields are usually mixed with neutron and gamma-ray components. In recent times, there has been a need to improve radiation detection devices due to regulatory bodies requiring revised standard specifications. Therefore, research and development in this area have been concerned with introducing new sensors with improved response that can be used for neutron spectrometry in general, and for neutron dosimetry in particular. A review of the past and current status of personal dosimeters has been given [2, 3].

Even though some experiments with gamma radiation have been carried out, this paper is primarily concerned with neutrons. The main challenge arises since neutrons are present in a wide range of energies, for example from thermal to around 15 MeV in nuclear power plants. Most neutron sensors are limited due to their detection efficiency and energy dependence, which come from the basic physical properties of the sensors [4]. Due to its composition of hydrogen, carbon, and boron, the boron-loaded plastic scintillator sensor has been investigated by different research groups and previous studies have indicated the possible use for fast as well as for thermal neutron detection using two different nuclear processes; mainly the neutron absorption process on the boron nuclei for thermal neutron detection and the scattering process on hydrogen for fast neutron detection [5-8].

This paper aims to outline the simulated and measured response functions of the boron-loaded scintillator. The scintillator has been mounted on a photomultiplier tube and connected to a compact data acquisition system for pulse processing and irradiated with gamma-rays and neutrons at the UOIT

Neutron Facility. Simulations have been performed using Monte-Carlo N-Particle eXtended code (MCNPX).

2. Methodology

Neutrons may interact with the scintillator through either absorption or scattering reactions. Boron has been typically used for thermal neutron detection due to its large neutron absorption cross section of 3840 barns. Neutrons interact with ^{10}B with two possible outcomes, an alpha particle with a ^{7}Li recoil nucleus in its excited or ground state. The two reactions are as follow:

$$ {}^{1}_{0}n + {}^{10}_{5}B \rightarrow {}^{7}_{3}Li^{*} + {}^{4}_{2}He \tag{1} $$

$$ {}^{1}_{0}n + {}^{10}_{5}B \rightarrow {}^{7}_{3}Li + {}^{4}_{2}He \tag{2} $$

94% of the time the outcome is the excited state (Equation 1), and 6% of the time the outcome is the ground state (Equation 2). These reactions are exothermic and their Q-values are 2.310 MeV and 2.792 MeV, respectively. The energy is distributed between the alpha particle and the ^{7}Li. In the excited state, the alpha particle has an energy of 1.47 MeV and the ^{7}Li has an energy of 0.84 MeV. In the ground state, the alpha particle has an energy of 1.78 MeV and the ^{7}Li has an energy of 1.02 MeV. When in its excited state, ^{7}Li will de-excite into stable ^{7}Li releasing a gamma-ray of 0.478 MeV.

The presence of hydrogen and carbon will lead to elastic scattering reactions with neutrons due to their large scattering cross section. In these reactions, recoil protons and recoil carbon are produced. The energy transferred from the incoming neutron to the hydrogen or carbon nuclei is determined by the scattered angle.

Regarding gamma radiation, when it interacts with plastic scintillators, the dominant process of interaction is Compton scattering due to the low Z element that composes the scintillator [9].

2.1 Boron-loaded Plastic Scintillator

The boron-loaded plastic scintillator has 5% boron loading containing about 1% of ^{10}B isotope. The polymer base is polyvinyltoluene which is made up of carbon and hydrogen. It has a cylindrical geometry of 2.5 cm length and 2.5 cm in diameter. The density of the scintillator is 1.026 g/cm^3. The decay time is 2.2 ns, which makes it a fairly fast scintillator. During the experiment, a paraffin moderator was placed around the scintillator to moderate neutrons emitted from an AmBe neutron source. The model for neutron simulations is shown in Fig. 1.

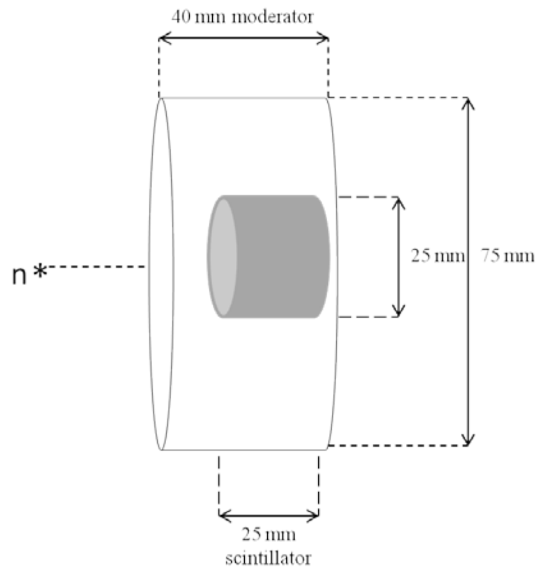

Figure 1: Model of the Scintillator with Moderator for Neutron Response Function Simulations

2.2 Experiment

For neutron experiments, the UOIT Neutron Facility that houses an AmBe neutron source of 40 mCi has been used while for gamma radiation, the detector has been irradiated with standard sources of 1 μCi each. The detection system included the EJ254 scintillator from Eljen Technology with a surrounding paraffin moderator, a R3998-02 Photomultiplier Tube (PMT) from Hamamatsu, and an eMorpho Multichannel Analyser (MCA) from Bridgeport Instruments LLC. The scintillator was mounted to the PMT that was connected to the socket and the MCA was connected to a computer.

3. Results and Discussion

3.1 Simulated Response Functions to Gamma-rays and Neutrons

For gamma radiation, the scintillator was irradiated with ^{137}Cs and ^{60}Co sources. The ^{137}Cs source emits a gamma-ray of 0.662 MeV and the ^{60}Co source of 1.173 MeV and 1.332 MeV. The response function is given with ideal resolution in Fig. 2. For neutron radiation, the scintillator and moderator were irradiated with various neutron energies. Fig. 3 gives the response function to 1 MeV neutrons with ideal resolution.

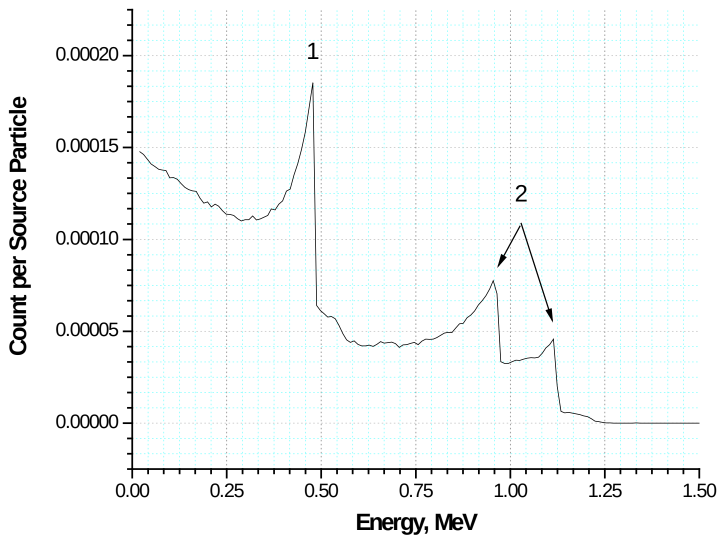

Figure 2: Simulated Response Function to Gamma Radiation

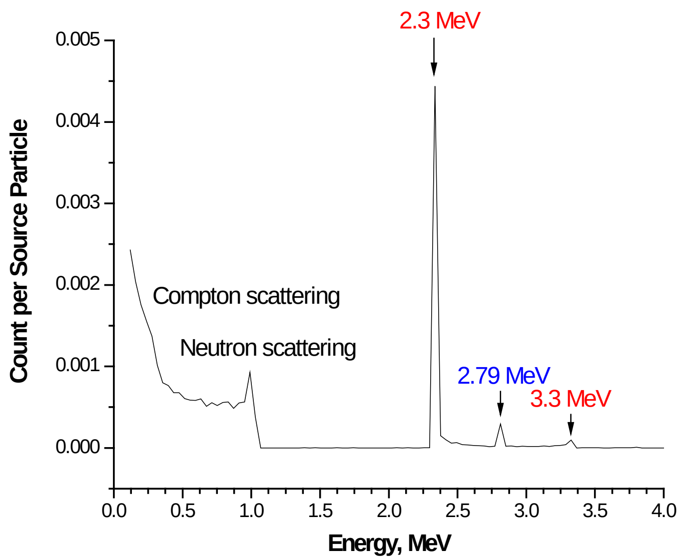

Figure 3: Simulated Response Function to Neutron Radiation

From Fig. 2, the Compton edges for ^{137}Cs (labeled as 1) and ^{60}Co (labeled as 2) can be seen. They are 0.48 MeV, 0.96 MeV, and 1.12 MeV, respectively. From Fig. 3, the thermal peaks can be seen. The first reaction (Equation 1) is at 2.3 MeV and the second reaction (Equation 2) is at 2.79 MeV. The peak at 3.3 MeV is the kinetic energy of the incoming neutron in addition to the Q reaction. Another peak is present at 3.79 MeV, however due to the probability of Equation 2, it cannot be seen. The lower end of the spectrum has a distribution of energies due to scattering. The scattering from the neutrons with hydrogen can be seen by its edge at around 1 MeV for hydrogen. The scattering with carbon is also a part of this continuum but its edge is not distinct due to it being less than that of hydrogen. The Compton scattering from the 0.478 MeV gamma-ray from Equation 1 can be seen from its edge at 0.311 MeV.

3.2 Measured Response Functions to Gamma-rays and Neutrons

The detector has been irradiated with two gamma-ray sources, ^{137}Cs and ^{60}Co, and thermalized neutrons from an AmBe source. The response functions for these measurements can be seen in Fig. 4.

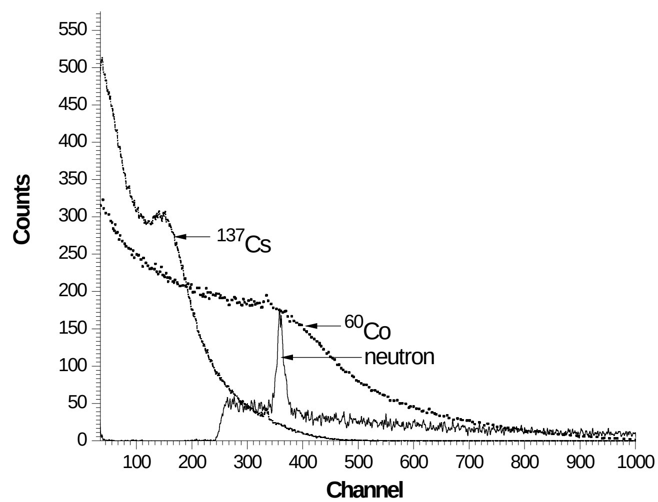

Figure 4: Measured Response Function to Mixed Gamma-ray and Neutron Fields

In Fig. 4, the Compton distributions can be clearly seen up to channel 180 and up to channel 450 for the ^{137}Cs and ^{60}Co sources, respectively. It should be noticed that the Compton edge for the low energy of ^{60}Co cannot be resolved on the spectra due to the poor resolution. A notable thermal peak can be seen around channel 380. This scintillator also has the ability to discriminate the gamma radiation of the ^{137}Cs source; however, at high energy gammas (^{60}Co), the scintillator shows a limited discrimination capability due to the small Q reaction. The calibration of the energy scale shows that a good discrimination can be achieved up to around 0.8 MeV, and for further development of a good spectrometer, another sensor where the Q reaction is larger, must be considered such as a lithium based scintillator.

4. Conclusion

A boron-loaded plastic scintillator has been investigated for its response to neutron and gamma radiation. A Monte-Carlo model has been developed to simulate the response functions of the scintillator and measurements have been carried out with neutrons, gamma radiation, and mixed fields. The scintillator along with its data acquisition has shown a neutron-gamma discrimination ability up to 0.8 MeV.

5. References

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