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Design Validation of a $^{10}B_4C$ Coated RSP with Multi-layered structure for Homeland Security

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1. Introduction

It is a national priority to prevent radiological threats including radiological terrorism and smuggling nuclear material and devices. For this purpose, many governments and relevant organizations have been exploiting radiation detection technology. Especially, radiation portal monitor (RPM) is a widely used type of radiation detectors when it comes to homeland security and commonly deployed at strategic sites like airports and ports. [1]

In the most cases, they could be divided into two types of primary screening and secondary screening. In the latter case, hand-held detectors are mainly used for a closer inspection. On the other hand, RPMs for the primary screening, our concern, are stationary mounted type and comprise gamma-ray detector and neutron detector in many cases. A typical RPM is displayed in Fig. 1. [2]

Fig. 1. A typical radiation portal monitor developed by Korea Atomic Energy Research Institute and comprises sensor panel made of PVT and NaI.

For the neutron detector, it is essential to make use of a proper neutron-sensitive material. ^{3}He has been the “golden standard” for neutron detections so far. However, as ^{3}He gas is being depleted, the replacement of it should be contrived. For instance, $^{10}B_4C$ has been considered one of the powerful candidates for that since its total cross section is large enough to regard as a neutron-sensitive material. [3−5]

In this study, we have validated a design of a sensor for neutron detectors to be mounted on radiation portal monitor system. Being a suitable material for thermal neutron detections, $^{10}B_4C$ has been employed in this study. And we have tested the performance of it by using Monte Carlo method, and the Geant4, which is a widely used simulation toolkit, has been utilized.

2. Detector Configuration

This section provides the conceptual design of the neutron detector to be a part of a radiation portal monitor. The detector has been designed following the criteria to appropriately preform, which are summarized in subsection 2.1.

2.1 Criteria for Neutron Detector

There are requirements, which should be meet, for the radiation detection system to be deployed ports-of-entry into the U.S. The criteria are applied at each detection volume level, which is called radiation sensor panel (RSP) based on the performance of a single RSP and an ingredient of the RPMs. One of the criteria for neutron detection panel is displayed below: [6]

- The absolute detection efficiency for such a ^{252}Cf source, located 2 m perpendicular to the geometric midpoint of the neutron sensor, shall be greater than 2.5 cps/ng of ^{252}Cf. The neutron detector center shall be 1.5 m above grade for this test.

To evaluate the expected performance of the detector design, the requirement is benchmarked as an important factor

2.2 Design of Neutron Detector

We have proposed the design of a RSP for the neutron detection, which is based on $^{10}B_4C$ thin films with 90% enhanced ^{10}B. To increase the detection efficiency, the design is shaped as a multi-layered structure. $^{10}B_4C$ is coated on both sides of an aluminum plate with thickness of 3 μm. In other words, the RSP consists of 10 layers of $^{10}B_4C$ in total.

The RSP comprises five doubly boron-coated plates, whose dimension is 100 mm (W) × 900 mm (H). The detector will be covered with a moderator to thermalize fast neutrons. In this study, we assume that the moderator is made of high-density polyethylene with the thickness of 5.0 cm. The schematic view is displayed in Fig. 2.

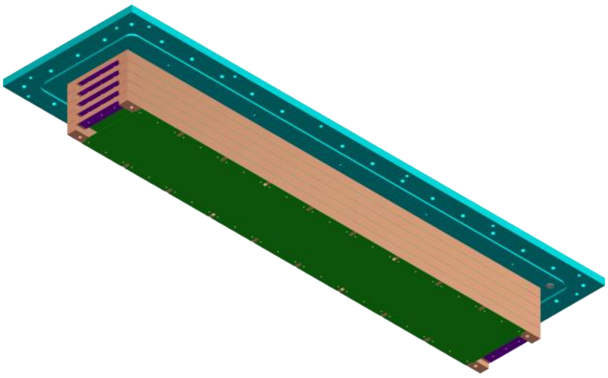

Fig. 2. The drawing of the multi-layered RSP. This comprises five layers with doubly coated $^{10}B_4C$ thin films and an aluminum housing.

3. Methods

This section describes the method for the simulation of the proposed design, which includes simulation toolkit and how to make samples. In this study, we take advantage of the Geant4 and make an acceptable sample for the Watt spectra by using the inverse transform sampling.

3.1 Geant4

For the simulation of the detection efficiency of the multi-layered neutron detector, two different steps of calculations should be perform at a physical process level. First of all, nuclear reactions between neutrons and boron-10 atoms, which include heavy ion productions, are the key components to the simulation. In contrast with a radiation transport analysis, the total cross section of the nuclear reactions strongly depend on its kinetic energy. Because of that, it needs to be considered with a combination of precision nuclear data and Monte Carlo model rather than using a single model. Second, a typical radiation transport analysis should be carried out for the transportation and energy depositions of heavy ions.

Geant4 is a powerful tool to calculate those processes. At first, the tool had been developed for high energy physics research. The application sectors of the Geant4 have been rapidly expanded such as accelerator science, medical, astrophysics and radiation science. In this study, the physics model named QGSP_BERT_HP 3.0, which was released by Geant4 collaboration, is employed, and commonly used physics models for Geant4 are displayed in Table 1. [7−9]

Table 1. The employed PhysicsList. The physical models are properly selected according to energy of particles.

Name	Model	Range
QGS	Quark Gluon String Model	>~20 GeV
BERT	Bertini Cascade Model	<~10 GeV
HP	High Precision Neutron Model	< 20 MeV

3.2 Simulation

As that has already been mentioned in section 2, the average energy of neutrons from ^{252}Cf is 2.35 MeV. [10] The energy spectrum of neutrons produced by spontaneous fission can be expressed by Watt spectrum, which is given by

$$f(E) = A\exp\left(-\frac{E}{1.025}\right)\sinh(2.926E)^{1/2} \qquad (1)$$

where E is the neutron energy in MeV. [11]

We assume that the neutron energy spectrum from spontaneous fission of ^{252}Cf is fairly agrees with the Watt spectrum expressed by Eq. (1). The inverse transform sampling is employed for sampling, and the sample was exploited for Monte Carlo simulation. Fig. 3 and Fig. 4 show the processes of sampling.

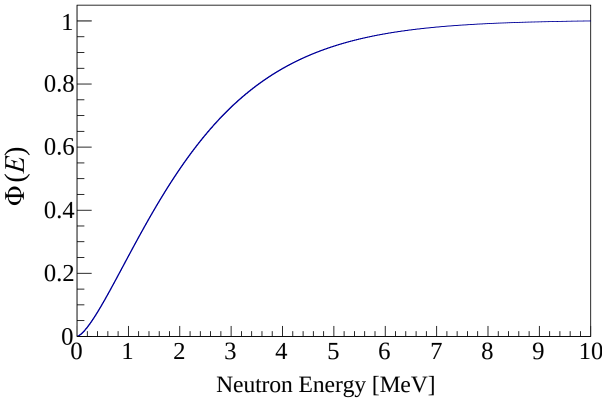

Fig. 3. Cumulative distribution function of the Watt spectrum

4. Results

In this section, a summary of the simulation results is described. The detection efficiency and the transportation tendency of particles have been demonstrated by using Geant4.

4.1 Reactions

To begin with, the leading branch for the reaction between ^{10}B atoms and neutrons is ^{10}B(n, α)^{7}Li. Then, the generated ions such as n and α interact with a detection volume so that signal can be induced. [12−13] The process is demonstrated and given in Fig. 5.

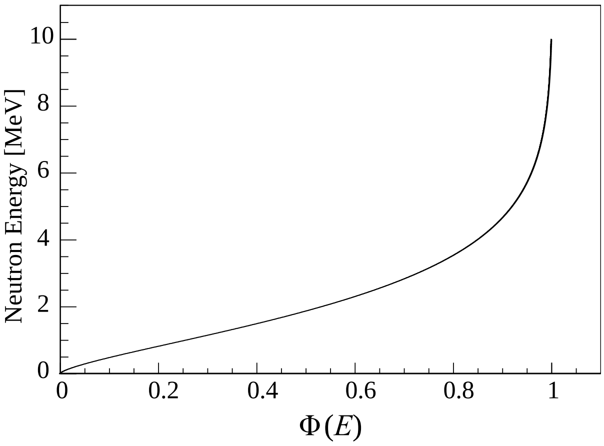

Fig. 4. Inverse function of the Cumulative distribution function, which is obtained from Fig. 3.

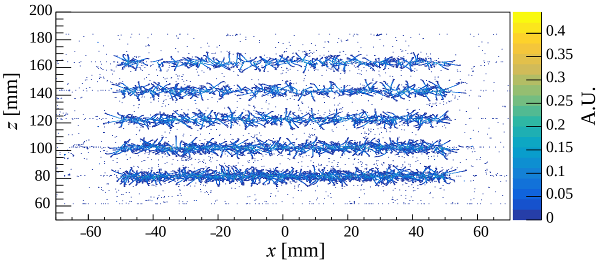

Fig. 5. Deposited energy from ions such as α and ^{7}Li. The traces of the ions are seen on the histogram.

4.2 Detections

In addition, the number of detected events is a key factor to evaluate the detection efficiency. The counted events in the spatial coordinate are displayed in Fig. 6. As the result, the count of events with the proposed RSP design is 0.9 cps/ng at 2 m with a ^{252}Cf source.

4. Conclusions

The expected performance of the design of a RSP has been demonstrated. According to the results of the simulation, three RSPs should be needed to meet the criterion mentioned in subsection 2.1.

The design still can be validated when taking into account that the geometrical acceptance will be increased since it has been planned that the RPM is going to installed with four RSPs. Furthermore, the geometrical design will be being revised by referring to this results.

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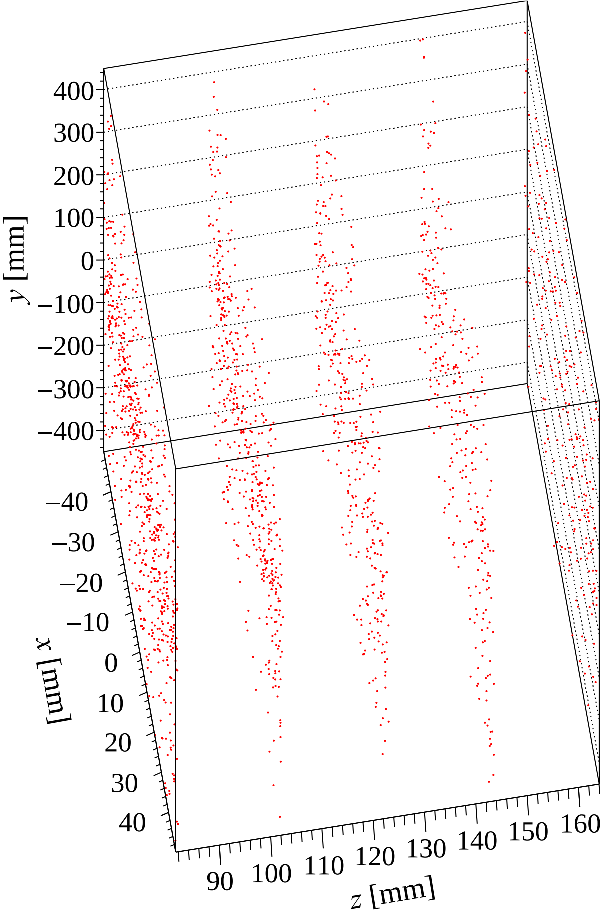

Fig. 6. The reaction points between neutrons and ^{10}B atoms. Each point are corresponds to the registered events.

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