The Characterization of Liquid Scintillator Detector for a PGNAA System at TRR-1/ M1 with MCNP

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Abstract

The aim of this work is to optimize and characterize the liquid scintillator detector that will use for the mixed n/γ radiation field at the Prompt Gamma Neutron Activation Analysis System (PGNAA) at the Thai Research Reactor (TRR-1/M1). The study was carried out using the Monte Carlo N-Particle code (MCNP). The model of the liquid scintillator consists of the aluminum housing, thick 0.085 cm, and the scintillation material. The scintillation layers were varied with the difference thicknesses between 1 cm and 5 cm and the surface area of 20.09 cm^2. The neutron and photon response functions for mono-energetics energies were obtained. The results show that the detection capability depends on the scintillator thickness. In addition, the resolution function of the scintillator was reported and folded to the response function. The neutron detection efficiencies were calculated and compared to the theoretical one. The results show that the detection efficiencies were affected by the detector thickness and the energy threshold. The detector diameter (e.g. thickness, radius) will be suggested and purposed to the experimental at the PGNAA system in the future.

Keywords: Liquid scintillator: MCNP: Response function: Detection efficiency

Introduction

The prompt gamma neutron activation analysis (PGNAA) is a non-destructive elemental analysis technique [1-3]. It is used to measure samples to obtain the prompt characteristic γ-rays of the elements in the samples. This technique is powerful in the industrial such as the application of the process control of the cement manufacturing and other applications. The PGNAA use the prompt characteristic γ-ray produced from the neutron inelastic scattering (n,n′γ) and thermal neutron capture (n_{th},γ), thus the characteristic γ-ray from element composition are produced and determined.

At Thai Research Reactor (TRR-1/M1), the PGNAA system designed and installed [4], the neutrons are produced from the core reactor with one-inch diameter of neutron beam. The epithermal neutron flux is 4.5×10^5 particles/cm^2 and the thermal neutron flux is 6.5×10^6 particles/cm^2. Therefore, with this high neutron flux the moderator are needed for the PGNAA system.

The aim of this work is to study and characterize the liquid scintillator detector to measure the background neutron in the PGNAA system. The liquid scintillator is the one of the most effective detector used in the γ/n mixed fields [5,6]. It is known to present the high detection efficiencies for the neutron and photon spectrometry and capable for the n/γ pulse shape discrimination. The information of the background neutron in the system is important because it useful for the system upgraded at Thai research reactor PGNAA. Moreover, works in this report will investigate the applicability of the liquid scintillation detector to PGNAA system and to other neutron experiments.

Materials and Methods

Model and Calculations

The models in this work were designed separated into two sections: *i*) the PGNAA system and *ii*) the liquid scintillator detector.

PGNAA System Model

The geometry of the PGNAA model was designed to be similar the existing PGNAA system at Thai Research Reactor. The system mainly consisted of two parts. The first part is a series of a cylindrical neutron moderator and collimator as shown in Figure 1(a). The second part of the system is the neutron beam shutter and biological shield as shown in Figure 1(b).

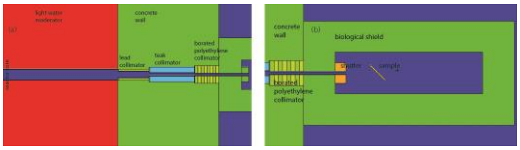

Figure 1 MCNP model of the TRR-1/M1 PGNAA: (a) collimator and moderator, (b) neutron beam shutter and biological shield.

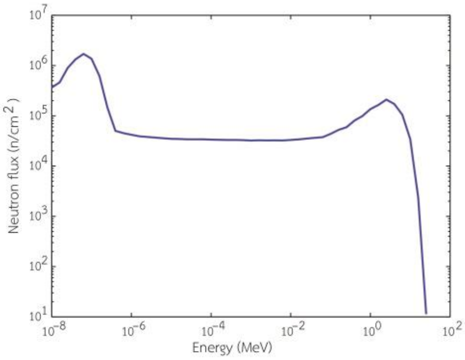

Figure 2 The neutron energy spectrum at 6-inchs beam for the TRR-1/M1 PGNAA system.

The TRR-1/M1 PGNAA uses the six-inch beam neutron flux from the Thai Research Reactor which has the neutron spectrum energy shown in Figure 2.

Liquid Scintillator Detector Model

The liquid scintillator model consists of the radiation source and the cylinder detector. The outer layer of the detector is the 0.085 cm thick of the aluminum housing. The scintillator layer with the surface area of 20.09 cm^2 was varied with the difference thicknesses of 1, 2, 3, 4 and 5 cm. The uniform neutron and photon source is placed at 10 cm in front of the detector.

Results and Discussion

The n/γ Spectra at Sample Position

As describe above that the radiation in the PGNAA system is mixed of the neutron and photon radiations. In this work, the background radiations at the sample position (end of the neutron collimator) are calculated. Figure 3(a) show the neutron spectrum at the sample position. It consists of the epithermal, thermal and fast neutrons. The background photon radiation from the neutron capture interaction in the surrounding structure is presented in Figure 3(b). The result shows a high photon flux at the energy below 1 MeV. The results show the mixed neutron and photon radiation at the sample position in the PGNAA system.

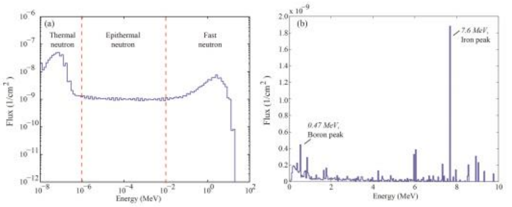

Figure 3 (a) The neutron energy spectrum and (b) the photon energy spectrum at the sample position.

The Resolution Function

To consider the size of the liquid scintillator for the background radiation measurement in the PGNAA system, the characterization and optimization of the scintillator is needed. The simulations of the detector parameters such as resolution function, neutron and photon response function and the neutron detection efficiency have been studied and presented.

For the liquid scintillator detector, the charged recoil particle produces due to the interaction of the neutral particle. In the case of photon energy, the Compton scattering between the energetic photons and the electrons in the liquid scintillator produces recoil electrons. The scattering collision between photon and the liquid scintillator are characterized by a scattering angle that can vary from 0 to 180 degrees resulting in a continuous energy distribution of the electron recoil particle from zero up to maximum energy value. The maximum energy of recoil electron for the incident photon energy $\boldsymbol{h\nu}$ is given by:

$$E_c = \frac{2(h\nu)^2}{m_0c^2 + 2h\nu}$$

where m_0c^2 is the electron rest mass energy (0.511 MeV). E_c is known as the Compton edge.

For this work, the incident mono-energetic photon energy 0.66 MeV of ^{137}Cs source is used. The Compton edge energy of ^{137}Cs source is 0.44 MeV. The response function of the liquid scintillator is obtained and shown in green in Figure 4. However, due to the finite detector resolution of the liquid scintillator, the sharp Compton edge is broadened as can be seen in the experimental spectrum (blue) in Figure 4.

In order to obtain the resolution function of the detector, the function Gaussian energy broadening (*GEB*) in MCNP code is used. The resolution parameters (*a*, *b* and *c*) specify the full width at half maximum (FWHM) for specific energy broadening is given by:

$$FWHM = a + b\sqrt{E + cE^2}$$

where *E* is the energy of the particles. The unit of the parameters *a*, *b* and *c* are MeV, MeV$^{1/2}$ and 1/MeV, respectively. The resolution parameter was folded to the response function of the detector and then was compared to the experimental spectrum.

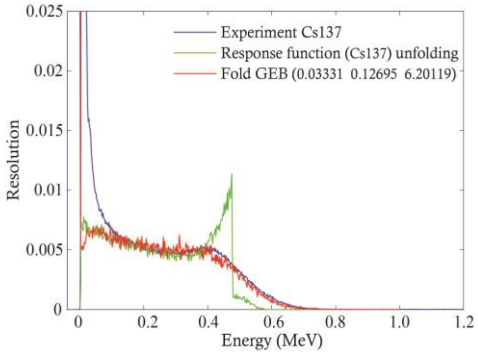

Figure 4 The comparison of the experimental (blue), unfolded response function (green) and folded response function (red) energy spectra of ^{137}Cs.

The resolution parameters *a*, *b* and *c* which equal to 0.03331, 0.12695 and 6.20119, respectively are obtained in order to match the calculation spectrum (red) to the experimental one (blue). This obtained resolution parameters were folded to all calculations in this work.

The Photon Response Function

The photon response function was calculated with the difference thicknesses of the scintillation layers between 1 cm and 5 cm in order to study the capability of the scintillator. The calculation is performed using the mono-energetic photon energy 0.66 MeV which give the Compton edge energy of 0.44 MeV.

The simulated photon response functions show in Figure 5. The results show the higher efficiency due to increasing of thick layer of scintillator.

The Neutron Response Function

Neutrons interact mainly with the nuclei of the liquid scintillator producing the recoil protons (from the collision with the hydrogen) and recoil carbon atoms. The scattering collision between neutron and the liquid scintillator are characterized by a scattering angle (**θ**) that can vary from 0 to 90 degrees resulting in a continuous energy distribution of the proton recoil particle from zero up to maximum energy value. The maximum energy of recoil proton (**E_p**) for the incident neutron energy (**E_n**) is given by:

$$E_p = E_n cos^2\theta$$

which resulting of the recoil proton energy spectrum with an ideally constant amplitude extending from the incident neutron energy all the way to zero. In this work, the neutron response function is performed for the mono-energetic neutron energy of 2.52 MeV. The results show in Figure 6.

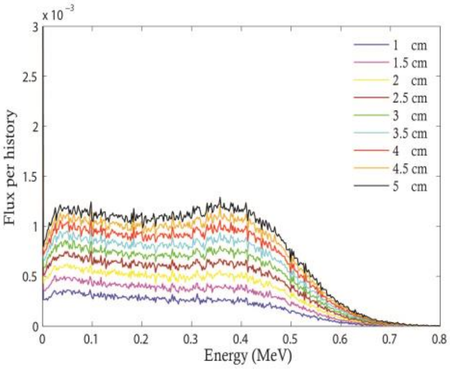

Figure 5 The photon response function of the difference thicknesses of the scintillator.

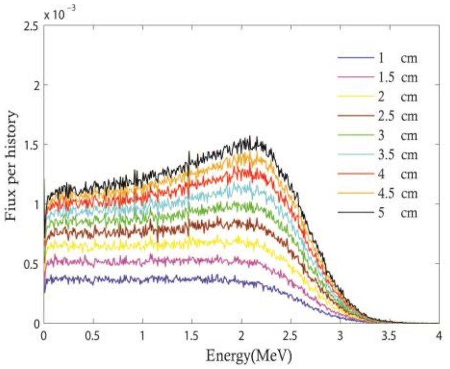

Figure 6 The neutron response function of the difference thicknesses of the scintillator.

The results show the higher neutron detection efficiency when the thick of the scintillator layer increased. Moreover, the efficiency is not increase linearly due to the recoil energy.

In both cases (photon and neutron response function), the broadened of the Compton edge due to the finite detection resolution is shown.

The Neutron Detection Efficiency

The estimation of the liquid scintillator's neutron detection efficiency is obtained in this work. The efficiency is the important parameter of the detector in order to link the measured count rate to the true count rate produced in the system. In this work, the neutron detection efficiency is calculated for the difference thicknesses of the scintillation layers between 1 cm and 5 cm using the MCNP code. In addition, the calculated neutron detection efficiency is compared to the theoretical one.

The theoretical detection efficiency of a liquid scintillator can be calculated from the scattering cross section of the composition materials. For the liquid scintillator the carbon is combined to the hydrogen thus the competing effects of the carbon scattering are taken into account. Moreover, the detection efficiency of the liquid scintillator is affected by the threshold energy (**E_{th}**) [7], thus the threshold energy much be taken into account too. The theoretical detection efficiency is given by [7]:

$$\varepsilon = \frac{1 - E_{th}}{E} \frac{N_H \sigma_H}{N_H \sigma_H + N_C \sigma_C} \times \left(1 - e^{-(N_H \sigma_H + N_C \sigma_C) d}\right)$$

where ε is the theoretical detection efficiency, E_{th} is the threshold energy, E is the proton recoil energy, N_H is a number density of the hydrogen nuclei, N_C is a number density of the carbon nuclei, σ_H is the scattering cross section for the hydrogen nuclei, σ_C is the scattering cross section for the carbon nuclei and d is the scintillation thickness.

The theoretical neutron detection efficiency in percent is obtained in Figure 7 (dashed lines). The results show that the neutron detection efficiency is affected by the scintillator thickness and the energy threshold. The efficiency increase when the thickness increases. At the same thick, the efficiency decreases when the threshold energy increase.

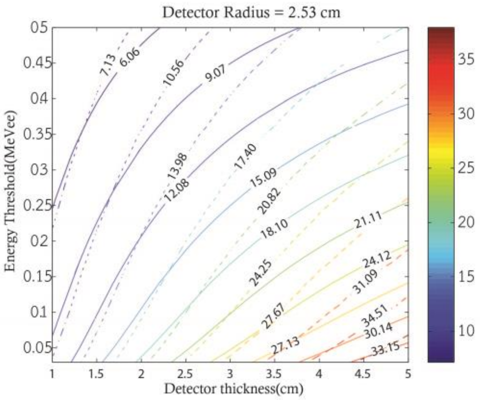

Figure 7 The percent neutron detection efficiencies obtained use the theoretical formula (dashed lines) and MCNP calculation (solid lines).

The MCNP simulated neutron detection efficiencies are presented in solid lines and compared to the theoretical one. The agreement of the results is found at the low threshold energy below 0.25 MeVee (electron recoil energy) for scintillator thick 1 cm to 3 cm.

Conclusions

The characterization parameters of the liquid scintillator such as the resolution function, neutron and photon response function and the neutron detection efficiency are studied and obtained with the Monte Carlo code MCNP. The agreement of the simulated results and the theoretical results of the neutron detection efficiency is found. The liquid scintillator shows the high capability to measure a neutron and photon, and due to the capability for the n/γ pulse shape discrimination, thus it can be benefit for the neutron measurement in the PGNAA system. The suggested size and dimension of the scintillator will be proposed for the experimental at PGNAA system at TRR-1/M1 in the future.

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