Upgrade of Neutron Energy Spectrometer with Single Multilayer Bonner Sphere Using Onion-like Structure

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Background: In order to measure neutron energy spectra, the conventional Bonner Sphere Spectrometers (BSS) are widely used. In this spectrometer, several measurements with different size Bonner spheres are required. Operators should, therefore, place these spheres in several times to a measurement point where radiation dose might be relatively high. In order to reduce this effort, novel neutron energy spectrometer using an onion-like single Bonner sphere was proposed in our group. This Bonner sphere has multiple sensitive spherical shell layers in the single sphere. In this spectrometer, a band-shaped thermal neutron detection medium, which consists of a LiF-ZnS mixed powder scintillator sheet and a wavelength-shifting (WLS) fiber readout, was looped to each sphere at equal angular intervals. Amount of LiF neutron converter is reduced near polar region, where the band-shaped detectors are concentrated, in order to uniform the directional sensitivity. The LiF-ZnS mixed powder has an advantage of extremely high light yield. However, since it is opaque, scintillation photons cannot be collect uniformly. This type of detector shows no characteristic shape in the pulse height spectrum. Subsequently, it is difficult to set the pulse height discrimination level. This issue causes sensitivity fluctuation due to gain instability of photodetectors and/or electric modules.

Materials and Methods: In order to solve this problem, we propose to replace the LiF-ZnS mixed powder into a flexible and Transparent RUbber SheeT type LiCaAlF₆ (TRUST LiCAF) scintillator. TRUST LiCAF scintillator can show a peak shape corresponding to neutron absorption events in the pulse height spectrum.

Results and Discussion: We fabricated the prototype detector with five sensitive layers using TRUST LiCAF scintillator and conducted basic experiments to evaluate the directional uniformity of the sensitivity.

Conclusion: The fabricated detector shows excellent directional uniformity of the neutron sensitivity.

Keywords: Bonner sphere spectrometer, Neutron spectrometer, Eu:LiCAF

Introduction

Neutron spectrometers are widely used in nuclear facilities, space applications and medical applications. Information of neutron energy spectrum is required to evaluate neutron dose and also to estimate a degree of neutron activation for structural materials of facilities. Estimation of the amount of radioactive wastes activated by neutrons is quite important when decommissioning nuclear facilities. In the decommissioning works, discrimination of the wastes, in which the wastes are discriminated into radioactive or normal ones, is essential because a large amount of wastes are generated in
these procedures. In order to efficiently discriminate a large amount of the wastes, the estimation of radioactive wastes based on the information of neutron flux and spectrum at interest fields is quite helpful. Although information of neutron flux and spectrum can be obtained with calculation-based estimation, measurement-based estimation is also essential for complex fields in which numerical calculations are difficult.

To obtain the neutron spectrum, Bonner sphere spectrometers (BSS) are widely used [1]. The BSS consists of several neutron detectors with different energy responses. Each detector is a thermal neutron detector such as 3He or BF3 counter surrounded with a polyethylene moderator sphere. The energy response of each detector depends on the sphere size. A large moderator sphere detector is more sensitive for fast neutrons than a small one. The BSS uses the outputs from several detectors with various size moderators to obtain a neutron spectrum. The detector outputs are the count rates obtained from each detector. The detector output vector \( \tilde{c} \) is described as

\[
\tilde{c} = R \tilde{\phi}
\]

where \( R \) and \( \tilde{\phi} \) are a detector response matrix and neutron spectral fluence, respectively. The neutron spectrum can be reconstructed by solving this equation with an unfolding technique.

In measurement procedures using the conventional BSS, the outputs from several detectors should be obtained. This means that several measurements are required at an interest measurement point. In order to reduce works for setting the detectors and measurements, a neutron spectrometer using a single detector, which has several outputs with different energy responses, is required to be developed. So far, our research group proposed and fabricated a new neutron spectrometer, which is a single moderator sphere with multiple neutron sensitive shell layers or an onion-like structure. The fabricated spectrometer has five sensitive layers. Each sensitive layers are scintillator sheets made of a LiF-ZnS mixed powder, which is sensitive only to thermal neutrons. The scintillation photons are collected with the wavelength-shifting (WLS) fiber readout, which is usually used for scintillation signal readout from large area scintillators. The scintillation sheets and WLS fibers only partially cover each shell surface because of difficulty in arranging the scintillators on the whole surface. The scintillators are uniformly and symmetrically arranged so that the detector shows no directional response dependence. The fabricated spectrometer can show appropriate outputs depending on neutron spectra and uniform directional response due to its geometric symmetry. However the spectrometer has difficulty in setting the discrimination signal level and determining the sensitivity. This is because the LiF-ZnS scintillator is opaque and shows no characteristic shape, such as a peak, in a signal pulse height spectrum [2]. We, therefore, propose to replace the scintillator into a Transparent Rubber SheeT type Eu:LiCaAlF6 (TRUST Eu:LiCAF) scintillator (\(^{7}\)Li, 95%) [3, 4]. This scintillator is flexible so that it is relatively easy to fabricate the sensitive shell layers. In this paper, we fabricate the prototype single moderator sphere neutron spectrometer with five sensitive layers using the TRUST Eu:LiCAF scintillator. We also evaluate the discrimination ability between neutrons and gamma rays. In addition, the directional response uniformity is confirmed through basic experiments using an Am-Be neutron source.

**Materials and Methods**

1. **Details of the fabricated neutron spectrometer**

The proposed detector is a single moderator sphere with five sensitive shell layers. Figure 1 shows the schematic drawing of the proposed single sphere neutron spectrometer with multiple sensitive layers. The moderator sphere is made of polyethylene. The outer diameter of the sphere is 216 mm. In this spectrometer, four band-shaped thermal neutron detection mediums, which consist of the TRUST Eu:LiCAF scintil-
erator and the WLS fiber readout, are looped on each shell with equal angular intervals. The Eu:LiCAF scintillator has high lithium content for neutron detection. Although the scintillation decay is not so fast and 1.6 μs decay time, it has high light yield, high transparency and no hygroscopicity [5]. However, this scintillator suffers from gamma-ray interference due to its low α/β ratio, which is the ratio of the scintillation efficiencies between alpha particles and fast electrons. In the TRUST Eu:LiCAF scintillator, a large number of small pieces of Eu:LiCAF scintillators are dispersed in a transparent resin or rubber sheet. In size controlled small scintillators, reaction products of 6Li(n,t) reactions can deposit their whole energy but fast electrons induced by gamma rays escape out with a large fraction of original energy due to difference between each range. A large fraction of fast electron energy is deposited into the rubber sheet. Since this rubber sheet is soft and flexible, the band-shaped scintillator, which can be looped on the shell surface, is relatively easy to be fabricated. The width of the scintillator band is 5 mm. The scintillation light signal can be readout with the WLS fiber accompanied with the scintillator band. The each scintillator band is wrapped with Teflon reflection sheets. If a band-shaped scintillators with uniform thickness are looped along meridians and overlapped at the pole, the response to the polar direction increases because the surface density of lithium content near the polar region is high. In order to uniform the directional response, the thickness of the scintillator band decreases near the polar region. The thickness of the thickest point scintillator is 5 mm. The both ends of WLS fibers are bundled in each layer and connected to five photomultiplier tubes (PMTs). The whole detector is covered with a black sheet for ambient light shielding. Photographs of the fabricated neutron spectrometer are shown in Figure 2. The scintillators are located at five radial distance (2.3, 7.3, 8.8, 10.3, 10.8 cm). The density of polyethylene shell sphere is 0.96 g·cm⁻³.

We, finally, calculated the response matrix R using Monte Carlo simulation code PHITS (Particle and Heavy Ion Transport Code System) [6]. Figure 3 shows the calculated response functions, which is the neutron energy dependences of the detector sensitivity, of each layers. The detector sensitivity was calculated as the number of 6Li(n,t) reactions per incident neutrons when the mono-energy and parallel neutron beam was uniformly irradiated over the whole detector.

2. Experimental setup
We first conducted the evaluation of neutron and gamma-ray responses of the fabricated prototype detector. For neu-

**Fig. 2.** Photographs of the fabricated prototype neutron spectrometer.

![Fig. 2. Photographs of the fabricated prototype neutron spectrometer.](image)

**Fig. 3.** Calculated detector response function. These responses were calculated using the PHITS code.

![Fig. 3. Calculated detector response function. These responses were calculated using the PHITS code.](image)
For evaluation of the directional response, we also used the $^{241}$Am-Be neutron source. In order to cancel out the influence of neutron scattering from the walls and the floor, shadow cone measurements were conducted. The polyethylene

Fig. 4. Geometrical arrangement in the directional response evaluation experiments.

Fig. 5. Pulse height spectra obtained from the neutron detection elements of each sensitive layer. (A) 1st layer (most inner layer), (B) 2nd layer, (C) 3rd layer, (D) 4th layer, and (E) 5th layer (most outer layer).
shadow cone of 250 x 250 x 300 mm$^3$ was located between the neutron source and the detector to evaluate influence only of scattering neutrons. We measured the dependence of the detector sensitivity on azimuth and elevation angle of incident neutrons. The geometrical arrangement in the directional response evaluation experiments is shown in Figure 4. The elevation and azimuth angle dependence was measured by rotating the detector around the X and Z axis, respectively. The discrimination levels in the signal pulse height spectra were set for each shell layer as shown in Figure 5. The signals above the discrimination levels were recorded as neutron counts.

**Results and Discussion**

Figure 5 shows the pulse height spectra obtained from the neutron detection elements of each sensitive layer when irradiated with neutrons and gamma rays. Clear peaks corresponding to neutron absorption events. Therefore, we can easily determine the discrimination level. We can also confirm that the signal pulse height for gamma-ray events is preferentially suppressed. Gamma-ray events can easily be discriminated in the pulse height spectra by setting an adequate discrimination level.

Figure 6 shows the dependence of the detector sensitivity measured in experiments on elevation and azimuth angle of incident neutrons. The variation of the sensitivity is small in all directions. However, only the direction of -90 degrees of the elevation angle has a little bit lower sensitivity than other directions. In this direction, there are PMTs, their supporting structures and a hole in the moderator sphere for drawing out the WLS fibers. Neutrons in this direction may be interfered by the PMTs and their supporting structures. We quantitatively evaluate the sensitivity variation for elevation and azimuth angle dependence. Table 1 lists the averages and standard deviations of the detector counts of each layer. The most outer layer can strongly be affected by geometrical influence so this layer has the largest variation. For inner layers, the sensitivity modulation is milder than the most outer layer because of neutron scattering and moderation. For all detector directions, the relative standard deviations of the sensitivity in each layer are less than 12%. Excepting -90 degrees of the elevation angle, the standard deviation are less than 7%. The fabricated detector shows excellent directional uniformity of the neutron sensitivity.

**Conclusion**

We fabricated the prototype single sphere neutron spec-

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**Table 1. Averages and Standard Deviations of the Detector Counts of Each Layer Measured in the Experiments**

| Layer number | Averaged counts [×10$^4$ counts] | RSD of counts [%] | Relative counts [-] |
|--------------|----------------------------------|------------------|--------------------|
| 1 (Most inner) | 5.9 | 5.8 | 0.44 |
| 2            | 15.5 | 5.6 | 1.15 |
| 3            | 13.5 | 4.7 | 1.00 |
| 4            | 6.9 | 6.3 | 0.51 |
| 5 (Most outer) | 2.8 | 12.0 | 0.21 |

**Table 1. Averages and Standard Deviations of the Detector Counts of Each Layer Measured in the Experiments**

| Layer number | Averaged counts [×10$^4$ counts] | RSD of counts [%] | Relative counts [-] |
|--------------|----------------------------------|------------------|--------------------|
| 1 (Most inner) | 6.5 | 2.4 | 0.41 |
| 2            | 17.4 | 2.1 | 1.11 |
| 3            | 15.6 | 2.0 | 1.00 |
| 4            | 8.2 | 4.2 | 0.52 |
| 5 (Most outer) | 3.5 | 6.0 | 0.22 |
trometer with five sensitive layers using the TRUST Eu:LiCAF scintillator and the WLS fibers. We confirmed that the fabricated detector shows a clear neutron peak and can discrimination neutron and gamma-ray events in the signal pulse height spectra. We additionally checked the directional uniformity of the detector sensitivity. The variation of the sensitivity is confirmed to be less than 12%. Excepting the direction, in which there are PMTs, their supporting structures and a hole in the moderator sphere for drawing out the WLS fibers, the variation of the detector sensitivity is less than 7%. The fabricated detector shows excellent directional uniformity of the neutron sensitivity.

As future works, we will experimentally obtain the detector response to several mono-energy neutron beams in order to check the detector response function. We should perform neutron spectrum reconstruction for a given field with a known spectrum to evaluate the performance as a neutron energy spectrometer.

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