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Simulation study on the four-scintillator detectors to identify gamma-emitting radionuclides

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1. Introduction

The scintillation detector is one of conventional radiation detectors used in various applications such as radiation monitoring, medical imaging, and the industrial field. It absorbs the incident gamma-rays and converts some of them into ultra-violet or visible light. This process makes it possible to identify and quantify the gamma-ray emitting radionuclides, which is called the gamma spectroscopy technique. Although a semiconductor detector such as high purity germanium (HPGe) detector and a Cadmium zinc telluride (CZT) detector can replace a scintillation detector with higher detection efficiency, it is preferred due to its cost competitiveness and simplicity. Moreover, some inorganic scintillators, such as sodium iodide (NaI) and cesium iodide (CsI), are available in large volumes with their low cost and mature manufacturing techniques [1]. However, it is still hard to identify gamma-ray emitting radionuclides with small volume scintillators due to the penetrability of gamma-ray [2]. It is known that the energy resolution decreases as the volume of the scintillator decreases because the scintillator cannot fully absorb the incident gamma-ray [3, 4]. Therefore, it seems like traditional scintillation detector is unsuitable for small size of Personal Radiation Detectors (PRDs) that adopt general gamma spectroscopy technique.

In previous studies, we suggested the gamma-ray energy estimation algorithm based on the ratio of scintillation light output (SLO) [5]. We compared the SLO ratios from Monte Carlo N-Particle (MCNP) simulations and experimental results. Based on the derived relationship, the energy of ^{137}Cs can be estimated without gamma spectroscopy.

In this study, we derived the relationship between the SLO ratios and the gamma-ray energies based on the physical properties of the scintillators. We selected the three kinds of inorganic and plastic scintillators with different scintillation properties, such as attenuation coefficients, density, and light yield. The SLO ratios of inorganic to plastic scintillators are calculated with MCNP simulations. The three relationships between the SLO ratios and the gamma-ray energies according to inorganic scintillators can be divided into three regions with a quasi-linearity.

2. Method and Results

2.1 Method

When gamma-ray impinges on the scintillator, it transfers all or part of its own energy with continuous interactions. Since this process obeys Beer-Lambert law, the energy deposition mainly depends on the effective atomic number of the scintillator. Based on this theory, three kinds of inorganic scintillators such as Bismuth Germanate (BGO, Z_{eff} = 84), Cerium doped Gadolinium Aluminum Gallium Garnet (GAGG:Ce, Z_{eff} = 48.27), and Europium doped Calcium Fluoride (CaF2:Eu, Z_{eff} = 17.1) and a plastic scintillator (Eljen EJ200 equivalent, Z_{eff} = 5.7) are selected. In this work, they are modeled in the form of cylinder with 15 mm length and 3 mm diameter. The brass with a density of 8.07 g/cm^3 is used for the frame of the sensor. The total size of the sensor is 19 mm thick, 19 mm width, and 15 mm height. The distance between the sensor and the 5 mm diameter of circular gamma-ray source is set at 10 mm. The overall geometry modeled for MCNP simulation is presented in Fig. 1.

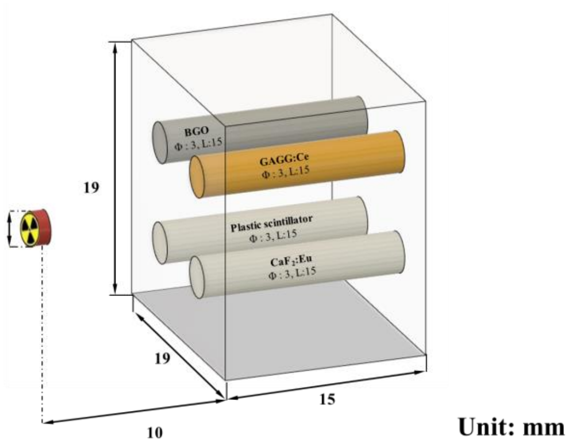

Fig. 1. Geometry for MCNP simulation

The SLO emitted from each scintillator can be derived as the product of the energy deposition and luminescence parameter [6].

$$SLO = \frac{E_d}{2.5E_p}\eta \tag{1}$$

where E_d is deposited energy, E_p is energy of scintillator photon, η is overall quantum efficiency. The energy deposition calculated with MCNP simulation is substituted into equation (1) to calculate the SLO. And SLO ratios of inorganic to plastic scintillators can be derived by dividing the SLOs between inorganic and plastic scintillators.

2.2 Results

Fig. 2 shows the total energy deposition (TED) in each scintillator with gamma-ray energy. In cases of BGO and GAGG:Ce, the amount of TED increases in the low-energy regions where photoelectric absorption is dominant since the largest energy is transferred with photoelectric absorption. However, the amount of TED decreases as the mass attenuation coefficient for photoelectric absorption decreases in some middle energy region and it increases again in energy region where Compton scattering is dominant. On the other hand, the amount of TED increases gradually as gamma-ray energy increases in both CaF_2:Eu and plastic scintillators.

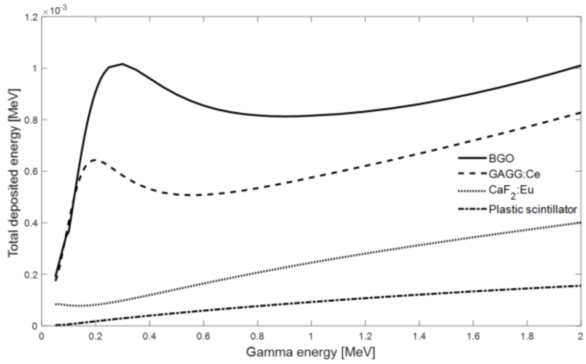

Fig. 2. Energy depositions in inorganic scintillator as a function of the energy of gamma-ray

Fig. 3 shows the calculated SLO ratios between inorganic and plastic scintillators. Since the amount of energy deposition depends on the physical properties of scintillator as shown in Fig. 2, each peak and slope in the graphs also depend on the physical properties of scintillators. Table 1 shows the scintillations properties of selected scintillators.

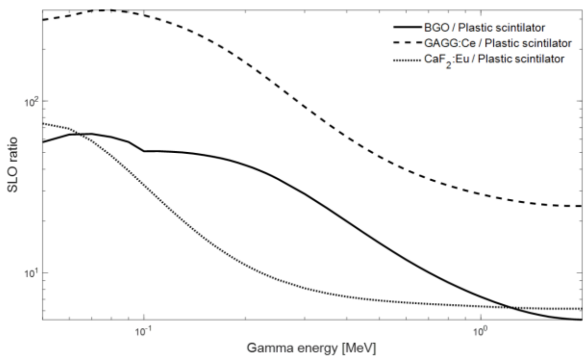

Fig. 3. SLO ratio as a function of the energy of gamma-ray

Table I: Physical properties of the scintillators

	Density [g/cm^3]	Light yield [photons/Mev]	Attenuation length for 511-kev gammas [cm]
BGO	7.13	8200	1.11
GAGG:Ce	6.6	46000	1.61
CaF_2:Eu	3.18	24000	3.72
Plastic scintillator	1.032	10000	10.5

The energy of gamma-ray can be divided into three regions considering the discontinuity due to the K-edge of scintillation material, peak, and slope. Due to the absence of inflection point in low energy regions, the SLO ratio of CaF_2:Eu to plastic scintillator is adopted in the energy range from 50 to 80 keV. The SLO ratio of GAGG:Ce to plastic scintillator occupies the energy range from 80 to 400 keV because its variance is obvious with a high light yield of GAGG:Ce. And the SLO ratio of BGO to plastic scintillator is adopted in a high energy region above 400 keV because its SLO ratio is not saturated in high energy region. The energy of gamma-ray emitted from the radionuclides can be determined by substituting the SLO ratio into the derived graph. The calculated energies of radionuclides that emit poly-energetic gamma-rays are shown in Fig. 4.

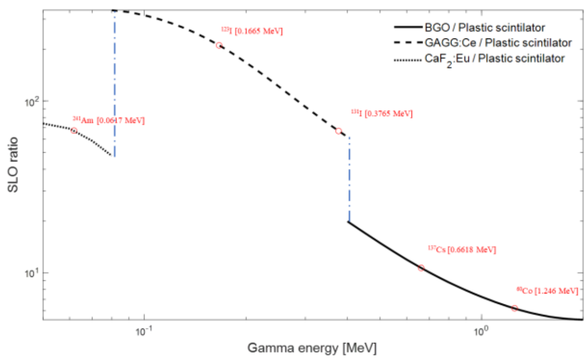

Fig. 4. SLO ratio to determine the energy of incident gamma-ray

3. Conclusions

In this study, SLO ratios are calculated with MCNP simulation. Since the SLO depends on the energy deposition that is affected by physical properties of scintillator, the gamma-ray energy can be divided into three regions with a quasi-linearity.

In further study, the energy of gamma-ray except for ^{137}Cs can be also estimated with derived relationship between SLO ratio and energy of gamma-ray.

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