Comparison of scintillation light output ratios between simulation and experiment

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1. Introduction

The scintillation detector has been traditionally employed for various fields to identify and quantify the gamma-ray emitting radionuclides. Although it has relatively low accuracy and detectability than radiochemical analysis and high-purity germanium (HPGe) detector, it is preferred with cost competitiveness and well suited to in-situ measurement. It is hard to identify gamma-ray emitting radionuclides if no specific peaks in the gamma spectrum are measured because the traditional gamma spectroscopy highly relies on the full-energy peak. An ideal scintillator for gamma spectroscopy should have a large volume and high attenuation coefficient due to the penetrability of gamma-ray. However, growing a large inorganic scintillator has a high manufacturing cost and complexity because they have grown with single-crystal growth methods. Therefore, traditional gamma spectroscopy has restrictions concerning the selection of scintillators.

In a previous study, we manufactured the plastic optical fiber-coupled scintillator detector which is composed of different kinds of scintillator. Since the ratio of scintillation light output (SLO) between inorganic and plastic scintillator depends on the energy of incident gamma-ray, different kinds of gamma-ray emitting radionuclides can be distinguished from each other with the photon-counting values.

In this study, Monte Carlo N-Particle (MCNP) simulations are carried out to compare the ratios of SLO obtained from MCNP simulation and experiment. To calculate the ratio of SLO, deposited energy in each scintillator was calculated, and SLO was derived with a mathematical SLO model composed of several luminescence parameters.

2. Methods and Results

2.1 Simulation setup

When gamma-ray interacts with absorbing materials, it loses all or part of its own energy with interactions. Due to the difference in attenuation coefficient, different amount of energy was transferred to each scintillator detector with different elemental composition. And scintillator emits visible photons proportional to this transferred energy. Based on the theory, different kinds of scintillators such as bismuth germanate (BGO, Z=83/32/8, Epic-crystal), cerium doped gadolinium aluminum gallium garnet (GAGG:Ce, Z=64/31/13/8, Epic-crystal), and plastic scintillator (BC-408, Saint-Gobain) were selected to measure the different energy depositions. In this work, scintillators were designed as cylindrical shape with 3 mm diameter, and 15 mm length. The brass with a density of 8.07 g/cm^3 was selected for the frame of the scintillator assembly. The total size of the scintillator assembly was thick of 19 mm, the width of 19 mm, and the height of 26 mm. In the simulations, a plane gamma-ray source with a diameter of 5 mm was located at 15.77 mm from scintillator assembly, considering the geometry of the previous experiments [1]. The overall geometry for simulation is described in Figure 1. And Figure 2 shows the experimental setup to measure the ratio of SLO with photon-counting modules.

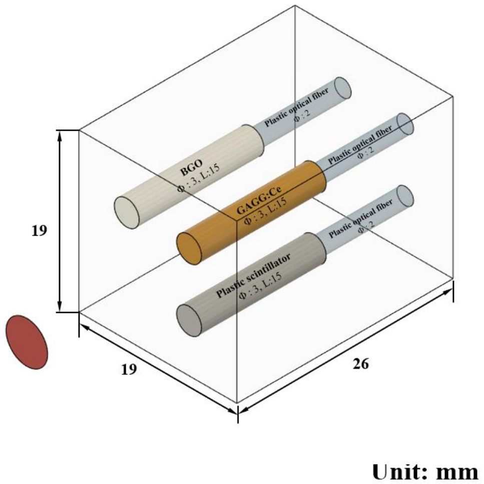

Fig. 1. Geometry of MCNP simulation

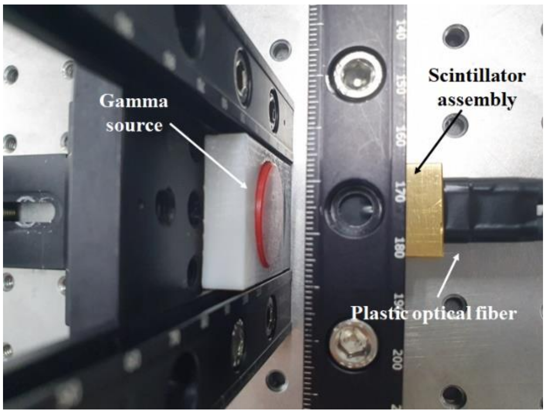

Fig. 2. Experimental setup to measure the ratio of SLO

2.2 Scintillation light output

SLO is defined as the total number of visible photons emitted from the scintillator. In principle, it can be defined as the product of the deposited energy and the light yield which was derived in earlier studies [2,3]. Therefore, the SLO of inorganic scintillator can be defined as equation (1):

$$SLO_{inorganic} = \frac{E_d}{2.5E_g}\eta = \frac{E_d}{2.5E_g}\beta SQ \qquad (1)$$

where E_d is deposited energy, E_g is bandgap energy of scintillator, η is overall quantum efficiency, β is conversion efficiency, S is transfer efficiency, and Q is luminescence quantum efficiency. And it is known that 2 ~ 4% of deposited energy is converted into visible photons in an organic scintillator [4]. In the same manner, the SLO of plastic scintillator can be roughly derived as equation (2):

$$SLO_{plastic} = \frac{E_d}{E_p}\eta \qquad (2)$$

where E_p is the energy of the emitted photon. In this work, we assumed Ep as 2.92 eV, considering the wavelength of 425 nm which is the maximum emission of the plastic scintillator, and η is also assumed as 0.03.

2.3 Results

Figure 3 shows the relationship between the ratio of SLO calculated with MCNP and the energy of emitted gamma-ray from radionuclides. The emitted energies of radionuclides are listed in Table I.

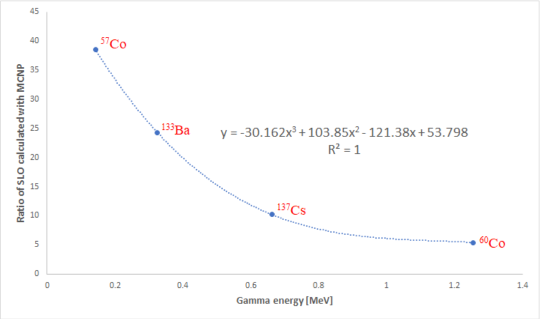

Fig. 3. Ratio of SLO calculated with MCNP as a function of the energy of emitted gamma-ray

Table I: Energies of the gamma-ray sources

	Energy [MeV]
^{57}Co	0.014, 0.122, 0.136
^{133}Ba	0.081, 0.356
^{137}Cs	0.662
^{60}Co	1.173, 1.332

In this work, three kinds of gamma-ray emitting radionuclides such as ^{60}Co, ^{133}Ba, and ^{57}Co were used to obtain the relationship between the ratio of SLO measured in the experiment and the same calculated with MCNP simulation as shown in Figures 4 and 5.

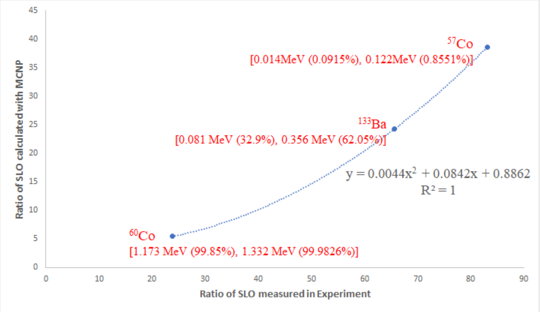

Fig. 4. Ratio of SLO between BGO and plastic scintillator

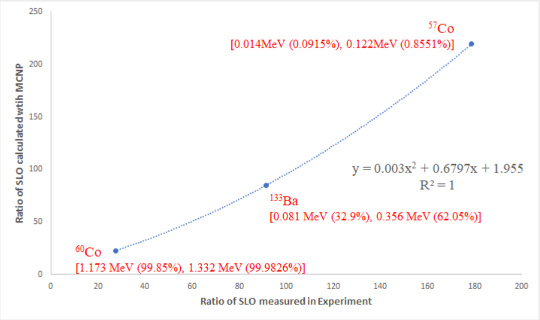

Fig. 5. Ratio of SLO between GAGG:Ce and plastic scintillator

The SLO ratio of ^{137}Cs was derived from the curve fitting model. ^{137}Cs can be identified with the ratio of SLO measured using scintillator assembly by comparing the SLO ratios between simulation and experiment as listed in Table II.

Table II: SLO ratio of ^{137}Cs

	Curve fitting	Experiment
Model_BGO	37.451	37.281
Model_GAGG	41.765	41.773

Since the precise thickness of TiO_2 reflector paint and aluminum tape adopted on the surface of the scintillator were not considered in simulations, the attenuation of low-energy gamma-ray might be underestimated. Additionally, the emission spectrum of each scintillator was assumed to be a single wavelength with its bandgap energy. The attenuation spectrum of plastic optical fiber and sensitivity of photon-counting modules are also not be considered in the simulation. Therefore, there is a little difference between the two ratios of SLO in simulation and experiment.

3. Conclusions

In this study, SLO ratios between MCNP simulation and experiment were compared. From the result, gamma-ray emitting radionuclides can be identified with ratios of SLO between inorganic scintillator and plastic scintillator.

Further studies will be carried out to measure the ratios of SLO from various gamma-ray emitting radionuclides.

ACKNOWLEDGMENT

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korean government (MIST) (No. 2020M2D2A2062457, 2020M2D8A2066404)

REFERENCES

[1] S. Kim et al., "Measurements of light-output ratios using inorganic and organic scintillators to identify gamma-ray emitting radionuclides", Proceedings of the KNS spring meeting, 2021. Korea, Republic of: KNS.
[2]A. Lempicki et al., "Fundamental Limits of Scintillator Performance," (in English), Nucl Instrum Meth A, vol. 333, no. 2-3, pp. 304-311, Sep 1993, doi: 10.1016/0168-9002(93)91170-R.
[3]T. Yanagida, "Inorganic scintillating materials and scintillation detectors," (in English), P Jpn Acad B-Phys, vol. 94, no. 2, pp. 75-97, Feb 2018, doi: 10.2183/pjab.94.007.
[4]G. Ros et al., "On the design of experiments based on plastic scintillators using GEANT4 simulations," (in English), Radiat Phys Chem, vol. 153, pp. 140-151, Dec 2018, doi: 10.1016/j.radphyschem.2018.09.021.