Optimization studies of 3D-printed plastic scintillator for Compton-suppression detection system using Monte Carlo calculations

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1. Introduction

When multiple radionuclides are present in the actual analysis, the Compton continuum of the high-energy peak radionuclide overlaps with the energy of the low-energy peak radionuclide, make it difficult to analyze the low-energy peak radionuclide. To solve this problem, a method to eliminate the Compton continuum through Compton suppression technique was devised, and research is still ongoing to achieve better performance [1]. The Compton suppression system consists of a Main detector surrounded by a Secondary detector. The coincidence events generated by the two detectors can be removed using anti-coincidence gating, achieving the suppressed Compton effect. Among them, the Secondary detector mainly uses inorganic scintillators such as BGO and NaI(Tl), but there are problems with their high overall cost. Given that 3D-printed plastic scintillators offer cost advantages and the flexibility for customized designs, they allow for efficient use of the internal space within the Compton suppression shield without any voids, potentially enhancing the Compton suppression performance. In this context, this study applied 3D-printed plastic scintillators as a secondary detector. Through simulations, the Compton suppression effect was compared to that of using BGO.

2. Materials and Methods

2.1 3D-printed plastic scintillator

The 3D-printed plastic scintillators, named RMPS470, were produced by RAYMETRICS Co. [2]. These scintillators were developed using 3D printing technology, with an optimized mixture of D0241 (monomer), PPO (primary dye), ADS086BE (wavelength shifter), and TPO (photoinitiator). The basic characteristics of the RMPS470 are shown in Table 1 [3]. Additionally, we also evaluated the incorporation of Pb powder to enhance the efficiency of the Compton Suppression System.

2.2 Compton Suppression System Simulation

To evaluate the Compton suppression system, we used MCNP6, a simulation based on Monte Carlo methods. A coaxial HPGe (GC3018; CANBERRA) was used as the

Table I: Characteristics of RMPS470 scintillator

Light output [photons/MeV]	6700 ± 243
Absorption/Emission wavelength [nm]	403/470
Fast Decay time constants[ns]	2.31 ± 0.10 (81%)
Slow Decay time constants[ns]	7.18 ± 0.94 (19%)
Density [g/cc]	1.22
H/C ratio	30:35
Molecular weight	546
Hygroscopic, Cleavage	No
Performance changes over time	No

main detector. And for suppression, a secondary detector with a height of 25.6cm was used, with an annular radius for BGO and RMPS470 being 3cm and 10.19cm, respectively. For BGO, we modeled the geometry based on current research practices and used commercial crystal BGO [4]. The simulation model is shown in figure 1.

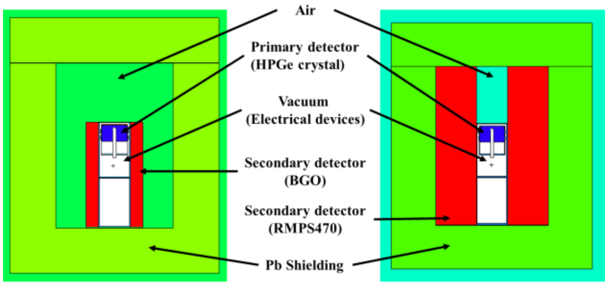

Fig. 1. Geometry of Compton suppression for the MCNP6 simulation.

In simulation, the pulse-height tally (F8) was used, and the tallies were broadened by using the Gaussian energy broadening (GEB) feature available in MCNP. To remove coincidence particles, we used the time bin card (FT) and PHL option in pulse-height tally.

2.3 Comparison factor

The Figure of Merit used to compare the efficiency of Compton suppression is defined as the Compton suppression factor (CSF), is given by the equation

$$(1) \quad CSF = \frac{PCR_{suppressed}}{PCR_{unsuppressed}}$$

Table II: Comparison of the BGO and 3D-printed plastic scintillator suppression factors for the 358-382 keV energy range

Annular radius	Case	PCR		CSF	System efficiency [%]
		Unsuppressed	Suppressed		
3cm	BGO	13.35 ± 0.01	85.52 ± 0.30	6.41 ± 0.02	-
10.19cm	RMPS470		50.95 ± 0.11	3.82 ± 0.01	59.57
	RMPS470 + 5wt% Pb		89.72 ± 0.33	6.72 ± 0.02	104.90

where PCR is the peak-to-Compton ratio, which is defined as the ratio of the count in the highest photo peak energy to the count in a typical energy of the Compton continuum associated with that peak. The value used from the Compton continuum for the 662 keV gamma rays from ^{137}Cs, is 358 keV to 382 keV [5].

3. Results and Discussions

The Peak-to-Compton ratio and Compton suppression factors derived from simulations are summarized in Table 2.

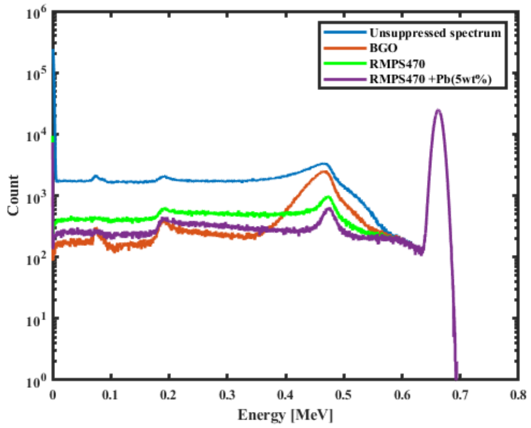

Fig. 2. Simulation results for a ^{137}Cs gamma-ray source: pulse height spectra with and without Compton suppression.

As shown in Fig. 2, the Compton continuum for gamma-ray energies under the photo peaks is effectively suppressed when using the secondary detector. The Compton suppression factors for BGO and RMPS470 were 6.41 and 3.82, respectively. However, when 5wt% of Pb powder was incorporated into RMPS470, the Compton suppression factor increased to 6.72, exhibiting an efficiency improvement of approximately 4.9% compared to the use of BGO.

4. Conclusions

We obtain the simulation results of Compton suppression effect using RMPS470. When used alone, the value of CSF for RMPS470 was 3.82, which represents only 59.57% of the efficiency observed with BGO. This indicated that using RMPS470 by itself for the Compton suppression system did not have satisfactory results. To enhance its efficiency, we added 5wt% of Pb powder into the RMPS470. The modified material showed an increased efficiency of 4.9% compared to BGO, suggesting the potential for RMPS470 with added Pb powder to serve as an alternative to the conventionally used BGO in Compton suppression systems. Furthermore, considering the production cost of 3D-printed plastic scintillators, the modified material is estimated to be approximately 55% cheaper than BGO. This suggests significant potential from an economic perspective. Future work could focus on optimizing the geometry of the 3D-printed scintillator in various fields where a Compton suppression system is required.

REFERENCES

[1] Q. Zou, J.J. Zhu, Z. An, Y.P. Zhang, Monte Carlo optimization of a Compton suppression system for gamma-ray diagnosis of combustion plasma, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, Vol. 879, 2018

[2] https://raymetrics.co.kr/customPrinted

[3] Lee, S. M., Development of a plastic scintillator for dosimeter applications with a DLP 3D printing technique, Doctoral dissertation, 2021

[4] S. Garti, J. Dumazert, R. Coulon, Q. Lecomte, F. Carrel, G. Corre, M. Imbault, C. Theroine, C. Jammes, Charsacterizing low-activity waste containers: A case study for Compton Suppression Systems under challenging signal-to-noise ratio, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, Vol. 949, 2020

[5] ANSI/IEEE Standard 325, Test Procedures for Germanium Gamma-ray Detectors, 1986