

Characteristics of Polystyrene-based Plastic Scintillators

Wooseub Kim^a, Yewon Kim^a, Giyoon Kim^a, Kyungtaek Lim^a, Kyeongjin Park^a, Hojic Kim^a and Gyuseong Cho^{a*}
^aDept of Nuclear and Quantum Engineering, Korea Advanced Institute of Science and Technology, Daejeon 291
*Corresponding author: gscho1@kaist.ac.kr

1. Introduction

Plastic materials are mainly composed of low atomic number (Z) elements, e.g., hydrogen ($Z=1$) and carbon ($Z=6$) so that plastic scintillators have relatively low stopping power and poor energy resolution to detect gamma rays or X-rays compared to inorganic scintillators. The light yield of typical plastic scintillators (10,000/MeV) is also lower than inorganic scintillators, e.g., NaI:Tl (38,000/MeV) and CsI:Tl (65,000/MeV) [1]. However, it has the merits of having a short fluorescence lifetime to reduce detector dead-time, processing into any desired shapes easily and minimizing the loss of optical photons due to good optical properties in visible wavelength range.

Generally, plastic scintillators are fabricated with a polymer base, primary fluors and secondary fluors. When polymer molecules are excited by radiation, this excitation energy is delivered to primary fluors through Förster mechanism. The energy is emitted as ultraviolet (UV) photons from primary fluors. However, the wavelength of UV photons is not well matched with the sensitive wavelength range of photomultiplier tube (PMT). Therefore, secondary fluors called as wavelength shifter are added to absorb the UV photons and re-emit longer wavelength optical photons by Stokes shift. Finally, the emitted optical photons from the secondary fluors can efficiently contribute to PMT signals [2].

In this study, polystyrene based plastic scintillators were fabricated with styrene monomer, 2,5-Diphenyloxazole (PPO) and 1,4-Bis(5-phenyl-2-oxazolyl)benzene (POPOP). The concentrations of PPO and POPOP determine the luminescence properties of a plastic scintillator. When PPO and POPOP are added a lot, self-absorption effects become dominant. On the contrary, when PPO and POPOP are mixed a little, emitted UV photons from primary fluors have low probabilities to be absorbed into secondary fluors but high probabilities to be re-absorbed into polystyrene itself. Both cases result in the low light yield of plastic scintillator. For those reasons, the optimal concentrations of PPO and POPOP should be selected for the outstanding luminescence properties of a plastic scintillator.

To analyze the variations of luminescence properties, styrene monomer was variously mixed with PPO (3, 5, 10 wt%) and POPOP (0.15, 0.25, 0.5 wt%) for thermal polymerization. With the fabricated plastic scintillators, gamma ray spectra were measured by using Cs-137, Co-60, Mn-54 and Na-22 gamma ray sources. Light yields of the plastic samples were relatively compared by Compton edge features in gamma ray spectra.

The energy linearity of a sample with the highest scintillation light yield in the plastic samples was calculated by comparing channel numbers and gamma ray energies in gamma ray spectra.

2. Materials and methods

2.1. Fabrication of plastic scintillators

Polystyrene based plastic scintillators were fabricated with styrene monomer (95% purity), PPO and POPOP. Styrene monomer was mixed with the different concentrations of PPO (3, 5, 10 wt%) and POPOP (0.15, 0.25, 0.5 wt%) for thermal polymerization as described in Table I. Additional 25 mm thick plastic scintillator sample containing 3 wt% PPO and 0.15 wt% POPOP was fabricated to representatively evaluate the energy linearity.

The mixtures of styrene monomer, PPO and POPOP were placed under the condition of 60°C temperature, heated overnight and cooled down slowly to prevent thermal shrinkage. Fabricated plastic scintillators were cut with a cutting machine to process a cylinder form and polished to minimize light scattering near surfaces. In order to reduce the outflow of optical photons from the scintillators, Teflon (PTFE) tape with 98% reflectivity in visible wavelength range was covered on the surfaces except the surface in contact with PMT as shown in Fig. 1, 2. The comparative light yield measurements were performed with the fabricated plastic scintillators.

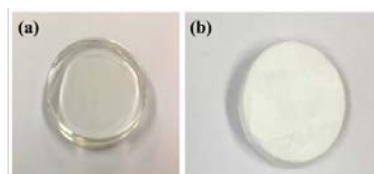


Fig. 1. (a) 5 mm thick plastic scintillator, and (b) Teflon covered plastic scintillator.

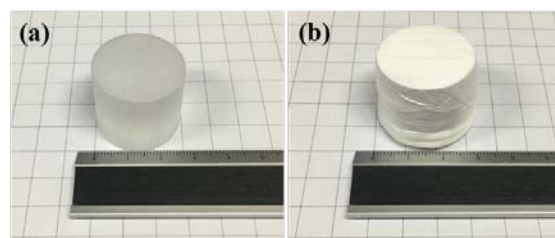


Fig. 2. (a) 25 mm thick plastic scintillator, and (b) Teflon covered plastic scintillator.

Table I: The list of fabricated plastic scintillators.

Sample number	Styrene [wt%]	PPO [wt%]	POPOP [wt%]	Size [mm]
1	96.85	3	0.15	∅27 × 5
2	96.85	3	0.15	∅27 × 25
3	94.75	5	0.25	∅27 × 5
4	89.5	10	0.5	∅27 × 5

2.2. Experimental setup

The fabricated plastic scintillators were coupled to PMT (Hamamatsu, R329-02) one by one. Optical grease (Saint-Gobain, BC-630) was used to remove an air layer and smoothly connect the scintillator and PMT. Co-60, Mn-54, Cs-137 and Na-22 gamma ray sources were used to achieve gamma ray spectra. The gamma ray sources were positioned 5 cm away from the plastic scintillator. Lead bricks surrounded gamma ray detection system for radiation shielding (Fig. 3). High voltage power supply (ORTEC 556) was set to -1300 V. Then, the signals from PMT passed a shaping amplifier (ORTEC 672) with 0.5 μ s shaping time. The amplified signals were fed to a multichannel analyzer (Amptek, MCA8000D) and finally to a personal computer. DDP MCA software recorded gamma ray spectra during 900 sec live time (Fig. 4).

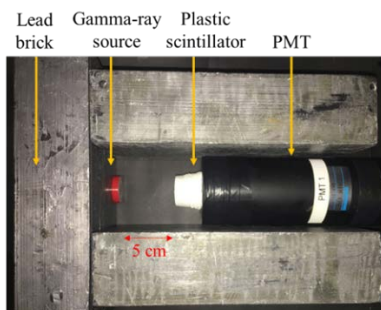


Fig. 3. Gamma ray detection system.

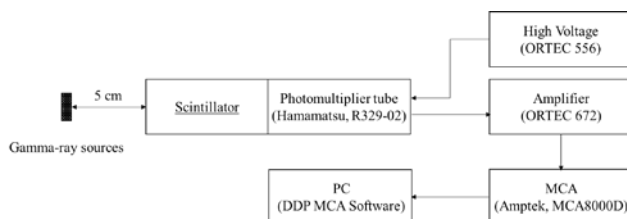


Fig. 4. A schematic diagram of gamma ray spectroscopy setup.

At plastic scintillators, photoelectric effects rarely occur due to very low atomic number elements so that photopeaks are missing. Instead, Compton edge features

can be used for energy calibration. Incident gamma ray photons collide with electrons in a scintillator by Compton scattering process. In the Compton scattering, fully back-scattered events (180 degrees) can deposit the highest energy at a plastic scintillator. The events determine the Compton edge in a gamma ray spectrum.

The Compton edge energies of gamma ray sources were calculated as shown in Table II. The position of a Compton edge event was assumed as a channel number where the half value of Compton peak is located in the gamma ray spectra. Based on this approach, the light yields of the plastic samples were relatively compared and the energy linearity of a plastic sample was calculated.

Table II: The Compton edge energies of gamma sources.

Radionuclide	Gamma energy [keV]	Compton edge energy [keV]
Co-60	1173 / 1333	1040.78
Mn-54	835	639.36
Cs-137	662	477.65
Na-22	511	340.67

3. Results and discussion

The scintillation light yields of plastic scintillators were compared by the gamma ray spectra of Cs-137. When more optical photons are emitted per the same deposited energy, Compton edge is positioned at a higher channel number. Experimental results show that a plastic scintillator containing 3 wt% PPO and 0.15 wt% POPOP was superior in luminescence properties to other plastic scintillator samples (Fig. 5).

Based on the experimental result of luminescence properties, 25 mm thick plastic sample containing 3 wt% PPO and 0.15 wt% POPOP (#2 plastic scintillator) was additionally fabricated. The energy linearity of #2 plastic scintillator was 99.774% (Fig. 6, 7).

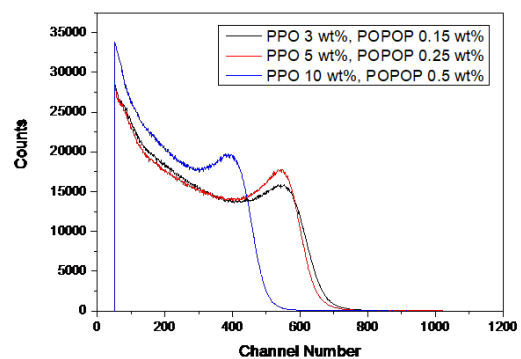


Fig. 5. The gamma ray spectra of Cs-137 gamma source using fabricated plastic scintillators.

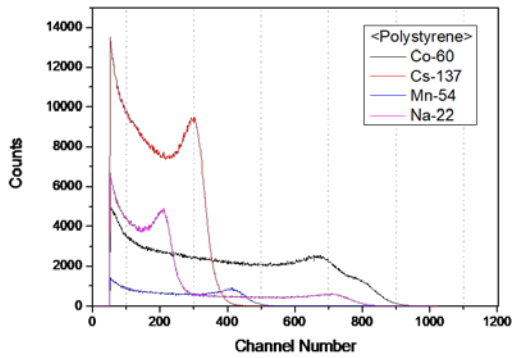


Fig. 6. The gamma ray spectra of Co-60, Cs-137, Mn-54 and Na-22 gamma sources using #2 plastic scintillator.

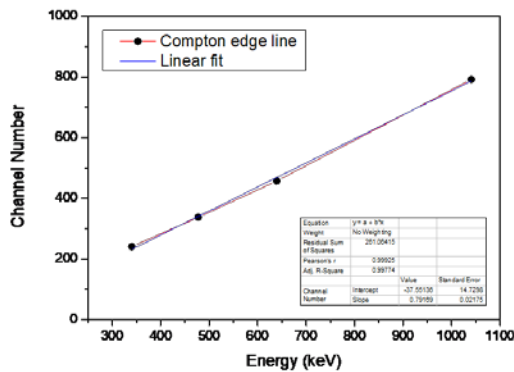


Fig. 7. The energy linearity of #2 plastic scintillator using Compton edge features.

4. Conclusion

In this research, three different concentrations of PPO and POPOP were mixed with styrene monomer for thermal polymerization to fabricate polystyrene-based plastic scintillators. Co-60, Mn-54, Cs-137 and Na-22 gamma ray sources were used to achieve gamma ray spectra. Gamma ray spectroscopy setup consisted of plastic scintillator, PMT, Shaping amplifier, High voltage power supply and MCA.

The experimental results showed that the plastic scintillator containing 3 wt% PPO and 0.15 wt% POPOP has the highest scintillation light yield than other plastic scintillator samples. When the concentration of PPO is greater than 3 wt% and the concentration of POPOP is also greater than 0.15 wt% in a plastic scintillator, the luminescence properties decrease due to self-absorption effects. The energy linearity of 25 mm thick plastic scintillator containing 3 wt% PPO and 0.15 wt% POPOP was 99.774%.

It is generally known that 1 wt% primary fluors and 0.05 wt% secondary fluors in organic scintillators have optimal luminescence properties [3]. Therefore, adding

the fluors beyond the concentrations may deteriorate the luminescence properties.

For further study, different concentrations of PPO and POPOP will be added to verify an optimal concentration that polystyrene-based plastic scintillator can have the best performance in the luminescence properties.

5. Acknowledgements

This work was supported by the Nuclear Research & Development Program of the National Research Foundation of Korea (NRF) grant funded by the Ministry of Science, ICT and Future Planning (MISP) (Grant code: 2017M2A2A6A02020807, 2018M2A8A5023361).

This work was partly supported by a National Research Foundation of Korea (NRF) grant funded by the Korean government (MSIP) (NRF-2017M2A8A5015084).

REFERENCES

- [1] G. F. Knoll, Radiation Detection and Measurement, 4th edition, John Wiley & Sons, New York, 2010.
- [2] A. Wiczorek, K. Dulski, S. Niedzwiecki, et al., Novel scintillating material 2-(4-styrylphenyl) benzoxazole for the fully digital and MRI compatible J-PET tomograph based on plastic scintillators, PLoS One, Vol.12(11), e0186728, 2017.
- [3] S. Ahmed, Physics and Engineering of Radiation Detection, 2nd edition, Elsevier, 2014.