Characterization of Plastic Scintillator Samples

Produced by a University-SME Collaboration

Mustafa Kandemir

May 2024

Supported by TUBITAK (Project no:122F271)

OPEN ACCESS

RECEIVED
7 December 2023

REVISED
6 March 2024

ACCEPTED FOR PUBLICATION
19 March 2024

PUBLISHED
4 April 2024

PAPER

Characterization of plastic scintillator samples produced by a university-SME Collaboration

Bora Akgün[1,2,3,*], Sertaç Öztürk[3,4], Kıvanç Nurdan[3,5], V Erkcan Özcan[1,6], N Gökhan Ünel[7], Asuman Kolbaşı[2], Emre Elibollar[1], Arda Ünal[1], Mustafa Kandemir[1], Yağızhan Şahin[1], Burak Kara[1], Zeynep Akbulut[8], Cengizhan Koyutürk[9], Hazal Candan Kaçar[1], Sungur Özkan[1] and Efe Mert Yüksel[1]

1 Department of Physics, Boğaziçi University, İstanbul, Turkey
2 Center for Life Sciences and Technologies, Boğaziçi University, İstanbul, Turkey
3 CRONUS Technology, İstanbul, Turkey
4 Department of Basic Sciences, İstinye University, İstanbul, Turkey
5 Information Technologies Institute, TÜBİTAK BİLGEM, Gebze, Turkey
6 Feza Gürsey Center for Physics and Mathematics, Boğaziçi University, İstanbul, Turkey
7 Department of Physics and Astronomy, University of California at Irvine, Irvine, CA, United States of America
8 Department of Chemistry, Yıldız Technical University, İstanbul, Turkey
9 Department of Physics, Middle East Technical University, Ankara, Turkey
* Author to whom any correspondence should be addressed.

E-mail: bora.akgun@boun.edu.tr and bora.akgun@bogazici.edu.tr

Keywords: plastic scintillator, particle detector, gamma radiation, light yield

Outline

- Abstract
- Introduction
- Synthesis of Plastic Scintillator Samples
- Optical Properties
    - Transmission Factor
    - Emission Wavelength Distribution
    - Light Yield
- Conclusion

Abstract

Three plastic scintillator samples with different flour additives are synthesized.

Optical properties are compared with a high-light-yield EJ-204 reference sample.

The plan is to use the same flour additive concentration to produce application-specific scintillators that are not commercially available for nuclear reactor monitoring and medical applications.

Introduction i

Detection of radiation is important for medical imaging, nuclear reactor monitoring, agricultural and environmental areas.

Many different radiation detection materials exist.

- Eljen Technology
- Amcrys
- Hamamatsu Photonics

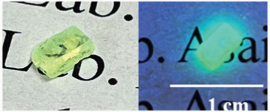

Figure 1: Organic Scintillator Samples

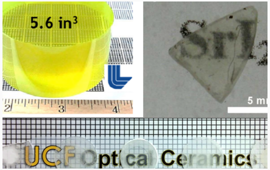

Figure 2: Inorganic Scintillator Samples

Plastic scintillators are polymer-based materials that emit light when interacted with ionization radiation and offer

- Low Cost
- Easy Manufacturing

Figure 3: Plastic Scintillators

Introduction iii

Initial emissions of plastic scintillators are in the ultraviolet (UV) range. The UV light then turned into visible light when doped with wavelength shifters.

The main purpose is to convert ionizing radiation into light, therefore the synthesized scintillators must perform well with respect to

- Light Emission Spectrum
- Light Transmission Factor
- Light Yield

Introduction iv

New types of scintillators are produced by the addition of organometallics, nanoparticles, high concentration of organic flour for pulse shape discrimination.

Many companies produce plastic scintillators, however, they do not normally provide gadolinium or lithium-doped products.

Gadolinium-doped plastic scintillators are considered for nuclear reactor monitoring.

CRONUS Technology has started to produce commercial plastic scintillators with and without gadolinium organometallic doping.

Synthesis of Plastic Scintillator Samples i

The common approach is thermal polymetrization of a solution of liquid monomer containing specific additives.

A plastic scintillator consists of three components;

- Polymer Base
- Primary flour (first additive)
- Wavelength Shifter (second additive)

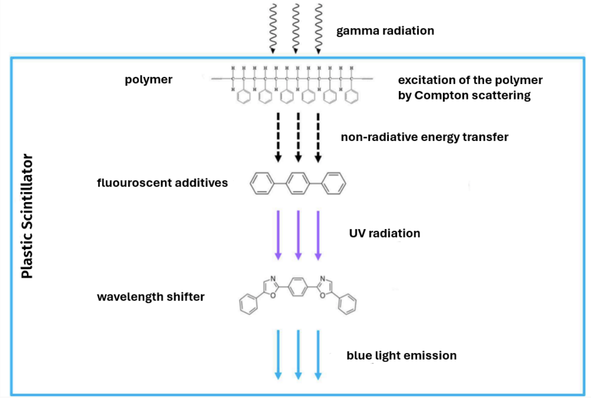

Figure 4: Inside of a plastic scintillator

Polymer Base: Polystrene - Polyvinyltoulene

The selected monomer is purified with activated alumina sorbent to remove inhibitors or water.

Primary Flours:

- 2,5-Diphenyloxazole (PPO)
- p-Terphenyl (PTP)

Wavelength Shifters:

- 1,4-bis(5-phenyl-2-oxazolyl)benzene (POPOP)
- 1,4-Bis(2-methylstyryl)benzene (Bis-MSB)

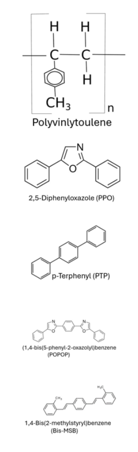

Figure 5: Ingredients

Synthesis of Plastic Scintillator Samples iv

Additives are poured into the volume of purified monomer and stirred with a magnetic stirrer for 6 hours at 40 °C.

High-purity argon gas is blown through the homogeneous solution for two minutes for oxygen removal.

The mixture is poured into a glass jar and sealed under argon atmosphere and kept at 100-120 °C for 5 days.

Cut and shaped into a cubic shape with dimensions of 10mm.

Samples

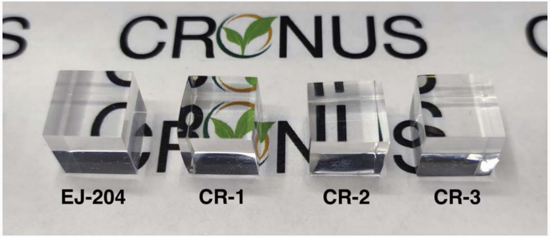

Figure 6: The synthesized plastic scintillator samples and the reference sample.

Sample Name	Primary Additive (wt%)	Secondary Additive (wt%)
CR-1	1.5% PPO	0.08% POPOP
CR-2	1.5% PTP	0.08% Bis-MSB
CR-3	0.75% PPO + 0.75% PTP	0.04% POPOP + 0.04% Bis-MSB

Table 1: List of scintillator samples and their incorporated additives.

The optical properties of the synthesized plastic scintillator samples in the visible light wavelength range are investigated using a Jasco V-730 UV-Vis spectrophotometer.

The results are compared with an EJ-204 plastic scintillator reference sample of the same geometrical shape.

Figure 7: Jasco V-730 UV-Vis Spectrophotometer

Transmission Measurment i

The transmission factor refers to the ratio of the intensity of light transmitted through the scintillator material to the intensity of incident light.

It represents the fraction of light that passes through the scintillator without being absorbed or scattered.

A higher transmission factor means that more incident radiation can penetrate the scintillator material and interact with the scintillation material, leading to a higher detection efficiency.

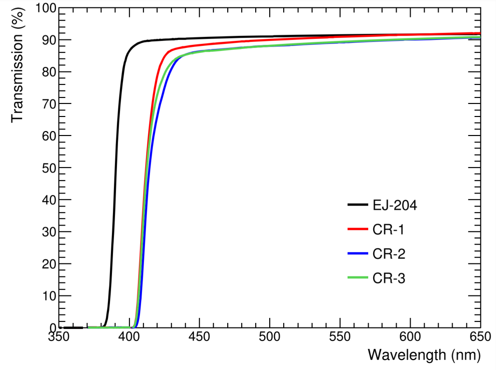

Figure 8: Transmission Factors

The transmission factors of all produced samples are comparable with EJ-204 and surpass 86% after 440nm.

Emission Measurement i

The emission distribution refers to the spatial distribution of light emitted by the scintillator material when it interacts with ionizing radiation.

It describes how the emitted light is distributed in terms of intensity across different directions or angles.

Optimizing the emission distribution is essential for achieving accurate, sensitive, and reliable measurements.

The emission wavelength distributions are measured using Jasco FP-8300 spectrofluorometer by scanning excitation wavelength from 200 nm to 400nm.

Since the samples consist of different types of primary and secondary flour, the peak emission wavelength shows up at different values.

Figure 9: Jasco FP-8300 Spectrofluorometer

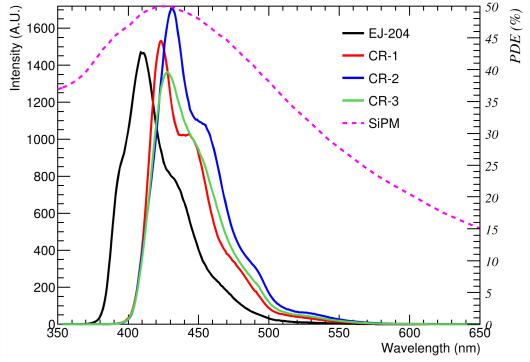

Figure 10: Emission Distribuitons

EJ-204: 410nm **CR-1:** 423nm
CR-2: 431nm **CR-3:** 428nm

The photon detection efficiency (PDE) curve of the Onsemi-J series silicon photomultiplier (SiPM) is also presented. The PDE of the scintillator samples at the emission peak values differ by about 1%

Light Yield Measurement i

The light yield (LY) of a plastic scintillator corresponds to the number of produced photons per unit of deposited energy in scintillators.

Higher LY values provide better energy resolution

To determine the relative LY of a scintillator

- reference radioactive source with a known energy
- reference plastic scintillator sample with a known LY is needed.

The main approach is to use the Compton-edge of the Compton spectrum which is the maximum energy transfer value of between the photon and the electron.

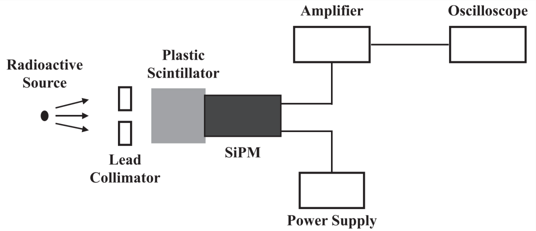

Figure 11: Schematic Diagram of the Experimental Setup

An Onsemi J-series SiPM with size 6x6 mm is used as a photodetector.
10x10 mm plastic scintillator samples are coupled to SiPM using EJ-550 optical silicon grease. The optical silicon grease has a refractive index of 1.46 and its transmission is about 99% for the thickness of 0.1mm.

A low-voltage power supply is connected to the SiPM biasing board. The output signal is amplified with CAEN N978 fast amplifier. The signal shape is digitized and recorded by a Keysight MXR254A oscilloscope.

^{137}Cs is selected as the radioactive source since it has a Compton edge at 477.3 keV

The plastic scintillators are wrapped with aluminum foil and plastic tape and located inside a wooden box with a wall of thickness of 2 cm.

The ^{137}Cs source is positioned 20 cm away from the scintillator.

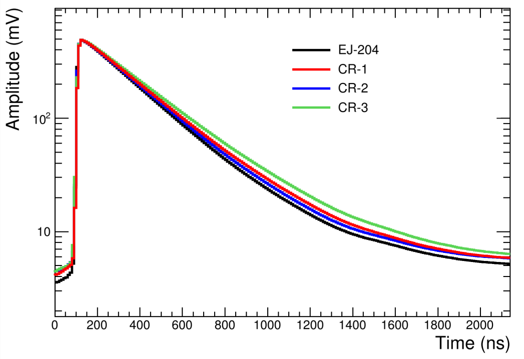

Figure 12: Signal Shapes of EJ-204 and produced samples

Since the flours in the plastic scintillator samples have different timing properties, the signal width of the scintillator samples are not identical.

Therefore energy deposition estimation was performed by measuring the area under the pulse shape instead of by measuring the pulse height.

Light Yield Measurement v

Since organic scintillators don't show photopeaks due to their low-Z content, the determination of LY is performed by measuring the Compton-edge position.

The edge region in the energy distribution is fitted with a Gaussian function, the height of the Gaussian peak is determined and the edge location is taken to be the energy corresponding to a certain percentage of the peak height.

Light Yield Measurement vi

The suggested values in the literature vary from 66% to 89% but the optimum value depends on the detector and scintillator.

Choosing a specific percentage of the local Compton maximum is not an ideal way to represent the Compton-edge location. Therefore the percentage values are chosen from 90% to 50% in 10% steps to determine the relative light output.

The relative light yields of the prepared plastic scintillator samples are determined from the EJ-204 sample by,

$$RLY_{sample} = RLY_{EJ-204} x \frac{A_{CE,sample}}{A_{CE,EJ-204}} \tag{1}$$

where RLY is the relative light yield and A is the signal shape area of the selected Compton-edge position.

The light yield information of EJ-204 is provided as 10 400 photons/MeV, therefore we take $RLY_{EJ-204} = 100$ and obtain the RLY for the samples with respect to it.

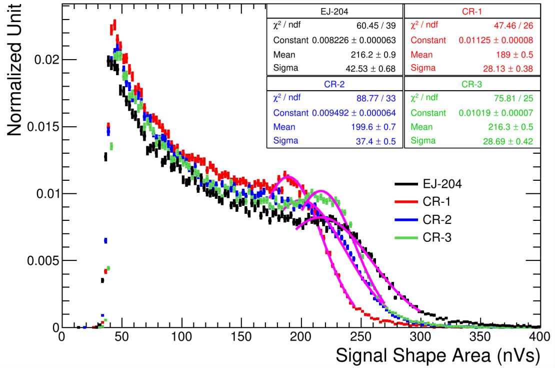

Figure 13: Signal Shapes Areas and Fit Parameters of EJ-204 and produced samples

The fit ranges of the Gaussian function of each distribution stay within the fit range and the lower end of the range is at least half a sigma away from the peak. Changing the lower and by $\pm 10nVs$ affects the relative light yield by less than 1%

Table 2: The RLY and LY values of the produced plastic scintillator samples with respect to EJ-204 with mean squared error estimation

Sample Name	RLY at 90%	RLY at 80%	RLY at 70%	RLY at 60%	RLY at 50%	Average RLY	LY (photons/MeV)
EJ-204	100	100	100	100	100	100	10 400
CR-1	85.7	85.0	84.5	83.9	83.4	84.5 ± 0.4	8788 ± 42
CR-2	91.9	91.8	91.6	91.5	91.5	91.7 ± 0.1	9537 ± 10
CR-3	97.3	96.2	95.3	94.6	94.0	95.5 ± 0.5	9932 ± 52

Conclusion

- Producing application-specific scintillators such as Gadolinium doped plastic scintillators is crucial since they are not commercially available.
- For any such application, determining the optimum flour content for best light yield is important.
- The results indicate that CR-3(0.75% PPO + 0.75 %PTP and 0.04% POPOP + 0.04% Bis-MSB) has the highest LY value among the produced samples.
- We conclude that the CR-3 combination is the most suitable for future gadolinium-doped scintillator production.
- The studies presented in this presentation are supported by the TUBITAK project number 122F271.