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Evaluation of Pixelated Plastic Scintillators Coupled to Multi-Channel Silicon Photomultipliers for Beta-Ray Detection and Source Localization

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ABSTRACT

This paper presents a novel detector design for radiation detection technology, based on pixelated plastic scintillators coupled to multi-channel silicon photomultipliers (SiPMs). This study investigated the performance of a detector that combines the efficiency of plastic scintillators with the sensitivity and versatility of SiPMs, overcoming the limitations of traditional photomultiplier tubes in terms of durability, power consumption, and sensitivity. The compact and modular nature of the detector makes it suitable for diverse environments and applications, such as portable radiation monitoring devices or integration into existing experimental setups. The performance of the detector was evaluated using beta-ray sources of ^{36}Cl and ^{90}Sr, and it was demonstrated that the detector can detect and localize the point source with high accuracy and resolution.

1. INTRODUCTION

Radiation contamination is a serious threat to human health and the environment. It can occur due to natural sources, such as cosmic rays or radon gas, or due to human activities, such as nuclear power generation, medical applications, or military operations [1]. Exposure to ionizing radiation, such as alpha and beta particles, can cause various diseases, such as cancer, genetic mutations, or radiation sickness [2]. Therefore, it is essential to monitor and measure the level and location of radiation contamination in different settings, such as water, soil, air, human body, or decommissioned materials.

One of the commonly used devices for radiation detection is the plastic scintillator detector, which consists of a plastic scintillator material and a light sensor. The plastic scintillator material emits light when it interacts with ionizing radiation, and the light sensor converts the light into an electrical signal. The plastic scintillator detector has many advantages, such as fast response time, low cost, optical uniformity, physical stability, high optical transmission, and ease of dopant addition [3]. These advantages make the plastic scintillator suitable for various

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applications such as radiation contamination detector for water [4], [5], soil [6], and air [7], radiation contamination at Fukushima Daiichi nuclear power station [8], and for the International Space Station (ISS) [9]. The plastic scintillator detector reported in research [4], [5], [6], [7], [8], [9], [10] uses a photomultiplier tube (PMT) as the light sensor.

The examination for radiation contamination from ionizing radiation is essential. Alpha and beta particles are known as ionizing radiation. It is dangerous if ingested or inhaled into the human body. Contaminated material can spread radiation to the environment. That is why the contamination check has become mandatory in many nuclear facilities.

However, the plastic scintillator detector also has some limitations, especially when it comes to localizing the contamination area. Most of the existing plastic scintillator detectors use a photomultiplier tube (PMT) as the light sensor, which is a large and bulky device that requires high voltage and is sensitive to magnetic fields. Moreover, the plastic scintillator detector usually has a single or a few channels, which means that it can only detect radiation contamination over a large area, but is unable to pinpoint the exact location of the source. This can be problematic for applications that require high spatial resolution and accuracy, such as whole-body check (WBC) [11], hand and foot contamination monitor (HFC) [12], or beta-ray measurements for decommissioned materials [13].

To overcome these limitations, we propose a novel detector design that uses a pixelated plastic scintillator coupled to a multi-channel silicon photomultiplier (SiPM). The SiPM is a solid-state device that consists of an array of microcells that act as independent photodetectors. SiPM has many advantages over PMT, such as low operation voltage, insensitivity to magnetic fields, fast response time, and compact size [14]. The pixelated plastic scintillator is a plastic scintillator material that is divided into small pixels that are optically isolated from each other. The pixelated plastic scintillator can improve the spatial resolution and light collection efficiency of the detector [15]. The time resolution on wide area plastic scintillator BC420 (92 × 92 × 5 cm) coupled with 18 SiPMs at each side reported can achieve 28 ps time resolution [16]. This result showed by combining the pixelated plastic scintillator and the multi-channel SiPM, we can create a detector that can detect and localize the radiation contamination with high accuracy and resolution.

The main objective of this paper is to evaluate the performance of the pixelated plastic scintillator coupled to the multi-channel SiPM detector for beta-ray detection and source localization. We use ^{36}Cl and ^{90}Sr beta-ray sources to test the detector and compare it with the conventional plastic scintillator detector with PMT. The paper is organized as follows: Section 2 describes the materials and methods used in the experiment, Section 3 presents the results and discussion, and Section 4 concludes the paper and suggests future work.

2. METHODOLOGY

Known for its high light output and widespread use in alpha and beta detection, the BC 400 boasts a light output of 65% anthracene, a maximum emission wavelength of 463 nm, a rise time of 0.9 ns, and a decay time of 2.4 ns. The plastic scintillator with a size of 100 × 100 × 0.5 mm is attached to an 8 × 8 SiPM array using optical grease, as depicted on the left side of Fig. 1.

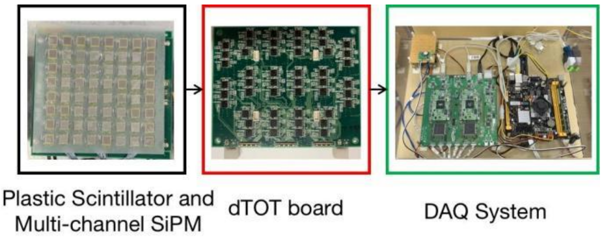

Fig. 1. Depiction of the Plastic Scintillator Detector System. From left to right, the components are a Plastic Scintillator coupled with a Multi-Channel SiPM Board, the dTOT Board, and the DAQ System.

When a beta particle interacts with the plastic scintillator, it emits light. This light is transferred to the SiPM and converted into an electric signal. The signal generated by the SiPM is proportional to the number of light photons entering the SiPM. For this research, we used the SiPM KETEK 6660, which has an active area of 6.0 × 6.0 mm², a micro pixel size of 60 × 60 μm², and 10,000 pixels. The breakdown voltage for the SiPM is 25 ± 3 Volts [17].

The dTOT system is employed to convert the analog signal from SiPM to a digital signal that can be read by the DAQ system. Each channel of the dTOT system consists of a pre-amplifier, shaper signal, comparator, and mono-stable. The signal from SiPM is amplified and inverted into a positive analog signal. The Shaper changes the signal into a Gaussian pulse. The dTOT board with 64 channels is shown at the center of Figure 1.

The dTOT method is a pulse processing technique that compares the amplitude of the analog signal from the shaper output with a preset threshold to produce a digital pulse [18]. In dTOT, the preset threshold is dynamic, changing based on the height of the amplitude signal. The digital pulse production is conducted by the mono-stable circuit. The rising edge of the digital signal is triggered by the signal that passes the preset threshold, and the falling edge is triggered when the analog signal passes the dynamic threshold.

The FPGA-based data acquisition system (DAQ) was used to store the digital signal from the dTOT board. This DAQ can acquire 128 channels in parallel, with the sampling rate of this DAQ at 1 ns. To operate this DAQ, a dedicated personal computer was set up. The DAQ system used in this study is shown on the right side of Figure 1.

The evaluation of plastic scintillation is conducted using two types of sources; point-type source ^{90}Sr and flat-type source ^{36}Cl. Both sources emit beta particles. The flat-type source was used to check the uniform response of the detector, while the point source was used to check the hot spot of the radiation source. To mimic a real-world whole-body counter (WBC) and hand-and-foot counter (HFC), we designed an aluminum light cover consisting of three layers of 3 µm aluminum, totaling 9 µm in thickness.

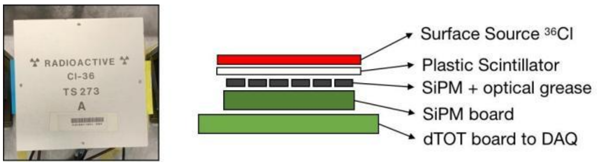

Fig. 2. Experiment setup with flat type source ^{36}Cl. The left side presents a photograph of the experiment, while the right side illustrates the layout of the structure.

Figures 2-4 illustrate the experiment setup with the flat-type source ^{36}Cl. This experiment aimed to evaluate the distribution of beta particles detected in the multi-channel SiPM. The flat-type source ^{36}Cl emits a beta particle in the 2π direction. The active area of the source is 100 × 100 mm, with an overall dimension of 100 × 100 × 3 mm. In this experiment, the flat-type source is located 5 mm above the plastic scintillator, which was attached to the multi-channel SiPM using optical grease.

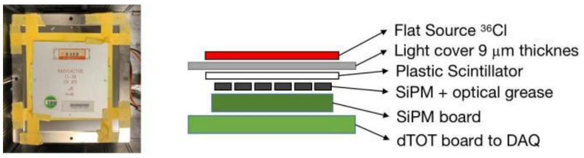

Fig. 3. Experiment setup with flat-type source ^{36}Cl and aluminum cover. The left side displays a photograph of the experiment, while the right side depicts the layout of the structure.

To imitate the real detector, an aluminum shield was installed. This shield serves as the light cover and filter for alpha particles. The light cover was installed 5 mm above the plastic scintillator. The flat-type source is directly placed above the light cover. The experiment setup with flat type source ^{36}Cl with aluminum cover is presented in Figure 3.

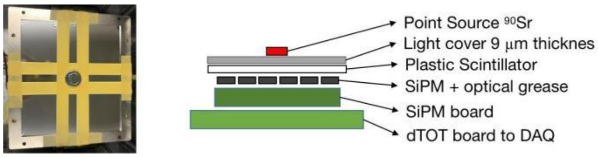

Fig. 4. Experiment setup with point type source ^{90}Sr with aluminum cover. The left side showcases a photograph of the experiment, while the right side outlines the layout of the structure.

The experiment setup to check the position of the source was conducted using the point-type source ^{90}Sr. The plastic scintillator is still covered light cover, and the ^{90}Sr was placed on the top surface of the aluminum. The source was set at the center of the detector. This experiment was conducted to check the multi-channel's ability to localize the radiation source position.

3. RESULTS AND DISCUSSION

The wide beta source ^{36}Cl was used to evaluate the performance of each channel in the detector system, as each channel possesses unique characteristics. The results of these measurements are presented in Table 1. Evaluating the count of each channel is crucial for understanding the performance of each one.

Before measuring the beta particle, a background check was conducted to check the number of counts of the detector without the radiation source. The background measurement was conducted for 10 minutes. During this period, the highest count recorded was 84, found on channel 14 out of the 64 channels. This could be attributed to several factors, such as high noise levels on the dTOT channel and the quality of the SiPM. The total count from all 64 channels over the 10 minutes was 250 counts, averaging 0.4 counts per second.

The experiment with a flat-type source without a light cover was taken in 5 minutes with three times repetition. The third column in Table 1 presents the average count on each channel. The total count over 5 minutes was 35817, with a count rate of 119 counts per second across 64 channels. Channels 41 and 56 recorded the lowest count, possibly due to the position of the SiPM on the edge of the detector.

Table 1. Count distribution in multi-channel SiPM during the flat type source ^{36}Cl experiment

Ch	Background	Without Light Cover	With Light Cover
	Count /10 min	Count / 5 min	Count / 5 min
		Avg	Avg
1	1	18	9
2	1	259	199
3	2	225	147
4	1	188	99
5	0	13	3
6	3	329	174
7	0	28	2
8	1	525	113
9	2	263	224
10	1	347	274
11	3	993	757
12	1	302	179
13	0	557	344
14	84	2891	1861
15	2	318	169
16	0	248	55
17	0	115	74
18	2	699	550
19	0	346	244
20	2	787	557
21	1	504	315
22	3	419	219
23	1	643	296
24	1	28	2
25	2	250	220
26	4	786	724
27	9	1352	1140
28	4	713	475
29	0	489	331
30	1	502	300
31	3	423	186
32	8	1158	514
33	2	50	25
34	5	927	779
35	2	826	698
36	8	1232	974
37	0	107	78
38	1	270	134
39	6	699	357
40	1	208	75
41	0	8	6
42	0	13	8
43	3	210	171
44	6	853	728
45	3	513	354
46	8	1913	1308
47	0	62	21
48	0	618	289
49	2	200	152
50	7	964	693
51	2	103	57
52	5	946	730
53	6	911	651
54	4	593	320
55	3	1435	950
56	0	9	3
57	3	349	201
58	5	1211	768
59	7	1084	651
60	3	264	147
61	3	137	70
62	10	1389	848
63	1	389	177
64	1	608	241
Total	250	35817	23423

The experiment with light cover and wide beta source ^{36}Cl is presented in the rightmost column of Table 1. The flat-type source is located at the center of the aluminum cover. The measurements were taken over 5 minutes and repeated three times. The results indicate that the average count in each channel was decreased. The total count in 5 minutes is 23422, with a counting rate of 78 counts per second. The sensitivity of the detector decreased by approximately 65% after the application of the aluminum cover, as the aluminum obstructed some beta particles.

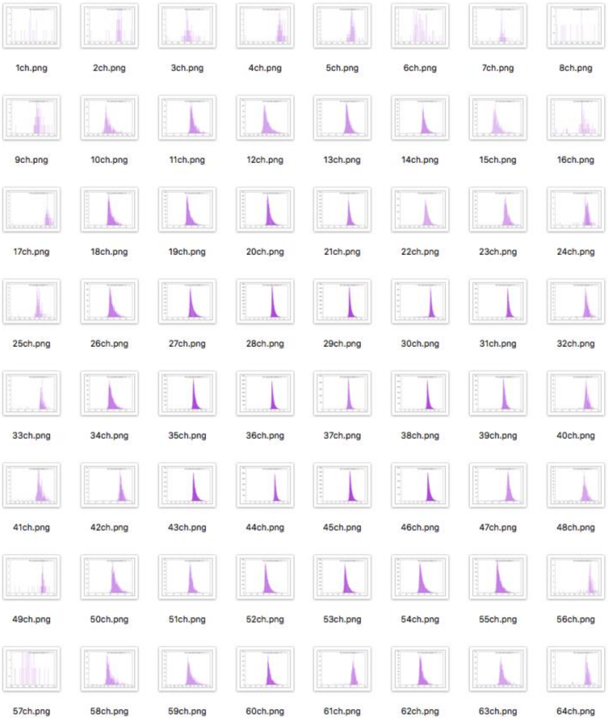

Fig. 5. Energy spectra captured by the plastic scintillator detector system.

The developed plastic scintillator detector system offers several advantages, including a high sampling rate of 1 ns, the ability to differentiate the incident energy interacting with the detector, and parallel event recording. Figure 5 displays the energy spectra recorded by the plastic detector system when using a ^{90}Sr source. The results show that the spectra at the center of the detector have a higher count than those at the edge area.

PD 1	PD 2	PD 3	PD 4	PD 5	PD 6	PD 7	PD 8
15	32	69	76	117	74	49	17
PD 9	PD 10	PD 11	PD 12	PD 13	PD 14	PD 15	PD 16
58	380	1245	2573	1913	1455	555	72
PD 17	PD 18	PD 19	PD 20	PD 21	PD 22	PD 23	PD 24
81	1090	4333	11082	6621	3317	1342	202
PD 25	PD 26	PD 27	PD 28	PD 29	PD 30	PD 31	PD 32
107	2954	21354	45214	78773	10464	6220	769
PD 33	PD 34	PD 35	PD 36	PD 37	PD 38	PD 39	PD 40
142	3470	18734	72275	35370	55954	5852	668
PD 41	PD 42	PD 43	PD 44	PD 45	PD 46	PD 47	PD 48
287	601	16510	44203	86830	56085	2963	739
PD 49	PD 50	PD 51	PD 52	PD 53	PD 54	PD 55	PD 56
50	1613	1533	8971	20281	10257	4372	127
PD 57	PD 58	PD 59	PD 60	PD 61	PD 62	PD 63	PD 64
33	602	1477	2842	540	2337	985	146

Fig. 6. Color maps representing the number of counts in each channel for the ^{90}Sr experiment.

Figure 6 presents color maps based on the number of counts in each channel, representing the position of the ^{90}Sr on the detector. High counts were recorded on Channels 28, 29, 30, 36, 37, 38, 45, 46, and 47, as indicated by the red line. Adjacent channels also recorded high counts due to the scattering of the beta ray by the aluminum and the plastic scintillator. The light emitted from the broad single plastic scintillator spread in all directions, causing the adjacent SiPM to receive scattered light and count it as an event. Despite this, the experiment demonstrated that the use of a multi-channel SiPM can localize the position of the beta source.

4. CONCLUSION

The performance of the plastic scintillator detector system, which utilizes BC 400 coupled with a multi-channel SiPM and an advanced DAQ system, has been thoroughly evaluated. Both a wide area beta source (^{36}Cl) and a point source (^{90}Sr) were employed to assess the performance of the detector system.

The evaluation with the flat beta source revealed that all SiPM channels responded to the beta rays emitted from the source. However, the detector's sensitivity was reduced to 65% after the application of a 9 µm aluminum light cover, as some beta rays were obstructed by the aluminum.

The evaluation with the ^{90}Sr point source demonstrated the detector's ability to localize the position of the beta source. This result validates the potential application of the multi-channel SiPM for localizing beta sources. It can be utilized to pinpoint beta contamination on the human body when implemented in whole-body counters and hand and foot counters. Furthermore, this detector can be used to localize the contamination of nuclear waste, thereby facilitating the clearance process during decontamination in nuclear facilities.

AUTHOR CONTRIBUTION

All authors are equally contributed as the main contributors of this paper. All authors read and approved the final version of the paper.

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