Scientific Research Publishing

Journal of Applied Mathematics and Physics, 2023, 11, 2156-2164
https://www.scirp.org/journal/jamp
ISSN Online: 2327-4379
ISSN Print: 2327-4352

Development of a Gamma Spectroscopy Detector Based on SiPMs and 1" Ce:GAGG Scintillator

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How to cite this paper: Wang, Q., Zhang, Z.T., Ding, Y.C., Hu, X.H., Xiao, X., Wang, B., Qu, J.J., Wan, Q.Y. and Xu, Y. (2023) Development of a Gamma Spectroscopy Detector Based on SiPMs and 1" Ce:GAGG Scintillator. *Journal of Applied Mathematics and Physics*, **11**, 2156-2164.
https://doi.org/10.4236/jamp.2023.117137

Received: March 16, 2023
Accepted: July 28, 2023
Published: July 31, 2023

Abstract

In the field of nuclear radiation detection, sodium iodide (NaI(Tl)) and lanthanum bromide ($LaBr_3$) are the primary scintillation crystals used for energy spectrum detectors. Furthermore, energy spectrum detectors based on gadolinium gallium aluminum garnet (Ce:GAGG) scintillation crystals are minor. In this work, a 1-inch Ce:GAGG and Silicon Photomultipliers (SiPMs) are employed to construct a detector, and the coupled medium was silicone oil. An optimal SiPMs quantity scheme for the energy resolution was determined by varying the number of SiPMs coupled to Ce:GAGG and studying the effect of the different number of SiPMs on the energy resolution of the detector. Energy-resolution contrast experiments between Ce:GAGG and NaI(Tl) were performed using this scheme. The experimental results demonstrate that increasing the number of SiPMs enhances the energy resolution of the detector significantly. Notably, the energy resolution of the Ce:GAGG detector is comparable to that of the NaI(Tl) detector. Additionally, both detectors exhibit an energy linearity exceeding 99.9%.

Keywords

Ce:GAGG, Gamma Spectroscopy, Detector, SiPMs, Energy Resolution

1. Introduction

Gamma spectroscopy detectors play an important role in the field of nuclear radiation detection, they are widely used in nuclear facilities monitoring and detection, environmental radiation monitoring, nuclear accident emergency handling, etc. Currently, the commonly used detectors mainly base on NaI(Tl), $LaBr_3$, etc. $LaBr_3$ has high energy resolution, but it is easy to deliquescence and expensive. NaI(Tl) is cheap, but it is easy to deliquescence and low detection efficiency. The frequently used photoelectric converter devices is photomultiplier tube (PMT), which has the advantages of radiation resistance and stable performance, but it has a large volume and needs to use high voltage [1] [2].

Ce:GAGG is a new type of inorganic scintillation crystal. Since it was grown in Japan in 2011 [3], it has been applied in medical treatment [4] [5], space detection [6], nuclear radiation detection [7] [8] and other fields. It has the advantages of high light yield, high detection efficiency, fast decay time, no deliquescence, no spontaneous radiation, stable physical and chemical properties. SiPMs is a novel photoelectric detection device, which is composed of avalanche diode array (APD) operating in Geiger mode. High sensitivity, good consistency, small size, low operating voltage, and insensitive to magnetic field are the merit of SiPMs. It is increasingly used in various fields of photoelectric detection, and is replacing the traditional PMT gradually [9].

In this paper, 1" Ce:GAGG, SiPMs, front-end circuit are used to compose the detector. Design 1 × 1, 2 × 2, 3 × 3's SiPMs array, the performance of detector composed of different arrays of SiPMs and Ce:GAGG is studied. Then the best SiPMs array scheme is selected to carry out the contrast experiment of Ce:GAGG and NaI(Tl), and the energy resolution, energy linearity and other parameters are compared.

2. Design and Assembly of Detector

2.1. Design of Detector

The design schematic of the energy spectrum detector is shown in **Figure 1(a)**. The detector is composed of 1" Ce:GAGG, SiPMs array, and front-end circuit. Except for the light-out surface of Ce:GAGG, all the rest are wrapped with Teflon as the reflective layer. The reflective layer is protected by the ABS outside. The model of SiPMs is Onsemi-FJ60035. SiPMs and Ce:GAGG are coupled with silicone oil, and the area not covered by SiPMs on the light-out surface of Ce:GAGG is filled by ESR. SiPMs, power supply interface and signal output connector are welded on the front-end circuit board. 1" Ce:GAGG detector is shown in **Figure 1(b)**.

Three types of SiPMs arrays are designed as shown in **Figure 2(a)**, including 1 × 1, 2 × 2, 3 × 3. The effective sensitive areas of three arrays are 7.3%, 29.1% and 65.5%. Three SiPMs arrays is shown in **Figure 2(b)**.

2.2. Design of Test System

The schematic of test system is shown in **Figure 3**, including radioactive source, spectrum detector, data acquisition module and PC. The spectrum detector

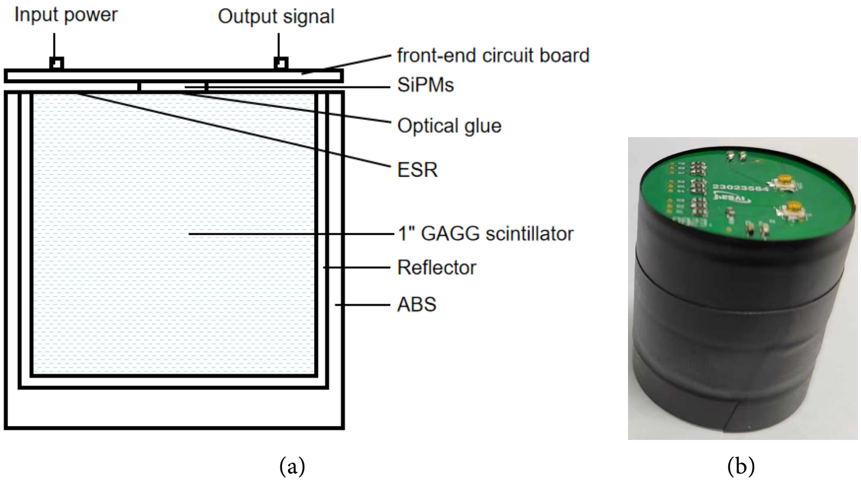

Figure 1. Diagram of detector. (a) Schematic of detector; (b) 1" Ce:GAGG detector.

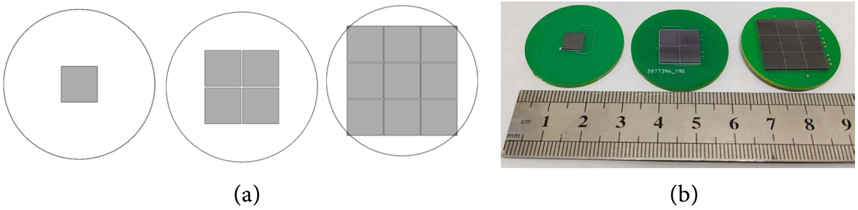

Figure 2. Diagram of SiPMs arrays. (a) Comparison of different SiPMs arrays; (b)SiPMs arrays.

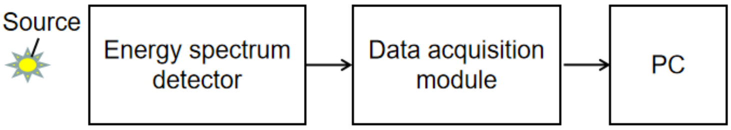

Figure 3. Schematic of test system.

converts the gamma rays emitted by the radioactive source into electrical signals. The data acquisition module accepts the analog signal output from the detector, and performs amplification, filtering and shaping, analog-to-digital conversion. The analysis of original pulse and spectrum are implemented on PC. The test system is shown in **Figure 4**.

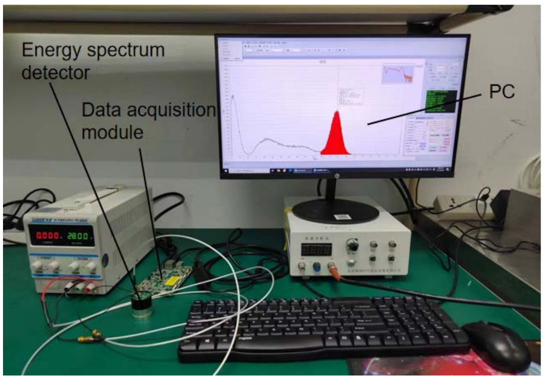

Figure 4. Test system.

3. Experiment

3.1. Different Arrays of SiPMs

Three types of SiPMs arrays with ESR is shown in **Figure 5**.

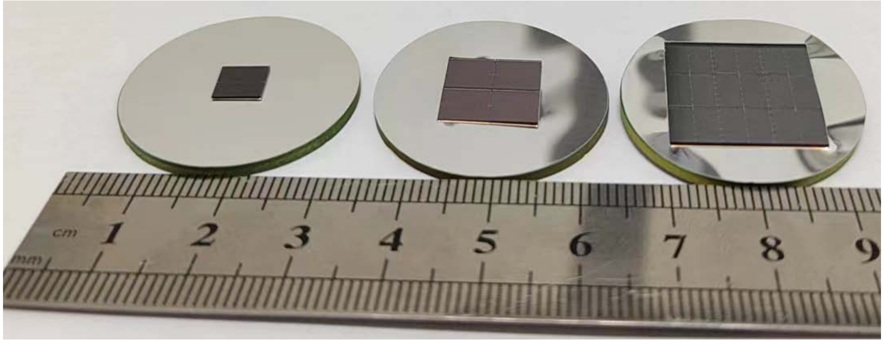

Figure 5. SiPMs arrays with ESR.

3.1.1. Background Spectrum

The background spectrum of these detectors are tested, measurement time is 300 seconds. The result is shown in **Figure 6**. It can be seen from the figure, in the case of less than 100 channels, the most counts is 1 × 1 SiPMs array, and the least counts is 3 × 3 SiPMs array. The counts of three types of detectors between 100 channels and 500 channels are equivalent.

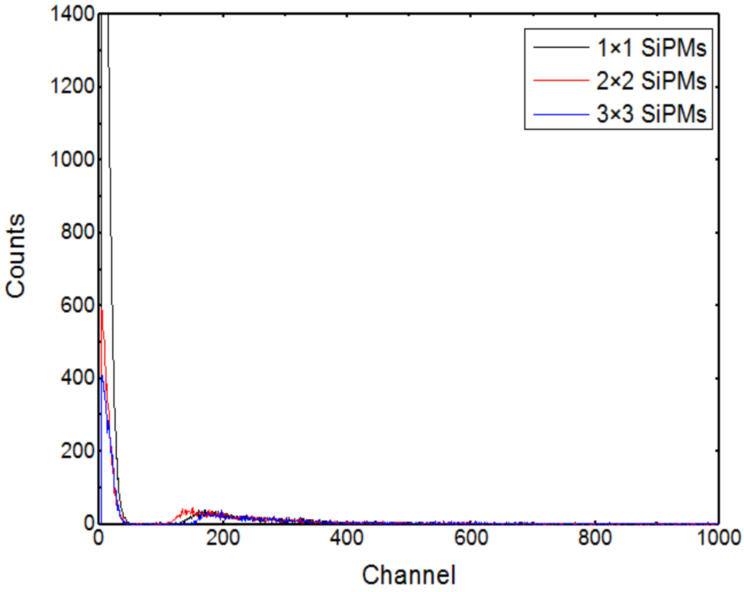

Figure 6. Background spectrum of three SiPMs arrays.

3.1.2. ^{137}Cs Spectrum

The ^{137}Cs spectrum of three detectors are tested. The result is shown in **Figure 7**. The energy resolution of three detectors are 11%, 9.2% and 7.1%. It can be seen that the energy resolution becomes better and better with the continuous increase of the effective sensitive area of SiPMs.

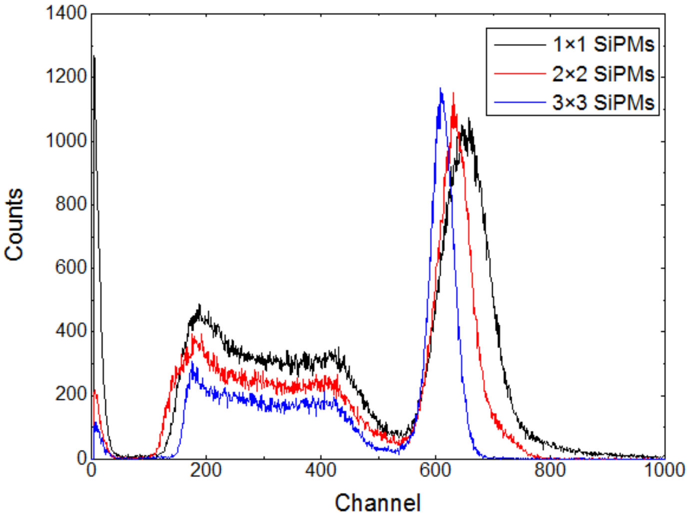

Figure 7. ^{137}Cs spectrum of three detectors.

3.2. Comparison Ce:GAGG with NaI(Tl)

In order to test the background spectrum, ^{137}Cs spectrum, multiple radioactive sources spectrum and energy linearity, 1" NaI(Tl) and 1" Ce:GAGG are coupled with the 3 × 3 SiPMs arrays by silicon oil. 1" NaI(Tl) and 1" Ce:GAGG is shown in **Figure 8**.

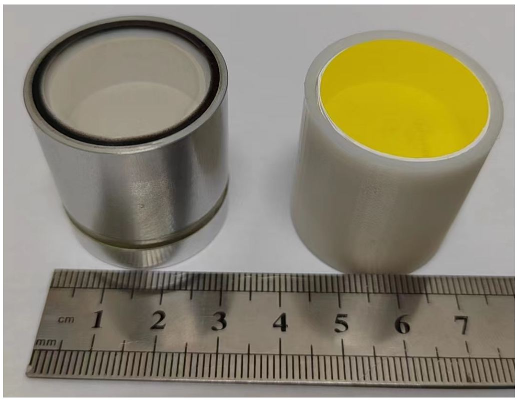

Figure 8. 1" NaI(Tl) and 1" Ce:GAGG.

3.2.1. Background Spectrum

The background spectrum of NaI(Tl) detector and Ce:GAGG detector are tested, measurement time is 300 seconds. The result is shown in **Figure 9**. It can be seen from the figure, under the condition of less than 100 channels, the more counts is NaI(Tl) detector. Under the circumstances between 100 channels and 500 channels, the Ce:GAGG detector has more counts. Indicating that the detection efficiency of Ce:GAGG is higher than NaI(Tl) , and the Ce:GAGG has a better ability to stop high-energy rays.

3.2.2. ^{137}Cs Spectrum

The ^{137}Cs spectrum of NaI(Tl) detector and Ce:GAGG detector are tested. The result is shown in **Figure 10**. The energy resolution of NaI(Tl) detector is 7.0%@661.6 keV, and that of Ce:GAGG detector is 7.1%@661.6 keV, they are at the same level, but the Ce:GAGG detector has a higher peak to Compton ratio.

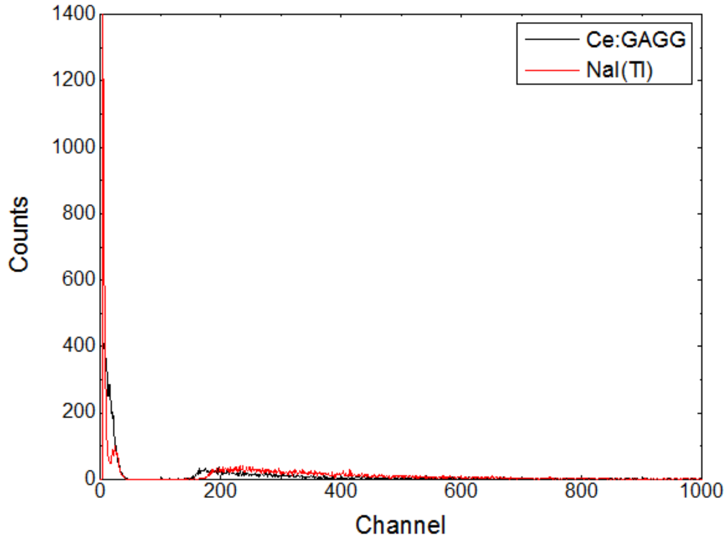

Figure 9. Background spectrum.

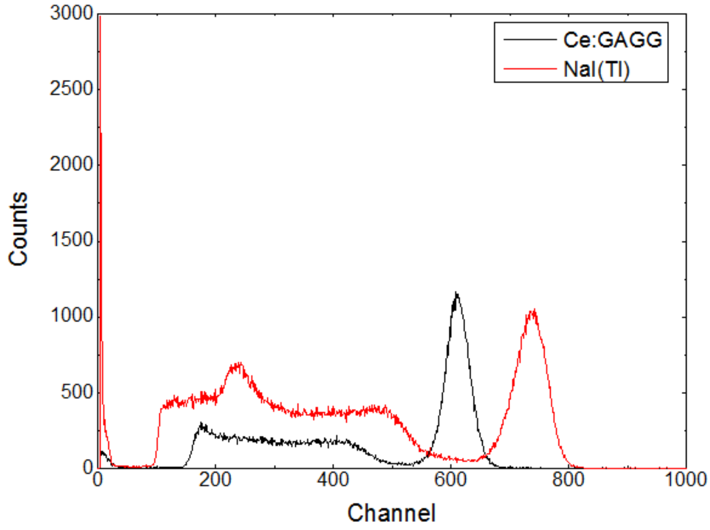

Figure 10. ^{137}Cs energy spectrum.

3.2.3. Multiple Radioactive Sources Spectrum

^{137}Cs (661.6 keV), ^{22}Na (511 keV, 1274.5 keV) and ^{241}Am (59.6 keV) radioactive sources were used in this experiment. Test conditions were set to let the peaks of the three radioactive sources appear at the same time. The multiple radioactive sources energy spectrum of NaI(Tl) detector and Ce:GAGG detector are tested. The result is shown in **Figure 11**. It can be seen from the figure that the peak of 59.6 keV is completely distinguished in NaI(Tl) detector's spectrum, while that is inapparent in Ce:GAGG detector's spectrum, indicating that the NaI(Tl) detector has better energy resolution for low-energy rays.

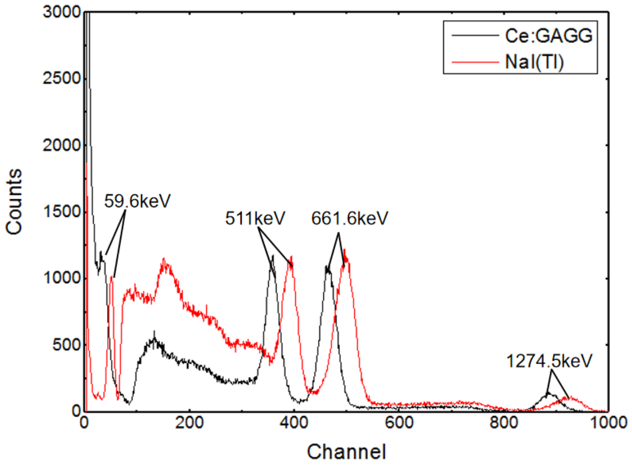

Figure 11. The multiple sources energy spectrum.

3.2.4. Energy Linearity

The channels of different energy rays in **Figure 11** are shown in **Table 1**.

Table 1. The channels of different energy rays.

radioactive source	Energy (keV)	Channel	
		Ce:GAGG	NaI(Tl)
^{241}Am	59.6	32.73	49.92
^{22}Na	511	357.24	389.06
^{137}Cs	661.6	464.60	495.17
^{22}Na	1274.5	866.09	920.24

The energy linearity of the two detectors was fitted, and the fitting curves are shown in **Figure 12**. The calculated correlation coefficients for the NaI(Tl) and Ce:GAGG spectrometers were both greater than 99.9%, indicating excellent energy linearity for both detectors.

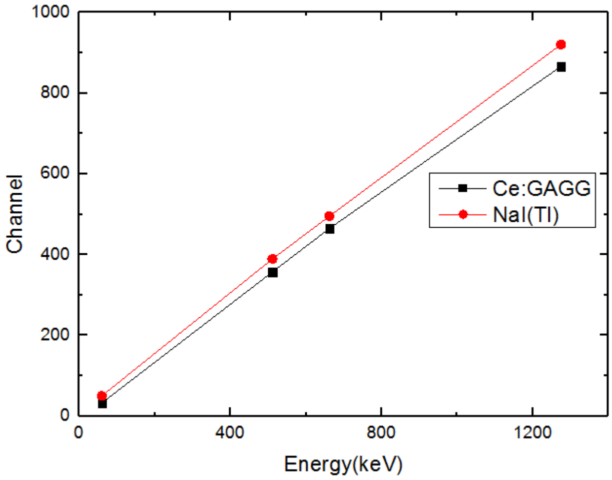

Figure 12. The energy linearity fitting result.

4. Conclusions and Discussion

Three detectors are constructed by SiPMs arrays of 1 × 1, 2 × 2, 3 × 3 and 1" Ce:GAGG scintillation crystal, the energy resolution comparison experiment is finished. The experimental results demonstrate that a higher number of effective sensitive areas in the SiPMs array leads to better energy resolution of the detector. The energy resolution of the detector reaches 7.1%@661.6 keV with 3 × 3 SiPMs array. A detailed energy spectrum experiment between 1" NaI(Tl) and 1" Ce:GAGG shows that the performance of these two scintillation is equivalent. Additionally, the Ce:GAGG offers advantages such as non-hygroscopicity and high detection efficiency, showcasing its significant potential for application in the field of spectrum detection.

The SiPMs used in this study is Onsemi-FJ60035, with a peak wavelength of 420 nm. However, the luminescent peak wavelength of the Ce:GAGG is ~540 nm, resulting in mismatched wavelengths and low quantum efficiency, which reduces the performance of the Ce:GAGG detector. Consequently, future research will focus on exploring photoelectric devices that match the luminescent wavelength of the Ce:GAGG to improve the performance of the Ce:GAGG detector.

Acknowledgements

This research was supported by National Key R & D Program of China (2022YFF0706400, 2022YFF0707900).

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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