Experimental evaluation of Gd$_3$Al$_2$Ga$_3$O$_{12}$:Ce (GAGG:Ce)
single crystals coupled to a silicon photomultiplier (SiPM)
under high gamma ray irradiation conditions

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Keywords: Inorganic scintillators, SiPM, GAGG:Ce, Compact Spectrometers

Abstract. Cerium (Ce) ion doped scintillators are of high interest in Medical Imaging systems and radiation monitoring devices, due to their very fast response and very good emission characteristics. In this study, a series of measurements regarding the energy resolution, photofraction, sensitivity, as well as the figure of merit, of Gd$_3$Al$_2$Ga$_3$O$_{12}$:Ce (GAGG:Ce) scintillator crystals, is presented. All GAGG:Ce crystals have a surface area of 3x3 mm$^2$ with varying thicknesses, from 4 up to 20 mm (4, 5, 6, 8, 10, 15 and 20 mm). These crystals were exposed to $\gamma$ radiation, using two different radioactive sources: $^{137}$Cs (0.662 MeV) and $^{60}$Co (1.173 MeV and 1.332 MeV). Each crystal was measured individually and was optically coupled to a KETEK PM3350 SiPM, an optical sensor with high gain, suitable to operate in room temperature. The digitization of the pulses was accomplished using CAEN DT5720 desktop digitizer and its corresponding digital pulse processing (DPP) firmware. Each measurement was performed in a light-tight box and had duration of 30 min. The best energy resolution value was measured for the GAGG:Ce crystal with dimensions 3x3x15mm$^3$, equal to 3.9% at 1.332 MeV. Results were evaluated and compared to previous published data.

1. Introduction

Radiation detectors used in Medical Imaging systems and radiation monitoring devices usually consist of scintillators coupled to optical sensors. Scintillators absorb X or $\gamma$ rays and convert a portion of their energy into visible light, that is recorded thereafter by the photodetector [1]. Among inorganic scintillators, those containing Cerium (Ce) ion dopants are of particular interest, due to their very promising characteristics [2]. Gd$_3$Al$_2$Ga$_3$O$_{12}$:Ce (GAGG:Ce) is nowadays a scintillator material of choice since it demonstrates a series of advantages compared to other scintillation materials: it has a high density of 6.63 g/cm$^3$, high light yield (46000 photons/MeV) and a short decay time of ~90 ns. Moreover, it is non hygroscopic, it does not contain intrinsic radioactivity and has an emission peak at 530 nm [3] - [6].

Silicon Photomultipliers (SiPMs) are a new type of optical sensor, consisted of a 2-dimentional array of micropixels in each pixel element. Each micropixel consists of an avalanche photodiode operating in Geiger mode [7]. SiPMs are promising detectors for the replacement of traditional
photomultiplier Tubes (PMTs). Their small size, insensitivity to magnetic fields and continuous cost
decrease are some of their attractive characteristics for application in Nuclear Imaging detectors and
radiation monitoring devices. In addition, they are very compact and they show excellent timing
resolution, which is crucial in the design of modern time-of-flight Positron Emission Tomography
(PET) detectors as well as to the modern personal gamma spectrometers [8], [9].

The aim of this study is to evaluate experimentally a γ ray detector composed of a SiPM optically
coupled to a number of GAGG: Ce scintillator crystals of various thicknesses (4, 5, 6, 8, 10, 15 and 20
mm) in order to establish the best matching between thickness, under high gamma ray irradiation
conditions. Such a detector could be used in Positron Emission Tomography (PET) or in modern small
sized gamma spectrometers for radiation monitoring devices, replacing previous technologies, such as
PMTs. Measurements regarding the energy resolution, photofraction, sensitivity and figure of merit
(FOM) were acquired, and compared to previous published data.

2. Materials and Methods

GAGG:Ce inorganic scintillators were purchased by Furukawa Co. Ltd, with surface area of 3x3 mm²
and thicknesses of 4, 5, 6, 8, 10, 15 and 20 mm. Each one of these crystals was optically coupled to the
SiPM's entrance window using BC-630 optical grease. All crystals' surfaces were polished and
coated with 4 layers of Teflon reflector - except for the light collection area - to optimize light
collection.

The optical sensor used in this study is KETEK PM3350, a SiPM with high gain (2x10⁶), suitable
to work in room temperatures. KETEK’s PM3350 active sensor area is 3x3 mm² and consists of 3600
micropixels, 50x50 μm² each. Its optical trench technology ensures a lower noise level, low dark count
rate (< 300 kHz/mm²), low crosstalk (~ 20%) and better timing properties, in comparison to non-
trench type detectors. KETEK PM3350 operates in a voltage area between 25 V and 35 V, with
Photon Detection Efficiency (PDE) at 530nm equal to 27% [7].

The digitization of the SiPM's analog output was achieved using CAEN DT5720 desktop digitizer.
The DT5720 is a 4-channel 12-bit 250 MS/s Desktop Waveform Digitizer with 2 Vpp single ended
input dynamics on MCX coaxial connectors. The DC offset is adjustable via a 16-bit DAC on each
channel in the ±1V range [10], [11]. CAEN’s Digital Pulse Processing for Charge Integration (DPP-
CI) firmware transforms the digitizer into a spectroscopy acquisition system, capable of providing
energy and timing information. DPP-Cl control software allows the setting of the acquisition
parameters in order to perform the data readout and collect the histograms [10], [11]. Using
appropriate parameters to optimize acquisition of the pulses, the energy histogram of each source was
acquired. The digitizer’s output file was then fed to a custom-made software program based on C++
code. This program uploads the file and displays the energy spectrum acquired.

The energy resolution value was calculated by applying a Gaussian fit on the photopeaks using a
±10% energy window. The number of events in each corresponding photopeak as well as in the whole
spectrum was taken under consideration, in order to calculate the sensitivity and photofraction values.
The figure of merit index equals the sensitivity (%) value divided by the energy resolution (%) value
and was calculated in order to find the optimal GAGG:Ce crystal thickness in each energy examined.

In order to find the best operation bias voltage of the SiPM, 6 measurements for each crystal were
performed, with duration of 30 min (1800 sec) each, within a defined bias voltage range (from 28 to
31 V) with a step of 0.5V. A 30.5 V bias voltage was chosen - as the one that provides the lowest
energy resolution values - using both types of radioactive sources. All measurements were conducted
inside a light-tight box. The radioactive sources were deposited just upon the crystals for the excitation
and have radioactivity equal to: ¹³⁷Cs =0.87 μCi (32325 Bq) and ⁶⁰Co=0.46 μCi (17182 Bq).

3. Results and Discussion
The resulted values regarding the energy resolution, photofraction, sensitivity and figure of merit of the examined GAGG:Ce crystals under irradiation conditions using three distinctive energy peaks are presented in table 1.

**Table 1.** Experimental data acquired from the evaluation of GAGG:Ce single crystals under high gamma ray irradiation conditions: energy resolution (R), photofraction (PF), sensitivity (S) and figure of merit (FOM) values are reported, for each of the applied energy peaks, 0.662 MeV, 1.173 MeV and 1.332 MeV.

| Crystal thickness (mm) | 137Cs 0.662 MeV | 137Cs 1.173 MeV | 137Cs 1.332 MeV | 60Co 0.662 MeV | 60Co 1.173 MeV | 60Co 1.332 MeV |
|-----------------------|------------------|------------------|------------------|------------------|------------------|------------------|
| R (%)                 | PF (%)           | S (%)            | FOM x10^3        | R (%)           | PF (%)           | S (%)            | FOM x10^3        | R (%)           | PF (%)           | S (%)            | FOM x10^3        |
| 4                     | 7.2              | 9.7              | 0.013            | 1.81            | 7.1              | 8.0              | 0.003           | 0.42            | 7               | 2.1              | 0.003            | 0.43            |
| 5                     | 7.1              | 10.9             | 0.016            | 2.25            | 6.3              | 8.8              | 0.004           | 0.64            | 6               | 2.3              | 0.004            | 0.67            |
| 6                     | 6.8              | 11.2             | 0.036            | 5.29            | 5.4              | 9.4              | 0.005           | 0.93            | 5               | 2.5              | 0.005            | 1.0             |
| 8                     | 6.9              | 11.8             | 0.040            | 5.80            | 4.8              | 9.5              | 0.007           | 0.15            | 4.4             | 2.6              | 0.007            | 1.6             |
| 10                    | 6.8              | 12.9             | 0.065            | 9.56            | 5.0              | 9.7              | 0.014           | 2.80            | 4.4             | 2.7              | 0.014            | 3.2             |
| 15                    | 6.7              | 13.0             | 0.070            | 10.45           | 4.9              | 11.1             | 0.019           | 3.88            | 3.9             | 2.9              | 0.019            | 4.9             |
| 20                    | 6.6              | 13.2             | 0.082            | 12.42           | 5.3              | 10.3             | 0.025           | 4.72            | 5               | 3.1              | 0.025            | 5.0             |

In general, we see that the photofraction and sensitivity values increase as crystal thickness increases, while the energy resolution values do not follow this behaviour. Moreover, it is shown that as the energy increases, the photofraction and sensitivity values decrease. As seen in Table 1, the best energy resolution value was achieved for the GAGG:Ce crystal with dimensions 3x3x15mm³, equal to 3.9% under 1.332 MeV excitation. In the case of 137Cs the best energy resolution was recorded for the 20 mm thick crystal equal to 6.6%. These results are very promising, especially by comparing them to previous measurements (R=13.6% for 662keV of the same 3x3x20mm³ GAGG:Ce crystal readout by SensL’s SPMM-3035 silicon photomultiplier) [12]. Moreover, in comparison with the Personal-SPECT system [9] used for radiation monitoring applications our results are slightly worse (i.e. R=5.8% at 662keV and 2.3% at 1.33 MeV) acquired by using the same dimension of GAGG:Ce crystal but different SiPM detector of Hamamatsu.

In figure 1, the energy resolution values in relation to the different crystal sizes are shown. Typical energy spectra of the corresponding radioactive sources are illustrated in figure 2.

**Figure 1.** Energy resolution values versus the 3x3mm³ GAGG scintillator’s thicknesses, at 30.5 V.
Figure 2. Typical energy spectra of $^{137}$Cs (left) and $^{60}$Co (right) acquired at 30.5 V, using a GAGG:Ce 3x3x20mm$^3$ scintillator crystal. Photopeaks and the corresponding Compton edges are well distinguished in both spectra.

Finally, the stability of our detector was examined by observing the count rate differences under $^{137}$Cs excitation for 8 hours and measuring the count rate performance change every 30 min: the experiment showed a rather stable behaviour because the number of counts recorded was always in the range between 9800 and 9930 counts. Additionally, to check the background counts, in the same manner, a 2-hour measurement was made without any activity close to the detector and the number of counts recorded in that time was only 603 counts.

4. Conclusion

The $\gamma$ ray detection capability achieved by our detector has been demonstrated in terms of sensitivity, photofraction, energy resolution and figure of merit. The energy resolution values obtained by these measurements are very promising, as is it shown by a comparison of the results with previous published data. Such a detector could be used in a variety of applications, including Medical Imaging detectors or small size gamma spectrometers used in modern radiation monitoring devices, replacing previous technologies, such as large NaI:Tl detectors based on PMTs. The best GAGG:Ce thickness regarding the high gamma ray irradiation conditions used in this study is found equal to 20mm according to its higher FOM index. This SiPM based detector will be used for further research including lower gamma rays in order to check its linearity of response as well.

Acknowledgement

This research is implemented through IKY scholarships programme and co-financed by the European Union (European Social Fund - ESF) and Greek national funds through the action entitled “Reinforcement of Postdoctoral Researchers”, in the framework of the Operational Programme “Human Resources Development Program, Education and Lifelong Learning” of the National Strategic Reference Framework (NSRF) 2014 – 2020.

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