Comparative Evaluation of Cesium Iodide Scintillators Coupled to a Silicon Photomultiplier (SiPM): Effect of Thickness and Doping on the scintillators

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Abstract. Cesium Iodide (CsI) crystals are referred as the ‘state of art’ scintillator materials used in most of Nuclear Medical Imaging systems, because of their high light yield outputs and low cost. In this work, a characterization in terms of energy resolution, photo-fracti, sensitivity as well as the figure of merit (FOM), of CsI:Na and CsI:Tl scintillators, are presented. A set of samples with 9 mm² of cross section and a thickness ranging from 1 to 7 mm have been tested on a silicon photomultiplier (PM3350) using two different radioactive sources: ¹³⁷Ba (0.081 MeV and 0.356 MeV) and ¹³⁷Cs (0.662 MeV). The best energy resolution value was achieved by the 3x3x7 mm³ CsI:Na at 0.662MeV equal to 8%. For the CsI:Tl scintillator with the same dimensions the energy resolution was equal to 8.2%. At 0.081MeV the best energy resolution was recorded for crystals with 3x3x5 mm³ dimensions equal to 18.9% for CsI:Na and 24.9% for CsI:Tl. Results were compared to a reference NaI:Tl 3x3x5 mm³ and 3x3x10 mm³ as well as with previous published data.

1. Introduction
Cesium Iodide has been known as a scintillator for over half a century and thus has been studied extensively [1]. It is one of the brightest scintillators with medium γ-ray stopping power, due to its relative high density and atomic number. For scintillation counting, it is usually used in its doped form with sodium (Na) or thallium (Tl) activators [2]. When doped with Tl ions, CsI exhibits a light yield of more than 60000 ph/MeV at room temperature [3], [4]. A good match of the Tl emission band (maximum at 560 nm) to the spectral sensitivity of photodiodes and a relatively short decay time constant (0.6-0.9 μs) makes this scintillator ideal for detecting ionizing radiation in many applications [5], such as medical diagnostics [6]. Compared to the most widely used NaI:Tl, it is less hygroscopic with higher photo-fraction, due to its higher effective atomic number than that of NaI:Tl [2]. On the other hand, CsI:Na is a less bright crystal than CsI:Tl, but comparable in light output and in emission spectrum to NaI:Tl.
Silicon Photomultipliers (SiPMs) are promising detectors for the replacement of traditional PMTs in Single Photon Emission Tomography (SPECT) and Positron Emission Tomography (PET) systems, principally for their small size, insensitivity to magnetic fields and continuous cost decrease [7].

The purpose of the work is to characterize a SiPM based gamma detector by CsI:Tl and CsI:Na, of various thicknesses, in order to establish the best matching between thickness and type of doping ion. For the experimental evaluation, radioactive sources that emit at low (used in gamma cameras [8] and SPECT scanners [8], [9]), at medium (like Iodine isotopes [10]) and at high energies (used by PET systems [8], [9]) were applied, analysing scintillator crystals performances at energy levels conditions of specific medical imaging techniques.

2. Materials and Methods

The experiments were made with a SiPM (PM3350-B63T75S-P4 [11]) light photon detector, purchased by KETEK GmbH Company, with 3x3 mm² active sensor area. This optical detector has high gain (~1.5 x10⁶ at 12% Overvoltage [11]) and it is suitable to operate at room temperature. The inorganic scintillator crystal materials (CsI:Tl and CsI:Na) tested in this study were provided by Hilger Crystals: tetragonal shape, 9 mm² of cross section, with all surfaces polished. The crystals were wrapped with Teflon tape reflector, except for the light collection surface, and optically coupled with a BC-630 optical grease to the SiPM. The signal of the SiPM detector was amplified and fed to a CAEN DT5720 desktop digitizer with specific acquisition parameters, selected for the best acquisition of pulses. A 30.5 V bias voltage was chosen - after optimization tests at seven different bias voltages with step of 0.5 V (from 28 to 31 V) - as the one that provided the best energy resolution values for both types of CsI crystals, using 137Cs radioactive source. All measurements were conducted inside a light-tight box with 2 hours duration each one, to ensure good statistics. The radioactive source to scintillator crystal distance was set 4 cm.

The examined parameters energy resolution, photo-fraction, sensitivity and FOM, acquired by CsI:Tl and CsI:Na scintillators, were computed with a custom made calculation program based on C++ code. Photo-fraction (%) was calculated after the division of the number of photons recorded in the photopeak area of the spectrum by the number of photons recorded in the whole spectrum. Sensitivity (%) was calculated after the division of the number of photons recorded in the whole spectrum by the number of gamma photons impinging to the detector surface. Energy resolution values of the detector were extracted from full width at half maximum values of photopeaks acquired using Gaussian fit [12] within a ±10% energy window. Gaussian fit showed a correlation coefficient (R²) up to 98% in all cases. FOM was thereafter calculated after the division of the sensitivity by the energy resolution values.

In order to examine the stability of the detector we measured, with CsI:Tl of 7 mm thickness, the count rate of the gamma rays from 137Cs for 8 hours and the count rate change was estimated every 30 minutes. Additionally, to check the background counts, in the same manner, a 2-hours measurement was made without any activity close to the detector.

3. Results

In figure 1.a. the energy resolution values at 0.662 MeV obtained for the different bias voltages applied on the SiPM detector coupled by a 6 mm thick CsI:Tl scintillator are reported. Energy resolution decreased by increasing the bias voltage until the chosen voltage 30.5 V, that exhibited the best energy resolution value (8%), and then it started increasing again, similarly to the behaviour found in literature [12], [13], [14]. On figure 1.b. it can be noticed that, as we could expect, the photopeak centre translated to higher channel numbers relatively to an increase of bias voltage in an approximately linear manner [15]. At 30.5 V bias voltage energy resolution values achieved by the 3x3x7 mm³ CsI:Na at 0.081MeV was equal to 20.3% and at 0.356 MeV was equal to 12.7% (figure 2.a.). At 0.662 MeV it reached the best energy resolution result, respect to the whole set of samples, equal to 8% (figure 2.b.). A slightly worse energy resolution, equal to 8.2%, was obtained for the CsI:Tl scintillator with the same dimensions. In Table 1, sensitivity, photo-fraction, energy resolution as well as the figure of merit values are reported for the whole set of samples, distinguishing between...
the three different energy peaks of $^{133}$Ba and $^{137}$Cs. The CsI:Na crystal of 1 mm thickness is not present in Table 1, because of the bad quality of its acquired spectra.

![Figure 1](image1.png)

**Figure 1.** (a) Points define energy resolution values at bias voltages 28:0.5:31 V for CsI:Tl crystal of 6 mm thickness with $^{137}$Cs radioactive source; (b) stars (**) represent experimental photopeak centre values relative to an increasing bias voltage for the same measurements of figure 1.a. The continuous line shows the linear fit ($R^2=0.98$).

![Figure 2](image2.png)

**Figure 2.** (a) Energy spectrum of $^{133}$Ba achieved with 7mm CsI:Na. The first photopeak corresponds to 0.081 MeV and the last one to 0.356 MeV; (b) Energy spectrum of $^{137}$Cs achieved with 7mm CsI:Na. It can be noticed that the $^{137}$Cs characteristic X-rays first peak at the left, the backscattered peak as well as the Compton edge of the $^{137}$Cs spectrum are clearly illustrated.

**Table 1.** Experimental data: sensitivity (Sens.), photo-fraction (P.F.), energy resolution (R) and figure of merit (FOM) of the analysed set of samples, relatively to the applied radioactivity sources. Best (R) values are underlined.

| Crystal Thickness | Sens. (%) | P.F. (%) | R (%) | FOM | Sens. (%) | P.F. (%) | R (%) | FOM | Sens. (%) | P.F. (%) | R (%) | FOM |
|-------------------|-----------|----------|-------|-----|-----------|----------|-------|-----|-----------|----------|-------|-----|
| **CsI:Tl scintillator crystals** | | | | | | | | | | | | | |
| 7 mm | 95.3 | 58.3 | 29.9 | 3.2 | 95.3 | 12.1 | 13.1 | 7.3 | 24.4 | 14.1 | 8.2 | 2.9 |
| 6 mm | 81.8 | 61.1 | 35.1 | 2.3 | 81.8 | 11.1 | 13.2 | 6.0 | 21.8 | 14.6 | 8.6 | 2.5 |
| 5 mm | 78.2 | 60.6 | 24.9 | 3.1 | 78.2 | 9.6 | 13.4 | 6.1 | 17.8 | 13.7 | 9.0 | 1.9 |
| 4 mm | 73.6 | 60.4 | 25.1 | 2.9 | 73.6 | 8.4 | 12.5 | 5.9 | 14.9 | 12.8 | 8.2 | 1.8 |
| 3 mm | 68.0 | 59.5 | 26.3 | 2.6 | 68.0 | 6.3 | 13.2 | 5.2 | 10.6 | 12.0 | 8.8 | 1.2 |
| 2 mm | 53.2 | 67.3 | 25.5 | 2.1 | 53.2 | 5.2 | 13.8 | 3.9 | 7.9 | 11.3 | 8.6 | 0.9 |
| 1 mm | 43.9 | 61.7 | 22.6 | 1.9 | 43.9 | 2.9 | 14.0 | 3.1 | 4.9 | 7.1 | 9.9 | 0.5 |
| **CsI:Na scintillator crystals** | | | | | | | | | | | | | |
| 7 mm | 92.3 | 43.3 | 20.3 | 4.5 | 92.3 | 10.7 | 12.7 | 7.3 | 23.4 | 13.1 | 8.0 | 2.9 |
| 6 mm | 87.5 | 43.2 | 19.6 | 4.4 | 87.5 | 10.8 | 10.8 | 8.1 | 21.5 | 13.6 | 8.0 | 2.7 |
| 5 mm | 86.3 | 41.1 | 18.9 | 4.6 | 86.3 | 9.6 | 14.1 | 6.1 | 17.1 | 13.2 | 9.0 | 1.9 |
| 4 mm | 74.1 | 43.7 | 21.1 | 3.5 | 74.1 | 6.7 | 13.2 | 5.6 | 13.9 | 10.3 | 9.4 | 1.5 |
| 3 mm | 60.3 | 44.3 | 21.4 | 2.8 | 60.3 | 4.4 | 12.4 | 4.9 | 11.7 | 10.1 | 9.7 | 1.2 |
| 2 mm | 60.6 | 41.1 | 20.0 | 3.0 | 60.6 | 2.8 | 11.1 | 5.4 | 7.8 | 8.1 | 10.9 | 0.7 |
CsI:Na scintillator crystals showed in general better energy resolution values than that of CsI:Tl, for the different energies and thicknesses examined. This mainly happen because CsI:Na emits in the blue region of the spectrum (420 nm), coupling better with the spectral response of the SiPM used in this study than CsI(Tl) [11].

At 0.081 MeV the best energy resolution was recorded, for crystals with 3x3x5 mm$^3$ dimensions, equal to 18.9% for CsI:Na and to 24.9% for CsI:Tl. Results were found better when compared to a reference NaI:Tl 3x3x5 mm$^3$ and a 3x3x10 mm$^3$: the thinner NaI:Tl showed energy resolution values of 28%, 17.4% and 8%, respectively for low, medium and high energies; in the same manner, the thicker NaI:Tl resulted with energy resolution values of 36.1%, 18.6% and 8%.

Finally the experiment could be considered stable in time because the number of counts rate of the gamma rays from $^{137}$Cs, recorded every half-an-hour in the 8 hours measurement, was always between 6080 and 6430 counts.

Additionally, in the 2-hours measurement made without any activity close to the detector the background counts resulted very low (equal to 596 counts).

4. Conclusions
In general CsI:Na scintillator crystals showed better energy resolution values than that of CsI:Tl, under conditions examined. In the present study the best CsI thickness regarding energy resolution, at 0.081 MeV, was found equal to 5mm, for both doping materials. At 0.356 MeV, a crystal thickness of 6mm CsI:Na exhibited the best energy resolution, while, at 0.662 MeV, even thicker than 7mm crystal can be used, because the best energy resolution value was measured for the maximum analysed crystal thickness (7 mm).

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