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CHARACTERIZATION OF THE SEGMENTED HIGH-PURITY GERMANIUM CLOVER DETECTOR FROM THE ELIADE ARRAY AT ELI-NP

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Semiconductor detectors are routinely used in gamma-ray spectrometry. Their characterization is crucial in order to perform quantitative and qualitative analysis. Some steps are needed to this end: energy resolution (FWHM) and full-energy peak efficiency determination.

The ELI-NP Array of Detectors (ELIADE) from the Extreme Light Infrastructure - Nuclear Physics facility (ELI-NP) contains eight HPGe segmented clover detectors and four LaBr3 detectors and it will be used to detect with high efficiency the gamma-rays with energies of up to several MeV in the presence of the high radiation background produced by the gamma beams. The segmented HPGe clover detectors are built by closely packing four single HPGe crystals, connected to the same cryostat. Each of the crystals is electrically divided in eight segments.

The performance of the ELIADE array relies heavily on the performance of the individual detectors. As a result, one of the main priorities is the testing and characterization of the segmented clover detectors. Energy resolution and efficiency measurements (both absolute and relative) are carried out using the analog and digital acquisition system and 152Eu and 60Co point-like sources.

In this work we report the steps performed for the characterization of the segmented high-purity germanium detector by using the current ISO standards. We confirmed the excellent energy resolution and high efficiency. Also, the characterization of the detector at higher energies was performed.

The obtained results were compared with the technical specifications provided by the supplier, being in good agreement.

Keywords: Segmented clover germanium detector, digital and analog acquisition systems, efficiency, energy resolution

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1. Introduction

Gamma-ray detectors are used in a wide range of activities, including fundamental research in nuclear and atomic physics as well as applications in materials analysis techniques, radiological protection, etc.

Semiconductor detectors are the most used due to their excellent energy resolution as well as their high efficiency [1]. Their characterization includes the energy and energy resolution calibration (for peak identification) and determination of the full-energy peak efficiency (for quantitative analysis).

The Extreme Light Infrastructure – Nuclear Physics in Bucharest, Magurele, Romania, is a major European undertaking with the aim of constructing a facility that can produce the world's highest intensity laser beams as well as unique high-intensity, narrow-bandwidth gamma-ray beams using laser-based inverse Compton scattering [2].

One of the main instruments being constructed for nuclear physics and research activity applications gamma-beams is the ELIADE detector array comprising eight segmented HPGe clover detectors [3], [4].

The Gamma Beam System diagnostics of ELI-NP requires a precise determination of the gamma beam parameters up to 19.5 MeV. Part of the diagnostics will involve the use of the high efficiency HPGe detectors for in-beam measurements [5].

One solution for having a high efficiency is that of closely packing several segmented crystals in a single cryostat. The segmentation is achieved by dividing the outer detector contact in several regions, electrically isolated from each other and collecting independently the signal from them, together with the full-volume signal from the inner contact. One of the configurations of 4 HPGe detectors packed in a single unit is the so-called clover detector. The layout of the crystals and contacts of the segmented clover detector can be seen in Figure 1.

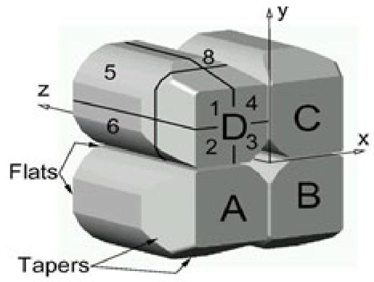


Fig. 1. The CLOVER detector crystal's geometry. The 4 crystals are labeled A, B, C, D. The segments of each crystal are labeled 1 to 8 [6].

The crystals of the detector are electrically divided in eight segments. The crystals and segments are connected to charge sensitive preamplifiers yielding a total of ten signal channels for each crystal, including two identical signals coming from the central contact of each crystal, which can be used as separate signals for different processing of the information.

An important feature of this segmentation is the fact that each of the segments behaves like an independent miniature HPGe detector.

The detector array for the ELI-NP experiments (ELI-NP Array of Detectors, ELIADE) contains eight HPGe segmented clover detectors and four LaBr3 detectors and will be used to detect with high efficiency the gamma-rays with energies of up to several MeV [7].

The germanium crystals for the ELIADE array are of n-type HPGe having a diameter of 60 mm and a length of 90 mm and typical properties like impurity concentration between 0.5 and 1.2 x 10^{10} at/cm^3 [8]. The recommended operating voltage is around +3500 V for all crystals.

The focus of the ELI-NP team involved in the development of the ELIADE array is the construction and testing of the Data Acquisition and Analysis (DAQ) systems and the full characterization of the detectors.

For testing and evaluation purposes, an analog DAQ system consisting of spectroscopic amplifiers (Canberra model 2026) is coupled to a Multiport II MCA (Canberra) and Genie2000 data acquisition software was used [9].

To characterize these detectors, energy resolution and relative efficiency measurements are routinely carried out using in parallel the analog and digital acquisition system and ^{152}Eu and ^{60}Co point-like sources by using the current ISO standards [10, 11].

The current ISO standards cannot be applied to characterise the gamma beam due to its unique properties, therefore to obtain the higher interval of energies for γ-rays, some experiments to test and characterize the detector efficiency were performed.

2. Theoretical aspects of the full-energy peak efficiency (absolute and relative) and energy resolution (FWHM) determination

The characterization of the ELIADE array consists in efficiency and energy resolution measurements using in parallel the digital and analog acquisition systems and ^{152}Eu and ^{60}Co calibrated point-like sources.

To obtain high quality results in gamma ray spectrometry it is necessary to perform energy and efficiency calibration of gamma detectors as accurately as possible.

The ratio of the number of counts produced in the peak by the detector to the number of gamma-rays emitted by the source (in all directions) represents the absolute efficiency of the germanium detectors.

In order to calculate the absolute efficiency of the detector the following equation is used:

$$\varepsilon_a = \frac{A_n}{\left(\Lambda \cdot t \cdot p_\gamma\right)} \tag{1}$$

where, A_n is the net area in the corresponding peak, Λ is the activity of the source, t is the acquisition time and p_γ represents the emission probability of the gamma-ray photon.

The standard parameter to characterize the detector efficiency is the so-called relative efficiency, defined as the ratio of the absolute efficiency for this detector to the absolute efficiency of a standard 3 x 3 inch NaI(Tl) detector for the measurements of the 1332 keV photon emitted by ^{60}Co source located at 25 cm from the detector. Taking into account the value $1.2\cdot10^{-3}$ of the efficiency of the standard 3 x 3inch NaI(Tl), the relative efficiency can be determined by using the following equation:

$$\varepsilon_{rel} = \frac{A_n}{\left(\Lambda \cdot t \cdot p_\gamma \cdot 1.2 \cdot 10^{-3}\right)} \tag{2}$$

The capability to discriminate photons with close energies is controlled by the energy resolution. The parameter characterizing the resolution is the full width at half maximum (FWHM) of the peak. This parameter is obtained by evaluating the difference in the energy between the point located at 1/2 from the peak height, on the right and left side of the peak, commonly for the 1332 keV peak of ^{60}Co and 122 keV peak of ^{57}Co. Better (lower FWHM value) resolution enables the system to more clearly separate close peaks within a spectrum. A better resolution also improves the detection limit of the system due to an improved peak-to-background ratio.

3. The digital and analog acquisition systems

The data acquisition system that will be used in the experiments is based on 14 bit 250MS/s digitisers (v1725 by CAEN). The DAQ takes data from more than 300 channels, making it a complex data acquisition system. The DAQ is based on the new MIDAS framework [12] coupled to custom made software.

The digital acquisition system covers a high number of spectroscopic channels including pulse shape analysis and pulse height analysis software.

The digitizers for HPGe detectors have a density of 16 channels/module, specifically designed for CAEN boards to manage the acquisition, execute the readout, unpack data [13].

The digital acquisition system for ELIADE is based on the idea that part of the data filtering (energy, time) is performed inside the digitizer board and one has to save only a short part of the signal pulse corresponding to the leading edge for further pulse shape analysis.

The digital data from one segmented clover detector is sent to one Local Processing PC with enough data storage space and high processing power.

The software used in combination with digital acquisition system is Midas Control & Data Acquisitions.

To test and evaluate the data obtained using the digital acquisition system, an analog DAQ system consisting of spectroscopic amplifiers (Canberra model 2026) coupled to a Multiport II MCA (Canberra) and Genie2000 data acquisition software was used [14]. To perform in parallel the analog acquisition measurements, one of the full volume preamplifier outputs of each crystal is amplified by a spectroscopy amplifier and sent to Multiport II MCA.

4. Experimental results

4.1. Low energy measurements

The detector used in these measurements was one of the segmented high-purity germanium clover detectors of the ELIDE array. The measurements were performed in order to test the energy resolution and the efficiency of the detector.

The measurements were performed in parallel with Analog DAQ and digital DAQ systems in order to compare the obtained results.

The detector efficiencies and energy resolution values were determined experimentally using ^{152}Eu and ^{60}Co point-like at 25 cm for all acquired data.

The reference activities and the uncertainties of the sources were (92270 ± 461) Bq on 27.08.2015 for ^{60}Co and (543500 ± 3261) Bq on 27.08.2015 for ^{152}Eu.

For the analog measurements a shaping time of 6 μs and pole zero adjustments were used. The measurement time for each source was chosen to be long enough to collect data with good statistics. The count rate was kept in the 2-4 kHz range.

The number of counts in the peaks were obtained by integration of the peaks with the GASPware data analysis package [15] and background subtraction was applied.

The obtained results concerning the energy resolution and relative efficiency for each crystal and associated segments are summarized in Table 1 and Table 2. In the Tables, FV1 and FV2 represent the full volume signals of the detector.

Table 1

Energy resolution and relative efficiency measurements for 1332 keV γ-ray of ^{60}Co using analog and digital acquisition system.

Crystal	Channel	FWHM Analog [keV]	FWHM Digital [keV]	ε_{rel} Analog [%]	ε_{rel} Digital [%]
A	FV1	2.11 ± 0.06	-	38 ± 2.6	-
Blue	FV2	-	2.16 ± 0.07	-	38 ± 2.6
	1	2.98 ± 0.06	3.01 ± 0.07	2.17 ± 0.75	2.21 ± 0.76
	2	2.79 ± 0.06	2.87 ± 0.06	2.25 ± 0.75	2.27 ± 0.75
	3	2.79 ± 0.06	2.85 ± 0.06	1.82 ± 0.56	1.84 ± 0.57
	4	2.87 ± 0.06	2.91 ± 0.06	2.08 ± 0.71	2.11 ± 0.72
	5	2.77 ± 0.06	2.82 ± 0.06	1.78 ± 0.61	1.81 ± 0.61
	6	2.59 ± 0.05	2.67 ± 0.05	1.7 3 ± 0.61	1.74 ± 0.61
	7	2.76 ± 0.06	2.81 ± 0.06	2.10 ± 0.69	2.11 ± 0.69
	8	2.81 ± 0.06	2.87 ± 0.06	1.75 ± 0.63	1.77 ± 0.63
B	FV1	2.16 ± 0.04	-	39 ± 2.7	-
Green	FV2	-	2.19 ± 0.05	-	38 ± 2.6
	1	2.61 ± 0.08	2.67 ± 0.08	2.17 ± 0.75	2.18 ± 0.77
	2	2.64 ± 0.08	2.69 ± 0.08	2.33 ± 0.75	2.34 ± 0.75
	3	2.91 ± 0.09	2.95 ± 0.09	1.83 ± 0.60	1.84 ± 0.61
	4	2.69 ± 0.08	2.72 ± 0.08	2.17 ± 0.75	2.16 ± 0.75
	5	2.63 ± 0.08	2.65 ± 0.08	1.61 ± 0.55	1.65 ± 0.57
	6	2.71 ± 0.08	2.74 ± 0.08	1.43 ± 0.59	1.49 ± 0.61
	7	2.78 ± 0.08	2.74 ± 0.08	1.71 ± 0.61	1.74 ± 0.62
	8	2.67 ± 0.08	2.73 ± 0.08	1.42 ± 0.59	1.46 ± 0.60
C	FV1	2.15 ± 0.04	-	38 ± 2.6	-
Red	FV2	-	2.22 ± 0.04	-	37.5 ± 2.6
	1	2.72 ± 0.08	2.74 ± 0.08	2.39 ± 0.77	2.36 ± 0.78
	2	2.58 ± 0.07	2.63 ± 0.07	2.17 ± 0.75	2.19 ± 0.76
	3	2.64 ± 0.08	2.67 ± 0.07	1.71 ± 0.61	1.73 ± 0.62
	4	3.16 ± 0.09	3.19 ± 0.09	2.17 ± 0.74	2.19 ± 0.76
	5	2.71 ± 0.08	2.75 ± 0.08	1.52 ± 0.63	1.59 ± 0.65
	6	2.81 ± 0.08	2.83 ± 0.08	1.25 ± 0.53	1.29 ± 0.55
	7	2.91 ± 0.08	2.94 ± 0.08	1.53 ± 0.64	1.59 ± 0.65
	8	3.01 ± 0.09	3.04 ± 0.09	1.70 ± 0.61	1.73 ± 0.63
D	FV1	2.29 ± 0.04	-	38 ± 2.7	-
White	FV2	-	2.31 ± 0.04	-	37.5 ± 2.6
	1	2.5 ± 0.06	2.54 ± 0.06	2.34 ± 0.75	2.36 ± 0.76
	2	2.6 ± 0.06	2.64 ± 0.06	2.25 ± 0.77	2.26 ± 0.78
	3	2.71 ± 0.07	2.73 ± 0.07	1.67 ± 0.59	1.72 ± 0.61
	4	2.54 ± 0.06	2.57 ± 0.06	2.25 ± 0.77	2.28 ± 0.78
	5	2.72 ± 0.07	2.75 ± 0.07	1.61 ± 0.55	1.65 ± 0.59
	6	2.82 ± 0.08	2.84 ± 0.08	1.41 ± 0.59	1.45 ± 0.61
	7	2.83 ± 0.08	2.84 ± 0.08	1.53 ± 0.64	1.59 ± 0.67
	8	2.91 ± 0.09	2.92 ± 0.08	1.75 ± 0.68	1.79 ± 0.70

Table 2

Energy resolution measurement for 122 keV γ-ray of ^{152}Eu

Crystal	Channel	FWHM Analog [keV]	FWHM Digital [keV]
A	FV1	1.36 ± 0.02	-
Blue	FV2	-	1.39 ± 0.02
	1	1.91 ± 0.04	2.02 ± 0.04
	2	1.77 ± 0.03	1.83 ± 0.04
	3	1.76 ± 0.03	1.8 ± 0.04
	4	1.81 ± 0.04	1.86 ± 0.04
	5	1.78 ± 0.04	1.83 ± 0.04
	6	1.84 ± 0.04	1.88 ± 0.04
	7	1.88 ± 0.04	1.92 ± 0.04
	8	1.92 ± 0.04	1.98 ± 0.04
B	FV1	1.46 ± 0.02	-
Green	FV2	-	1.53 ± 0.03
	1	1.74 ± 0.03	1.79 ± 0.04
	2	1.72 ± 0.03	1.77 ± 0.03
	3	1.81 ± 0.04	1.85 ± 0.04
	4	1.75 ± 0.03	1.8 ± 0.04
	5	1.86 ± 0.04	1.91 ± 0.04
	6	1.85 ± 0.04	1.91 ± 0.04
	7	1.81 ± 0.03	1.85 ± 0.03
	8	1.89 ± 0.04	1.95 ± 0.04
C	FV1	1.49 ± 0.02	-
Red	FV2	-	1.51 ± 0.02
	1	1.69 ± 0.03	1.75 ± 0.03
	2	1.77 ± 0.04	1.82 ± 0.04
	3	1.81 ± 0.04	1.85 ± 0.04
	4	1.71 ± 0.03	1.78 ± 0.04
	5	1.85 ± 0.04	1.89 ± 0.04
	6	1.83 ± 0.04	1.86 ± 0.04
	7	1.86 ± 0.04	1.91 ± 0.04
	8	1.89 ± 0.04	1.95 ± 0.05
D	FV1	1.41 ± 0.02	-
White	FV2	-	1.49 ± 0.03
	1	1.71 ± 0.03	1.77 ± 0.03
	2	1.74 ± 0.03	1.75 ± 0.04
	3	1.78 ± 0.03	1.83 ± 0.04
	4	1.76 ± 0.03	1.81 ± 0.04
	5	1.93 ± 0.04	1.95 ± 0.05
	6	2.04 ± 0.05	2.08 ± 0.05
	7	2.07 ± 0.05	2.11 ± 0.05
	8	2.06 ± 0.05	2.11 ± 0.05

The obtained results using ^{60}Co and ^{152}Eu point-like sources were compared with the technical specifications provided by the supplier where the energy resolution and efficiency were reported at 122 Kev and 1332 keV.

It can be easily seen that the values from Table 1 and 2 obtained by using both acquisition systems are in good agreement with each other.

The measured values were in good agreement with the technical specification provided by the supplier, except for the values obtained at low energy which are bigger than values from the technical specifications. One of the reasons can be the noise due to electronics. This behaviour will be further investigated.

The experimental uncertainties dependence on time and distance were negligible thus the standard deviation on relative efficiency was determined by the uncertainties on A_n, p_γ, Λ and it was calculated by the propagation of uncertainty equation [16], [17].

Figure 2 presents the relative efficiency values for all crystals as a function of gamma-ray of ^{60}Co and ^{152}Eu point-like sources.

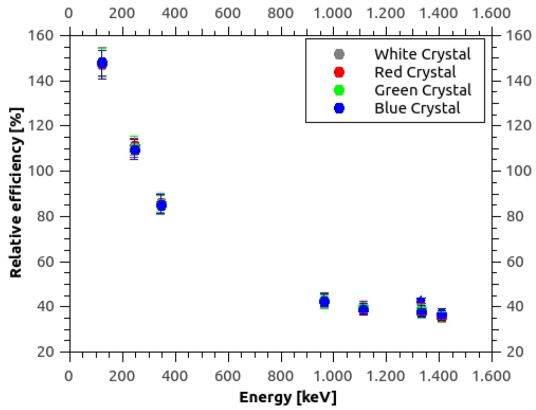
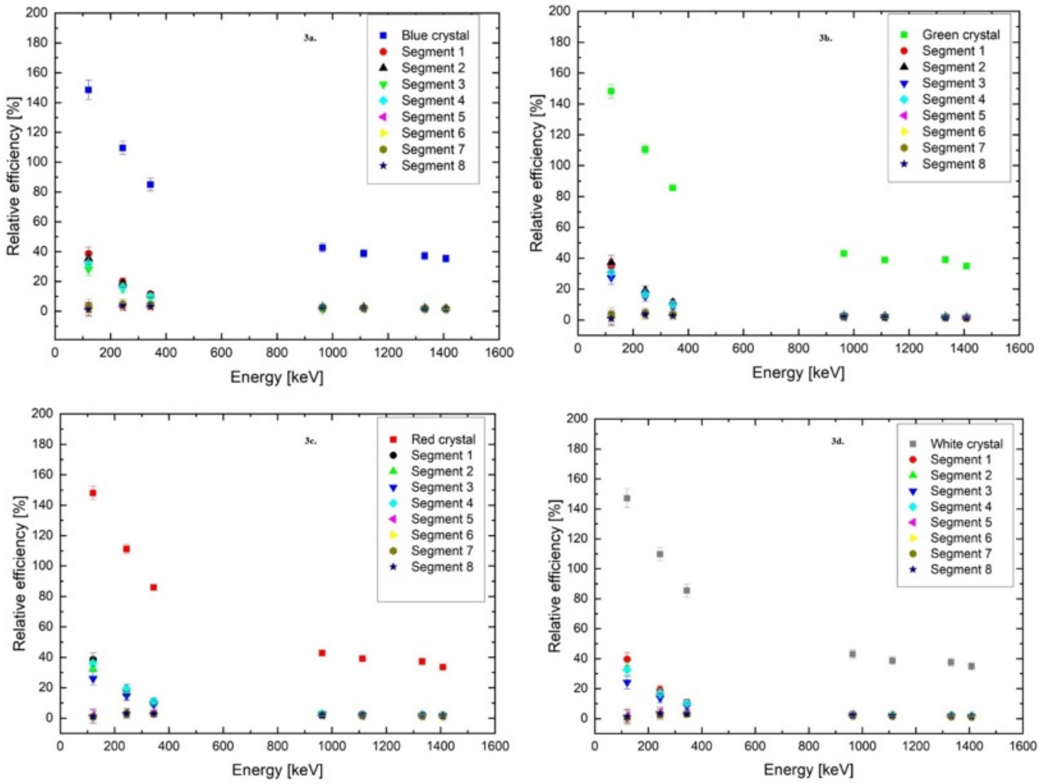


Fig. 2. The relative efficiency measurements for all crystals as a function of gamma-ray energy of ^{60}Co and ^{152}Eu point-like sources. The displayed values represent the measured absolute efficiency normalized to $1.2 \cdot 10^{-3}$ of the standard 3 x 3 inch NaI(Tl) detector.

In the Figures 3a., 3b., 3c., 3d., the relative efficiency values for each crystal and associated segments as a function of gamma-ray energy of ^{60}Co and ^{152}Eu point-like sources are plotted.



Figs. 3a., 3b., 3c., 3d. The relative efficiency values for each crystal and associated segments as a function of gamma-ray energy of ^{60}Co and ^{152}Eu point-like sources. (See caption of Fig. 2)

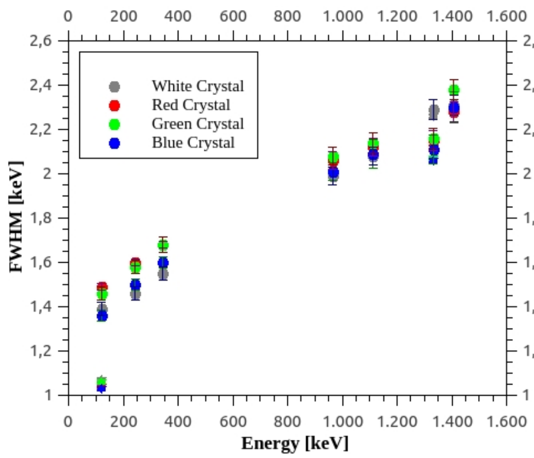
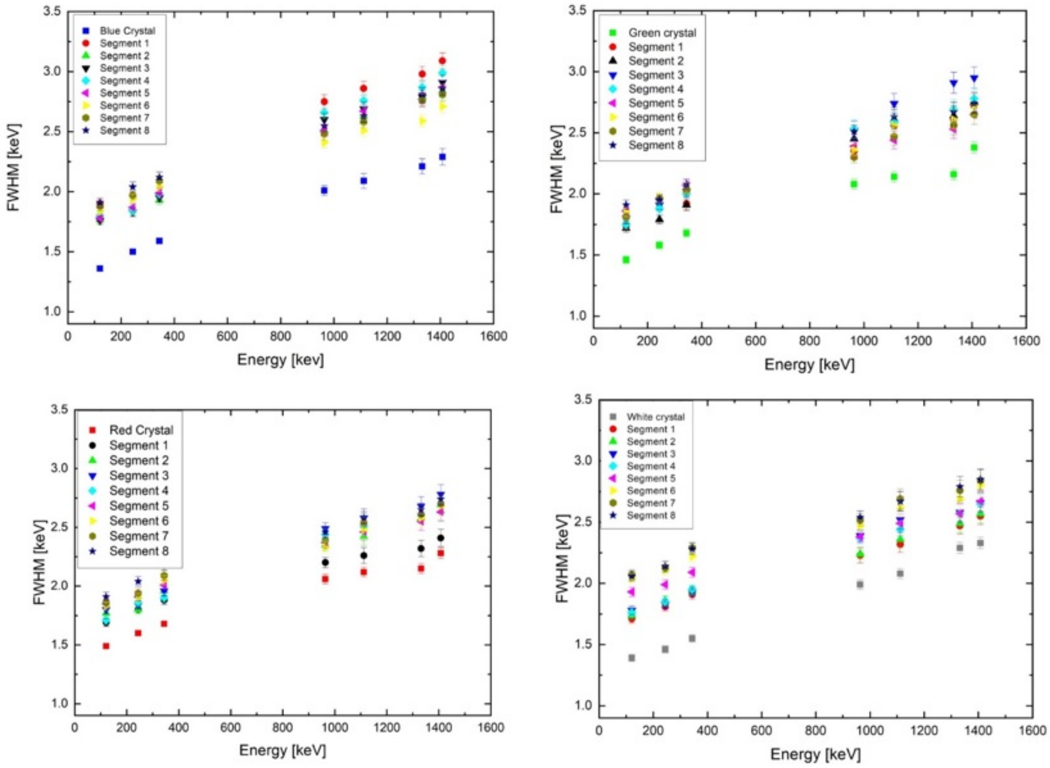


Fig. 4. The FWHM values for all crystals as a function of gamma-ray energy of ^{60}Co and ^{152}Eu point-like sources.

In the Figures 5a., 5b., 5c., 5d., the FWHM values for each crystal and associated segments as a function of gamma-ray energy of ^{60}Co and ^{152}Eu point-like sources are plotted.



Figures 5a., 5b., 5c., 5d. The FWHM plots for each crystal and associated segments as a function of gamma-ray energy of ^{60}Co and ^{152}Eu point-like sources.

As it can be seen from the figures presented above the obtained values of the relative efficiency have the same behavior for all crystals and associated segments of the Clover detector. The values of FWHM increase with increasing gamma ray energy, as expected.

The measured values were in good agreement with the technical specification provided by the supplier.

4.2. High energy measurements

The results presented above show that low energy detection efficiency can be routinely obtained using standard calibration sources. In order to know the detector's efficiency over the 0.2-18 MeV energy range, the energy limit imposed by standard calibration γ-ray sources needed to be extended to the required energy region via nuclear reactions. For high energy photons, several (p,γ) or (n,γ) reactions are required.

The production of gamma rays in the 1.7–12.3-MeV range was reached by using two reactions of proton capture, mentioned in Table 3.

In Table 3, $\mathbf{E_{\gamma1,2,3}}$ are the gamma ray energies of the product nucleus and branching ratio between $E_{\gamma2}$ and $E_{\gamma1}$.

Table 3

Nuclear reactions for efficiency measurements

Reaction	$E_{\gamma1}$ [MeV]	$E_{\gamma2}$[MeV]	$E_{\gamma3}$ [MeV]	Branching ratio
$^{27}Al(p,\gamma)^{28}Si$	1.78	10.76	12.33	0.806(10)

The measurements were performed at the 3 MV Tandem accelerator of IFIN-HH [18] by using a proton beam energy of 1.05 MeV and average current of 11.6 μA [19].

The experimental setup containing the clover detector involved in measurements at the 3MV Tandem accelerator is presented in Figure 6.

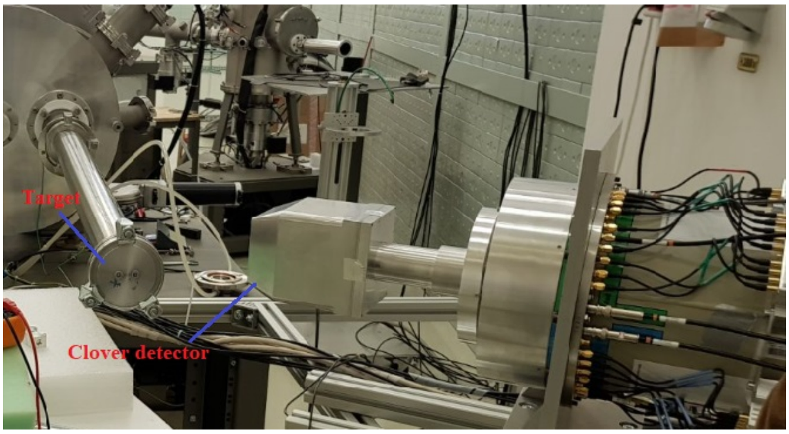


Fig. 6. The experimental configuration of the clover detector used for measurements at 3MV accelerator.

The analysis of the experimental data was made using the two-line method [20].

This method is used because the emission probability ratio between two gamma-rays in cascade is known with better accuracy compared with a single emission. The two-line method can be used in decays where high energy and low energy gamma transitions are present. Since the efficiency for the low energy photon can be obtained from standard calibration sources, the determination for the high energy gamma-ray is straightforward.

Figure 7 presents the measured relative efficiency of the clover detector in the 1 - 12 MeV range, where it is observed the same behavior for all crystals.

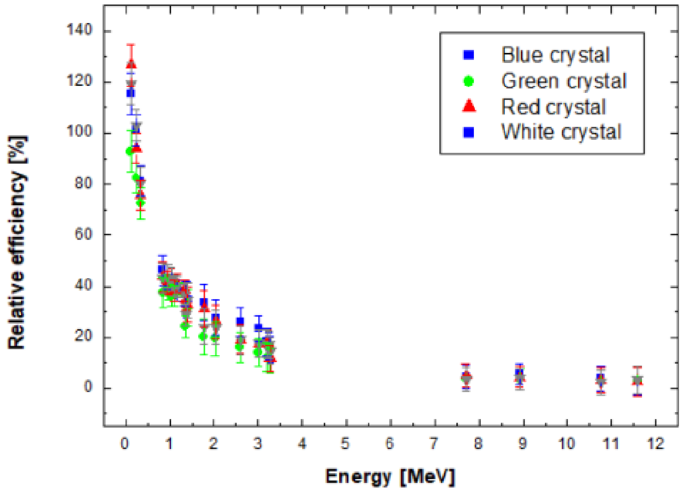


Fig. 7. Relative efficiency of the clover HPGe detector by using experimental data for the 1-12 MeV range.

5. Conclusions

In this work we have performed the required steps for the characterization of the segmented clover high-purity germanium detector for low energies by using the current ISO standards.

Measurements of the detection efficiency at higher energies were also investigated showing a proper behaviour for all crystals.

For low energy resolution and relative efficiency measurements were carried out using in parallel the analog and digital acquisition systems and ^{152}Eu and ^{60}Co point-sources.

Digital electronics and digital pulse processing methods have shown radiation spectrometry systems to be capable of accepting higher throughputs when compared with analog electronics. This opens up new opportunities in high resolution spectrometry at high count rates, an area of great interest to researchers using high intensity neutron beam and γ-ray beams.

In this work, the analog acquisition system was used to test and verify the data obtained with the digital acquisition system, taking into account the fact that the ELIADE array will be used in complex experiments and the DAQ needs to take data from more than 300 channels, making it one of the most complex data acquisition systems.

The digital acquisition results are in good agreement to the analog acquisition results, and both compare very well with the technical specification provided by the supplier demonstrating a good performance of the segmented clover detector.

The use of the digital acquisition system offers a very flexible expanded off-line analysis, reduces the number of electronic modules and the risk of electronic failure.

Considering these aspects, the digital data acquisition is the best choice for future experiments where the detectors and will be used to detect with high efficiency the gamma-rays with energies of up to several MeV in the presence of the high radiation background produced by the gamma beams.

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