OPTIMIZATION OF HPGe DETECTOR RESPONSE USING FAST AND RELIABLE METHOD

by

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Safeguards system with high effectiveness and efficiency must comprise a set of measurements with capabilities satisfactory for the verification of nuclear materials. In this paper, we present key parameter measurements of detector modeling in a commercial *n*-type low energy germanium detector of a planar crystal with a relative efficiency of nearly 15 %. The detector optimization will hold a significant function in measuring nuclear materials for safeguards application. Standard nuclear materials with diverse enrichment (depleted and low enriched) of uranium and point-like sources (^{137}Cs, ^{60}Co) and mixed radioactive source for Eu isotopes (^{152}Eu, ^{154}Eu, and ^{155}Eu) were benefited to explore the energy resolution and detector efficiency. The energy resolution is measured over a wide range of rise time and flattop. In addition to the experimental work, the Monte Carlo simulation code is used for modeling the setup configuration to obtain the absolute efficiency at different energies. A fast and reliable method was applied in detector efficiency measurements. The data are discussed and interpreted.

Key words: HPGe detector, digital signal processing, gamma-ray, resolution non-destructive assay technique

INTRODUCTION

Uranium enrichment measurements are of high significance in nuclear measurements. Such measurements are regarded as a crucial metric for ensuring that numerical materials (NM) are monitored toward peaceful objectives in nuclear applications and technology, especially for inspectionf nuclear safeguards intentions on a local and international basis.

Conducting such inspections without interruption of the nuclear facilities while operating can be realized by verifications of high speed and more accuracy. Such inspection techniques are supposed not to influence the quantity of NM, *i. e.*, non-destructive assay (NDA), and this can be performed by the use of detection techniques based on gamma-ray spectrometry for characterization and measurement of NM [1].

To maximize effectiveness as well as the efficiency of a State System of Accounting for and Control as a measuring system, covering all types as well as categories of NM is a must, which reflects its measuring capability, but it should meet the measuring criteria as well. Accordingly, a variety of measuring techniques should be utilized with adaptation to the resources available. Such techniques can be bulk measurements in addition to destructive and non-destructive systems. In the case of non-destructive NM assay, the gamma spectrometer is one of the accessible tools with powerful features, including an HPGe detector [2, 3].

For each verified NM, efficiency calibration must be accomplished for the utilized detector. Throughout the selection of appropriate NM standards for the calibration of the measuring system, both verified NM features and experimental set-up configuration are of great importance to consider. Such techniques may be categorized as relative, semi-absolute, or absolute depending on the physical standards for the calibration of measuring devices. Obtaining precise results can be achievable when standard NM, with features analogous to the verified samples, is utilized in the calibration process. Nevertheless, due to the lack of acceptable standards, a suitable calibration curve often cannot be established. However, overcoming this issue can be realized using the Monte Carlo method. Such a method can be employed for simulating the experimental set-up as well as the radiation detection process, which permits each modeled experiment to acquire efficiency calibration curves [4, 5].

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Since many years ago, the increasingly popular Monte Carlo simulation technique [6-8] was employed by several authors for simulating the gamma-ray detection process. The technique was exploited for calculating the response traits of diverse types of germanium detectors at mono-energetic as well as diverse ranges of gamma-ray [9-17]. Besides, Monte Carlo method was also utilized to calibrate detectors effectively, either by a direct method or with other experimental measurements in combination [6, 7, 18-26]

The HPGe detectors with the required efficiency of gamma radiation registration can be cooled by the liquid nitrogen or the electromechanical cooler. The efficiency calibration was made using the standard sources in point geometry as well as by using the complex calculation of the efficiency curves using the Monte Carlo simulation method. The usage of volumetric activity sources was necessary for detector calibration [27].

It is more probable than many assume that gamma-ray measurements with HPGe detectors at high count rates are demanded to be performed. For instance, this can be found in radiochemistry, safeguards, neutron activation analysis, and nuclear medicine. Count rates cannot be reduced by increasing the distance or by utilizing collimators. In this measurement situation, the obstacle is to acquire the *best* data. The *best* is a combination, over a wide span of count rates, of statistical (number of counts) and spectral quality considerations (peak width and position). Multi-channel analyzers (MCA) development by the assistance of digital signal processing (DSP) makes it likely to develop a broader range of shaping times values and detector signal processing in different pathways for performance improvement with pulse-by-pulse adjustments [28].

The biggest problem is the extensive count-rate range counting as it puts extreme constraints on the stability of the system: peak location as well as resolution. However, regarding temperature and count rate, DSP-based spectrometers as the newest generation demonstrate incredibly high stability. The spectrum peak full with at half maximum (FWHM) is dependent on the shaping time where a short shaping time does not comprise all the preamplifier pulse, while in the case of long shaping time, it contains excessively signal noise. With the shaping time adapted to the output signal of the detector preamplifier, the best (smallest) FWHM is attained [29].

The purpose of this study is the optimization of the HPGe detector response using a fast and reliable method. The main target of this paper is achieving the stability and smooth behavior in FWHM values for the photo peaks and maintain the Gaussian shape without appearing tail and obtained other parameters. All samples measured are authorized by the Egypt-IAEA safeguards agreement. Samples of reference NM belong to the key measurement point located outside the facility at Egyptian Nuclear & Radiological Regulatory Authority.

EXPERIMENTAL SET-UP AND TECHNIQUES MEASUREMENT

In the experimental work, the system of measurement involves a germanium detector of high purity with the Canberra GL0515R model and an active area of 540 mm^2. While the height is 1.5 cm, the FWHM is 540 eV at 122 keV. A cryostat [model 7905 SL-5], as well as the cooling system of 5 L Dewar containing liquid nitrogen, are provided to the measuring system. Collecting the pulses of energy input was accomplished by using a MCA [inspector, model IN2K], whereas the detector was set at a high voltage of 2500 V, and the computer was employed for system control [30-32]. For experimental measurements, two samples of standard NM samples have been utilized with a cylindrical shape, depleted and low enriched (2.95 %). The samples were positioned in an aluminum cylindrical can (aluminum type 6061 (ASTM-GS T6)), which contains 200.1 g of U_3O_8 (the specifications in tab. 1) [33]. The can external diameter is 80 mm, the internal diameter is 70 mm, and the height is 89 mm, while compact powder fill height is (20.8 0.5) mm for all samples. The sample was placed facing the detector. Also, point sources were used in this measurement with the specifications presented in tab. 2 [34, 35]. Figure 1 shows the experimental set-up configuration to measure the count rates and FWHM at different energy lines. The live time is adjusted at 900 seconds, for Point Sources and standard nuclear materials (SNM). The used samples are closed to the Al- cape of the detector. The DSP filter is adjusted where the rise time (RT) is changed from 0.4 to 38 μs, and the flattop if fixed at the default value at 0.8 μs. The resulted spectrum is shown in fig. 2.

Table 1. Characteristics of some uranium-bearing cylindrical sources [33]

Source No.	*E* mass percent*	Total mass of sample [g]	Total mass of U in a sample [g]	Mass of ^{235}U (g)
S1	0.3166 0.0002	200.1	169.681	0.526
S2	2.9492 0.0021	200.1	169.681	5.006

**E* is ^{235}U enrichment in mass percent

Table 2. Gamma radiation from some point sources [34, 35]

Source	^{152}EU			^{137}Cs	^{60}Co	^{154}Eu	^{60}Co	^{152}Eu
Energy line [keV]	121.8	244.7	344.3	661.7	1173.2	1274.8	1332.5	1408.01
Activity (Bq) × 10^4	1.1766			3.7	31.957	1.2099	31.957	1.1766

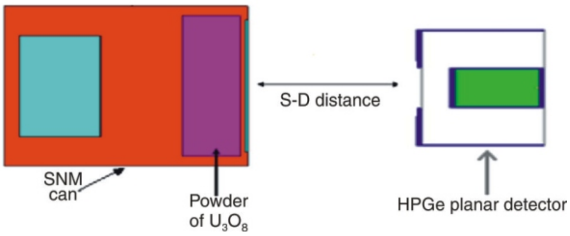

Figure 1. The experimental set-up configuration of the HPGe detector and SNM

MCNP CALCULATIONS

The MCNP is an advanced Monte Carlo simulation program that provides all required cross-sectional data for measurements of the neutron, photon as well as electron transport. Monte Carlo simulation is regarded as a random numbers sequence that takes place throughout the simulation. The simulation, based on repeating this sequence, will yield results in agreement with the obtained ones by the first sequence to within some *statistical error* [36]. Computing the absolute detector efficiency was attained by the general Monte Carlo code (MCNP-5) [24]. For the intention of simulating the experimental setup and according to available details, modeling of both specifications and characteristics of planar HPGe detector as well as utilized samples was accomplished. To run this calculation, eight input created files are required, which use 10^8 histories (number of photons) with a run time of 35 minutes. The employed laptop has specifications of 2.5 GHz Intel Core i5 processor, where the detector pulse height can be determined by tally F8. The absolute detector efficiency was calculated by F8 at different energy lines.

RESULTS AND DISCUSSION

Energy resolution

Energy resolutions of germanium detectors commonly denote the FWHM of a gamma peak. Good energy resolutions are critical for narrowing the region of interest, separating the signals from the background, and improving the sensitivity of the experiment [37]. The DSP, which is built into MCA, is the best selection of measuring performance at a variety of rise times and flattops. It has become a standard in the nuclear spectroscopy measurement field for high performance laboratory instruments.

RISE TIME AND FLAT TOP OPTIMIZATION

In the case of the uranium sample, the rise time is changed from 0.4 µs to 38 µs, the flat top still constant at 0.8 µs. Each time, the FWHM is recorded. The used samples are with different enrichment (low and depleted).

Figure 3 shows that the changes of FWHM with the rise time. It is evident that the values of two curves were closed to each other until at rise time <5 µs and it diverged above that value. At those values, the FWHM increased with increasing the rise time for SNM. In tab. 3, the rise time is fixed at 13.6 µs at different values of the flat top.

The results in tab. 3 presented that the preferred range for the flat top values that gave close and stable values for FWHM at energy line 185.7 Kev was from 0.4 to 2.2 µs. Before this range, the results appeared great deviation in FWHM values *vs*. the flat top values but after this range, the results appeared slightly changed in FWHM values with the flat top values.

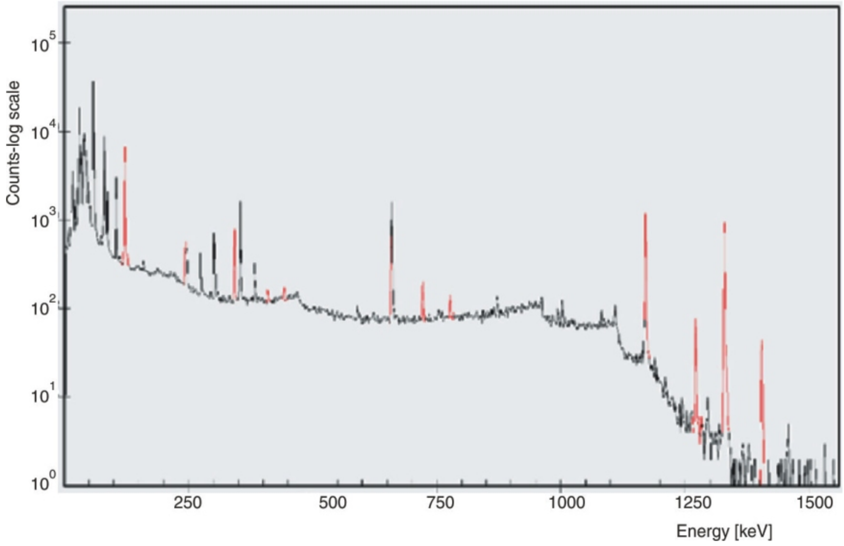

Figure 2. The full spectrum of the point sources

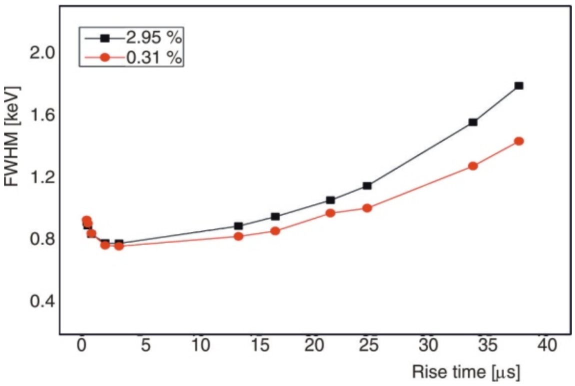

Figure 3. The effect of rise time changes with the FWHM at energy line 185.7 keV

In the case of point sources, the changing of FWHM with the rise time values had the same behavior in a wide range of energy lines. The energy lines that used in this analysis were 121.8, 244.7, and 344.3 Kev for ^{152}Eu, 661.7 Kev for ^{137}Cs, and 1173.2, 1332.5 Kev for ^{60}Co as shown in fig. 4. The results showed that the FWHM value slightly fluctuated at rise time <11.2 μs and became more stable after this value until reached to 30 μs and then began to deviate from the stability range, while the rise time was fixed at 13.6 s that was laid in the stability range from fig. 4.

Table 3. Data spectrum FWHM for low enriched SNM (2.95 %) at energy line 185.7 keV for fixed rise time

Flat top [μs]	Rise time [μs]	FWHM [keV]
3	13.6	0.805
2.6		0.823
2.2		0.825
1.8		0.817
1.4		0.823
1		0.838
0.8		0.851
0.6		0.865
0.4		0.888
0.2		1.283

Table 5 describes the data spectrum FWHM for point sources at different energy lines for fixed rise time 13.6 s. The flat-top was changed between 0.1 s and 3 s. The data showed that the change of FWHM slightly fluctuated at flat top values less than 0.6 s and then began to be more stable until 3 s.

From this optimization the FWHM was obtained at (rise time = 13.6 and flat top = 0.8) for point sources and fitted as a function of the gamma peak energy (in keV) by [38]

$$FWHM \quad a \quad \sqrt{E} \quad b \ldots \tag{1}$$

Table 4. Data spectrum FWHM for point sources at different energy lines for fixed rise time

Flat top [μs]	^{152}Eu			^{137}Cs	^{60}Co	
	121.8 keV	244.7 keV	344.3 keV	661.7 keV	1173.2 keV	1332.5 keV
0.1	0.700	0.631	0.959	1.333	1.769	2.018
0.6	0.681	0.734	0.890	1.26	1.613	1.701
1.2	0.704	0.704	0.959	1.219	1.659	1.726
1.8	0.719	0.831	0.972	1.25	1.681	1.746
2.2	0.714	0.798	0.988	1.232	1.671	1.768
3	0.726	0.845	0.906	1.205	1.654	1.708

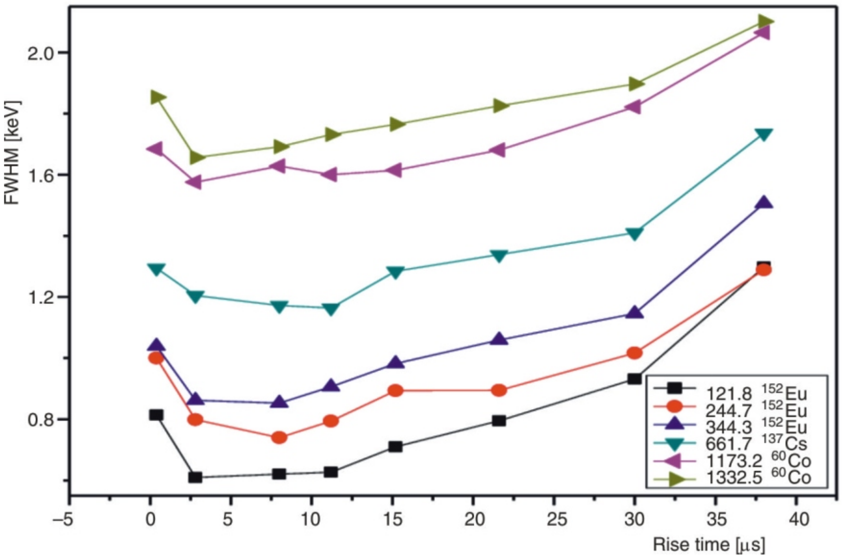

Figure 4. The effect of rise time changes with the FWHM at different energy lines

where E is the gamma peak energy and a, b are the coefficients that obtained from linear fitting equation $y = a + b\,x$ where $a = -0.5698$ and $b = 20.56385$. The results shown in fig. 5 present the FWHM of energy lines 121.8, 244.7, 344.3, and 1408.01 keV for ^{152}Eu, 1173.2, 1332.5 keV for ^{60}Co and1274.8 keV for ^{154}Eu.

OPTIMIZATION OF LIVE TIME AND FWHM

The live time was optimized by increasing its values from the 300-1800 seconds. Each run the FWHM was recorded. The results showed that there were slight changes in FWHM values in the range from 300 to 800 seconds after which the values began to be more stable. This indicates that the preferred value of live time has been started from the 900 seconds and it was chosen in this work. The effect of FWHM with live time is shown in fig. 6.

LINEARITY

The linearity of germanium detector responses to different energy depositions is typically outstanding, which is reflected by the goodness when the energy calibration curve is fitted to a linear function. Good linearity gives rise to a definite distinction between various physical events based on energy information. For studying the linearity for energy response of HPGe detector, corresponding point-like sources described in tab. 2, were measured. Considering that the gamma-ray with the largest energy is the 1408.01 keV for ^{152}Eu, the summation peak that resulted from the coincidence effect of the two gamma rays of ^{60}Co was also utilized for compensation of the probable deviation from linearity in the high energy region during the fitting process. The linearity of the detector is notably good, as observed in fig. 7. where the energy lines that used are 121.8, 244.7, 344.3, and 1408.01 Kev for ^{152}Eu, 661.7 Kev for ^{137}Cs, 1173.2, 1332.5 Kev for ^{60}Co and 1274.8 Kev for ^{154}Eu and the linear fitting coefficients are $a = -4.00938$ and $b = 5.24973$.

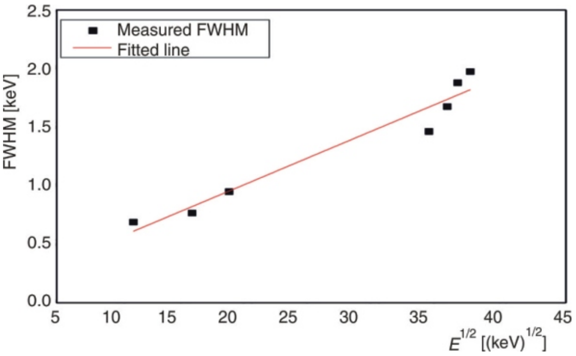

Figure 5. Energy resolutions of the HPGe detector

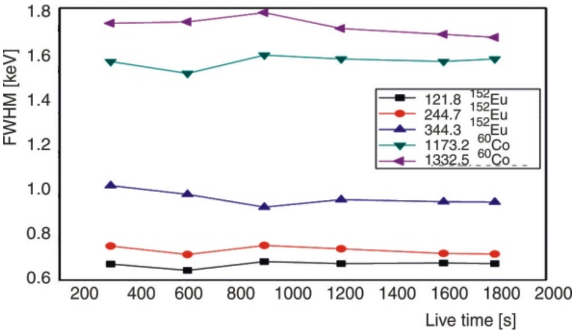

Figure 6. The effect of live time changes *vs*. the FWHM at different energy lines

EFFICIENCY

The absolute detection efficiencies of the (HPGe) detector were measured using the certified Point sources (^{137}Cs, ^{60}Co, and mixed radioactive source for Eu isotopes), and the involved gamma rays are listed in tab. 2, fig. 8 shows the efficiency curves for the experimental and calculated results as a function of the gamma-ray energy (in keV), which is fitted by

$$eff \quad A_1 \exp \quad \frac{E}{t_1} \quad y_0 \tag{2}$$

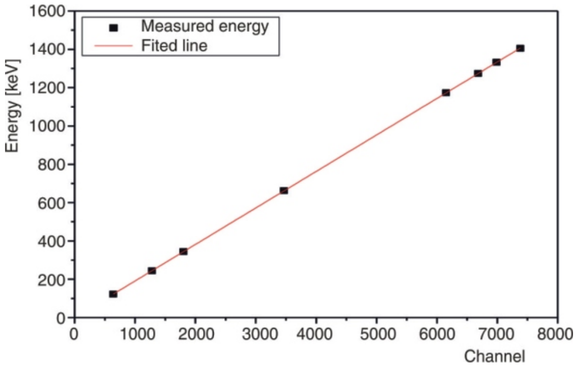

Figure 7. Linearity of the energy response of the HPGe detector

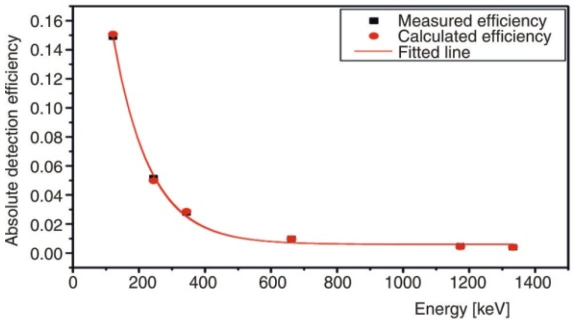

Figure 8. Absolute detection efficiencies of the HPGe detector

where *eff* is the absolute detection efficiency, E – the gamma-ray energy, and the coefficients A_1, t_1, and y_0 have values 0.00514, 0.41781, and 113.90 for the experimental curve and 0.00525, 0.43379, and 111.02 for the calculated curve.

The absolute detection efficiencies were calculated by MCNP code. Eight input files were created for each energy line to calculate the absolute efficiency using tally (F8). The input file contains accurate internal dimensions for the used detector, as well as, the setup configuration, as a whole. The calculated results were matched with the experiment within an accuracy of less than 4 %. So, the measured efficiency curves with the calculation of efficiency curves by the Monte Carlo simulation code provide a fast and reliable method in safeguards application.

Coincidence summing corrections for the point sources at each measured peak energy (E_i) were taken into consideration. The coincidence summing correction factor (F_corr) was calculated by establishing the ratio between the certified activity ($A(E_\mathrm{i})$) of the radionuclide and the calculated activity ($A_\mathrm{cal}(E_\mathrm{i})$) from the evaluation of the gamma-ray spectra [39].

$$F_\mathrm{corr}(E_i) \quad \frac{A(E_i)}{A_\mathrm{cal}(E_i)} \tag{3}$$

CONCLUSIONS

The significant parameters in safeguards measurements using HPGe detector are optimized in measuring of NM and point-like sources. Studying the shaping time is the main factor for FWHM improvement. We have found from result analysis, that there is a certain range of shaping time at which the compatibility in the measurements takes place where the rise time at range 13.6-21.6 μs is considered as the best range that gave the best value of FWHM at energy line 185.7 keV for SNM samples. The dead time can be treated by geometrical setting, and flattop at a range from 0.4 to 2.2 μs, while for point sources the best flat top value is from 0.6 to 3 μs, in which the FWHM is at stable values and gave perfect shape for the photopeak at used energy lines that covered a wide range in measurement scale. The perfect rise time range for point sources was 11.2 to 30 μs. This range showed the stability and smooth behavior in FWHM values, as well as, the peak shape takes Gaussian shape without appearing tail that destroyed the peak shape and causes disturbance in the area under the peak and the measurement results as a whole. Therefore, those values can be recommended. Fast and reliable methods were applied by modeling the experimental set-up using MCNP-5 code with different point sources. The comparison of the calculated absolute efficiency and those obtained from the measured results demonstrate that the accuracy is less than 4 %. This method gave accurate and fast optimization for the detector response and it could be recommended in safeguards application.

AUTHORS' CONTRIBUTIONS

The idea of the work was suggested by the authors during a scientific meeting of the team. Relationship building, implementation, the work of codes, writing, and revising the paper were achieved through joint and equal efforts of the four authors.

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ОПТИМИЗАЦИЈА ОДЗИВА HPGe ДЕТЕКТОРА КОРИШЋЕЊЕМ БРЗЕ И ПОУЗДАНЕ МЕТОДЕ

Систем сигурносне заштите са високом постојаношћу и ефикасношћу мора да садржи скуп мера са особинама задовољавајућим за верификацију нуклеарних материјала. У овом раду представљају се кључни параметри мерења детектора моделованог у комерцијалном *n*-типу нискоенергетског германијумског детектора равног кристала са релативном ефикасношћу од скоро 15 %. Оптимизација детектора има значајну функцију у мерењу нуклеарних материјала при безбедној примени. Стандардни нуклеарни материјали са разноврсним обогаћењем, осиромашеним и слабо обогаћеним уранијумом и тачкастим изворима (^{137}Cs, ^{60}Co) и мешани радиоактивни извор са изотопима еуропијума (^{152}Eu, ^{154}Eu, и ^{155}Eu), били су коришћени за истраживање енергетске резолуције и ефикасности детектора. Енергетска резолуција мерена је у широком опсегу времена раста и заравњења на врху. Поред експерименталног рада, Монте Карло симулациони код коришћен је за моделовање конфигурације подешавањем како би се добила апсолутна ефикасност при различитим енергијама. У мерењу ефикасности детектора примењена је брза и поуздана метода. Подаци су разматрани и тумачени.

Кључне речи: HPGe детектор, процесуирање дигиталног сигнала, гама зрак, недеструктивна техника резолуције