Influence of Aspect Ratios in Resolutions of High Purity Germanium Detectors in Nuclear Measurements

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Abstract

Six HPGe detectors with various crystal diameters were investigated for data related to the aspect ratio, energy resolution, peak shape, Peak-to-Compton ratio and efficiencies as they affect nuclear analytical measurements. The germanium crystal diameters ranged from 4.47 cm to 5.88 cm with lengths varying from 3.34 cm to 7.63 cm. These detectors were classified into two main groups- the Low Aspect Ratio (LAR) and High Aspect Ratio (HAR) group. The efficiencies of the HAR and LAR were investigated as functions of energies within the range of 121.78 keV to 1332.5 keV, for various source detector geometries. The Peak-to-Compton ratio and peak shape measurements were investigated with respect to HAR and LAR. The result shows that Peak-to-Compton ratio and peak shape increased proportionately with all the six GEM-series detectors used. These translate to the six detectors having accurate counting statistics of photons/gamma rays. However, detectors D4, D5, and D6 classified as HAR were higher in resolutions.

Keywords: CERT, NIRR-1, Efficiency of High Aspect Ratio (EHAR), ELAR, Neutron activation analysis (NAA)

1. Introduction

In nuclear analytical measurements, the aspect of instrumentation deals with detection instruments, methods, and experimental techniques for the measurements of radiations. Six germanium series coaxial HPGe-detector instruments with similar geometry arrangement of different crystal depths, diameters, and model/serial numbers were used as shown in Table 1. With these class of high purity germanium (HPGe) detectors, we aimed at obtaining the class that will provide accurate, fast, and short-time counting of photons with energy E≥1 MeV produced or emitted in nuclear transitions. These classes were divided into two categories termed Low Aspect and High Aspect ratios marking reference to the different crystal diameters ranging between 4.47–5.88 cm and lengths 3.34-7.63 cm.

Generally, crystal sizes of HPGe-detectors come with different types of configuration which can be classified into aspect ratios. For these large HPGe-detectors employed in this work, the Full Energy Peak Efficiency (FEPE) relative to the efficiency of 7.62cm diameter x 7.62cm length of NaI(TI) detectors were given as $\varepsilon_{NaI} = 1.2\times10^{-3}$ for source distance of 25cm (Helmer, 1982). Full energy peak efficiency of High Purity Germanium (HPGe)-detectors is one of the basic characteristic and must be studied with accuracy (Jonah *et al.,* 2006). It plays important role in counting statistic especially in the evaluation of trace elements, activity of either Naturally Occurring Radioactivity in Materials (NORMS) or induced radioactivity from matrices irradiated in a research reactor.

Another important characteristic of HPGe detectors is the Peak-to-Compton ratio which measures the detector's ability to distinguish peaks from the background influence as a result of radiation from environment or surrounding and electronic noise (Debertin and Helmer 1988). This factor (P/C ratio), ultimately defined the sensitivity for many detectors. Interference from Compton plateau of high energy γ-rays strongly hampers with; identification of nuclides with lower energy, increases number of counts in background, unreliable peak integration in lower energy region, poor detection limits due to poor background reduction, sum and escape of peaks. In the area of biological and environmental analysis of materials this interference of the Compton plateau result in difficulties such as; detection limit of important nuclides, accuracy and precision measurements of elements in food matrices, accurate measurement of elements in human nutrition and elements composition and their role in food consumption.

Another factor which forms one of the basic parameters that govern HPGe detector characteristics is the peak resolution defined as the measure of the width of the peak at half its height (Knoll, 1989). This is usually specified at either 1332.5 keV photo-peak of ^{60}Co or 122 keV gamma energy line of ^{57}Co (ANSI/IEEE, 1996).

2. Theory

Experimentally, the full energy peak efficiency factor "ε" for a particular sample to detector geometry is obtained by measuring the net counts under the photopeak energy of interest and using the formula in terms of count rate "A_D" and emission rate "ER" expressed as;

$$\varepsilon = \frac{A_D}{ERC_{SA}C_{SE}} \tag{1}$$

where ε is the full energy peak efficiency factor, C_{SA} and C_{SE} are the respective correction factors for self-absorption and summing effect.

The Full Energy Peak Efficiency (FEPE) factor ε of a HPGe detector is obtained placing point sources positioned at geometry of 'd' on a jig attached on a plexi-glass sample holder to ensure uniformity (Knoll, 1989). Gamma rays (photons) emitted equally in all directions covering a solid angle for a point source positioned at geometry 'd' is expressed as;

$$\text{Solid angle } \Omega\text{ (d)} = 2\pi \left[1-\left(1+\frac{R_D^2}{d^2}\right)^{-1/2}\right] \tag{2}$$

where; Ω (d) = Effective solid angle,

d = specific geometry, and

R_D = radius of the detector end cap.

The buildup of full energy peak efficiency factor "ε" is governed by the proportion of the intercepted space by the detector active area (A) given as (Knoll, 1989);

$$\text{Detector active area (A)} = 2\pi d^2\left[1-\left(\frac{d^2}{d^2+R_D^2}\right)^{\frac{1}{2}}\right] \tag{3}$$

3. Experimental

3.1 Aspect Ratio (AR) and Efficiency

A total of six HPGe-detectors used had different crystal diameters ranging between 4.47–5.88 cm and lengths 3.34-7.63 cm and were classified into two main groups i.e. Low Aspect Ratio (LAR) and High Aspect Ratio as shown in Table 2. The Efficiencies of High Aspect Ratio (EHAR) and Efficiencies of Low Aspect Ratio (ELAR) were investigated with the energies within the range of 121.78-1332.5 keV using the following point sources; ^{241}Am, ^{226}Ra, ^{152}Eu, ^{60}Co, ^{137}Cs and ^{22}Na each position at 5 cm away from the detector end-cap. The measuring times (T) were within the range 600 sec to 3600 sec while the initial activity (A) were within 36.5±1.5 kBq for ^{241}Am to 38.4±1.1kBq for ^{60}Co as from date of calibration within July 01, 2004 to July 15, 2004 and half live within 2.602y for ^{22}Na to 1600y for ^{226}Ra (Erdtmann and Soyka 1979). The experimental data shown in Table 3 for two HPGe-detectors (D1 and D2) of Low Aspect Ratio (0.74) and High Aspect Ratio (1.34) were plotted as full energy peak efficiency versus photon peak energy within the range 121.78 keV to 1332.5 keV as shown in Fig. 1.

3.2 Peak-to-Compton ratio, crystal diameter/depth and Aspect Ratio

The ^{60}Co source was placed at geometry of 5 cm away from detector's end cap, for each of the six HPGe-detectors investigated while the source counted for a live-time of 1800 sec. The values of P/C ratio were obtained from the spectrum generated for each of the six HPGe-detectors following the standard procedure (ANSI/IEEE, 1996). This was done by noting the mean count value registered under the peak amplitude of 1332.5 keV energy line of ^{60}Co within the 1040-1096 keV channels. The result of the variation of P/C ratio between the crystal diameters, crystal depth, Aspect Ratio and crystal volume of the six detectors are shown in Table 4 and the result interpreted in Fig. 1- 4 respectively.

3.3 Energy resolution and Peak shape

The ability of the detector to produce lines or peaks for monoenergetic photons is characterized by the peak width and peak efficiency (Debertin *et al.,* 1976). The width specified as the FWHM in keV is called resolution. For the six detectors having amplifier time constant of 6μs each making use of ^{60}Co point source and ensuring that the count rate remain less than 1 000 per second, a continuum spectrum was generated for measuring time of 1 200 sec, with count accumulation of above 20 000 counts in the peaks. The resolution or the Full Width at one-Half of the Maximum (FWHM) height above the energy of 1332.5 keV were measured as well as the Full Width at one Tenth (1/10th) of the Maximum (FWTM) height of the peak as well as the Full Width at one Fiftieth (1/50th) of the Maximum (FWFM) height of the peaks with experimental uncertainty in percentage were evaluated using the equation below and results illustrated in Table 5.

$$\text{Experimental Uncertainty} = \left(\frac{\chi|_{G2.45} - \chi|_{G2}}{\chi|_{G2}}\times 100\right)\% \tag{4}$$

The peak shape often defined as the FWTM/FWHM and FWFM/FWHM were also calculated as shown in Table 3. For a pure Guassian of both coaxial n- and p-type HPGe-detectors at a photo peak of 1332.5 keV, the standard ratio values quoted for FWTM/FWHM is 1.82 and the FWFM/FWHM is 2.38 (Debertin and Helmer 1988). However, the experimental data we obtained, making use of Eq. (4), deviated within 0.4% to 6.7% from the pure Guassian values of both FWFM/FWHM and FWFM/FWHM respectively as shown in Table 5.

4. Results and Discussion

High Aspect Ratio (HAR) implies that the crystal diameter is greater than the crystal depth and Low Aspect Ratio (LAR) means crystal depth greater than the crystal diameter. From Fig. 1, it is observed that FEPE of LAR detectors were higher than those of HAR detectors and both increases with decreasing energies. This is so because the crystal depths are higher for LAR detectors when compared to HAR detectors. This result strongly agreed with others (Erten *et al.,* 1988; Ewa *et al.,* 2002). Also, for the two classes of crystal sizes (LAR and

HAR), the full energy peak efficiencies increases with decrease in energy within the region E>200KeV as earlier agreed with those of Erten *et al.,* (1988), Osae *et al.,* (1999).

It was however observed that the peak-to-Compton ratio increases as the detector crystal-diameter size, depth size, increases Fig**s**. 2**-**5. The case of peak-to-Compton ratio and Aspect Ratio is that they **s**howed inverse relationship. Therefore, HPGe-detectors with large crystal diameter-depth also have high efficiency response as was suggested by Ray Gunnink. (1990). This implies that the factors in the crystal which contribute to peak broadening are under control. Thus, the peaks that are very closed and overlapping with each other are much differentiated. From Fig. 5, it was observed that the resolution of the HAR was the highest, implying that these classes of detectors measure much photon and cover larger areas of interaction within the specified solid angle than the LAR detectors. It was however, observed that energy resolution of 0.74 AR detector was followed closely by 1.03 AR, 1.34 AR and 0.77 AR. This suggests that when the crystal diameter and crystal depth are approximately equal, the energy resolution becomes high.

In investigating energy resolution and peak shape, it was observed that the experimental data for the six HPGe-detectors were very close to the pure Gaussian shape with a deviation range of 0.4% to 6.7% for the FWTM/FWHM and FWFM/FWHM peak shape. These results agreed well with the energy resolution values indicated in the technical report presented by Zvarai *et al.,* (1994).

Finally, the Aspect Ratio and energy resolutions for all the detectors appeared to be high (Fig. 5). This is because the crystal diameter and depth are approximately one or the same in terms of dimension. This then suggest that the peaks would become narrower when the crystal diameter-depth increases as is the case with all the six detectors, thus, suppressed the factors that influence the width of the peaks (FWHM) or the resolving power of the detector such as; the statistics of the charge creation process, the completeness of the charge collection process, and the electronic noise.

The relationships of the FWHM or peak resolution with respect to the Aspect Ratio for the six HPGe-detectors were carried out as shown in Fig. 5. The P/C ratios for the six HPGe-detectors were investigated in terms of the energy resolution as shown in Fig. 6

5. Conclusion

For the six High Purity Germanium (HPGe) detectors invested, we realized that those detectors classified as Low Aspect Ratio with values of 0.74 and 0.77 designated as D2, D3 respectively with germanium crystal depth greater than crystal diameter were observed to have high efficiency responses. However, those detectors grouped as High Aspect Ratios with value of 1.18, 1.29, and 1.03 designated as D4, D5, and D6 were observed to have peak shape values of 2.54 with deviation of 6.74%, 2.37 with deviation of 0.4% and 2.51 with deviation of 5.5% for FWFM/FWHM measurements respectively. These indicated that the peak shapes of these detectors were very close to the standard values of 2.38 for both co-axial n- and p-type leading to effective performances. These set of detectors (HAR) were also observed to have high peak-to-Compton ratios and this characteristic defined the ability of the detectors to highly distinguish peaks from the background influence as a result of radiation from environment or surrounding and electronic noise.

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Table 1. Physical properties of the six detectors used in this work

Detector Model Number	Serial Number	Crystal Diameter (cm)	Crystal Length (cm)
8111-10195	20-P667A	4.47	3.34 (D1)
GEM-25185-P	37-TP2.1100A	5.50	7.47 (D2)
GEM-30195	39-P21439A	5.88	7.63 (D3)
GEM-20190-P	37-TP11311B	5.50	4.68 (D4)
GEM-20190-P	29-TP30373A	5.76	4.46 (D5)
GCW2022	B91026	5.40	5.25 (D6)

(where D1, D2,….D6 referred to detector 1,2,…6)

Table 2. Classification of detectors in terms of Aspect Ratio

Crystal Diameter (cm)	Crystal Length (cm)	Aspect Ratio	Classes	Detectors
5.50±0.005	7.47±0.005	0.74	LAR	2
5.88±0.005	7.63±0.005	0.77	LAR	3
5.40±0.005	5.25±0.005	1.03	HAR	6
5.50±0.005	4.68±0.005	1.18	HAR	4
5.76±0.005	4.46±0.005	1.29	HAR	5
4.47±0.005	3.34±0.005	1.34	HAR	1

Table 3. The FEPE factor data generated for LAR and HAR HPGe-detectors

Energy (keV)	FEPE factor for LAR	FEPE factor for HAR
121.78	6.15E-02	2.96E-02
351.90	5.42E-02	2.60E-02
661.66	4.43E-02	2.11E-02
934.00	3.56E-02	1.66E-02
1112.0	2.99E-02	1.40E-02
1332.5	2.28E-02	1.05E-02

Table 4. Peak-to-Compton Ratios, Crystal Depth and Diameters

Crystal Diameter	Crystal Depth	P/C Ratio	Aspect Ratio	Detectors
5.88	7.63	70.7:1	0.77 (LAR)	6
5.50	7.47	64.9:1	0.74 (LAR)	5
5.40	5.25	46.0:1	1.03 (HAR)	2
5.76	4.46	56.3:1	1.29 (HAR)	4
5.50	4.68	54.9:1	1.18 (HAR)	3
4.47	3.34	40.0:1	1.34 (HAR)	1

Table 5. Experimental values of peak resolution, peak shape for the six detectors

Detectors	FWHM keV	FWTM/FWHM	FWFM/FWHM	P/C Ratios
5	1.70	1.79 ±1.6	2.37 ±0.4	64.9:1
6	1.82	1.88± 3.3	2.51 ±5.5	70.7:1
2	1.97	1.88 ±3.3	2.39 ±0.4	46.0:1
4	1.82	1.89 ±3.8	2.54 ±6.7	54.9:1
3	1.67	1.83 ±0.5	2.43 ±2.1	56.3:1
1	1.93	1.88 ±3.3	2.34 ±1.7	40.0:1

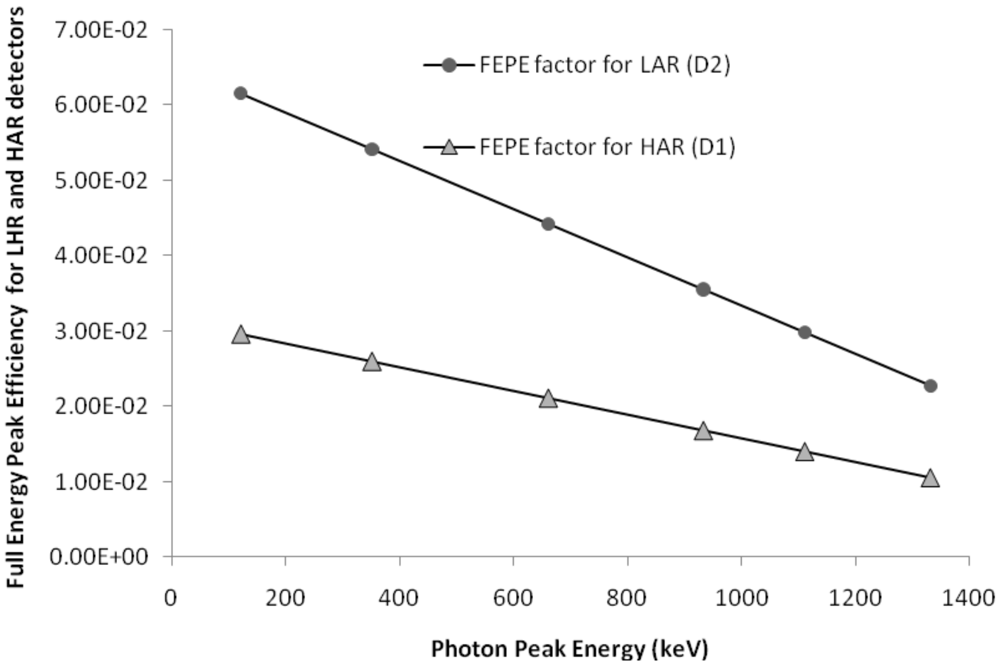

Figure 1. FEPE for HAR and LAR within photon peak energy range of 221.78-1332.5 keV

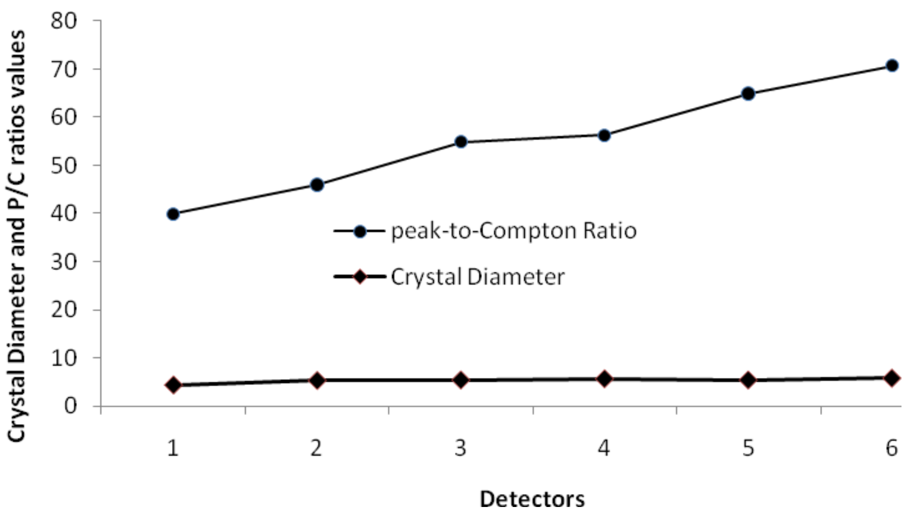

Figure 2. Peak-to-Compton ratio and Detector-crystal Diameters variations for six detectors

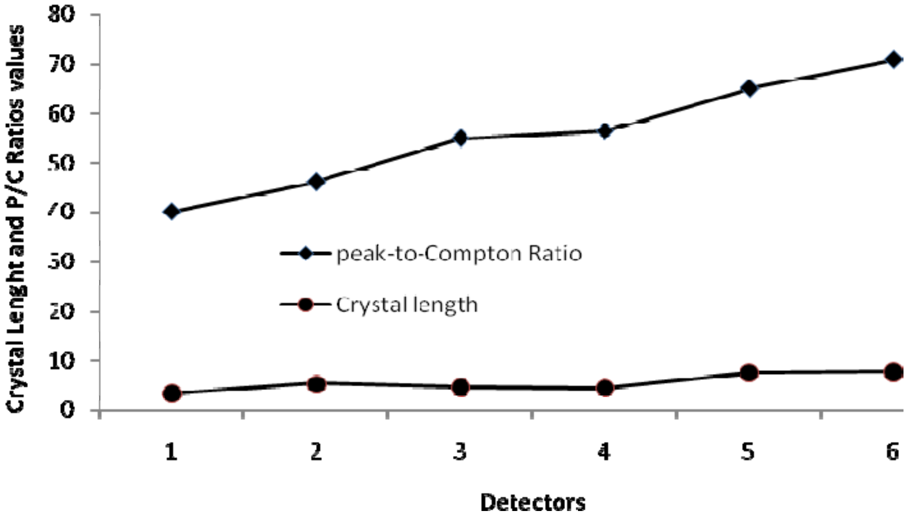

Figure 3. Crystal Length and Peak-to-Compton variations for six detectors

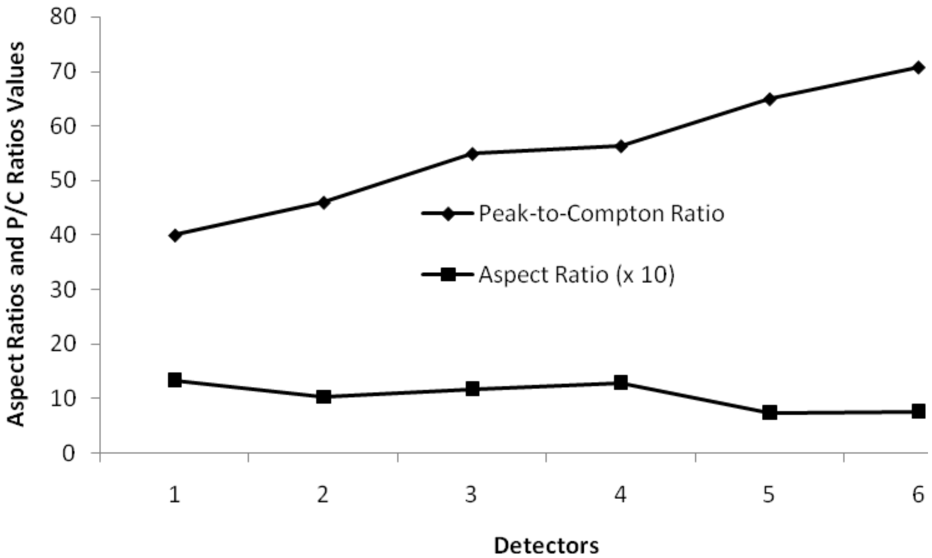

Figure 4. Aspect Ratio and Peak-to-Compton ratios variations for six detectors

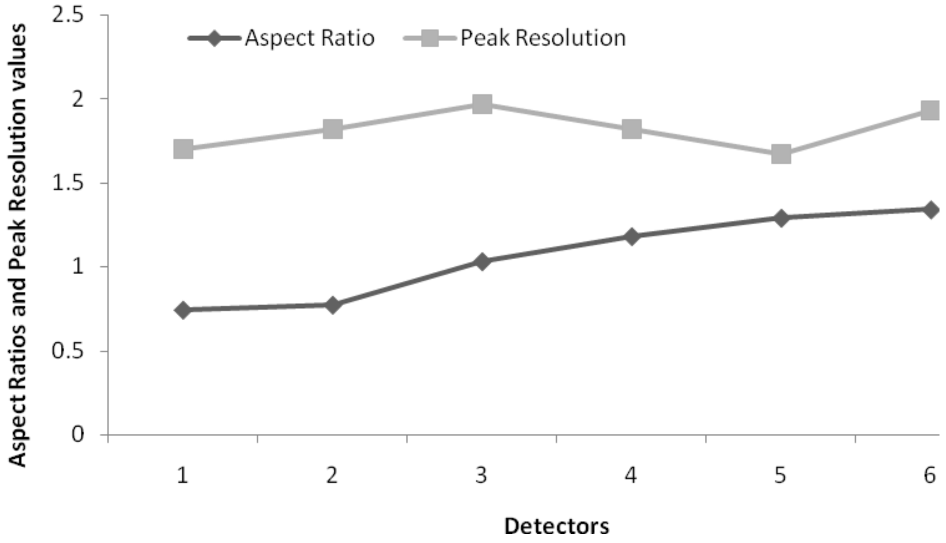

Figure 5. Variation of Aspect Ratios of the six detectors and peak resolution

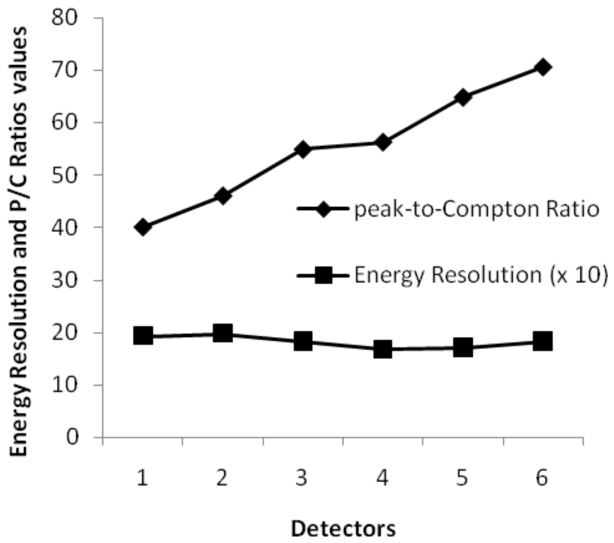

Figure 6. Energy Resolution and P/C ratios variation for six detectors