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Original Article

Experimental Investigation on the Photopeak Efficiency of a Coaxial High Purity Germanium Detector for Different Geometries

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Abstract

Purpose: Gamma spectrometer systems are complex instruments, and the quality of the numerical results they provide strongly depends on their reliable calibration. In this study, it was aimed to determine the full-energy peak efficiencies of a 40% p-type High Purity Germanium (HPGe) detector for point source, Marinelli beaker, and cylindrical container geometries in the 200-1500 keV energy range.

Methods: The efficiency calibration of the HPGe gamma spectrometry system was performed using certified calibration sources. Efficiency values were determined using the gamma ray spectrum acquired for every calibration source.

Results: Two different efficiency curves, at the linear scale and logarithmic scale-fitting, experimental efficiencies were plotted. The functions and parameters that fitted the efficiency curves were obtained by a computer program.

Conclusion: The photopeak efficiencies decrease as energy increases and the observed efficiency curves were closely with similar studies.

Keywords: Energy calibration, efficiency calibration, gamma spectrometry, high purity germanium gamma ray detector

INTRODUCTION

Detection efficiency has a great importance in nuclear investigations and in all experimental studies that measure radiation because the efficiency of detectors is the most important parameter used to determine the numerical results of a study. Gamma rays can pass through a material by making weaker interactions; therefore, their detection efficiency is lower than that of other radiation types. Therefore, an accurate knowledge of detection efficiency has greater importance.

The efficiency of a detection system strongly depends on many parameters such as the energy of gamma rays, dimensions of the detector, dimensions of the source, geometric arrangement of the detector and source, and density of the sample (1). Therefore, the efficiency calibration developed for one detector may not valid for another. The most reliable method for all detectors is to determine the efficiency calibration by means of experimental methods in their natural conditions, and a recalibration of detector efficiency for each sample-detector configuration is needed. Many studies were performed on the efficiency calibration of High Purity Germanium (HPGe) detectors for different source geometries (2-6).

A standard procedure to experimentally determine the detection efficiency of any detector–source configuration is to use radioactive calibration standard sources placed a distance away from the detector. The calibration standard source and measured sample should be physically and chemically similar and should have similar activity distributions.

This paper presents the full-energy peak efficiency calibration of a 40% p-type HPGe detector for point source, Marinelli beaker, and cylindrical container geometries.

METHODS

Gamma Spectrometer System

The system used in the present study was equipped with a coaxial p-type HPGe detector (AMETEC-ORTEC GEM40P4). The HPGe detector had a relative efficiency of 40% with a 3″×3″ cylindrical NaI (Tl) detector, an energy resolution of 1.85 keV at 1332.5 keV of ^{60}Co and of 0.87 keV at 122 keV of ^{57}Co with a peak-to-Compton ratio of 64:1, and an operating voltage of 3500 V. The detector was operated at liquid nitrogen temperature to reduce the leakage current and to increase the mobility of charge carriers. The detector with a 10-cm thick cylindrical lead shield with a low background radiation was used to shield the photons of cosmic and terrestrial origin. The detector was jacketed by a 9.5-mm low carbon steel outer housing. The inner lining was composed of a 1.5-mm thick tin layer and a 1.6-mm thick soft copper layer to prevent interference by lead X-rays. A spectroscopic amplifier (ORTEC, Model 672) with a 16 K analog-to-digital converter (ASPEC-927) was used to process the signals. The MAESTRO-32 multichannel analyzer emulation software (Ortec, South Illinois Ave., USA) was used for peak searching, peak evaluation, energy calculation, nuclide identification, data acquisition, storage, display, and online spectral analysis.

Radioactive Calibration Standard Sources

Three different geometries (point source, Marinelli beaker, and cylindrical container) of radioactive materials were used as calibration standard sources. Point sources of standard ^{152}Eu and ^{60}Co were provided from SPECTECH. Calibration standard sources with Marinelli beaker and cylindrical container geometries were prepared in volumes of 1000 mL and 100 cc, respectively. The IAEA-certified reference materials RGU-1 (U-ore), RGTh-1 (Th-ore), IAEA-375 Soil, and pure potassium chloride (Merck), whose properties are given in Table 1, were used for calibration standard sources.

Gamma Spectrometric Measurements

Before counting, point sources were mounted on a holder that was placed in a parallel plane at 25 cm away from the detector endcap and were aligned with the detector's axis. To avoid any uncertainty in the efficiency curve due to coincidence summing, such a large distance was chosen (3, 7, 8). Sources with Marinelli beaker and cylindrical container geometries were placed on the detector endcap for counting. The accumulating times of the spectral sources were high enough to obtain a gamma spectrum with a uncertainty of less than 1%. Gamma ray energies and their intensities used for the determination of the detector's efficiency are presented in Tables 2, 3 for point source geometry and Marinelli beaker and cylindrical container geometries, respectively. The measured information consisted of count rates of the full-energy peak area. To determine background distribution due to naturally occurring radionuclides in the environment around the detector, empty Marinelli beakers and cylindrical containers were used. The background counts of the peak area at the same energies were measured and subtracted from the source measurements to correct the net peak area of the gamma rays of the measured isotopes. In addition, the areas under each full-energy peak were corrected for dead time and Compton effect by the MAESTRO-32 software.

This study is written in accordance with the Helsinki declaration.

RESULTS

The efficiency calibration of the HPGe gamma spectrometry system was done using the above-mentioned certified calibration sources. The efficiency values were determined using the gamma ray spectrum acquired for every calibration source. Figure 1 shows the measured multi-gamma ray spectrum of the ^{152}Eu point source. From the measured gamma ray spectrum at certain source geometry, the photopeak efficiency values for gamma ray energies of the radionuclides mentioned in Tables 2-3 were calculated by the following formula:

Table 1. Certified reference materials used as calibration standard sources with Marinelli beaker and cylindrical container geometries

Certified reference material	Nuclide	Concentration	Origin
IAEA/RGU-1[1]	^{238}U	400 µg g-1	Beverlodge, Saskatchewan, Canada
IAEA/RGTh-1[2]	^{232}Th	800 µg g-1	Oka, Quebec, Canada
IAEA-375[3]	^{137}Cs	5280 Bq kg-1	Bryansk area, Russia
	^{226}Ra	20 Bq kg-1	
	^{232}Th	20.5 Bq kg-1	
	^{40}K	424 Bq kg-1	
Merck[4]	^{40}K	1605 Bq kg-1	

[1]International Atomic Energy Agency-certified Uranium Standard
[2]International Atomic Energy Agency-certified Thorium Standard
[3]International Atomic Energy Agency-certified Cesium-137 Standard
[4]Merck Potassium Standard

Table 2. Gamma ray energies used for the determination of the detector's efficiency for point source geometry

Nuclide	Energy (keV)	fγ (%)[1]
^{152}Eu	121.78	28.58
^{152}Eu	244.70	7.58
^{152}Eu	344.25	26.50
^{152}Eu	411.12	2.23
^{152}Eu	443.97	2.82
^{152}Eu	778.90	12.94
^{152}Eu	867.38	4.25
^{152}Eu	964.08	14.61
^{152}Eu	1085.87	10.21
^{152}Eu	1089.74	1.73
^{152}Eu	1112.07	13.64
^{60}Co	1173.2	99.97
^{152}Eu	1212.95	1.42
^{152}Eu	1299.14	1.62
^{60}Co	1332.5	99.99
^{152}Eu	1408.01	21.01

[1]gamma ray emission probability

$$\varepsilon(E) = \frac{\left[\frac{N_c}{t_c} - \frac{N_b}{t_b}\right]}{A.f\gamma(E)} \quad (1)$$

where $\varepsilon(E)$ is the photopeak efficiency; N_c, N_b and t_c, t_b are the net area in the region of certain energy peak and the counting times of the calibration source spectrum and background spectrum, respectively; A is the activity of calibration source, and $f\gamma(E)$ is the gamma ray emission probability. The present activities of sources were estimated from the following well-known activity relation, as disintegration per second,

$$A(t) = A_0 . e^{-\lambda t} \quad (2)$$

where A is the activity at time t, A_0 is the original activity, and λ is the decay constant of the nuclide taken into consideration.

Table 3. Gamma ray energies used for the determination of the detector's efficiency for Marinelli beaker and cylindrical container geometries

CRM[1] code	Nuclide	Energy (keV)	f_γ (%)[2]
RGU-1[3]	^{214}Pb	295	0.1829
RGU-1	^{214}Pb	352	0.3535
RGTh-1[4]	^{208}Tl	583	0.851
RGU-1	^{214}Bi	609	0.4689
IAEA-375[5]	^{137}Cs	662	0.9007
RGTh-1	^{212}Bi	727	0.0674
RGTh-1	^{228}Ac	911	0.29
RGU-1	^{214}Bi	1120	0.155
Merck[6]	^{40}K	1460	0.1066
RGU-1	^{214}Bi	1764	0.162
RGTh-1	^{208}Tl	2614	0.9983

[1]Certified Reference Materials
[2]Gamma ray emission probability
[3]International Atomic Energy Agency-certified Uranium Standard
[4]International Atomic Energy Agency-certified Thorium Standard
[5]International Atomic Energy Agency-certified Cesium-137 Standard
[6]Merck Potassium Standard

Figure 1. The measured gamma spectrum of ^{152}Eu point source

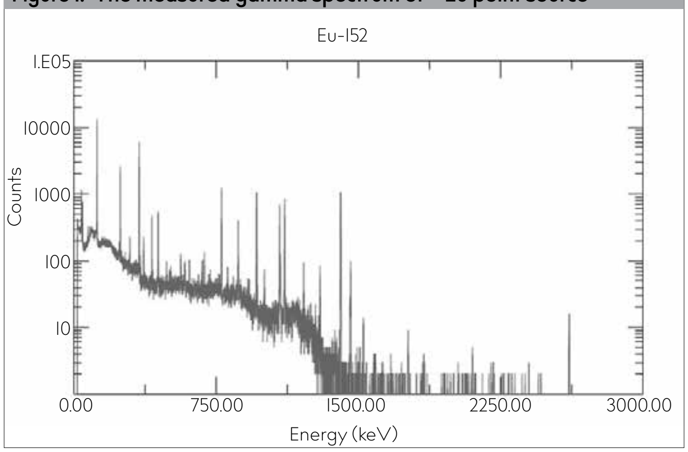
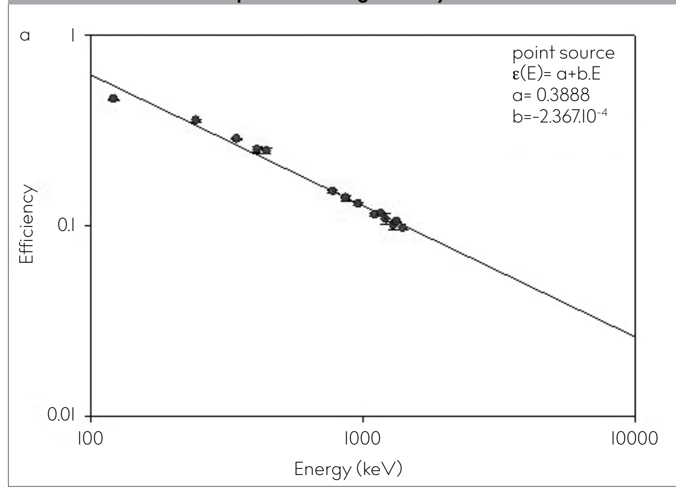
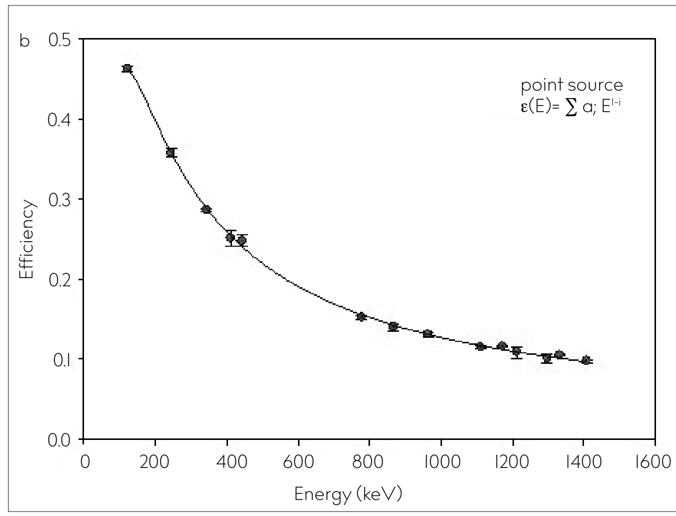


Figure 2. a, b. Efficiency calibration of the HPGe detector. (a) Efficiency calibration of the HPGe detector at logarithmic scale, (b) Efficiency calibration of the HPGe detector at linear scale for point source geometry





According to the above-mentioned calibration method, the photopeak efficiency curves for the used 40% p-type HPGe gamma spectrometry system are shown in Figure 2 for the point source geometry, in Figure 3 for the Marinelli beaker geometry, and in Figure 4 for the cylindrical container geometry. All these plotted efficiency curves, fitting functions, and parameters that fitted the efficiency curves were obtained using the Sigma Plot software, version 10 (Systat Software, London, United Kingdom). Some gamma lines are not included in the efficiency calibration curves. Uncertainties on experimental efficiency points are also shown in the figures and are derived from uncertainties on peak areas. As can be seen in these figures, the photopeak efficiencies decrease as the energy increases and the observed efficiency curves were closely similar.

For the point source geometry, efficiency fitting adopted a linear equation of the logarithm of the efficiency against the logarithm of energy and also given in Figure 2a with fitting coefficients. The efficiency fitting curve for the point source geometry (Figure 2b) at the linear scale was well adopted a third degree polynomial function to fit the efficiency to the energy:

$$\varepsilon\,(E) = \sum_{i=1}^{4} a_i E^{1-i} \qquad (3)$$

where ε is the efficiency at energy E (keV) and a_i is the fitting coefficient (a_1=0.0156, a_2=121.7033, a_3=-10379.7598, and a_4=266612.08). The experimentally determined efficiency values in this study were similar with those of a previous study (9).

For the Marinelli beaker geometry, efficiency calibrations were performed with different calibration standard sources. Namely, two calibrations were plotted using the certified reference materials of IAEA/RGU-1, IAEA/RGTh-1, Merck (Figure 3a), and IAEA-375 (Figure 3b). The efficiency fitting for the Marinelli beaker geometry was performed at the logarithmic scale in Figure 3 a. Another efficiency fitting curve for the Marinelli beaker geometry was well-adopted a third degree polynomial function as given in Equation 3 (Figure 3b). The fitting coefficients were a_1=-0.0055, a_2=27.05, a_3=-9374, and a_4=1.52×10^6.

Similar efficiency calibrations were conducted for the cylindrical container geometry and are shown in Figure 4.The efficiency fitting with IAEA/RGU-1, IAEA/RGTh-1, Merck reference materials was adopted a linear equation (Figure 4a), while other fitting with IAEA-375 reference material was adopted a third

Figure 3. a, b. Efficiency calibration of the HPGe detector. (a) Efficiency calibration of the HPGe detector with IAEA/RGU-1, IAEA/RGTh-1, Merck reference materials at logarithmic scale, (b) Efficiency calibration of the HPGe detector with IAEA-375 reference material at linear scale for Marinelli-beaker geometries

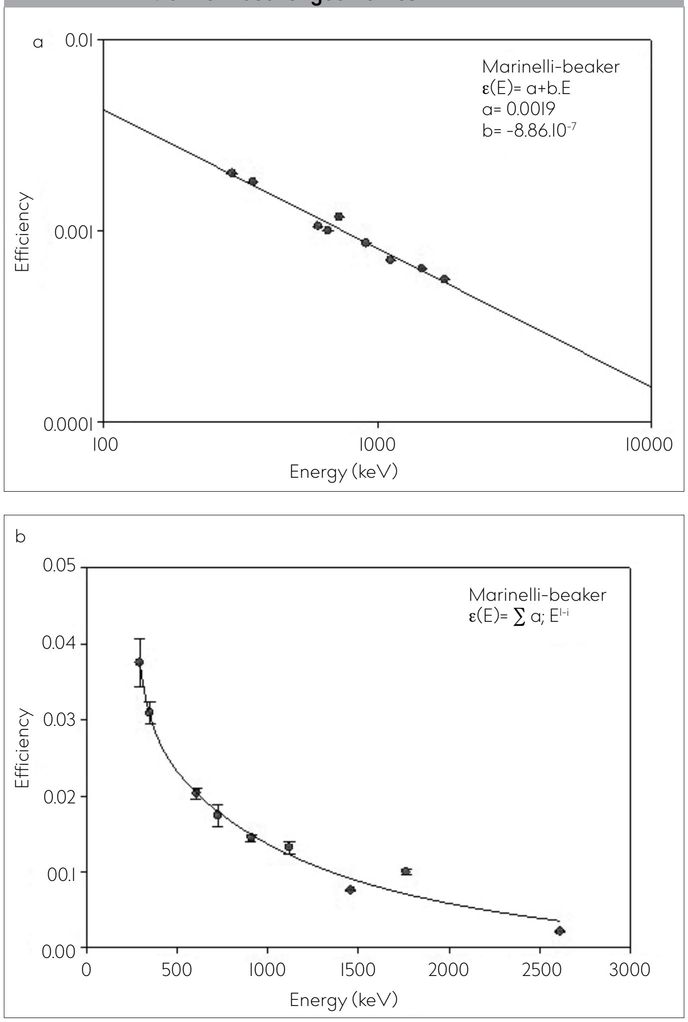
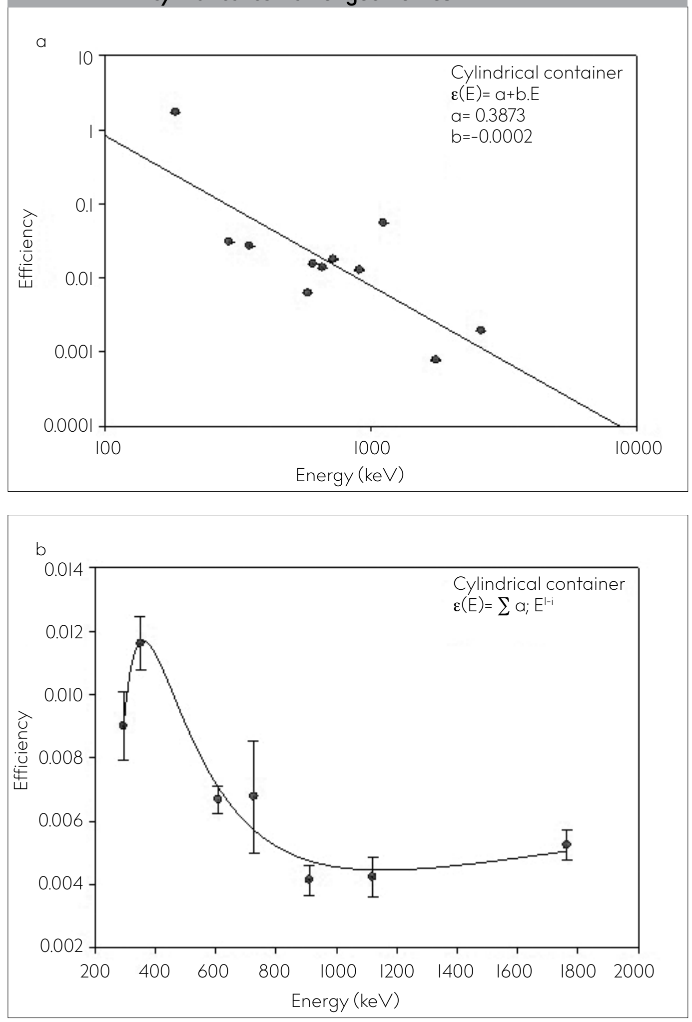


Figure 4. a, b. Efficiency calibration of the HPGe detector. (a) Efficiency calibration of the HPGe detector with IAEA/RGU-1, IAEA/RGTh-1, Merck reference materials at logarithmic scale, (b) Efficiency calibration of the HPGe detector with IAEA-375 reference material at linear scale for cylindrical container geometries



degree polynomial function with fitting coefficients of a_1=0.0103, a_2=−15.0377, a_3=11372.7, and a_4=−2.08x10^6 (Figure 4b). Uncertainties on experimental efficiency points were high due to the lower activity concentration of the cylindrical container with IAEA-375 reference materials.

DISCUSSION

Gamma spectrometer systems are complex instruments, and the quality of numerical results they provide strongly depends on their reliable calibration. In this study, the full-energy peak efficiency calibration of the 40% p-type HPGe detector for point source, Marinelli beaker, and cylindrical container geometries was determined. The efficiency curves were plotted using experimental efficiency values. The efficiency functions correspond to the efficiency curve at logarithmic and linear scales. At the linear scale, a third-degree polynomial function gives the best-fitted efficiency values for the three geometries. If one looks at the efficiency curve plotted at the logarithmic scale, it is noticed that it is a linear line in the 200-1500 keV energy range. Hence, the efficiency function in this range can be expressed as a linear equation. This equation is the simplest function to find the efficiency in that range, which makes it suitable for routine measurements of environmental samples.

Ethics Committee Approval: Authors declared that the research was conducted according to the principles of the World Medical Association Declaration of Helsinki "Ethical Principles for Medical Research Involving Human Subjects", (amended in October 2013).

Informed Consent: N/A.

Peer-review: Externally peer-reviewed.

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