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Efficiency curves of the Ghana Research Reactor-1(GHARR-1) Spectrometry System at Near and Far Geometries

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Abstract: The efficiency curves of the HPGe detector at different geometries were measured in a wide energy range of 53.16 to 1408keV. In this study emphasis was laid on the effects of the source energy and the source-to-detector distance. Due to the variation of the activity levels of various samples in gamma-ray spectroscopy, the source-to-detector distance is not fixed at a constant value. This means that the measurements of the absolute detector efficiency must be carried out for each geometrical arrangement used in gamma-ray measurements. The full energy peak efficiency in terms of the gamma-ray energy and the vertical distance from the detector surface has been obtained for an N-type high purity germanium (HPGe) detector using point-like calibrated sources at four different distances from the detector. Comparison of the calculated and the experimentally measured efficiency values for the energy range of 26.345-1408 keV and a source to detector distances of 36, 49, 62, and 75 mm showed that the calculated values agree with that of the experiment within the limits of uncertainty. The standard deviations of the calculated efficiency values from the experimental at the respective source-to-detector height were as follows: 0.05% for 36 mm, 0.08% for 49 mm, 0.03% for 62 mm and 0.01% for 75 mm.

Key words: Detector, energy peak, gamma-ray, germanium, HPGe, spectroscopy

INTRODUCTION

The full energy peak efficiency is one of the most important characteristics of gamma-ray detector. Since its accurate knowledge is essential for quantitative spectroscopy (Molnár *et al*., 2002). Samples in gamma-ray measurements may have relatively high activity, which forces the measurements to be carried out at large source-to-detector distance. Other measurements may require that sources be placed in the vicinity of a detector due to the low activity of the samples. Determination of the absolute efficiency of germanium detectors has been a long standing problem in gamma-ray spectroscopy and numerous reports have been published during the last decades. The absence of a universal method for the efficiency calculation is mainly as a result of two major factors; (1) the extended dimensions and (2) the self-absorption of the source. But still the experimental determination of the absolute efficiency is the most accurate method (Karamanis *et al*., 2002). The direct measurement of different calibration sources containing isolated gamma-ray emitters within the energy range of interest, and their subsequent fitting to a parametric function, yields the best results. Others however, adopt an economical alternative for the calculation of the efficiency values by Monte Carlo simulations. However, the lack of precise information about detector characteristics and matrix composition magnifies the errors on the low-energy efficiency values (Daza *et al*., 2001). Detection efficiency is generally a function of the detection system, sample shape, sample matrix with different density and also source-to-detector distance. Variability in the sample chemical composition is not a major problem, since mass attenuation coefficients differ slightly from one environmental sample to another (Harb *et al*., 2008). In this study however, emphasis is laid on the effects of the source energy and the source-to-detector distance.

MATERIALS AND METHODS

The experimental measurements were carried out in September, 2010 at the Neutron Activation Analysis Laboratory of the Ghana Research Reactor -1(GHARR-1) Centre, using a ORTEC N-type detector Model GMX40P4 of relative efficiency of 40%, an energy resolution of 1.95 keV at 1.33 MeV gamma-ray of ^{60}Co, and peak to Compton ratio of 59:1 of ^{60}Co. The detector efficiency curves were obtained using available certified

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gamma-ray standard sources obtained from Czech Metrological Institute Inspectorate for Ionizing Radiation; single (^{137}Cs) and multi (^{60}Co, ^{133}Ba, ^{152}Eu, and ^{241}Am) gamma-ray emitters. The counting time was prolonged to ensure at least 95% statistical significance curve. The efficiency was measured at various source-to-detector distances. These distances were measured from the point source to the top surface of the active volume of the crystal.

Experimental efficiencies: From the measurement of the activity of the calibration sources, experimental efficiencies were calculated. The experimental efficiency at energy E_γ for a given set of measuring conditions can be computed by:

$$\varepsilon_p\left(E_\gamma\right) = N_\gamma\, C_\gamma \,/\, N_s \tag{1}$$

$$N_s = t_r\, p_\gamma\, A_o\left(Exp(-t_e/\tau)\right) \tag{2}$$

where, N_γ is the number of counts in the photopeak corrected for dead-time and pile-up losses, N_s is the number of photons emitted from the source, t_e is the time elapsed since calibration up to measurement, A_o is the activity of the source on the reference date, p_γ is the branching ratio corresponding to the energy , E_γ, τ_r denotes the real time for the data run, and τ is the mean life time.

The net count rate used was corrected for radionuclide decay both, since the reference activity date and during the measurement. C_γ is a correction factor which comprises different effects depending on the specific features of the measurement. When the solid angle subtended between the detector and the sample is large, the use of radionuclides such as ^{152}Eu, ^{57}Co, ^{137}Cs, ^{85}Sr, ^{60}Co, and ^{88}Y requires correction for coincidence summing. If other corrections are not needed, C_γ becomes the coincidence summing correction factor for the efficiency calculated from the emission energy E_γ. This factor equals 1 when no coincidence summing exists.

Mathematical approach: The full-energy peak efficiency of a closed-end coaxial HPGe detector in the case of an isotropic radiating coaxial circular disk source is defined as:

$$(\varepsilon)_d = \frac{2}{S^2}\int_0^s \varepsilon\rho\, d\rho \tag{3}$$

where, ε is the full-energy peak efficiency of an HPGe detector using an isotropic radiating non-axial point source (Fig. 1) and is given as:

$$\varepsilon = \varepsilon_g \times \varepsilon_\gamma \tag{4}$$

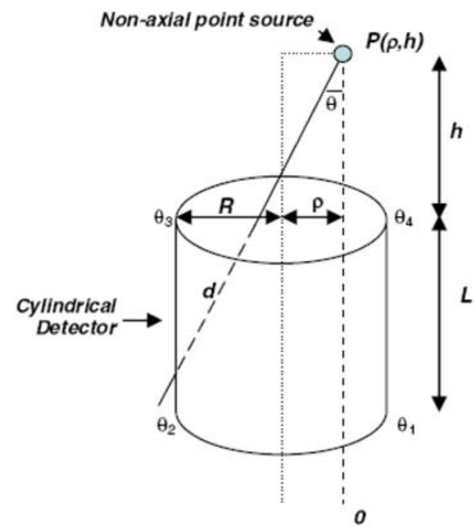

Fig. 1: Source-detector geometrical configuration (Abbas, 2007)

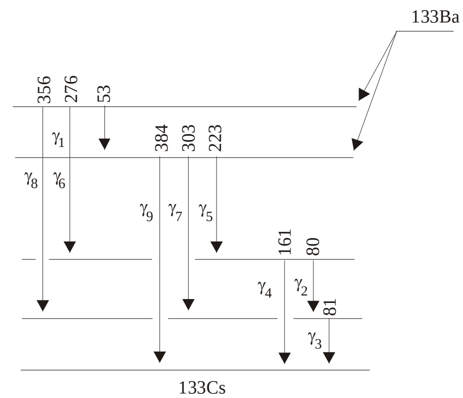

Fig. 2: Decay scheme of 133Ba with energies displayed in units of keV

where, ε_g is the geometrical efficiency and ε_γ is the intrinsic efficiency which is defined as:

$$\varepsilon_\gamma = f_{att}\left(1 - e^{-\mu\bar{d}}\right) \tag{5}$$

where, μ is the attenuation coefficient of the detector active medium for a γ-ray photon with energy E_γ, $\bar{d}$ is the average path length travelled by a photon through the detector active volume for an isotropic emission and the factor f_{att} determining the photon attenuation by the source container and the detector end cap materials (Abbas, 2007).

Coincidence summing corrections calculation: One of the important corrections to be applied arises from coincidence summing; a well-known example for this type of nuclides is ^{133}Ba which has a very complex decay

Table 1: Specifications of the Czech Metrological Institute Inspectorate for ionizing Radiation Radioactive sources used for the efficiency measurements

Source	E_γ (keV)	P_γ (per decay or capture)	Half-life (days)	Activity (kBq)
Ba-133	53.17	0.0220	3897	277.3
Ba-133	80.99	0.3420	3897	277.3
Eu-152	121.78	0.2840	4858	609.8
Eu-152	244.67	0.0754	4858	609.8
Ba-133	276.40	0.0717	3897	277.3
Ba-133	302.85	0.1846	3897	277.3
Ba-133	355.95	0.6222	3897	277.3
Cs-137	661.65	0.8510	11019	408.1
Eu-152	778.92	0.1294	4858	609.8
Eu-152	867.38	0.0416	4858	609.8
Eu-152	964.01	0.1460	4858	609.8
Eu-152	1112.06	0.1356	4858	609.8
Co-60	1173.21	0.9987	1925.4	704.9
Co-60	1332.47	0.9998	1925.4	704.9
Eu-152	1408	0.2080	4858	609.8

scheme as shown in Fig. 2. In this particular case, two or more photons can be emitted in cascade for a single decay and an empirical method to correct for them is complicated (Debertin and Helmer, 2001). If only relative efficiencies are determined, knowledge of the source activities and dead-time correction factors are not necessary. Moreover, all corrections become negligible with proper choice of conditions such as:

- Using only well-established standards,
- Eliminating or minimizing systematic errors (dead time, etc.)
- Generating a single interpolation curve for the whole energy range.

The coincidence summing correction factor associated with the γth gamma-ray emission of a given radionuclide at a particular counting geometry M corresponds to the ratio of the number of photons emitted by the source whose energy E_γ has been fully absorbed in the Ge crystal to the number of counts under the peak at E_γ. According to (Daza *et al*., 2001), it can be calculated as:

$$C_\gamma = \frac{N_\gamma^K}{N_\gamma^M} \times C_G\left(E_\gamma\right) \quad (6)$$

where, N_γ^R and N_γ^M are the count rates of the full-energy peaks corresponding to the γth emission in the reference geometry (referred to as R) and in the M geometry respectively. The factor $C_G(E_\gamma)$ accounts for the different probabilities of photons with energy E_γ reaching the detector at both geometries and it coincides experimentally with the ratio between the areas produced by an isolated energy E_γ emission at such geometries. C_G is expressed as:

$$C_G(E) = \begin{cases} a_1 E^{-a_2} e^{-a_3} E^{-s} e^{-a_4 E} & ,if\ E \le E_1 \\ a_5, & if\ E > E_1 \end{cases} \quad (7)$$

E_1 being 661.66 keV. Since the effect of the geometry is not energy dependent at energies above 400 keV and the total attenuation coefficient is dominated by the Compton effect for these energies, it is assumed that $C_G(E)$ is constant for energies higher than 661.66 keV. The parameters a_1, a_2 and a_3 contain the information about the source features affecting the measurements. The change in the solid angle subtended between detector and source depends on a_1, while a_2 is related to the geometrical characteristics of the counting set-up (a_2 appears in both geometrical factors). Finally, a_3 characterizes the self-attenuation associated with both matrix and volume during the measurement.

RESULTS AND DISCUSSION

Figures 4, 5, 6, and 7 show the experimental and calculated efficiency curves at distances of 36.0 mm, 49.0 mm, 62.0 and 75.0 mm respectively from the γ-ray source to the point of detection of the detector being used at the Ghana Research Reactor-1 (GHARR-1) center. Table 1 contains the gamma energies, half-lives, activities, and the branching ratios of the radioactive sources used for the efficiency measurements. Generally, the calculations are in good agreement with the experimental measurements carried out using certified γ-ray standard sources. Measurements were made in a laboratory isolated from any accelerator-based or reactor-based radioactivity. All measurements were made for a long enough period of time that the statistical uncertainties in the peak areas were below the corresponding uncertainties in the known relative gamma-ray intensities. The maximum difference between the measured efficiencies and the calculated value is 6.38% for the source to detector height of 36.0 mm, 9.76% for 49.0 mm, 7.15% for 62.0 mm and 6.78%

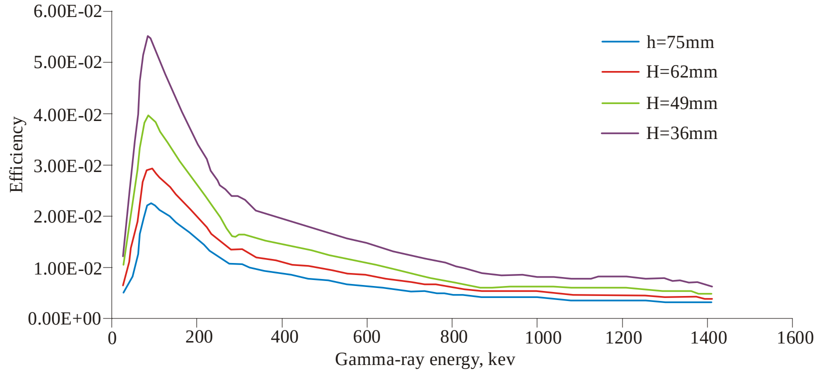

Fig. 3: Detector efficiency at variable distances with energy

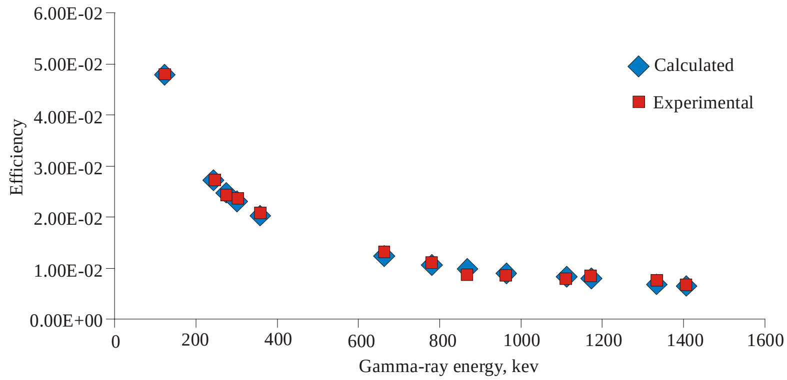

Fig. 4: Comparison of the experimental and calculated efficiency of an N-type HPGe detector at h = 36.0 mm

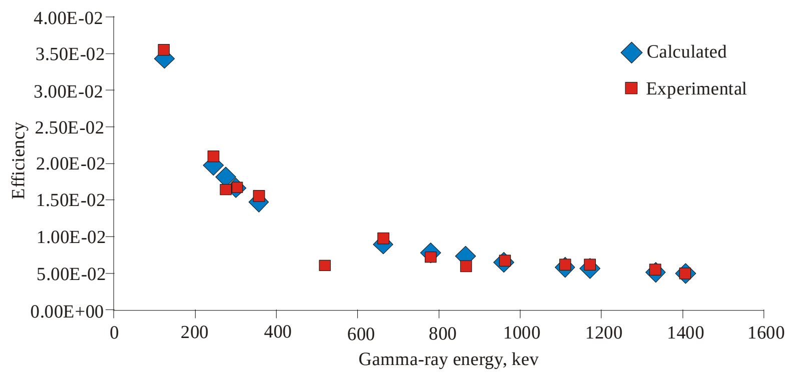

Fig. 5: Comparison of the experimental and calculated efficiency of an N-type HPGe detector at h = 49.0 mm

for 75.0 mm. A comparison of the experimental and the calculated efficiencies are given in Table 2 and 3. It can be observed from Fig. 3 that as the distances of the γ-ray sources from the detector increase their respectively efficiencies reduces. It was also observed the peak detection efficiencies occurred at 81 keV and declined beyond this energy. The closer the sample is to the detector, the larger the effect of summation and errors introduced by irreproducible dimension and position of sample and standard. Summation may take place when a radionuclide decays through coincidence events are counted in the sum peak with apparent energy equal to the sum of the energies of the individual γ-ray photons. Counting geometry errors can easily become the most important source of error when samples are counted close to the detector. A 1 mm difference in thickness between sample and standard will produce an error of approximately 10% when samples and standards are counted directly on the detector can. For this reason, measurements with samples close to the detector are

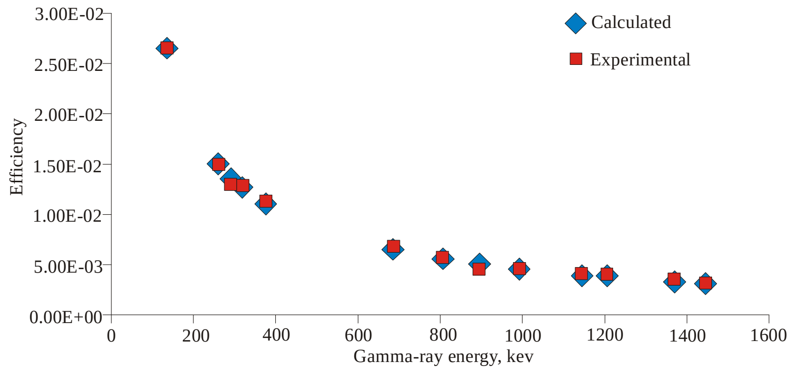

Fig. 6: Comparison of the experimental and calculated efficiency of an N-type HPGe detector at h = 62.0 mm

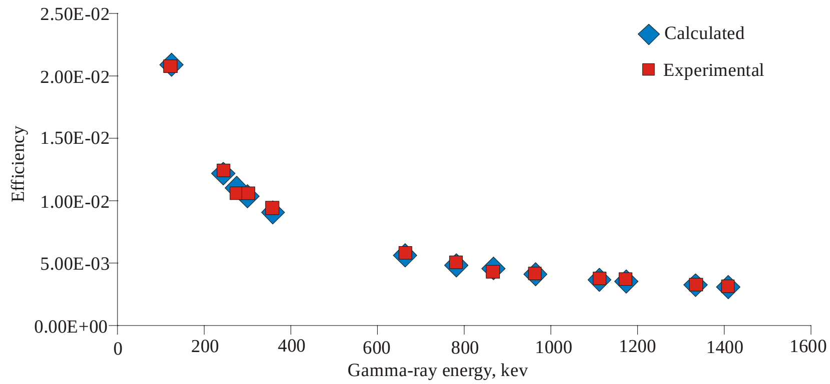

Fig. 7: Comparison of the experimental and calculated efficiency of an N-type HPGe detector at h = 75.0 mm

Table 2: Comparison of the experimental and the calculated efficiencies at heights h = 36.0 mm and h = 49.0 mm

Gamma-ray energy (E_γ), keV	Experimental h = 36.0 mm	Calculated	Deviation (%)	Experimental h = 49.0 mm	Calculated	Deviation (%)
121.78	4.78E-02	4.81E-02	- 0.63	3.55E-02	3.44E-02	3.10
244.67	2.74E-02	2.74E-02	0.00	2.09E-02	1.98E-02	5.26
276.40	2.44E-02	2.49E-02	- 2.05	1.64E-02	1.80E-02	- 9.76
302.85	2.36E-02	2.31E-02	2.12	1.66E-02	1.67E-02	- 0.60
356.02	2.08E-02	2.03E-02	2.40	1.54E-02	1.47E-02	4.55
661.66	1.32E-02	1.23E-02	6.82	9.70E-03	9.02E-03	7.01
778.92	1.10E-02	1.08E-02	1.82	7.47E-03	7.92E-03	- 6.02
867.38	8.75E-03	9.92E-03	- 13.37	6.03E-03	7.28E-03	- 20.7
964.11	8.66E-03	9.11E-03	- 5.20	6.59E-03	6.69E-03	- 1.52
1112.08	8.01E-03	8.12E-03	- 1.37	6.09E-03	5.98E-03	1.81
1173.24	8.31E-03	7.78E-03	6.38	6.12E-03	5.73E-03	6.37
1332.50	7.47E-03	7.02E-03	6.02	5.53E-03	5.18E-03	6.33
1408.00	6.54E-03	6.72E-03	- 2.75	5.06E-03	4.96E-03	1.98

Table 3: Comparison of the experimental and the calculated efficiencies at heights h = 62.0 mm and h = 75.0 mm

Gamma-ray energy (E_γ), keV	Experimental h = 62.0 mm	Calculated	Deviation (%)	Experimental h = 75.0 mm	Calculated	Deviation (%)
121.78	2.69E-02	2.69E-02	0.00	2.08E-02	2.10E-02	0.96
244.67	1.56E-02	1.56E-02	0.00	1.24E-02	1.22E-02	1.61
276.40	1.36E-02	1.42E-02	- 4.41	1.07E-02	1.11E-02	3.74
302.85	1.34E-02	1.32E-02	1.49	1.06E-02	1.03E-02	2.83
356.02	1.19E-02	1.16E-02	2.52	9.46E-03	9.12E-03	3.59
661.66	7.35E-03	7.15E-03	2.72	5.78E-03	5.64E-03	2.42
778.92	6.35E-03	6.29E-03	0.94	5.03E-03	4.96E-03	1.39
867.38	5.25E-03	5.78E-03	- 10.1	4.28E-03	4.57E-03	- 6.78
964.11	5.21E-03	5.33E-03	- 2.30	4.15E-03	4.21E-03	- 1.44
1112.08	4.75E-03	4.76E-03	- 0.21	3.72E-03	3.76E-03	- 1.08
1173.24	4.68E-03	4.57E-03	2.35	3.72E-03	3.61E-03	0.79
1332.50	4.24E-03	4.13E-03	2.59	3.36E-03	3.27E-03	2.68
1408.00	3.94E-03	3.96E-03	- 0.51	3.13E-03	3.13E-03	0.00

only allowed when both sample position and dimensions are precisely reproducible and identical for sample and standard. In view of the difficulty of producing samples and standards with exactly the same thickness, source-to-detector distance should be 10 cm or more whenever possible to reduce counting geometry errors. Even at 10 cm, a 1 mm thickness difference will produce an error of almost 1%. In the plots presented, the calculated efficiency values deviated from those obtained experimentally. Table 2 and 3 shows the percentage efficiency deviations at the various sources to detector distances.

CONCLUSION

Due to the wide variety of radioactive samples to be measured, calculation for gamma-spectrometry efficiency calibration is helpful. The efficiency curves of the HPGe detector at different geometries were measured in a wide energy range of 53.16 to 1408 keV. The standard deviations of the calculated efficiency values from the experimental at the respective source-to-detector height were as follows: 0.05% for 36 mm, 0.08% for 49 mm, 0.03% for 62 mm and 0.01% for 75 mm. It was also observed the peak detection efficiencies occurred at 81 keV and declined beyond this energy.

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