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Efficiency calibration of γ-ray detector for extended sources

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Abstract. Precise identification and quantification of radioisotope in a sample largely depend on the accuracy of the full-energy peak efficiency of the detector. It is generally observed that the efficiency for a given energy of point-like sources is not the same as the extended source. However, number of correction factors such as detector geometry, photon attenuation, coincidence-summing, etc. may reduce such a difference in efficiency regardless of sources, or they should be considered in the measurement of extended samples. In connection to this, the variation of absolute photopeak efficiency of a high-purity germanium (HPGe) detector with the distances from the surface of the detector as well as with the γ-ray energies were investigated using γ-ray standard point sources. We present a method to determine the loss of efficiencies in radioactivity measurement of the thin extended radioactive disc samples in comparison to point source.

Keywords. HPGe γ-ray spectrometry; efficiency; source–detector geometry; solid angle; standard point source; efficiency loss in extended samples.

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1. Introduction

Applications of high-purity germanium (HPGe) detector in γ-ray spectrometry are increasing day by day. HPGe detectors play important roles in the measurement of natural and artificial radioactivity via γ-ray spectrometry because of its excellent resolution with reasonable detection efficiency. The precise calibration includes: (i) energy calibration – energy per channel, (ii) peak width calibration – estimates the variation of peak width with energy and (iii) efficiency calibration – gives the relationship between the number of counts and disintegration rate [1,2]. As the signal processing systems of the detectors and computer programs for analysing the γ-spectrum are getting updated in time, the energy calibration and peak-width calibration processes are becoming easy with better accuracies, whereas, the precise calibration of efficiency is still a vital issue. The absolute efficiency is defined as the ratio of the number of counts detected in a peak to the total number of photons emitted by the source.

$$\varepsilon_{\mathrm{abs}}(E) = \frac{N}{A \times I_\gamma \times t_{\mathrm{m}}}, \tag{1}$$

where $\varepsilon_{\mathrm{abs}}(E)$ is the absolute efficiency at energy E, N is the net area of a photopeak at energy E, A is the known activity of the standard γ-source during the measurements, I_γ is the γ-emission probability and t_{m} is the measuring time.

Several parameters may affect the precision of counting of which the most important ones are source-to-detector distance, shape of the source, absorption within the source, random summing at high count rate, true coincidence summing at close geometry, decay of the source during counting and electronic timing problems [1]. Among these, source-to-detector distance and shape of the source are very important issues because the solid angle subtended by the detector at the radionuclide emitting γ-rays varies in accordance with these geometries and hence affect the count rate of the detector. Self-attenuation effect or absorption of γ-rays within a very thin source can be ignored. Both the random coincidence and true coincidence summing and dead time of counting can be reduced or avoided by controlling source-to-detector distance depending on the activity of the radioactive sources. Many researchers have reported mathematical approaches on the corrections for source-to-detector geometry and sample geometry [3–16]. Among them, Abbas [8] demonstrated a formula for the correction of coincidence summing of the extended disc samples. Recently, Guerra *et al* [10] reported a computational methodology for the characterisation of HPGe detector using Monte Carlo simulation. It is worth mentioning that use of volumetric sample is common in environmental radioactivity measurements. Furthermore, measurement of artificial radioactivity for various practical applications needs the use of extended samples. Note that the efficiency of HPGe detector for a given energy obtained using point-like source differs from that of the extended source. But, it is possible to deduce the efficiency for a given energy for the extended source from the efficiency of point-like source by using an approach known as the efficiency transfer method [17,18].

The aim of this work is to present a simple and easy method to make correction on efficiency loss in activity measurement of the thin extended circular disc sample at close distance from the surface of HPGe γ-ray detector in comparison to the point source and to study the variation of efficiency with the energy of γ-ray as well as with distances from the surface of the detector. It should be mentioned that the proposed method has already been applied in several recent studies [19–22] and expected results are found. In some cases, due to weak activities, the radioactive samples are counted directly on the surface of the detector to obtain relatively good counting statistics, and in those cases our proposed method was used to determine the efficiency loss for the extended sample. An approach using reported theoretical analysis [4] for the normalisation of the efficiency values to circular disc sources is applied and the variation in results with experimental measurements are presented with a comparative point of view.

2. Theoretical analysis

2.1 *The effect of source-to-detector distance*

The intensity of γ-rays emanating from a source falls off with distance according to the inverse square law. This is certainly applicable for point sources of γ radiation and point detectors [1]. A general geometric arrangement is shown in figure 1. From figure 1a, it is clear that we cannot directly measure the true source-to-detector distance. Since the total absorption of γ-rays often involves multiple scattering within the detector, the zero-distance point must be somewhere within the detector crystal. This point can be deduced experimentally. If the inverse square law is considered to be valid, then the count rate, R, varies as

$$R \propto \frac{1}{d^2}. \tag{2}$$

As seen in figure 1a,

$$d = D + d_0, \tag{3}$$

where d_0 represents the distance between the detector cap and the zero-distance point.

Combining these two equations and rearranging, we get

$$R^{-1/2} = kD + kd_0. \tag{4}$$

The distance d_0 depends upon the energy of the γ-ray [1].

2.2 *Effect of sample geometry*

At constant source-to-detector distance, distribution (both homogeneous and heterogeneous) of radioactive material in the volumetric source geometry behaves as an opponent of concentrating in a point-like source and hence decrease the γ-ray intensity at the detector. The solid angle subtended by the detector at a point source is straightforward, but it is complicated in the case of a distributed source by the fact that every point within the source has a different aspect on the detector and contributes to the overall γ-ray intensity to a different degree.

A mathematical relation between the peak efficiencies of a disc source of radius r and that of a point source can be expressed as [4]

$$\varepsilon_{\mathrm{c}}(E) = \varepsilon_{\mathrm{p}}(E)\,\frac{d^2}{r^2}\ln\left(1+\frac{r^2}{d^2}\right). \tag{5}$$

where $\varepsilon_{\mathrm{p}}(E)$ is the peak efficiency belonging to the point source at a distance d from the detector along its axis and $\varepsilon_{\mathrm{c}}(E)$ is the corresponding efficiency for the disc source. Figure 1b illustrates the geometry of such a disc source with an equivalent point source [4].

3. Experimental

3.1 *Determination of efficiency using point sources*

The efficiency vs. energy curve of a HPGe γ-ray detector (Canberra, 25% relative efficiency, 1.9 keV resolution

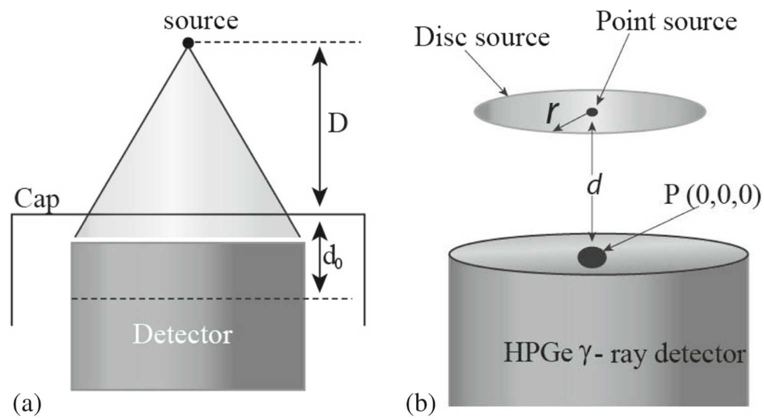

Figure 1. Geometry of HPGe γ-ray detector. (**a**) Geometric basis of the correction for source-to-detector distance and (**b**) geometry of a disc source of infinitesimal thickness and an equivalent point source on the detector axis.

at 1332.5 keV of ^{60}Co, coupled with ORTEC DSPEC jr 2.0^{TM}) at INST, Atomic Energy Research Establishment, Savar, Dhaka was determined using the standard point sources ^{241}Am, ^{137}Cs, ^{133}Ba and ^{152}Eu up to 50 cm from the detector surface. The γ-ray spectra of these sources were measured at 10, 20, 30 and 50 cm source–detector distances. Counting time was selected between 300 s and 3600 s depending on the activity of the source to obtain good counting statistics. After accumulating sufficient counts by a multichannel analyser (MCA) for each of the peak of the respective sources, the γ-ray spectrum was analysed by GammaVision software [23]. From the net area of photopeak characteristics to the radioactive sources and their known activity at the time of measurement the detector efficiency was determined using eq. (1). The decay data of the investigated radionuclides were generally taken from the LUND/LBNL database [24] and given in table 1. It is well known that in γ-spectra measurements using multienergy γ sources the counting loss ratios in every peak caused by the summing effect are almost the same and that can be ignored in this work. The uncertainties associated with the determined efficiencies were about 4%.

Due to the emission of almost single γ line of 661.66 keV in the decay of the radionuclide ^{137}Cs and its simple decay scheme, the sum-coincidence loss in

Table 1. Decay properties of the investigated radioactive sources.

Standard source	Half-life	γ-ray energy (keV)	γ-ray intensity (%)
^{241}Am	432.2 ± 0.7 y	59.5	35.9 ± 0.40
^{137}Cs	30.07 ± 0.03 y	661.6	85.1 ± 0.20
^{133}Ba	10.51 ± 0.05 y	81.0	34.1 ± 0.27
		276.4	7.2 ± 0.02
		302.8	18.3 ± 0.06
		356.0	62.0 ± 0.19
		383.8	8.94 ± 0.03
^{152}Eu	3.537 ± 0.01 y	121.8	28.6 ± 0.06
		244.7	7.6 ± 0.02
		344.3	26.5 ± 0.40
		411.1	2.2 ± 0.01
		443.9	2.8 ± 0.02
		778.9	12.9 ± 0.02
		867.4	4.2 ± 0.19
		964.1	14.6 ± 0.02
		1085.8	10.2 ± 0.02
		1112.1	13.6 ± 0.02
		1408.0	21.0 ± 0.02
^{58}Co*	70.86 ± 0.07 d	810.8	99.0
^{115m}In*	4.49 ± 0.004 h	336.2	44.8 ± 0.01
^{92m}Nb*	10.15 ± 0.02 d	934.5	99.0

measurement at close distances even at the surface of the detector is negligible. The γ-ray counting of the ^{137}Cs point source was performed at 5 cm and 3 cm and surface of the detector and correction factors for those positions were determined by the normalisation with the counts at 20 cm, where sum-coincidence loss even for all the above source can be considered as negligible. Thereafter, the absolute efficiency at 5 cm and 3 cm and the surface were determined by multiplying the efficiencies of various energies at 20 cm with their corresponding correction factors.

3.2 *Measurement of efficiency for extended samples*

High-purity foils of Ni, Mo and In (Goodfellow, chemical purity of >99.5%, thickness ∼ 100 μm) with natural isotopic compositions were cut in circular discs with 0.8 cm, 1.5 cm and 2 cm diameters, placed in an Al container, and then to an irradiation vial. It should be mentioned that there are more than one isotopes of natural abundance in the foil, which also produced some radioactivity but those may have shorter half-lives and did not contribute to the activity of the sample when counted after some time. Furthermore, activity of the investigated radionuclide was not interfered with the other long-lived radionuclides formed in natural foil. All the foils were irradiated together with neutrons at the dry central thimble (DCT) of TRIGA Mark II reactor. The irradiation was performed for 10 min at a reactor power of 1 MW. Sufficient cooling time was allowed to the decay out of the short-lived radionuclides and to suppress background. Thereafter, all the radioactive foils were counted both at the surface and at 10 cm from the detector surface, where the sample-size effect on the efficiency was negligible. The obtained activity at 10 cm was considered as standard value, using which the detector efficiency for the extended sample on the surface was calculated. The dead time in the measurements done was about 0.1%. Special attention was paid in counting to keep the count rate between 2 cps and 10 cps. Therefore, the uncertainty due to random coincidences was negligible. The effect of real coincidences was also considered. The investigated radionuclides have simple decay schemes, and so no coincidence loss was expected. In this study the associated uncertainty was estimated to be 6%.

The distance of the detector cap from the zero-distance point inside the detector crystal (d_0) was measured using eq. (4) and it was found to be about 1.8 cm. This was taken into account while calculating the efficiencies for extended samples of different radii at the cap of the detector using eq. (5).

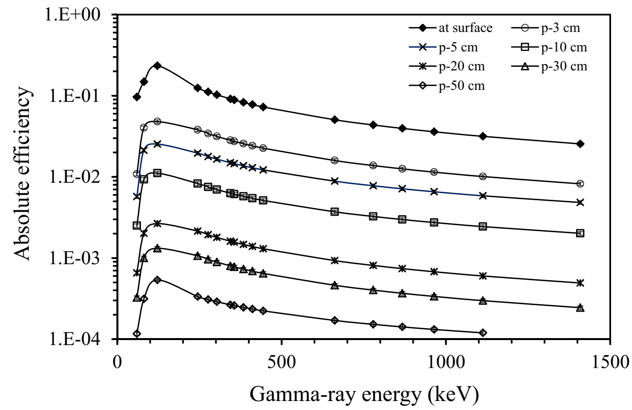

Figure 2. Efficiency vs. energy curves at various source–detector distances.

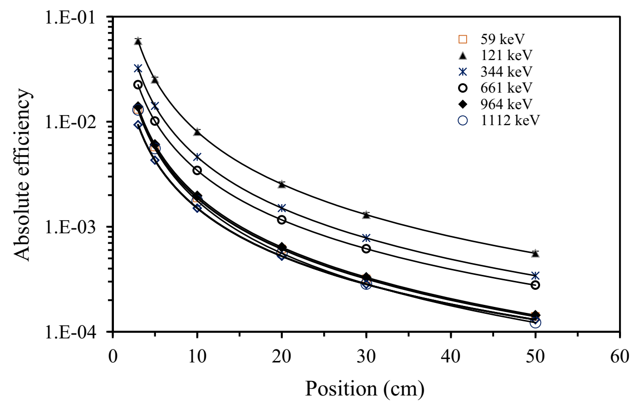

Figure 3. Variation of measured efficiencies with source–detector distances for the particular γ-ray energy.

4. Results and discussion

Source–detector geometry-dependent absolute photopeak efficiencies of a HPGe γ-ray detector were calibrated experimentally. The results are shown in figure 2. It is found that the systematic loss in efficiency increases with increasing source-to-detector distance, as the solid angle subtended by the detector decreases with increasing distance. Similar effects take place also for individual γ-ray energies, as shown in figure 3. It is clear from figure 3 that efficiency of the detector rises gradually up to 121 keV of γ-ray energy and then falls exponentially with the increase of energy.

The measured efficiency losses of the investigated extended samples are shown in figure 4. The efficiencies for an extended sample with 2 cm, 1.5 cm and 0.8 cm diameter on the surface of the detector were found to be 12.6%, 7.5% and 2% lower than that for a point source, respectively. As seen in figure 4, the loss of efficiency in extended disc source compared to that of the point source increases with the increase of diameter. The efficiency correction for a weak extended sample

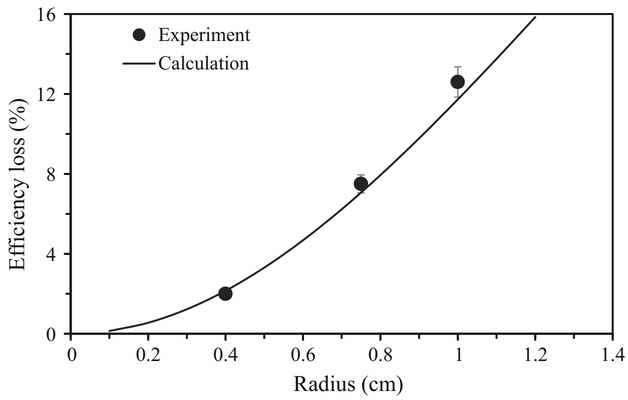

Figure 4. Variation of loss of efficiency in extended disc source with that of the point source at the detector surface.

of a diameter inside or outside the investigated range of 0.8–2 cm diameter can be done by using our established diagram.

The efficiency loss of the extended source with various diameters in comparison to the point source was also calculated using eq. (5) and the results are shown in figure 4. Uncertainties in the results were estimated to be about 4%. The theoretically obtained curve is consistent with the experimental results within the uncertainty limits. It should be mentioned that detailed simulation to compare various geometrical effect is beyond the scope of the present work.

5. Conclusions

In this paper, the efficiency vs. energy curves at various distances from the surface of HPGe γ-ray detector were drawn and from those curves a relation between efficiency and point of emission for a selected γ-ray energy has been extracted. We introduce a direct method that can be used to characterise γ-ray measurement for a weak radioactive extended thin disc sample.

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