Efficiency calibrations of HPGe detector for PGNAA system

S Sangaroon1,*, W Ratanatongchai2, C Wichaisri1, R Picha2, S Khaweerat2, J Channuie2

1Department of Physics, Faculty of Science, Mahasarakham University, Mahasarakham, 44150 Thailand
2Thailand Institute of Nuclear Technology (Public Organization), Bangkok, 10900 Thailand

Abstract. In this paper, the efficiency of a HPGe detector for a PGNAA system has been determined using the full peak energy of a $^{152}$Eu source. The efficiency is affected by the detector-source distance for the full energy range. The Monte Carlo method was used to determine the detector's dead layer thickness. A comparison of the simulated and the experimental data on the spectra and efficiency curve shows a very good agreement. The combined results of an experimental and calculation efficiency curve provide information about the dead layer thickness of 2.1 mm. It was found that the dead layer has the greatest effect on the detection efficiency of the low energy range.

1. Introduction

A high purity germanium (HPGe) detector has been widely used for gamma spectrometry in a prompt gamma neutron activation analysis system (PGNAA) due to its high efficiency and resolution. To perform a precise measurement of the PGNAA, it is important to know the detection efficiency over the energy region of interest. The efficiency depends on the gamma ray energy, detector geometry, and detector-source distance, etc. Its calibration can be carried out using the standard emitted gamma rays over the energy range of interested [1].

Moreover, the detection efficiency curve depends on the dead layer thickness (the inactive part of the detector), which is not provided by the manufacturer. Among all the parameters, the dead layer is the most important and effective for the detection efficiency. For the determination of the dead layer, the Monte Carlo code MCNP has been used. The MCNP code is the most widely used for all types of particle transport, e.g., neutron, photon, and electron, based on the evaluated nuclear data library (ENDF/B) [2]. It has been widely used to validate the HPGe detection efficiency and the dead layer thickness [3, 4].

The work here reports on the determination of the efficiency curve for the HPGe detector for the PGNAA system at TRR-1/M1 based on a combination of measurement and simulation. Due to the difficulty of searching mono-energetic gamma rays, the multi-gamma ray source $^{152}$Eu was used for the efficiency calibration. The source covers a wide energy range of 100-1500 keV. The dead layer thickness was optimized to match the simulation and the experiment efficiency.
2. Methodology

2.1. Experimental set up

The HPGe coaxial detector system was used for the experimental measurements. The detector model was an Ittech IGC35190 and Gravity Feed Portable Cryostats. The main performance specifications of the HPGe detector were as follows: i) relative efficiency at 1.33 MeV $^{60}$Co was 35%; ii) FWHM was 875 eV at 122 keV and 1.90 keV at 1332 keV, peak shape (FWTM/FWHM) was 1.90; and iii) the peak-to-Compton ratio for $^{60}$Co was 60:1. The crystal diameter was 57.6 mm and the length was 66.8 mm. The core hole diameter was 10.5 mm and the core hole length was 53.5 mm. The end cap to crystal distance was 3 mm. The cryostat window material was aluminium with a 1.27 mm thickness. The crystal was composed of Mylar 0.025 mm, aluminium foil 0.025 mm, aluminium cup 0.50 mm, and lithium contact 0.7 mm.

The $^{152}$Eu radioactive source was used to cover the energy range between 100 keV and 1500 keV. The source activity was 22.371 kBq. It was placed at different distances between 2 cm and 10 cm from the detector to study the effect of the detector-source distance on the detection efficiency. The counting time was 10 min.

2.2. Monte Carlo model

The data provided by the manufacturer in section 2.1 was used to develop the MCNP model. Nevertheless, the dead layer of the detector was not provided by the manufacturer. To determine the dead layer of the detector, simulations are needed. Different thicknesses between 1 $\mu$m and 3 mm for the dead layer were modified in the model to match the MCNP and experimental efficiencies.

Figure 1 shows a schematic of the detector model. The F8 tally (pulse height distribution tally) was used in this work for the photon-electron transport. The photon energy was considered in the $^{152}$Eu energy region with a maximum energy of 1.5 MeV. The number of histories was set to $1 \times 10^8$ particles to reduce statistical uncertainties. To obtain the resolution function of the detector and to broaden the simulation spectra, the Gaussian Energy Broadening (GEB) function [2] was applied to MCNP calculation to match the calculated and measured energy peaks.

![Figure 1](image1)

**Figure 1.** Schematic representation of HPGe detector. Aluminium is represented in dark blue and germanium crystal in red.

![Figure 2](image2)

**Figure 2.** Comparison of experimental and simulated pulse height spectrum where $^{152}$Eu source was placed at distance of 2 cm. Insert figure shows comparison spectra at 0.778 MeV and 0.867 MeV.
3. Results and discussion

Experimentally, the gamma ray spectrum of a HPGe detector using $^{152}$Eu and background spectrum were constructed. The measured spectrum with background subtraction is represented in solid line and shown in figure 2. The absolute efficiency at each energy of $^{152}$Eu was then calculated by dividing the net area counts in the full energy peak by the certified activities. For the photon energy ($E_\gamma$), the efficiency ($\epsilon$) was given by $\epsilon = N_\gamma / (At_f)$, where $N_\gamma$ is the net area under the full energy peak corresponding to $E_\gamma$ photons emitted, $A$ is a known activity, $f$ is the emission probability, and $t$ is the counting time.

3.1. Effect of detector-source distance

At the different detector-source distance measurements, the efficiencies were calculated. The resulting plot of the efficiencies versus detector-source distance is shown in figure 3. The results show that the efficiency depends on the experimental geometry. For all energies, the efficiencies decreased at an increasing detector-source distance.

The efficiency versus detector-source distance curve was fitted with an exponential with 95% confidence. It can be seen from the exponential fitting results that all efficiencies corresponding to $E_\gamma$ photons emitted by the $^{152}$Eu source were reduced by $\approx 25\%$ over the detector-source distance ($d$), as indicated by $\epsilon_0 = r^2 / 4d^2$, where $r$ is the radius of the detector surface facing the sample.

3.2. Dead layer determination

The initial MCNP simulations were performed with the detector dimensions obtained form the manufacturer as given in section 2.1. The source was placed at a 2 cm detector-source distance. To compare with the experimental one, the simulated count ($C_{\text{sim}}$) from the MCNP calculation was deduced by $C_{\text{sim}} = C_{\text{MCNP}} \cdot \epsilon_0$, where $C_{\text{MCNP}}$ is the MCNP result, $A$ is a known activity, $t$ is the counting time, and $\epsilon_0$ is the $E_\gamma$ photons emitted reduction factor of 25%.

The pulse height spectrum obtained by the MCNP simulation when not taking the dead layer thickness into account (No DL) is shown in dashed line in figure 2. The absolute efficiency at each energy of $^{152}$Eu was determined as shown in table 1. The overall experimental to MCNP ratio (Exp/MCNP) was 0.5628, which was far from the unity. To match the MCNP spectra to the experimental one and make the Exp/MCNP ratio close to the unity, dead layer thicknesses between 10 $\mu$m and 3 mm were developed in the MCNP model. An example of the pulse height spectra with the dead layer thickness is shown in dashed-dotted and dotted in figure 2 for dead layer thicknesses of 2.1 cm and 3 cm, respectively. Normally the precise dead layer value is not well known, this analysis can be useful to understand its effect. As can be seen in the figure, it has achieved satisfactory agreement between the experimental and simulated spectra, even in the peak resolution (FWHM), as shown in the insert figure.

The absolute efficiency for all $^{152}$Eu energy peak and dead layer thicknesses (10 $\mu$m-3 mm) were calculated and are reported in table 1. The Exp/MCNP ratio is shown. The results show that when the dead layer increases, the efficiency decreases due to the fact that the photons do not reach the active detection volume of the detector. As can be seen from the results, the active detector with the dead layer of 2.1 mm made the Exp/MCNP ratio close to unity. The exponential decay of the efficiency versus the energy from the experimental and simulations are shown in figure 4. An agreement between the experimental and MCNP efficiency over the interested energy range with the dead layer thickness of 2.1 mm was found.

4. Conclusion

The absolute full energy peak efficiency between energies of 100 keV and 1500 keV for a HPGe detector has been measured using a $^{152}$Eu source. From the results, the efficiency significantly depends on the detector-source distance. It is clear from the simulation results that the efficiency
Table 1. Measured and simulated detection efficiency.

| Energy (MeV) | Exp. No DL 10 μm | 1.8 mm | 2 mm | 2.07 mm | 2.1 mm | 3 mm |
|-------------|------------------|--------|------|---------|--------|------|
| 0.121       | 0.9740           | 1.7146 | 1.7131| 1.0365  | 0.9792 | 0.9599| 0.9515| 0.7352 |
| 0.244       | 0.6971           | 1.0725 | 1.0833| 0.7505  | 0.7177 | 0.7071| 0.7017| 0.5711 |
| 0.344       | 0.4343           | 0.7833 | 0.7847| 0.5449  | 0.5214 | 0.5136| 0.5103| 0.4140 |
| 0.411       | 0.4215           | 0.6609 | 0.6604| 0.4423  | 0.4244 | 0.4218| 0.4188| 0.3409 |
| 0.779       | 0.2340           | 0.3777 | 0.3822| 0.2561  | 0.2444 | 0.2397| 0.2375| 0.1900 |
| 0.867       | 0.1785           | 0.3460 | 0.3372| 0.2263  | 0.2161 | 0.2127| 0.2010| 0.1685 |
| 0.964       | 0.1765           | 0.3169 | 0.3177| 0.2125  | 0.2028 | 0.1995| 0.1982| 0.1576 |
| 1.085       | 0.1476           | 0.2956 | 0.2974| 0.1980  | 0.1893 | 0.1858| 0.1843| 0.1451 |
| 1.089       | 0.1471           | 0.2852 | 0.2893| 0.1850  | 0.1754 | 0.1712| 0.1700| 0.1323 |
| 1.112       | 0.1469           | 0.2648 | 0.2515| 0.1686  | 0.1598 | 0.1569| 0.1557| 0.1222 |
| 1.408       | 0.1204           | 0.2319 | 0.2320| 0.1543  | 0.1471 | 0.1445| 0.1434| 0.1128 |

Exp/MCNP 0.5628 0.5644 0.8494 0.8911 0.9062 0.9132 1.1490

Figure 3. Experimental efficiency in function of distance from detector to source.

Figure 4. Dead layer thickness effect on detection efficiency.

of the detector differs significantly when taking different dead layer thickness into the active detection volume. By matching the simulation and experimental results, the dead layer can be obtained. The dead layer thickness plays an important role that affects the efficiency of the detection, especially in the low energy region.

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