Determination of relative and absolute efficiency functions in the range of 122 keV ÷ 8.5 MeV of HPGGe detector

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(Received on April 6th 2015, accepted on June 5th 2015)

ABSTRACT
Construction of detector is necessary. However, on large energy range the manufacturers could not also support the explicit function of relative and absolute efficiencies of detectors. One of the reasons is a restriction of energy range of gamma sources (normally < 3 MeV). This paper presents the results of construction of relative and absolute efficiency functions within a range from 122 keV to 8.5 MeV. The sources are used combining $^{152}$Eu point source and $^{36}$Cl activated isotope by thermal neutron captured reaction $^{35}$Cl of Dalat nuclear reactor (DNR) by $^{35}$Cl(n, γ)$^{36}$Cl reaction. This result can be applied in determining quantitative analysis of samples of neutron activation and radioactivity chemistry.

Keywords: Relative efficiency; absolute efficiency; prompt gamma; $^{35}$Cl(n, γ)$^{36}$Cl reaction.

INTRODUCTION
In the experimental nuclear physics and radiation applications, the determination of relative and absolute efficiencies of spectrometry is necessary and research condition exactly. However, the construction of efficiency in large energy range is a restriction of energy range of gamma sources and method.

In the previous papers, the authors used point sources of a radioisotope, so the absolute efficiency functions were < 3 MeV limited range [1,2,3]. There was also some simulated MCNP method for absolute efficiency functions in large energy range [4].

In this research, $^{152}$Eu point source was used to select photo peaks, which are 122 keV ÷ 1408 keV range, and use neutron activation analysis method. The $^{35}$Cl was activated on the 3rd channel of DNR, measuring prompt gamma by $^{35}$Cl(n, γ)$^{36}$Cl reaction. The result was used to construct relative efficiency, absolute efficiency in 122 keV ÷ 8.5 MeV range, and determine the transformation factor corresponding to E energy of detector as well.

Detector efficiency functions in large energy range are the logarithm or exponential functions. There has been a large energy range to construct efficiency function, and usage of prompt gamma from activated thermal neutron of target is necessary. When targets capture thermal neutron, some of compound nucleus of target emit prompt gamma, and do not have any delayed gamma emission.
In the compound nucleus mechanisms, particle (a) interacts target (A), then a production of nuclear compound (C) occurs. Nuclear compound (C) produces particle (b) and nucleus (B) by the following function:

\[ a + A \rightarrow C \rightarrow b + B \] (1)

Compound reactions happen during a time of the order of about $10^{-16}$ s, so the activity of target is constant when the experimental time is about some hours, and the neutron flux and geometry arrangement are unchanged.

Let’s consider the case of the target and the point source are placed in the same geometry, the absolute photo peak efficiency relates the counter of detector and the number of gamma ray emitted by the sources, by following function:

\[ \varepsilon_{\text{abs}}(E) = \frac{\text{The counter of detector}}{\text{The number of emitted gamma ray}} = \frac{N}{A \times I \times t} \] (2)

where: $\varepsilon_{\text{abs}}(E)$ is absolute efficiency value at of energy $E$,

- $N$ is the area of the photo peak of energy $E$,
- $A$ is the activity of the gamma source (Bq),
- $I_\gamma$ is branching ratio of gamma ray (%),
- $t$ is the live time of the counting number (s).

The absolute efficiency error is:

\[ \sigma_{\varepsilon_{\text{abs}}}(E) = \left[ \left( \frac{\sigma^2_A}{A^2} + \frac{\sigma^2_N}{N^2} \right) (\varepsilon_{\text{abs}}(E))^2 \right]^{1/2} \] (3)

where $\sigma^2_A$ is the error of the gamma source activity; $\sigma^2_N$ is statistical counting error of the detector.

![Diagram](image)

**Fig. 1.** Point source located along the axis of cylindrical detector.
Absolute efficiency depends on the geometrical conditions and on the energy. As the Fig. 1, \( \varepsilon_{\text{abs}}(E) \) is following:

\[
\varepsilon_{\text{abs}}(E) = \varepsilon_G \times \varepsilon(E)
\]

(4)

where \( \varepsilon(E) \) is geometrical efficiency, \( \varepsilon(G) \) is intrinsic efficiency.

\( \varepsilon_G \) depends on only the source detector geometry, is defined by:

\[
\varepsilon_G = \frac{\Omega}{4\pi}
\]

(5)

where \( \Omega \) is the solid angle, \( d \) is distance the source to face detector, \( r \) is the radius of detector.

The absolute efficiency relates the relative efficiency function as follow [2]:

\[
\varepsilon_{\text{abs}}(E) = \alpha(E) \times \varepsilon_{\text{rel}}(E)
\]

(6)

where \( \alpha(E) \) is the transformation factor corresponding to \( E \) energy; \( \varepsilon_{\text{rel}}(E) \) is the relative efficiency value at energy of \( E \).

**MATERIALS AND METHODS**

First, an \(^{152}\text{Eu}\) point source is used. This source is covered by polymer. Its activity is 198.99 kBq. The distance between the source to the surface detector is 5.0 cm. Fig. 2 showed the geometry of \(^{152}\text{Eu}\) point source. In our laboratory, the gamma spectrometer based on a high purity Ge detector, GMX35, the detector diameter is 58 mm. The time of one experiment is 1 hour.

After that, to measure the background at the 3rd beam of DNR and to measure the activated target, the thermal neutron flux at the target local is \( \sim 9.25 \times 10^4 \) n/cm\(^2\)/s, neutron beam diameter is 1.3 cm, cadmi/goal ratio is 218 (measure 1 mm thickness cadmi box). The target is \( \text{NH}_4\text{Cl} \), which is 2.00 mm diameter, 1.00 mm thickness. The target is the same geometry of \(^{152}\text{Eu}\) point source. The parameters of the spectrometer are unchanged completely in this research. Fig. 3 shows the experimental arrangement. The experimental time per one measurement is 5 hours. Fig. 4, Fig. 5 are \(^{152}\text{Eu}\) spectrum, background spectrum and \( ^{36}\text{Cl} \) prompt gamma one.

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**Fig. 2.** \(^{152}\text{Eu}\) source.  
**Fig. 3.** Experimental diagram.
RESULTS

In the experiment on point source the target is also a point source. Using the (4) and (5) formulas, the distance between detector to source is \( d = 5 \) cm, detector radius is \( r = 29 \) mm, so:

\[
\varepsilon_{\text{abs}}(E) \cong 6.748 \times 10^{-3} \times \varepsilon(E) \tag{7}
\]

Thus, following the geometrical design in this research, the experimental absolute efficiency is \( \sim 6.748 \% \) of intrinsic efficiency detector.

To treat \(^{152}\text{Eu}\) spectrum, the photo peaks which have high branching ratio in the 122 keV to 1408 keV range are collected. Formula (2) and (3) are used to determine the absolute efficiencies. Those results are shown in Table 1.

### Table 1. Experimental values of absolute efficiency in the 122 keV to 1408 keV range.

| No. | \( E \) (keV) | \( I_\gamma \) (%) [5] | \( N \) | \( \sigma_N^2 \) | \( \varepsilon_{\text{abs}}(E) \) | \( \sigma_{\varepsilon_{\text{abs}}}(E) \) |
|-----|---------------|-----------------|-----|-----------------|-----------------|-----------------|
| 1   | 121.78        | 25.60           | 155097 | 1318           | 8.46E-03        | 6.11E-07        |
| 2   | 244.70        | 7.60            | 36590  | 311            | 6.72E-03        | 4.86E-07        |
| 3   | 344.28        | 26.50           | 113194 | 962            | 5.97E-03        | 4.31E-07        |
| 4   | 411.12        | 2.20            | 8720   | 74             | 5.54E-03        | 4.00E-07        |
| 5   | 443.96        | 3.10            | 12037  | 102            | 5.42E-03        | 3.92E-07        |
| 6   | 488.68        | 2.10            | 7855   | 67             | 5.22E-03        | 3.77E-07        |
| 7   | 688.65        | 1.90            | 6184   | 53             | 4.55E-03        | 3.28E-07        |
| 8   | 778.80        | 12.80           | 39402  | 335            | 4.30E-03        | 3.11E-07        |
| 9   | 867.35        | 4.20            | 12314  | 105            | 4.09E-03        | 2.96E-07        |
| 10  | 964.10        | 14.50           | 40462  | 344            | 3.90E-03        | 2.82E-07        |
| 11  | 1085.80       | 10.20           | 26867  | 228            | 3.68E-03        | 2.66E-07        |
| 12  | 1112.20       | 13.60           | 35397  | 301            | 3.64E-03        | 2.63E-07        |
| 13  | 1213.00       | 1.40            | 3451   | 29             | 3.44E-03        | 2.49E-07        |
| 14  | 1299.32       | 1.60            | 3890   | 33             | 3.40E-03        | 2.45E-07        |
| 15  | 1408.14       | 21.10           | 48549  | 413            | 3.21E-03        | 2.32E-07        |
To fit experimental data of $^{152}$Eu the non-linear least square method is used. And this fitting method in repeated until minimizing Chi-square. The absolute efficiency function of the range from 122 keV to 1408 keV is shown in Table 2 and Fig. 6.

Table 2. The parameters of absolute efficiency are curved in the 122 keV to 1408 keV range.

| Functions                      | Parameters |
|--------------------------------|------------|
| $\varepsilon_{rel}(E) = a - b \ln(E + c)$ | a  | $\Delta a$ | b  | $\Delta b$ | c  | $\Delta c$ |
| $R^2 = 0.99936$                | 0.01607    | 1.74511E-4 | 0.00178 | 2.45273E-5 | -51.46279 | 4.21548 |

Fig. 6. The absolute efficiency curve in the 122 keV to 1408 keV range.

To treat prompt gamma of $^{36}$Cl spectrum, a determination of area peaks and area peak errors must be carried out. After that, using the absolute efficiency function in the 122 keV to 1048 keV range to calculate the $^{36}$Cl activity under experimental data of 788.43 keV area peak (the experimental data showed in Table 3). The activity of $^{36}$Cl is calculated by the following function

$$A = \frac{N - N_P}{\varepsilon_{abs}(E) \times I_\gamma \times t} = 4890 \ (Bq)$$

Thus, $^{36}$Cl activity is determined. Efficiency in the 122 keV to 1408 keV assembly, we construct efficiency detector in the 122 keV to 8.5 MeV. The results are shown in Table 3, Table 4, and Fig 7, Fig. 8.
Table 3. Experimental values of relative efficiency and absolute efficiency in the 122 keV to 8.5 MeV range.

| No. | $E_r$  | $(\Omega)_{[5,6]}$ | $N$   | $\sigma_N^2$ | $\epsilon_{\text{rel}} (E)$ | $\epsilon_{\text{abs}} (E)$ | $\epsilon_{\text{rel}} (E)$ | $\epsilon_{\text{abs}} (E)$ |
|-----|--------|-------------------|-------|--------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
| 1   | 121.78 | 25.60             | 155097| 1318         | 100.00                      | 0.10                        | 8.46E-03                    | 6.11E-07                    |
| 2   | 244.70 | 7.60              | 36590 | 311          | 79.47                       | 0.02                        | 6.72E-03                    | 4.86E-07                    |
| 3   | 344.28 | 26.50             | 113194| 962          | 70.50                       | 0.07                        | 5.97E-03                    | 4.31E-07                    |
| 4   | 411.12 | 2.20              | 8720  | 74           | 65.42                       | 0.01                        | 5.54E-03                    | 4.00E-07                    |
| 5   | 443.96 | 3.10              | 12037 | 102          | 64.09                       | 0.01                        | 5.42E-03                    | 3.92E-07                    |
| 6   | 488.68 | 2.10              | 7855  | 67           | 61.74                       | 0.01                        | 5.22E-03                    | 3.77E-07                    |
| 7   | 688.65 | 1.90              | 6184  | 53           | 53.72                       | 0.01                        | 4.55E-03                    | 3.28E-07                    |
| 8   | 778.80 | 12.80             | 39402 | 335          | 50.81                       | 0.02                        | 4.30E-03                    | 3.11E-07                    |
| 9   | 867.35 | 4.20              | 12314 | 105          | 48.39                       | 0.01                        | 4.09E-03                    | 2.96E-07                    |
| 10  | 964.10 | 14.50             | 40462 | 344          | 46.06                       | 0.02                        | 3.90E-03                    | 2.82E-07                    |
| 11  | 1085.80| 10.20             | 26867 | 228          | 43.48                       | 0.02                        | 3.68E-03                    | 2.66E-07                    |
| 12  | 1112.20| 13.60             | 35397 | 301          | 42.96                       | 0.02                        | 3.64E-03                    | 2.63E-07                    |
| 13  | 1213.00| 1.40              | 3451  | 29           | 40.69                       | 0.01                        | 3.44E-03                    | 2.49E-07                    |
| 14  | 1299.32| 1.60              | 3890  | 33           | 40.13                       | 0.00                        | 3.40E-03                    | 2.45E-07                    |
| 15  | 1408.14| 21.10             | 48549 | 413          | 37.98                       | 0.03                        | 3.21E-03                    | 2.32E-07                    |
| 16  | 436.22 | 1.05              | 5046  | 423          | 64.52                       | 2.98                        | 5.46E-03                    | 3.84E-05                    |
| 17  | 517.08 | 24.30             | 109257| 1236         | 60.37                       | 0.16                        | 5.11E-03                    | 6.54E-07                    |
| 18  | 788.43 | 16.32             | 61702 | 1136         | 50.76                       | 0.39                        | 4.30E-03                    | 1.46E-06                    |
| 19  | 1131.25| 1.911             | 6063  | 308          | 42.60                       | 0.44                        | 3.60E-03                    | 9.30E-06                    |
| 20  | 1164.87| 27.2              | 85022 | 381          | 41.97                       | 0.01                        | 3.55E-03                    | 7.12E-08                    |
| 21  | 1327.42| 1.27              | 3811  | 262          | 40.29                       | 0.48                        | 3.41E-03                    | 1.61E-05                    |
| 22  | 1601.08| 3.484             | 9169  | 268          | 35.34                       | 0.13                        | 2.99E-03                    | 2.56E-06                    |
| 23  | 1951.14| 19.39             | 45278 | 243          | 31.35                       | 0.01                        | 2.65E-03                    | 7.61E-08                    |
| 24  | 1959.36| 12.56             | 29251 | 166          | 31.27                       | 0.01                        | 2.65E-03                    | 8.57E-08                    |
| 25  | 2676.30| 1.572             | 3100  | 175          | 26.48                       | 0.30                        | 2.24E-03                    | 7.16E-06                    |
| 26  | 2863.82| 5.77              | 10277 | 208          | 23.91                       | 0.04                        | 2.02E-03                    | 8.32E-07                    |
| 27  | 3061.86| 3.521             | 6155  | 173          | 23.47                       | 0.06                        | 1.99E-03                    | 1.57E-06                    |
| 28  | 3981.06| 1.028             | 1480  | 111          | 19.33                       | 0.27                        | 1.64E-03                    | 9.18E-06                    |
| 29  | 4979.71| 3.616             | 3716  | 142          | 13.80                       | 0.05                        | 1.17E-03                    | 1.71E-06                    |
| 30  | 5517.20| 1.689             | 1721  | 108          | 13.68                       | 0.15                        | 1.16E-03                    | 4.54E-06                    |
| 31  | 5715.19| 5.31              | 4600  | 127          | 11.63                       | 0.03                        | 9.84E-04                    | 7.51E-07                    |
| 32  | 6110.85| 20.58             | 15664 | 176          | 10.22                       | 0.01                        | 8.65E-04                    | 1.09E-07                    |
| 33  | 6619.64| 7.83              | 5158  | 117          | 8.84                        | 0.03                        | 7.48E-04                    | 3.85E-07                    |
| 34  | 6627.75| 4.69              | 3150  | 71           | 9.02                        | 0.02                        | 7.63E-04                    | 3.86E-07                    |
Table 4. The parameters of efficiencies are curved in the 122 keV to 8.5 MeV range.

| Functions | Parameters |
|-----------|------------|
| $\varepsilon_{rel}(E) = a - b \times \ln(E + c)$ | The parameters of relative efficiency |
| $R^2 = 0.99811$ | $a$ | $\Delta a$ | $b$ | $\Delta b$ | $c$ | $\Delta c$ |
| 173.30017 | 1.57773 | 18.83003 | 0.20733 | -101.31758 | 7.45894 |

The parameters of absolute efficiency

$R^2 = 0.99863$

| $a$ | $\Delta a$ | $b$ | $\Delta b$ | $c$ | $\Delta c$ |
| 0.01454 | 9.17835E-5 | 0.00157 | 1.17111E-5 | -80.2783 | 4.25766 |

Fig 7. The relative curve in the 122 keV to 8.5 MeV range

Fig 8. The absolute efficiency curve in the 122 keV to 8.5 MeV range
The result of fitting is squared

\[ \varepsilon_{\text{rel}}(E) = a - b \times \ln(E + c) \]

function in the 122 keV to 8.5 MeV range. The transformation factor corresponding to E energy \( \alpha(E) \) of detector determined on experiment to be \( \alpha(E) = 8.4615 \times 10^{-5} \pm 1.7024 \times 10^{-6} \).

**CONCLUSION**

By this experiment, using \(^{152}\text{Eu}\) point source and \(^{36}\text{Cl}\) \((^{35}\text{Cl}\) activated by thermal neutron of the 3rd channel of DNR), the relative and absolute efficiency functions of purity Ge detector in the 122 keV to 8.5 MeV range are constructed, determined on the transformation factor corresponding to E energy \( \alpha(E) \) of detector simultaneously. The result contributed spectra treatment, and improved quantitative analysis of samples in large energy range.

**ACKNOWLEDGMENTS:** The authors would like to thank Nuclear Research Institute (NRI) - Vietnam to support facility for carrying out this research.
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