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Determining of experimental absolute and intrinsic peak efficiency of HPGe detector and benchmarking with Monte Carlo code using MCNP

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ABSTRACT

A model of HPGe detector (ORTEC, GEM-15190, POP-TOP) used to determine of the absolute and intrinsic peak efficiency through experimental by using of 241Am, 152Eu, 137Cs, 60Co, 22Na standard radioactive point sources in 60-1330keV energy range. A comparison between experimental results with MCNP4C showed about a large thickness dead layer (DL) 2.5 mm, while the manufacturer 0.8 mm had quoted.

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INTRODUCTION

Before doing every γ-ray spectroscopy, sources which are either known or unknown, with HPGe detectors, we need to know about parameters of the detector. One of the most important parameter in each HPGe detector is efficiency. The importance of this subject is due to need for having net counts per time (e.g. net counting rate) in spectroscopy of sources. In other words, it relates to source activity. In order to measure source activity, having the detection efficiency is necessary. Thus, determining the efficiency is primary step. The detection efficiency can determine through experiment. For benchmarking of the experimental results, it needs to simulate the HPGe detector in MCNP code. It does with having dimensions of Germanium crystal and the source distance from detector, exactly the same value with experiments. However, having dimensions isn't exclusively enough to do the benchmarking, because variety of dead layer (DL) can change the absolute peak efficiency. The simulation must thus continue in other thicknesses of nominal DL (normally 2-5 times thicker), so that simulated absolute efficiency curve can be fit with experimental curve. One can then continue simulation in several source distances from detector, providing a good fitting.

Many authors studied benchmarking efficiency with considering DL influence on efficiency (Elanique *et al*., 2012; Abbas *et al*., 2006; Clouvas *et al*., 1998; Courtine *et al*., 2008; Dryak and Kovar, 2006; Hardy *et al*., 2002; Hau *et al*., 2009; Kinase *et al*. 2003; Rodenas *et al*., 2003) and Salgado *et al*., (2006) showed the DL thickness 0.5 µm, declared by manufacturer, had to be modified to 4 µm.

In the work reported here we primarily develop a method to determine DL thickness HPGe. The HPGe detector was fabricated in 1990, we then expected that the DL be much thick compared with recent HPGe detectors (which normally have DL<1µm). With having DL thickness, simulation of the absolute and intrinsic peak efficiency were achievable. A least-square fitting of a polynomial function also applied to absolute peak efficiency. In order to make sure, the absolute peak efficiency experimentally measured. The intrinsic peak efficiency can be experimentally measured using collimated beam of a disk source, but providing this kind of source is relatively hard. As an alternative approach, we used a semi-empirical method. Then the benchmarking carried out.

MATERIALS AND METHODS

2.1. Monte Carlo (MC) Simulation with MCNP4C:
2.1.1. Geometry:

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Definition of the geometry is the most important step in MC simulation. Table 1 shows the dimensions of a model of HPGe detector, so that with this information the simulation can be achievable. Fig. 1 shows the geometry which we simulated with MCNP code, and it then visualized with MCNPVised. Some authors, to make sure from dimensions of detector, took X-ray radiography of HPGe in their studying (J.Boson *et al.*, 2008; Elanique *et al.*, 2012), but this radiography can't show anything about radius and height of central core of the crystal. It only shows height and radius of the crystal. If one has all about dimensions, like Table 1 then taking X-ray radiography is not necessary. Furthermore, some other papers like Cabal *et al*. (2010) without using manufacturer information and X-ray radiography, the dimensions of HPGe measured, and then efficiency computed using collimated beam and simulation. However, to give the closest fit between the simulation and the experimental, taking an X-ray can be useful.

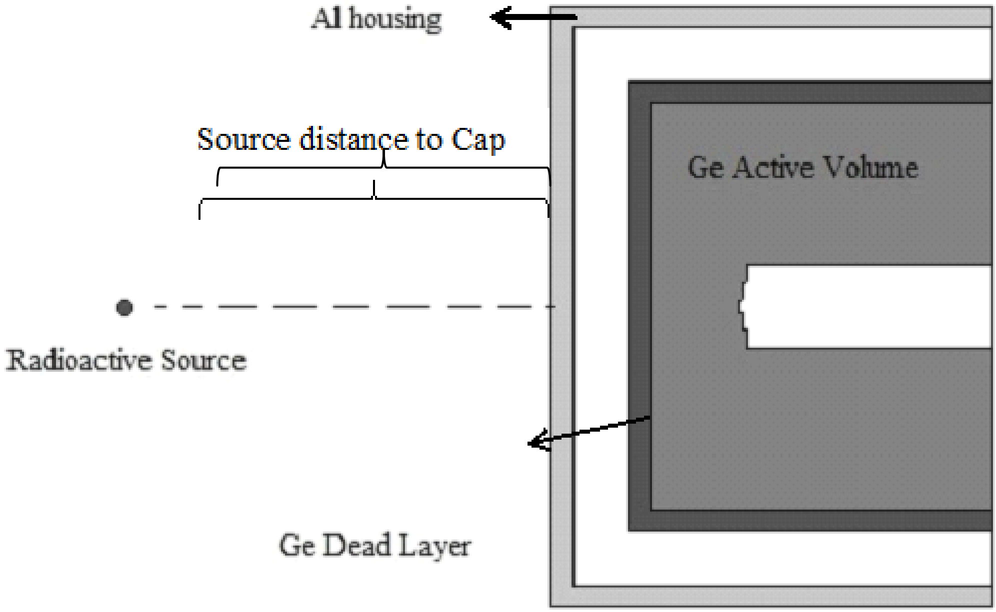

Fig. 1: The HPGe detector simulated with MCNP and represented with MCNPVised

Table 1: Characteristics of the HPGe detector used in the MCNP simulation

Parameter	Dimension (mm)
Type	EG&G Ortec, GEM-15190
Geometry	Closed – Ended coaxial
Material	HPGe π-type
Crystal radius	25.4
Crystal height	41.2
Core radius	4.65
Core height	27.7
Absorbing layer	2.45 (Aluminum)
Inactive Ge	2500
End cap to crystal distance	5

2.1.2. Absolute and intrinsic peak efficiency:

Pulse height distribution in a cell is reported as F8 tally in MCNP output. If one defines a point source, the output in that cell will simply be the absolute efficiency. In order to simulate the peak efficiency, by defining the F8 tally, we must define E8 card. Better results usually obtain by defining of surrounding materials on the Ge crystal, and round the front corners of the crystal and hole (in closed-ended coaxial configuration called bulletized). In the MCNP output, we found peak efficiency in energy bin (e.g. in E8 card) corresponding to energy sources (see energies in Table 2). To access to actual DL, we defined DL thickness from zero, which is conceptual, to thick values.

To measure intrinsic peak efficiency by using F8 tally, we defined a disk source perpendicular to detector axis uniformly emitting which has the same radius with the Ge crystal. Again, In the MCNP output, we found peak efficiency in energy bin corresponding to sources in Table 2.

2.2. Experimental:

Absolute peak efficiency is defined as number of pulses recorded per number of radiation quanta emitted by source. Intrinsic efficiency is defined as number of pulses recorded per number of radiation quanta incident on detector. In the following discussion, in order to measure peak efficiency, we used five radioactive standard point sources which were representative ten monoenergetic gamma rays. These sources were ^{241}Am, ^{152}Eu, ^{137}Cs, ^{60}Co, ^{22}Na. Table 2 lists radionuclides used for experiments, together with decay data necessary to compute efficiencies.

All the sources located perpendicular to detector axis in specific distance. In this way, the sources located in distance 3cm of central axis of the HPGe. The experiments measured during 200 seconds and replied ten times to decrease deviations. Then, area under peak in each energy counted. Consequently, value of the background subtracted from counts so that net count in each energy resulted. Therefore, absolute peak efficiency calculated by (Tsoulfanidis 1995)

$$\in (abs) = \frac{N}{t \times f \times A} \tag{1}$$

Table 2: Decay data for radionuclides used for efficiency

Source	*Energy (keV)	*Decay probability (%)	Activity (Bq)
^{241}Am	60	35.9	34595.7 ± 1104.1
^{152}Eu	121.8	25.6	29450.8 ± 620.0
^{152}Eu	244.65	7.6	29450.8 ± 620.0
^{152}Eu	344.37	26.5	29450.8 ± 620.0
^{137}Cs	662	94	37372.9 ± 685.7
^{152}Eu	775.23	12.9	29450.8 ± 620.0
^{152}Eu	958.5	14.6	29450.8 ± 620.0
^{60}Co	1170	99.88	39460.9 ± 494.3
^{22}Na	1275	100	16041.8 ± 458.3
^{60}Co	1330	100	39460.9 ± 494.3

* Source: Knoll (2000)

Where N is net count in each energy, t is counting time (here 200 seconds), f is fraction of decay, and A is source activity. The f and A can be extracted from Table 2.

Intrinsic efficiency can be calculated with using a semi-empirical relation (Knoll 2000)

$$\in (int) = \frac{N}{t \times f \times A \times e^{\sum_{i=1}^{4} -\mu_i d_i} \times \frac{\varphi}{4\pi}} \tag{2}$$

Where N , t ,f and A is defined the same way as absolute peak efficiency, but $e^{\sum_{i=1}^{4} -\mu_i d_i}$ is any attenuation of the gamma rays that may take place in the Ge crystal, material surrounding point sources, air between source and Aluminum cap and dead layer thickness. Table 1.shows approximate mass attenuation coefficient for these three elements per particle energy. Because the distance to the cap is little, calculations showed these attenuations are negligible (deviations<0. 1%). Thus, to simplify, we neglected these attenuations. The φ in relation (2) is the solid angle of the detector seen from the actual source position. It is given by

$$\varphi = 2\pi \times \left(1 - \frac{d}{\sqrt{r^2+d^2}}\right) \tag{3}$$

Where φ illustrared in Fig 2.

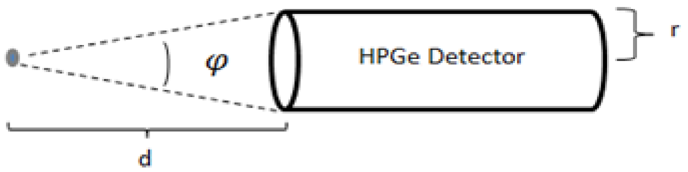

Fig. 2: Specified scheme showing solid angle position

Table 3: Mass Attenuation Coefficient (cm^2/g)

Energy (keV)	Air($\rho = 1.29 \times 10^{-3} \frac{g}{cm^3}$)	Al($\rho = 2.7 \frac{g}{cm^3}$)	Ge ($\rho = 5.32 \frac{g}{cm^3}$)
60	2.126×10^{-4}	0.278	2.023
121.8	1. 8×10^{-4}	0.15	0.402
244.65	1.5×10^{-4}	0.13	0.14
344.37	1.31×10^{-4}	0.985	0.112
662	1.016×10^{-4}	7.56×10^{-2}	7.19×10^{-2}
775.23	9.6×10^{-5}	7.1×10^{-2}	6.43×10^{-2}
958.5	8.5×10^{-5}	6.15×10^{-2}	5.8×10^{-2}
1170	8.3×10^{-5}	5.82×10^{-2}	5.7×10^{-2}
1275	7.5×10^{-5}	5.49×10^{-2}	5.1×10^{-2}
1330	7.08×10^{-5}	5.24×10^{-2}	4.85×10^{-2}

Sources: website www.nist.gov ; Cember, 2009

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RESULT AND DISCUSSION

3.1. Absolute efficiency:

Fig.3 illustrates results of the simulations and the experiments. With increasing dead layer thickness in simulation from imaginary value non-DL, in 2.5mm thickness, the efficiency curve dropped where it fitted with the experiment curve. Thus, 2.5 mm considered as dead layer thickness in this model of HPGe. Furthermore, as illustrated in Fig.3, in energy about 121keV efficiency of the detector is maximum.

With helping curves in Fig.4, results in other energies can be interpolated. However, if disk source or other shapes of source be used, values of Fig. 4 can't be valid, and some corrections is necessary (Nie Peng *et al.*, 2012).

A least-square fitting of a polynomial of the form $\in = \sum_{n=0}^{N} a_n E^n$ was done, where E is the energy in keV corresponding to the point source, and values for a_n are given in Table 4. Calculation showed a polynomial of order N=9 [i.e. Eq. (5)] normally is adequate for typical energies (see. Table 5).

$$\in (\text{abs}) = a_0 + a_1 E + a_2 E^2 + \ldots + a_9 E^9 \quad (5)$$

Table 4: The constant values of the relation (5)

Constant	Values
a_0	-0.0914
a_1	0.0026
a_2	-2.18061E-5
a_3	9.33101E-8
a_4	-2.35045E-10
a_5	3.68152E-13
a_6	-3.62689E-16
a_7	2.1854E-19
a_8	-7.35683E-23
a_9	1.05984E-26

3.2. Intrinsic efficiency:

Fig.5 shows the intrinsic efficiency of this model of HPGe detector. Simulation curve is little upper than semi-empirical results. It's caused by some factors, including some recorded tally from particles that primarily had interaction in out of active volume then penetrated into active volume, neglected attenuation between the source and detector. A comparison between absolute and intrinsic peak efficiency demonstrate $\in (\text{int}) \approx \frac{4\pi}{\varphi} \in (\text{abs})$, where φ is given in relation (3).

3.3. Calculating activity an unknown point source with absolute peak efficiency:

In order to calculate activity an unknown source, the results in Fig.3 can be used (due to lack of applying solid angle), because some correlation must be applied. Thus, true activity can be calculated from

$$A = \frac{\in (\text{abs}) \times N \times 4\pi}{t \times \varphi} \quad (6)$$

Where N is net count and t is counting time.

Now that the curve in Fig. 4 showed authentication of results in simulation, by using MCNP code, corrected absolute peak efficiency ($\frac{\in (\text{abs}) \times 4\pi}{\varphi}$) For isotropic point sources, distance from source to cap from 1cm to 9cm, from 60keV to 1.33MeV, simulated and sketched in Fig. 4 with helping this curve and using relation (3), activity of an unknown point source can be measured

3.4. Internal events:

Fig. 6 and Fig. 7 illustrate internal events in the HPGe detector (for point and disk source, respectively). Photon particles emitted from isotropic point source have interactions with Ge crystal volume. In 60keV, photons can hardly pass from the Al cap and the dead layer. Then, only a few secondary interactions (electron-hole) collected in detector (e.g. ~0.38%). in contrast, higher-energy photons can easily pass from the Al cap and the dead layer. Under this condition, most of the particles pass through the total active volume so that gamma rays neither have any interactions in active volume nor deposit all of their energies. Thus, efficiency in both ultimate situations has drop. Upper efficiency achieved between this two ultimate energy values.

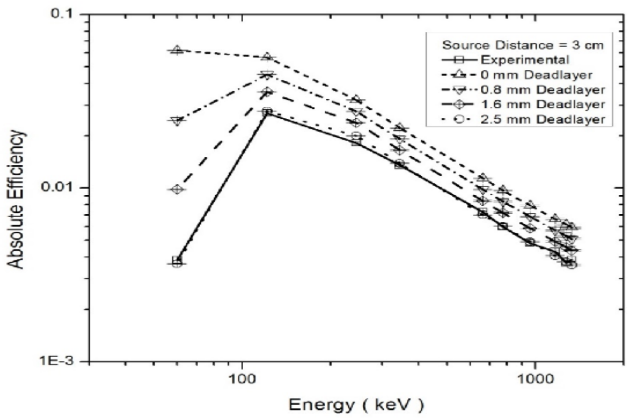


Fig. 3: Comparison of experimental peak efficiency with MCNP peak efficiency curves (expressed as a percentage) for dead layer thicknesses non_DL (conceptual), 0.8 mm, 1.6 mm and 2.5 mm.

Table 5: Simulated, experimental and fitted absolute peak efficiency points (%) shown in Fig 3. In each simulation, the dead layer thickness is 2.5 mm, and the deviation is less than 0.01%. Some fit values removed, because the relation (5) begins to fail.

Energy (keV)	Si($\times 10^{-2}$)	Ex($\times 10^{-2}$)	Fi($\times 10^{-2}$)
60	36	38.4	35
121.8	277.8	270	274
244.65	200.2	181.9	193
344.37	138.8	135.2	128
662	70.1	72.7	49
775.23	60.2	59.7	35
958.5	49.1	48.2	14
1170	40.6	43	-
1275	37.5	37	-
1330	36	38.5	-

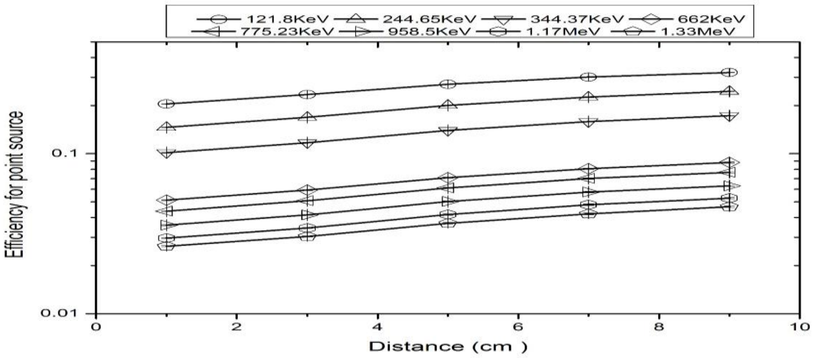


Fig. 4: absolute efficiency for isotropic point source. In order to avoid overlapping with 1.33MeV, results of 60 keV and 1.275 MeV are removed.

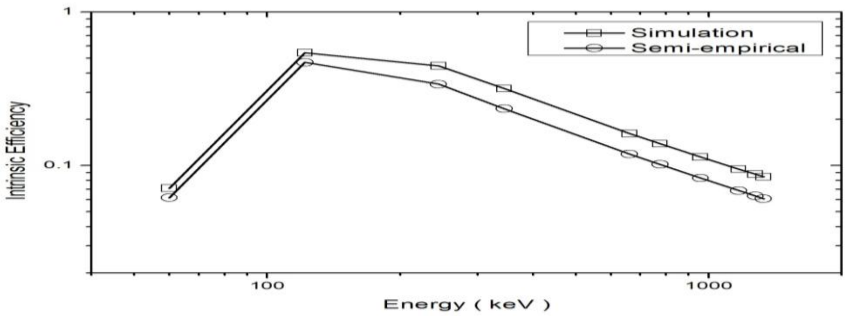
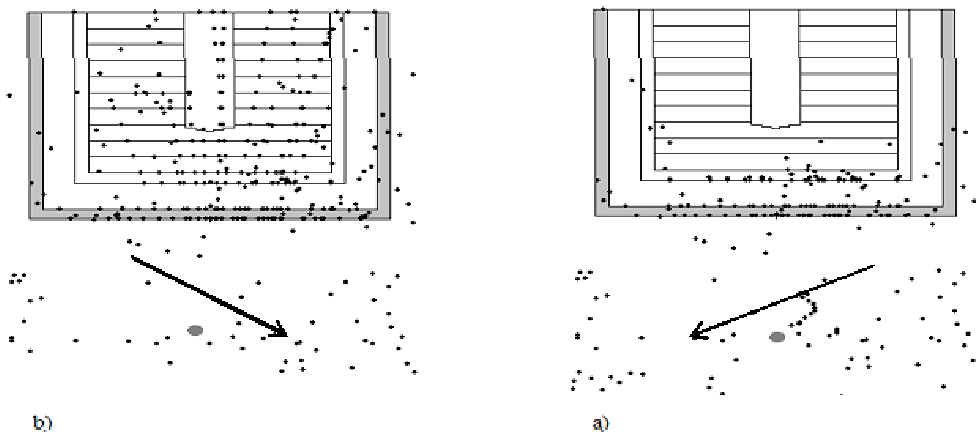
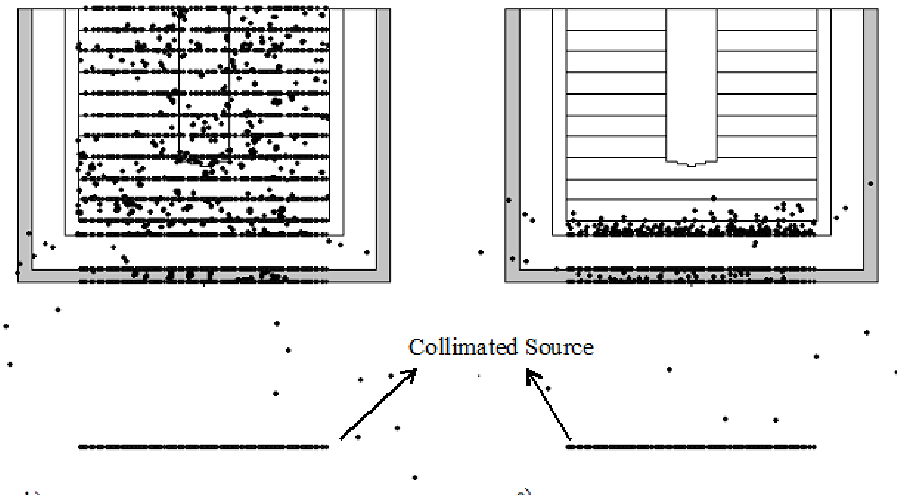


Fig.5. The intrinsic



a) Tally recorded in 60keV
b) Tally recorded in 1.33MeV



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