Monte Carlo simulation for evaluating the efficiency of an HPGe detector

Munkhsaikhan Jargalsaikhan[1], Jamiyansuren Terbish[1]*
[1]*Nuclear Research Center, National University of Mongolia, Ulaanbaatar 13330, Mongolia*
Email:* t.jamiyansuren@num.edu.mn

EXTENDED ABSTRACT

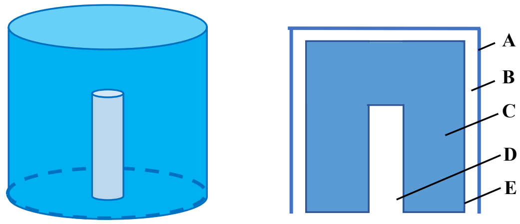
For research in radiation ecology, nuclear geochemistry, and radiation public health, it is essential to precisely determine the specific activity of natural and artificial radioactive isotopes/radionuclides in environmental samples (such as soil, water, air, and mountain rocks), mineral raw materials (including coal, uranium ore, and fertilizers), building materials, and food products. One of the most widely used techniques for measuring the amount and content of radioactivity is the gamma spectrometer, which determines radioactivity by detecting the photons emitted from a sample [1]. Its major advantages are being non-destructive, used for multi-element analysis, and simplified regarding sample preparation, i.e. mostly no need for any radiochemical separation processes [2,3]. In particular, precise detection and quantification of radionuclide activity are essential for reliable risk assessment and radiation safety management. Even small errors in determining radionuclide activity can lead to significant discrepancies in radiation dose estimates, affecting public health assessments and regulatory decisions. By ensuring accurate detector efficiency calculations, this work supports enhanced radiation protection strategies, enabling more reliable risk assessments and more effective public health protection measures.

In previous work [4], the absolute method of efficiency for determination of gamma-emitting radionuclides in the volume samples using gamma spectrometry was described. The chemical composition, gamma-ray attenuation coefficient, measurement geometry, density of the unknown sample and the standard sample need to be identical. Practically, the problem of preparing a standard sample that meets these conditions for each unknown sample is very complex. In particular, there are very limited food-based gamma standards available for purchase, and they are high in cost [5,6]. Therefore, an absolute method of gamma spectrometry has been developed to determine the detector efficiency for samples with a certain volume and density.

This study aims to accurately simulate the detector efficiency by modeling the actual experimental setup, with a particular focus on computational methodology. In the absence of calibration standards for varying geometries and densities, our approach offers an alternative for evaluating detector characteristics under real conditions. For the first time, detector efficiency was determined through a combination of simulations and experimental measurements. A standard Marinella beaker with a fixed volume was used in the experiment. By enclosing the detector over the entire surface, we increased the probability of detecting low-energy photons. Maintaining a constant sample position also improved the comparability between experimental and simulated results. We used the PHITS [7] code version 3.29 based on the Monte Carlo method developed by the Japan Atomic Energy Agency (JAEA), which simulates particle interactions randomly. The PHITS code demonstrates exceptional capabilities and is widely utilized across various fields. The research study on estimation of the detection efficiency of a gamma spectrometer equipped with a HPGe semiconductor detector was performed using a standard sample containing radioactive nuclides packed in a Marinelli beaker and calibration point source. Meanwhile, we determined values of energy resolution, a crucial part of the detector specifications. This research study is significantly important for further study to evaluate characteristics of the detector by computational analysis.

EXPERIMENTAL MEASUREMENT

Measurements were performed with a coaxial ORTEC GEM series HPGe coaxial detector system, DSpec-LF multichannel analyzer (up to 16384), lead shield and GammaVision program. The detector geometry is shown in Figure 1 provided by the manufacturer.



A. 1 mm-Al
B. 4 mm-end cap to detector
C. Ge crystal: Length-47.5 mm, dia-63.7
D. Inner hole: Length-31.7 mm, dia-12.1
E. 700 µm-dead layer

Figure 1. The geometric dimensions of the coaxial HPGe detector

The resolution is 0.85 keV at an energy of 122 keV (^{57}Co). The method of calculation included a Marinelli beaker standard and calibration point source. We utilized the 500 mL Marinelli beaker standard (No.1480-19-4) with multi-nuclide distributed in 0.65 g/cc epoxy matrix and the reference date was 01 Sep 2010.

The Particle and Heavy Ion Transport System (PHITS) calculates the interaction of all particles in the wide energy ranges based on the Monte Carlo method. The PHITS has been extensively applied in many fields including radiation protection, nuclear medicine, basic theoretical research, space science and environmental radiation research [8]. A T-deposit tally can be used to obtain accumulated energy in certain region and is suitable for estimating the detector responses. Specifically, this mode is capable for estimating the detector responses of semi-conductor devices, and it requires the setting of parameters to accurately represent the detector resolution.

RESULTS

We used PHITS version 3.29 to determine the detector efficiency. In the T-deposit tally, we have to set the width of the energy bin at 0.2 keV, the same as the HPGe detector used for experimental measurements. For the purpose of ensuring that the relative error would be less than one percent, the historical number 1 million and the batch number 500 were chosen. The calculation was performed in the three-dimensional coordination. Figure 4 depicts the process by which the PHITS was able to create a measurement configuration for a volume source. The results of the PHITS calculation for the Marinelli beaker standard, are the deposited gamma energies of ^{137}Cs and ^{60}Co isotopes. Figure 5 illustrates the comparison between the pulse height of the PHITS calculation and the measurement spectrum from the HPGe detector. We can indicate the values of efficiency for each position of the detector in Table 4 with the following high intensity gamma energies. The measured results at distances of 5, 10, and 15 cm in Figure 9 show that the efficiency decreases significantly as the distance increases.

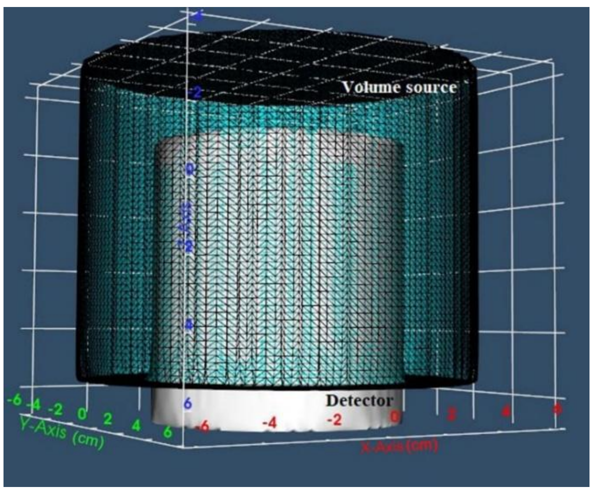


Figure 4. The three-dimensional geometry of the volume source and the detector was generated by PHITS.

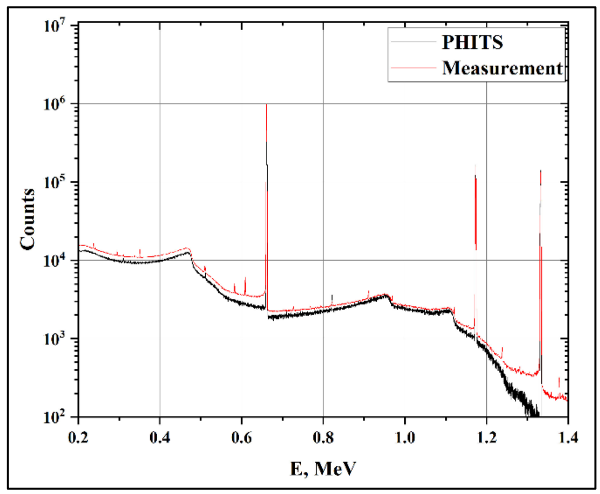


Figure 5. The gamma-ray spectrum from a certified standard volume source compared with the PHITS result

Table 4. Comparison of the detector efficiencies for a point source

E_γ (MeV)	Efficiency					
	(measured)			(calculated)		
	5cm	10cm	15cm	5cm	10cm	15cm
0.121	0.0311±0.0029	0.0116±0.0008	0.0057±0.0003	0.0320	0.0121	0.0061
0.245	0.0223±0.0021	0.0090±0.0006	0.0046±0.0002	0.0234	0.0092	0.0048
0.344	0.0154±0.0015	0.0062±0.0004	0.0031±0.0002	0.0163	0.0065	0.0034
0.778	0.0077±0.0007	0.0028±0.0002	0.0014±0.0001	0.0084	0.0033	0.0018
0.964	0.0063±0.0006	0.0025±0.0002	0.0012±0.0001	0.0069	0.0027	0.0014

0.1112	0.0057±0.0005	0.0022±0.0001	0.0011±0.0001	0.0061	0.0025	0.0013
0.1408	0.0045±0.0004	0.0018±0.0001	0.0009±0.0001	0.0047	0.0019	0.0010

CONCLUSION

In this work, the efficiency of a gamma spectrometer with a germanium detector was calculated by the PHITS code in a wide energy range. The T-deposit tally of the PHITS code was applied to obtain the accumulated energy in the detector region. The comparison of calculations and measurements was performed using the Marinelli beaker containing a homogeneous mixture of radioactive isotopes, and a ^{152}Eu point source. The results indicate that the PHITS code effectively simulates both source and detector responses, and quantifies the agreement between simulated and measured data. We aimed to validate the results by carrying out another measurement of the point source. It has been confirmed for detector response to photon energy ranges of 0.0–3.2 MeV compared to the measured one. Practically, we analyze a large volume of environmental samples, some factors were neglected for the point source. However, uncertainty of independent parameters was accounted for. Therefore, it can yield excellent results in terms of the detector efficiencies within that energy range. This work has significant implications for risk assessment, radiation safety, and management in environmental monitoring and nuclear industries. By providing insights into detector performance, it supports the enhancement of radiation protection strategies and the optimization of radiation safety protocols. Despite these advancements, limitations exist, such as the simplified modeling of point sources. Future research should address these limitations by including more detailed simulations of diverse radiation sources and energy ranges, along with exploring the application of this approach to real-world environmental monitoring and risk mitigation.

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