Monte Carlo simulation of the efficiency response of a well-type HPGe detector at 46.54 keV

Yasser Morera Gómez[1-4], Héctor A. Cartas Águila[1], Carlos M. Alonso Hernández[1], José L. Bernal Castillo[2,3], Aniel Guillén Arruebarrena[1]

[1]Centro de Estudios Ambientales de Cienfuegos. Cienfuegos, Cuba
[2]Instituto Superior de Tecnologías y Ciencias Aplicadas (InSTEC)
Ave. Salvador Allende y Luaces. La Habana, Cuba
[3]Instituto de Física, Universidad de Sao Paulo, Sao Paulo, Brasil
[4]Departamento de Química y Edafología. Universidad de Navarra, España
ymore24@gmail.com
yasser@ceac.cu

Abstract

In this paper, we used the Monte Carlo simulations method in a well-type HPGe detector using directly the manufacturer supplied data in order to simulate the efficiency response at 46.54 keV. The efficiency values were calculated as a function of the filling height of the sample into the measurement geometry and results were found in good agreement with experimental data. The main deviations were less than 2.5 % with a mean of 0.9 %, which is totally satisfactory for the purposes of environmental samples measurements. We also present a brief discussion about the response of the detector to different values of its geometric parameters.

Key words: *high-purity Ge detectors; Monte Carlo method; calibration; accuracy; efficiency*

Simulación por Monte Carlo de la respuesta de eficiencia de un detector HPGe tipo pozo a la energía de 46.54 keV

Resumen

En el trabajo se utilizaron los métodos de simulación por Monte Carlo en un detector HPGe tipo pozo, usando directamente los parámetros del fabricante para simular la respuesta de eficiencia a la energía de 46.54 keV. Los valores de eficiencia se calcularon en función de la altura de la muestra en la geometría de medición y los resultados se correspondieron con los valores experimentales. Las mayores diferencias fueron menores que el 2.5 % con un promedio de 0.9 %, lo que es totalmente satisfactorio para la medición de muestras ambientales. Se presentó una breve discusión sobre la respuesta del detector para diferentes parámetros geométricos.

Palabras clave: *detectores de Ge ultrapuro; método de Monte Carlo; calibración; precisión; eficiencia*

Introduction

Well-type HPGe detectors are very useful for radionuclide activities quantification in small environmental samples, especially when low energy photons are to be measured, because the near 4π geometry results in a high counting efficiency and a lower limit of detection. For example, these detectors are widely used for detections of the naturally occurring ^{210}Pb (T1/2 = 22.3 years) via its 46.5 keV (4 %) gamma ray [1,2]. ^{210}Pb has numerous applications in atmospheric, oceanography and marine geology research [3–5]. However, in lots of these studies, the available sample mass is limited so it is essential to have an accurate efficiency calibration at the given energy, which often requires a large experimental work because it is necessary to take into account the coincidence summing and self-absorption effects [6–8].

In these cases, Monte Carlo (MC) simulations could be a potential tool to replace or complement the calibration processes. However, the MC calculations require a precise knowledge about the characteristics of the detector and sample [9]. Generally, the efficiency values obtained experimentally and by MC simulation based on nominal values of the parameters supplied by the manufacturer show significant differences due to the inaccuracy in some critical parameter such as the thickness of the dead cap, the relative position of the Ge crystal and the active volume [10,11]. In many cases the optimization of these parameters can result in a substantial decrease of the deviations between the experimental and calculated values [12–14]. However, even when precise geometrical data are available, it is necessary to refine the model by feeding it back with experimental results when accuracy is desired. This is because some parameters involved in the response of the detector cannot easily be assessed. They include the distribution of the electrical field in the crystal and its mounting [15] and the dimensions and properties of the dead layers [16].

In this work we focused on the MC efficiency calibration of a well-type HPGe detector for the ^{210}Pb measurement in small environmental samples. The main purpose of this work is to show that the efficiency calibration at 46.54 keV by MC simulation provides accurate results for small sample volumes even when an environmental sample is studied. We aim to verify the accuracy of the calculated values to extend the use of the detector model and MC calculations to other environmental matrices. In order to refine the model we made an analysis of the detector's response to different values of some of its geometric parameters.

Materials and Methods

We used the MC code MCNPX 2.6 to build a well-type HPGe detector model just using the data supplied by the manufacturer. In a second step, we calculated the efficiency values for different filling heights of the sample into the measurement geometry. This procedure was applied for the Certificated Reference Material DL-1a and results were compared with experimental efficiency values obtained from ^{210}Pb activity reported for this material [17].

Detector: We used a Canberra HPGe well detector model EGPC100 P-15, with an absolute efficiency of 12.1 % at 661 keV and a resolution (FWHM) of 1.15 keV at 122 keV and 1.86 keV at 1332 keV. This detector is surrounded by a cylindrical low-background chamber made with the following elements: 240 mm of steel, 37 mm of lead, 1 mm of copper and 1 mm of aluminum from outside to the inner region. The data acquisition system consists of a PSC822 preamplifier, Canberra amplifier model 7245 and electronic card MCA 5000 which includes a 7602 ADC with 8192 channels and InterFast multichannel analyzer connected to a PC. The spectra were recorded and analyzed using Winner 6.0 software.

Experimental efficiency determination: In order to calculate the efficiency values of the well-type HPGe detector at 46.54 keV for different sample volumes, the Certified Uranium-Thorium Reference Ore DL-1a was measurement as a function of the filling height *h(cm)* of the sample into the measurement geometry. The geometry is a cylindrical polystyrene vial of 4.5 cm^3 and internal diameter of 1cm, placed in the well of the detector as shown in figure 1. The vial was virtually divided into 9 sections (0.5 cm each of them) for the measurement. For each section, the experimental efficiency value e (h) was calculated considering the activity concentration of ^{210}Pb $A\left(\frac{Bq}{g}\right)$ reported for DL-1a (1.40 ± 0.02 Bq/g) and mass of the sample packed $m(h)\,(g)$, according to the following equation:

$$\varepsilon(h) = \frac{T(h)}{\gamma A m(h)} \qquad (1)$$

where *T (h)* is the experimental count rate (s^{-1}) and is the gamma decay probability at 46.54 keV for ^{210}Pb.

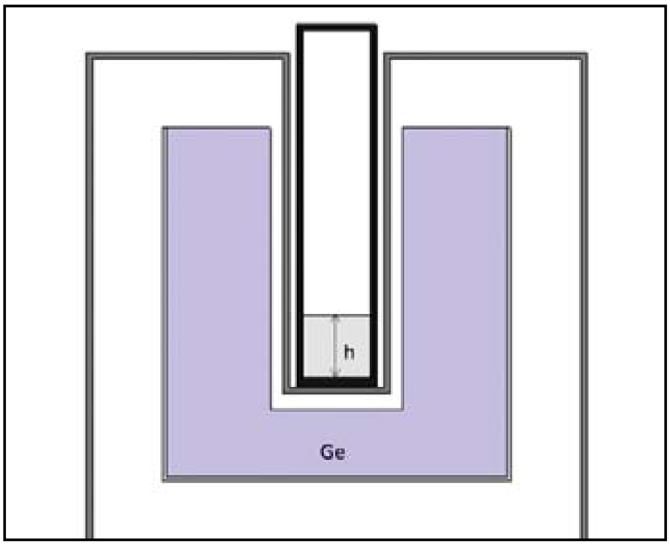

Figure 1. Representation of the detector and the measurement geometry.

Monte Carlo simulation: At present work, the MC code MCNPX 2.6 was applied to calculate the efficiency values of the well detector at 46.54 keV just using the nominal values of the parameters supplied by the manufacturer. Table 1 shows the values of these parameters and vial's dimensions. For the thickness of the internal dead cap we considered 50 nm. Metallic conductors were not taken into account because its influence is negligible at low energies in well configuration. We used the pulse-height tally (F8) per photons emitted from the source to compute the absolute efficiency and we generally obtained relative errors lower than 0.1 %.

Table 1. Parameters of the detector supplied by the manufacturer and vial dimensions

Parameter	Nominal value (mm)
Thickness ofthe Al end cap	1.0
Diameter of the Al well	15.0
Height ofthe Al well	53.3
Height of the Ge crystal	56.4
Diameter of the Ge crystal	55.6
Diameter of the Ge well	21.0
Height of the Ge well	45.0
Distance between the Ge crystal and the Al end cap	11.0
Thickness of the external dead cap	0.5
Thickness of the vial walls	1.0
Internal diameter of the vial	10.0

The chemical composition reported for DL-1a [17] was used for the matrix implementation during the MC simulation processes. The results obtained by MC calculation were compared with the experimental values in order to verify the accuracy of the calculated values using the detector model.

Results and Discussion

Figure 2 shows the measured and calculated efficiency for DL-1a as a function of the filling height of the sample into the measurement geometry. As we can see, there is a good agreement between measured and calculated efficiency. The main deviations do not exceed 2.5 % with a mean of 0.9 %. For all heights considered, the measurement uncertainty is greater than the difference between the measured and calculated values, therefore, these values do not show significant differences [18]. For this result, we just used the manufacturer's supplied data. Nevertheless we obtained a very good result for an environmental sample. This is not always the case at such a low energy. Significant discrepancies have been reported in many works when the manufacturer's data is directly used [12,19]. In these cases, it is necessary to explore the sensitivity of the simulation to geometrical parameters of the detector or to optimize the simulation within the expected uncertainties associated with these ones.

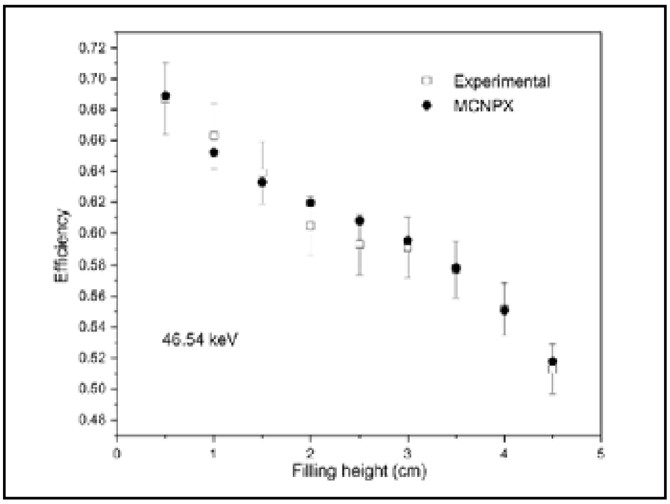

Figure 2. Measurement and calculated efficiency versus filling height of the sample into the measurement geometry for DL-1a at 46.54 keV.

At the energy of 46.54 keV in well configuration, the most significant parameters to take into account during MC calculation are those which can change the solid angle of the source-detector geometry. The thickness of the internal dead cap (ion implanted) for the detector considered here is around 50 nm and slight changes in this parameter can be neglected [20]. Figures 3 and 4 show the behavior of the calculated efficiency for different values in two parameters i.e., the diameter of the Ge well and the distance between Al end cap and the Ge crystal. As it can be noticed, the largest deviations are observed for heights greater than 3 cm. However, the deviations related to nominal values are less than 2 %. Therefore, the detector model is sufficient to describe the efficiency response at this energy in the well configuration by MC calculations.

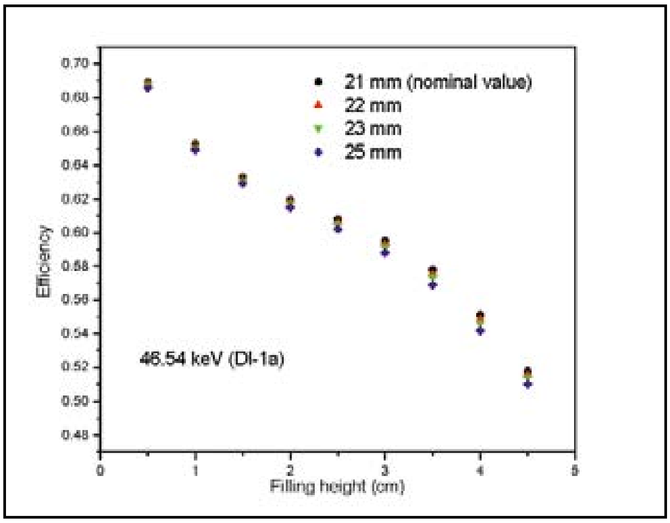

Figure 3. Calculated (MCNPX) efficiency for different diameter values of the Ge well.

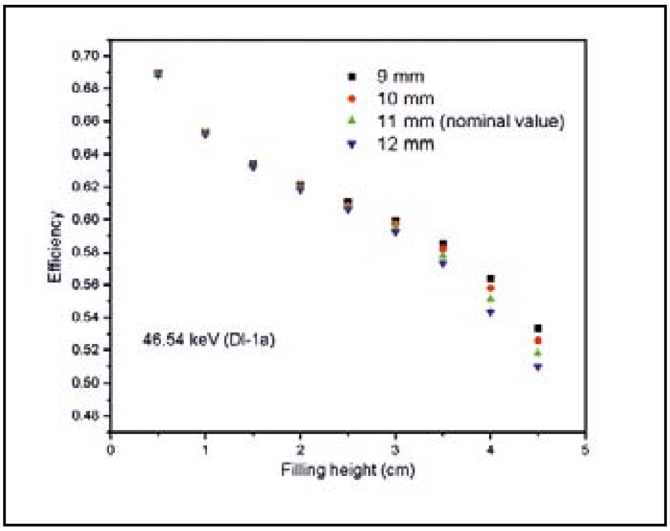

Figure 4. Calculated (MCNPX) efficiency for different distance values between the Al end cap and the Ge crystal.

In order to obtain an efficiency calibration for the entire range of heights, the calculated efficiency values can be fitted to a third-degree polynomial function. Following this approximation we can calculate the efficiency at a given height (***h***) according to the equation,

$$\varepsilon(h) = (73.5 \pm 0.4)10^{-2} - (11.2 \pm 0.7)10^{-2}h + (3.7 \pm 0.3)10^{-2}h^2 - (5.1 \pm 0.4)10^{-3}h^3 \quad (2)$$

with $R^2 = 0.998$

The efficiency dependence on the filling height as a cubic function is driven by the self-absorption of the photons in the used Reference Ore and the solid angle of measurement. With the increase of the filling height the self-absorption effect is more significant due to the increase of sample mass, at the same time the solid angle decrease.

This calibration is very useful in the laboratory when the amount of the sample to be analyzed is insufficient to complete the measurement geometry and is necessary to be interpolated between two heights of the sample under study [7, 21, 22].

Following the procedure described above the detector model can be used in the MC efficiency calculation with other environmental matrices in the same configurations and energy used here.

Conclusions

In this work, we applied the MC simulations methods to a well-type HPGe detector using the nominal values of the parameters supplied by the manufacturer. These calculations reproduced the experimental efficiency values at 46.54 keV for different volumes of the Certificated Reference Material DL-1a with a mean deviation of 0.9 %. Furthermore, we found that it is not necessary to optimize the geometrical characteristics of the detector for the MC efficiency calibration at this energy in the well configuration. Now, the detector model and MC calculations obtained in this paper can be used in the laboratory to complement the efficiency calibrations processes when small environmental sample are to be measured. Moreover, the simple procedure described here can be applied to other well-type HPGe detectors in the well configuration.

Acknowledgements

This research work was under taken in the framework of the IAEA TC Project CUB/7/008 "Strengthening the National System for Analysis of the Risks and Vulnerability of Cuba's Coastal Zone through the Application of Nuclear and Isotopic Techniques". The authors hereby would like to acknowledge the EJDS program at ICTP.

References

[1] RENFRO AA, COCHRAN JK, COLLE BA. Atmospheric fluxes of 7Be and 210Pb on monthly time-scales and during rainfall events at Stony Brook, New York (USA). J Environ Radioact. 2013; 116: 114-123. doi:10.1016/j.jenvrad.2012.09.007.

[2] ALONSO HERNÁNDEZ CM, MORERA GÓMEZ Y, CARTAS ÁGUILA H, GUILLÉN ARRUEBARRENA A. Atmospheric deposition patterns of 210Pb and 7Be in Cienfuegos, Cuba. J Environ Radioact. 2014; 138: 149-155. doi:10.1016/j.jenvrad.2014.08.023.

[3] BASKARAN M. Po-210 and Pb-210 as atmospheric tracers and global atmospheric Pb-210 fallout: a Review. J Environ Radioact. 2011; 102(5): 500-513. doi:10.1016/j.jenvrad.2010.10.007.

[4] ABRIL JM, BRUNSKILL GJ. Evidence that excess Pb-210 flux varies with sediment accumulation rate and implications for dating recent sediments. J Paleolimnol. 2014; 52(3): 121-137. doi:10.1007/s10933-014-9782-6.

[5] SAARI HK, SCHMIDT S, CASTAING P, et. al. The particulate 7Be/210Pbxs and 234Th/210Pbxs activity ratios as tracers for tidal-to-seasonal particle dynamics in the Gironde estuary (France): implications for the budget of particle-associated contaminants. Sci Total Environ. 2010; 408(20): 4784-4794.

[6] VARGAS MJ, TIMÓN AF, DÍAZ NC, SÁNCHEZ DP. Monte Carlo simulation of the self-absorption corrections for natural samples in gamma-ray spectrometry. Appl. Radiat. Isot. 2002; 57(6): 893-898.

[7] SAÏDOU, BOCHUD F, LAEDERMANN JP, et. al. Calibration of an HPGe detector and self-attenuation correction for 210Pb: Verification by alpha spectrometry of 210Po in environmental samples. Nucl Instruments Methods Phys Res Sect. 2007; 578(3): 515-522.

[8] LABORIE JM, LE PETIT G, ABT D, GIRARD M. Monte carlo calculation of the efficiency calibration curve and coincidence-summing corrections in low-level gamma-ray spectrometry using well-type HPGe detectors. Appl. Radiat.Isot. 2000; 53(1-2): 57-62.

[9] BOSON J, AGREN G, JOHANSSON L. A detailed investigation of HPGe detector response for improved Monte Carlo efficiency calculations. Nucl Instruments Methods Phys Res Sect. 2008; 587(2-3): 304-314.

[10] MORERA GÓMEZ Y, CARTAS AGUILA HA, ALONSO HERNÁNDEZ CM, et. al. Application of the Monte Carlo efficiency transfer method to an HPGe detector with the purpose of environmental samples measurement. Appl. Radiat. Isot. 2015; 97: 59-62. doi:10.1016/j.apradiso.2014.12.013.

[11] DÍAZ RIZO O, LÓPEZ PINO N, D'ALESSANDRO K, et. al. Characterization of the InSTECs low-background gamma spectrometer for environmental radioactivity studies. Nucleus. 2009; (46): 21-26.

[12] ELANIQUE A, MARZOCCHI O, LEONE D, HEGENBART L, BREUSTEDT B, OUFNI L. Dead layer thickness characterization of an HPGe detector by measurements and Monte Carlo simulations. Appl. Radiat. Isot. 2012; 70(3): 538-542.

[13] BUDJAZ D, HEISEL M, MANESCHG W, SIMGEN H. Optimisation of the MC-model of a p-type Ge-spectrometer for the purpose of efficiency determination. Appl. Radiat. Isot. 2009; 67(5): 706-710.

[14] PADILLA CABAL F, LOPEZ PINO N, LUIS BERNAL CASTILLO J, et al. Monte Carlo based geometrical model for efficiency calculation of an n-type HPGe detector. Appl. Radiat. Isot. 2010; 68(12): 2403-2408.

[15] HERNÁNDEZ F, EL-DAOUSHY F. Accounting for incomplete charge collection in Monte Carlo simulations of the efficiency of well-type Ge-detectors. Nucl Instruments Methods Phys Res Sect. 2003; 498(1-3): 340-351.

[16] COURTINE F, PILLEYRE T, SANZELLE S & MIALLIER D. Ge well detector calibration by means of a trial and error procedure using the dead layers as a unique parameter in a Monte Carlo simulation. Nucl Instruments Methods Phys Res Sect Accel Spectrometers Detect Assoc Equip. 2008; 596(2): 229-234.

[17] STEGER HF, BOWMAN WS. DL-1a: A certificated uranium-thorium reference ore. CANMET Reportm80-10E. Ottawa: CANMET; 1980.

[18] LINSINGER T. Comparison of a measurement result with the certified value. Application Note 1 [online]. European Reference Materials, 2010. <http: www.erm-crm.org>.

[19] RÓDENAS J, PASCUAL A, ZARZA I, et. al. Analysis of the influence of germanium dead layer on detector calibration simulation for environmental radioactive samples using the Monte Carlo method. Nucl Instruments Methods Phys Res Sect. 2003; 496(2-3): 390-399.

[20] BOCHUD F, BAILAT CJ, BUCHILLIER T, et. al. Simple Monte-Carlo method to calibrate well-type HPGe detectors. Nucl Instruments Methods Phys Res Sect. 2006; 569(3): 790-795.

[21] PÉREZ MORENO JP, BOLÍVAR JP, GARCÍA TENORIO R, et al. A simple method for efficiency calibration of HPGe detectors in gamma-spectrometric measurements. Radiat. Phys. Chem. 2001; 61(3-6): 437-438.

[22] SAN MIGUEL EG, PÉREZ MORENO JP, BOLÍVAR JP, et. al. 210Pb determination by gamma spectrometry in voluminal samples (cylindrical geometry). Nucl Instruments Methods Phys Res Sect. 2002; 493(1-2): 111-120.

Received: October 15, 2014
Accepted: April 23, 2015