Efficency of a HPGe extended range detector for determination of ^{7}Be concentration in air filters

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Abstract. Using the GEANT4 Monte Carlo simulation software, the efficiency of the HPGe extended range detector of the Environmental Radiological Surveillance Laboratory of CIMAV was modeled. A ^{137}Cs certified point source was employed to determine the experimental gamma efficiency in the desired geometry for the energy of 662 keV. The resulting value was compared with the theoretical efficiency obtained by the Monte Carlo simulation. The results of the simulation were consistent with the experimental one. The same method was applied to calculate the theoretical efficiency in the same detector for borosilicate filters in an extended geometry. The energy then was 477 keV, of the gamma quanta from ^{7}Be, to determine its concentration in air. This efficiency value was applied for air sampling in the city of Chihuahua.

1. Introduction

^{7}Be is a β^- and γ radionuclide, which emits a 477 keV gamma ray. Its half-life is short, 53.22 days, making a certified source of ^{7}Be scarce and nonprofit. The ^{7}Be and ^{10}Be nuclei are produced in the atmosphere by the interaction of cosmic rays and they mix in air as suspended particles. ^{10}Be, which has a half-life of 1.39 million years, can be very useful to date objects in the order of millions of years old [1]. The concentration of ^{10}Be in the environment can be indirectly calculated by measuring the concentration of ^{7}Be via gamma-ray spectroscopy. In order to monitor the concentration of ^{7}Be in air by gamma-ray spectroscopy, not having a certified source, a computational simulation method is the alternative.

The detection equipment used to perform the experimental measurement for this work is a Extended Range Hiperpure Germanium Detector (HPGe XtRa) manufactured by CANBERRA, model GX1020 type p. The detector and its parameters are shown in figure 1. This detector was characterized previously in [2]. Figure 1 (left) also shows a plexiglass sample-holder with adjustable height.

The detection system is conformed by a vacuum sealed HPGe crystal covered by an aluminum protection and a carbon composite window. The detector is shielded by a 10 cm layer of lead, followed by layers of tin, steel and copper of 0.27, 0.3 and 0.3 cm thickness.

Photons interacting with the detector produce pulses, where the pulse's amplitude is proportional to the photon's deposited energy. When a photon succesully deposits all its energy in the detector it contributes to the formation of a full energy peak (FEP) [2, 3, 4, 5, 6].

The detection's efficiency generally is measured by the full energy peak efficiency, $\varepsilon(E)$, which is the ratio of the number of counts, $N(E)$, in the FEP corresponding to the energy E, and the
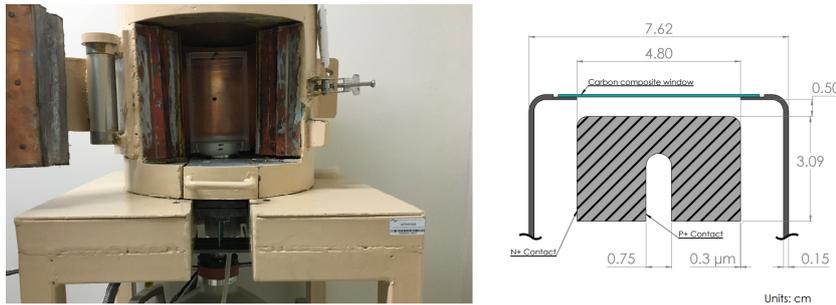
Figure 1. Extended Range Hiperpure Germanium Detector (HPGe XtRa) manufactured by CANBERRA, model GX1020 type p (left). HPGe XtRa detector's crystal dimensions(right).

number of photons with energy E emitted by the source. This number of photons is proportional to the source's activity, A, and the probability of emission of the photon of interest, $P_\gamma(E)$. The efficiency is defined as:

$$\varepsilon(E) = \frac{N(E)}{A \cdot P_\gamma(E)} \prod^i k_i \,,\tag{1}$$

where k_i in equation 1 represent correction factors, usually caused by the detection's geometry, the detector and the source [2, 3, 4, 6].

In order to perform an efficiency calibration some authors make computational simulations applying Monte Carlo Methods [2, 3, 6, 7, 8, 9, 10]. In this work, a Monte Carlo Simulation using GEANT4 was performed.

2. GEANT4 simulation

GEANT4 (GEometry ANd Tracking) is a toolkit for the simulation of the passage of particles through matter. It offers to the user the possibility to virtually build its own detector and other solids using their chemical composition and density, to simulate particles with physical properties and the interaction mechanisms, to save the information generated in the simulation and to visualize the simulation [7, 8, 11, 12].

The GEANT4 simulation is composed by seven classes and a main file. The main file request the mandatory classes for the simulation, and each class completes a specific task. Figure 2 shows how the classes interact and their main methods in a class diagram.

The main file uses the `RunManager` to instance the mandatory classes: `DetectorConstruction`, `PhysicsList` and `ActionInitialization`. `ActionInitialization` comands the optional classes: `PrimaryGeneratorAction`, `RunAction`, `EventAction` and `StackingAction`.

In `DetectorConstruction`, the geometry is constructed using basic primitive figures. The HPGe crystal, for example, is made from cylinders and tori. Radioactive sources are defined with density to consider the self absorption in the source. Figure 3 shows the detector modeled in GEANT4, highlighting the germanium crystal in red.

To extract data from the simulation, primitive scorer was used. Primitive scorers provide common scorers for physicals quantities, allowing the users to get the information they need without implementing their own classes. First the HPGe crystal is registered as a `MultiFunctionalDetector` object and `G4SDManager` creates a pointer where the physical quantity is stored. `G4VPrimitiveScorer` uses the method `G4PSEnergyDeposit`, therefore the scorer will store energy. Finally the HPGe crystal is set as a sensitive detector associating its
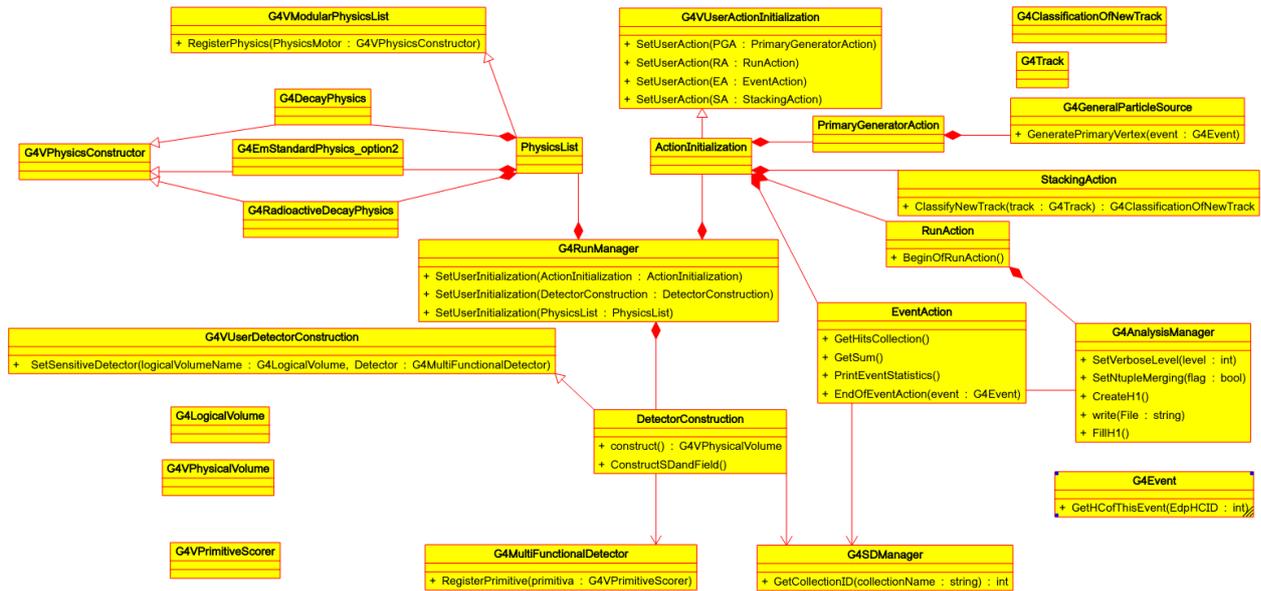
Figure 2. Class diagram for the GEANT4's simulation.

spacial location with the pointer that stores the deposited energy. The stored energy is used in `EventAction`.
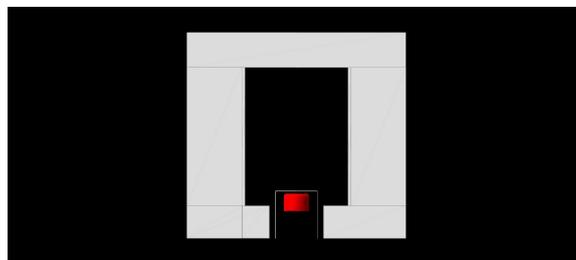

Figure 3. HPGe XtRa detector modeled in GEANT4. Gray color corresponds to the shielding and other interacting materials, red to the HPGe crystal set as sensitive detector, and black to vacuum in the surroundings of the crystal and air elsewhere.

`PhysicsList` defines the physics models for the simulation, this class uses 3 models: `G4DecayPhysics`, `G4RadioactiveDecayPhysics` and `G4EMStandardPhysics_option2`. `G4DecayPhysics` defines all the particles and their decay processes. `G4RadioactiveDecayPhysics` simulates the decay of radioactive nuclei for GenericIon objects. It uses the Monte Carlo method in order to emit particles in random directions and includes the branching ratio for a large number of isotopes using a database (which can be modified). Radioactive decay may be restricted to only specific nuclides, in order to avoid tracking extremely long-lived daughters in decay chains which are not of experimental interest. `G4EMStandardPhysics_option2` includes electromagnetic physics processes common in experimental environments. It includes Compton scattering, e^-e^+ pair production, Photo-electric effect, Bremsstrahlung, ionisation and atomic deexcitation. All the interactions have a probability of occurrence which is calculated via Monte Carlo [12].

`PrimaryGeneratorAction` generates the primary particles for the simulation. It instances the class `G4GeneralParticleSource`, which allows the specifications of the spectral, spatial and angular distribution of the primary source particles. This allows the simulation of extended sources [11, 12].

`RunAction` give orders to the `AnalysisManager`, which creates histograms and stores them in a `.root` file. The `AnalysisManager` defines the energy range, units and number of channels.

`EventAction` takes the information stored in the pointer created by `G4SDManager`, defined in `DetectorConstruction`, and fills the histograms created in `RunAction`. `StackingAction` kills the track of the neutrino created in beta decays which contributes no useful information for gamma-ray spectroscopy.

In order to validate the simulation an efficiency calibration was performed for the point-like source GF-ML 1748-58, this allowed comparing the experimental results with the Monte Carlo simulation. The point source contained the isotopes ^{210}Pb, ^{241}Am, ^{109}Cd, ^{57}Co, ^{123m}Te, ^{113}Sn ^{137}Cs, ^{60}Co and ^{88}Y. Results are shown in table 1 and figure 4.

Table 1. Measurements and simulations for the efficiency calibration for the point source GF-ML 1748-58 at 15 cm.

| Energy [keV]	Isotope	Experimental efficiency	Simulated efficiency	Energy [keV]	Isotope	Experimental efficiency	Simulated efficiency
46.54	^{210}Pb	0.00416(17)	0.00422(19)	661.66	^{137}Cs	0.000660(21)	0.000633(16)
59.54	^{241}Am	0.00420(13)	0.00409(10)	898.04	^{88}Y	0.000485(15)	0.000462(13)
88.03	^{109}Cd	0.00438(14)	0.00395(20)	1173.2	^{60}Co	0.000366(11)	0.000350(11)
122.06	^{57}Co	0.00393(13)	0.00370(39)	1332.5	^{60}Co	0.000322(10)	0.000318(10)
158.97	^{123m}Te	0.00326(10)	0.00316(36)	1836.06	^{88}Y	0.000233(70)	0.000228(10)
391.7	^{113}Sn	0.00120(36)	0.00116(25)				
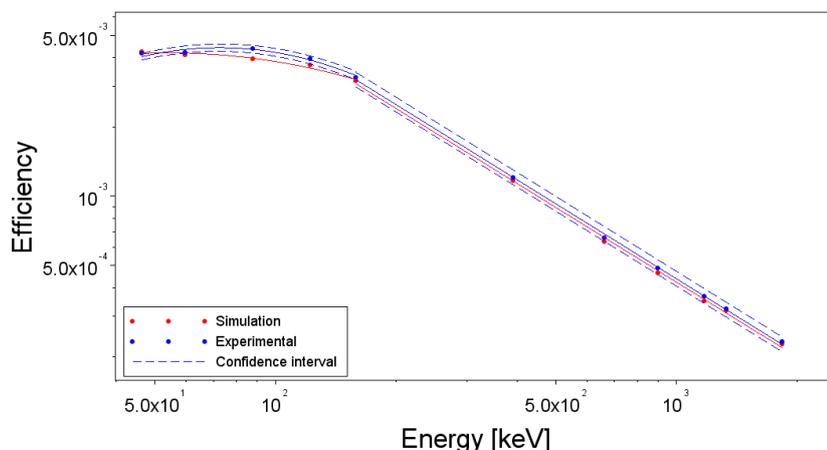
Figure 4. Efficiency calibration for the point-like source GF-ML 1748-58 at 15 cm over a broad energy range. The confidence interval represents one standard deviation.

In order to validate the simulation for an extended source, the liquid multi-nuclide standard source LPR/45/00 MULTLM479 was evaporated and impregnated in a borosilicate air collector filter. The measurement and simulation focused on the 661.66 keV gamma-ray because it lies close to the 477 keV gamma-ray from ^{7}Be. Results are shown in table 2.

Table 2. Efficiency for the 661.66 keV energy in the air collector filter impregnated by the source LPR/45/00 MULTLM479.

Energy [keV]	Isotope	Experimental efficiency	Simulated efficiency
661.66	^{137}Cs	0.00964(60)	0.00954(3)

3. Measurement of ^{7}Be in air collector filters

After validating the GEANT4 simulation with the point-like and extended sources, there was enough confidence to assume that the simulated efficiency can be applied in equation 1.

Table 3. Simulated efficiency value for the 477 keV energy gamma-ray of ^{7}Be for air collector filters.

Energy [keV]	Isotope	Simulated efficiency
477	^{7}Be	0.01364(10)

Having the simulated efficiency value for for the desired energy, shown in table 3, the experimental measurement for air collector filters with the same characteristics was performed. The suspended particles concentration of ^{7}Be in the Chihuahua's air during the month of april 2019 was measured. Results are shown in table 4.

Table 4. Results of the measurement of suspended particles ^{7}Be concentration in Chihuahua's air during the month of april 2019.

Filter	Sample collection	Sample measurement	^{7}Be activity concentration [mBq/m^3]
Filter 1	April 8-9	April 26-30	4.5(3)
Filter 2	April 9-10	April 11-15	4.6(2)
Filter 3	April 22-23	April 24-26	6.4(4)

These results provides a methodology for the calculation of ^{7}Be concentration in air and others gamma-ray emitters suspended as particles in air. Future work will include a more detailed development of the method and the ^{10}Be characterization.

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