MODELING OF GERMANIUM DETECTOR AND ITS SOURCELESS CALIBRATION

by

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The paper describes the procedure of adapting a coaxial high-precision germanium detector to a device with numerical calibration. The procedure includes the determination of detector dimensions and establishing the corresponding model of the system. In order to achieve a successful calibration of the system without the usage of standard sources, Monte Carlo simulations were performed to determine its efficiency and pulse-height response function. A detailed Monte Carlo model was developed using the MCNP-5.0 code. The obtained results have indicated that this method represents a valuable tool for the quantitative uncertainty analysis of radiation spectrometers and gamma-ray detector calibration, thus minimizing the need for the deployment of radioactive sources.

Key words: gamma-ray spectrometry, HPGe modeling, sourceless calibration, Monte Carlo method

INTRODUCTION

Nowadays, gamma-ray spectrometry has numerous scientific and technological applications: radioactive waste disposal, characterization of landmines, geophysical and environmental studies [1-4], *etc*. The role of high-precision germanium (HPGe) detectors in gamma-ray spectrometry is significant. Almost each of these applications calls for the detailed knowledge of detector peak efficiency over the specific energy range and its response function (pulse height distribution) [5]. One regular way to overcome this problem is by measuring the detector response to multi-nuclide standard sources that have well defined energies and intensities of their gamma lines, within a predefined geometrical configuration, comprising both the shape and the position of the sample relative to the detector. This approach has two major disadvantages: (a) the deployment of standard sources eventually increases the amount of radioactive waste and is money consuming, and (b) in those cases where radioactive samples to be characterized do not match predefined geometrical configuration, the efficiency of detection cannot be determined successfully.

State-of-the-art approach to deal with these disadvantages is to numerically calculate the efficiency of the detector-sample system. At the present level of computer technology this can be achieved with sufficient accuracy, so it has been the focus of investigation for a number of authors [6-14]. On the other hand, many manufacturers deliver the detectors with the adequate software packages, providing the possibility for users to describe the actual shape of their samples and to correct the measured activity accordingly. These packages use data bases with results obtained by well-known Monte Carlo simulation codes (*e. g.* MCNP [15]) and may be utilized either in a laboratory or in nuclear facility environment. The recognized examples of the above mentioned packages are the LabSOCS (Laboratory Sourceless Calibration Software) [16] and the ISOCS (In Situ Object Counting System) [17]. However, the number of the available sample shapes and positions is limited, and the corrections for the inserted absorbers are based on approximations (build-up factors *e. g.*), which often could result in insufficient precision. In addition to this, the application of these or similar packages assumes the precise description of the detector system (geometry,

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material composition, *etc*.) which usually can be done only by the manufacturer.

In this paper we describe the procedure used to model our own coaxial HPGe for photon energies ranging from 100 keV to 1.7 MeV, and further to apply it as an *in situ* object counting device. We use the MNCP code both for the characterization and for the calculation of detector efficiency.

DETECTOR MODELING

The specifications of the detector crystal physical dimensions and position, given by the manufacturer, are frequently insufficient. The simplified geometry of the detecting system, consisting of the HPGe detector enclosed within an aluminum holder and cryostat, is depicted in fig. 1.

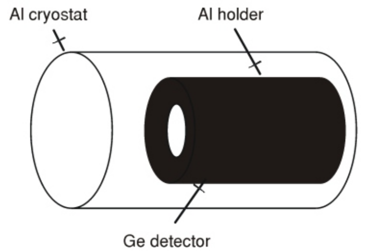

Figure 1. Layout of the HPGe detector system

To perform the proper characterization of the system we employ a collimated ^{137}Cs gamma source within a small lead container with a circular bore of 1 mm in diameter, providing an almost parallel beam. Having no possibility to determine the axial distance between the holder and the cryostat, in our model they are replaced with one aluminum cylinder, 70 mm in radius and 200 mm in height, with 2.7 mm thick walls. The surface of the Ge crystal represents a thin tin (Sn) layer, depicted in fig. 2 as a circular disc between the aluminum holder and detector base. The height (*H*) and diameter (*D*) of the Ge crystal were determined by measuring the response to ^{137}Cs source while moving it in the axial and radial direction, respectively (see fig. 2).

The precision of this movement is better than 1 mm. The distribution of the detector response with respect to the axial and radial position of the source is given in figs. 3(a) and 3(b).

Based on our previous experience with scanning the position of waste fuel elements [18], we adopted $H = 40$ mm and $D = 50$ mm, as determined by FWHM of the detector response in fig. 3. The precision of the measurement allows the diameter of the cylindrical hole (*d*) to be estimated approximately to about 10 mm, being in good agreement with the manufacturer's data ranging from 8 to 12 mm. For simulation purposes we adopted $d = 12$ mm. The measurements also indicate (fig. 3b) that the detector is not coaxial with the cryostat. The shift between their axes is assessed to be 10 mm.

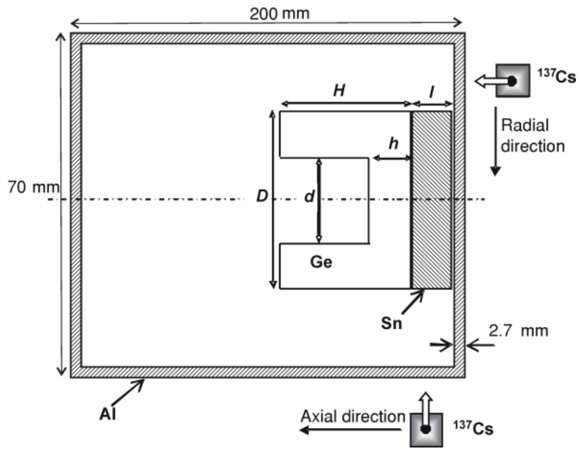

Figure 2. Adopted geometrical configuration of the detector system (not to scale); axial and radial movement of a ^{137}Cs collimated source is used for estimation of the corresponding dimensions *H* and *D*

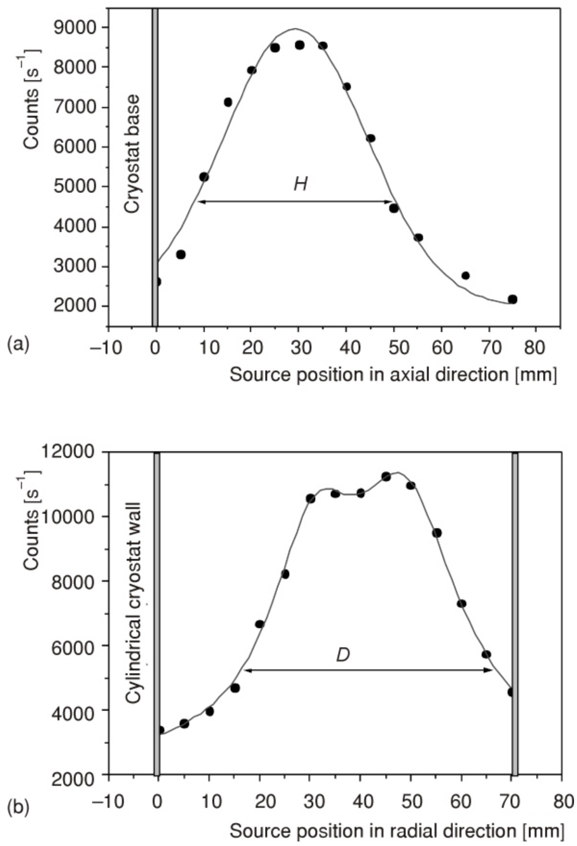

Figure 3. Detector response to (a) axial and (b) radial movement of ^{137}Cs source; results are used to determine the values of *H* and *D* as defined in fig. 2

The thicknesses of the detector base (h) and the superficial tin layer (l) could not be estimated experimentally. In order to determine these parameters, the series of Monte Carlo simulations were performed. The values of h and l were varied until good agreement with the measurements of several standard sources was achieved, resulting in the following adopted values: $h = 10$ mm, $l = 0.27$ mm. In order to adapt our detector for *in situ* measurements we have equipped it with an appropriate, 50 mm thick leaden cylindrical shield and a collimator, as presented on the photograph below (fig. 4).

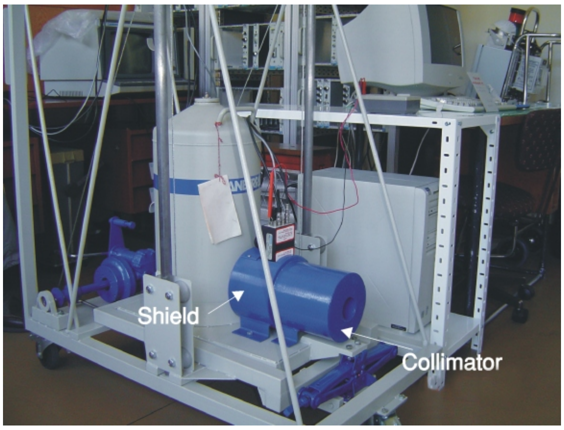

Figure 4. Photograph of the mobile coaxial Ge detector

The heights of the shield and collimator are 200 mm and 78 mm, respectively. They have common diameter equal to 170 mm, while their inner diameters are 70 mm and 50 mm, respectively. Two additional collimators for different geometrical configurations are also available. The shield and collimators serve both for decreasing the background radiation and defining the geometrical conditions of the measurement.

MODEL VERIFICATION

The main criterion for verification of our model was the degree of agreement with the results obtained by the measurement of the standard source activities. The corresponding calculated detector efficiencies were obtained by extensive Monte Carlo simulations, using the MCNP-5.0 code.

As a first check of the consistency of our model we calculate the efficiency of the detector system and compare it to the measured one. The efficiency measurements were performed with standard sources based on ^{54}Mn, ^{57}Co, ^{60}Co, ^{65}Zn, ^{133}Ba, and ^{137}Cs radionuclides. The MCNP geometry model of the experimental setup is presented in fig. 5. The absorbed energy in the detector was modeled using the standard MCNP F8 tally. The corresponding results are shown in fig. 6.

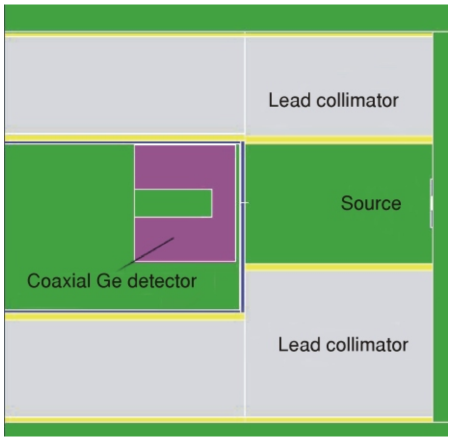

Figure 5. Schematic presentation of the horizontal cross-section in MCNP geometry, used to model the standard calibration sources

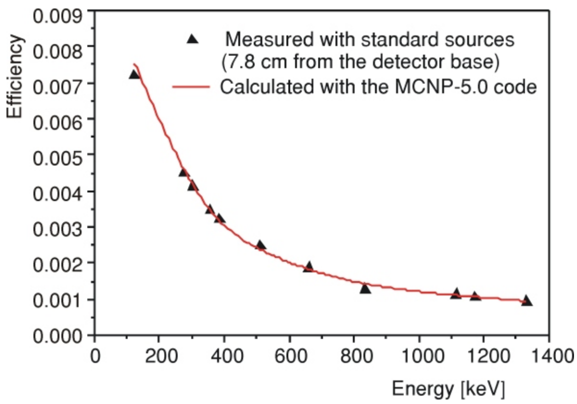

Figure 6. Comparison of the calculated with the measured Ge detector efficiency

The agreement between the calculated and measured efficiency within the full energy range is better than 5%, while for the gamma ray energy $E > 1$ MeV the differences are even smaller (less than 1.6%).

In addition to this, as a second check of the consistency of our model, the energy spectra of ^{137}Cs, ^{133}Ba, ^{57}Co, and ^{60}Co standard sources were measured and calculated.

In order to model the gamma line broadening in the process of its detection in Ge detector as realistically as possible, we measured the dependence of the line width ΔE at half maximal level (FWHM) at the gamma ray energy E. These results are shown in fig. 7. The ΔE *vs.* E dependence in the MCNP simulations is adopted to be of the form $\Delta E = a + b(E + cE^2)^{1/2}$, which presents an improvement compared to our previous

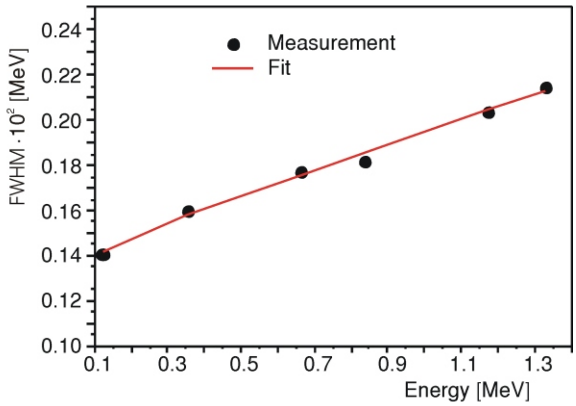

Figure 7. Measured and fitted dependence of the line width ΔE at half maximum (FWHM) for gamma ray energy E

model [19]. Least square fit through the measured points gives the following values for the fitting parameters: $a = 1.249735 \cdot 10^{-3}$, $b = 4.454468 \cdot 10^{-4}$, and $c = 1.465648$.

The obtained energy spectra of ^{133}Ba, ^{137}Cs, ^{57}Co, and ^{60}Co are given in figs. 8, 9, 10, and 11, respectively. The comparison between the calculated

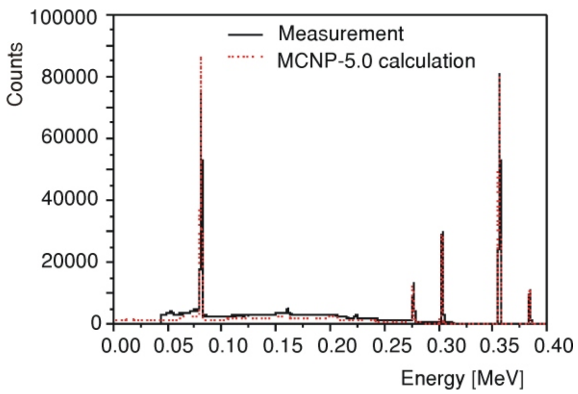

Figure 8. Comparison of measured and calculated energy spectra of ^{133}Ba source

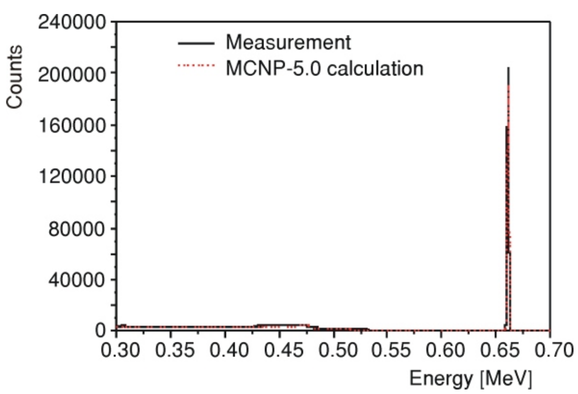

Figure 9. Comparison of measured and calculated energy spectra of ^{137}Cs (^{137m}Ba) source

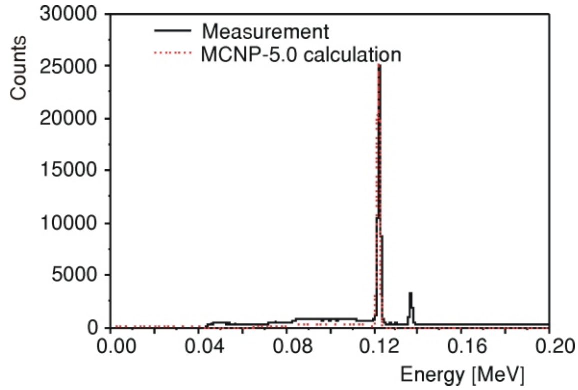

Figure 10. Comparison of measured and calculated energy spectra of ^{57}Co source

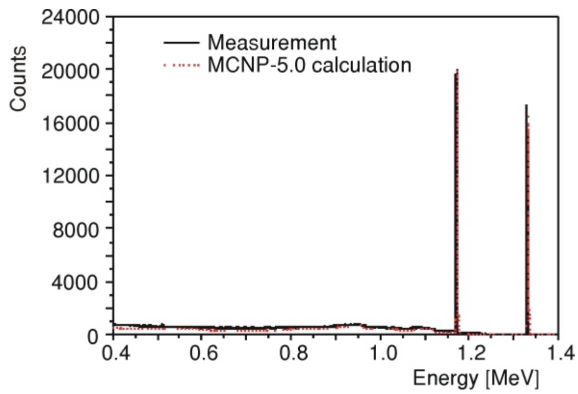

Figure 11. Comparison of measured and calculated energy spectra of ^{60}Co source

and measured results show that maximal relative differences in the energy range from 0.1 MeV to 1.7 MeV lie between –3% and +3%, while in the peaks they are below 0.3%. In order to achieve this level of uncertainty $2\ 10^9$ histories were simulated.

APPLICATION OF THE HPGe DETECTOR AS SOURCELESS CALIBRATION DEVICE

After the successful verification of the model using multi-nuclide standard sources, the testing was extended to realistic radioactive objects with complex geometry and unknown activity. The described MCNP geometry model was used for the calibration of the coaxial Ge detector for activity measurements of small bottle-shaped samples with water taken from reactor pools or stainless steel containers filled with the RA reactor spent fuel elements [20]. Due to different specific activities of the samples, each one was measured at various distances from the detector base, far enough to preserve the detector dead time less than 1%. The identification of the radionuclides present in the sample was achieved by identifying their characteristic gamma peaks in the measured energy spectrum. These data were used for modeling the gamma source of the sample in Monte Carlo simulations.

The MCNP geometry of the coaxial Ge detector used to model the response of water samples is presented in fig. 12. The calculated detector efficiency for two identified nuclides (^{137}Cs and ^{60}Co) in the samples at the given distance from the detector depending on the water weight in the sample is shown in fig. 13. Based on these calculations, the efficiencies for six water samples were determined and the corresponding activities were calculated. As the referent results for comparison we use the measurements of the sample activities performed by the referent Extended Range Ge detector GX5020 calibrated with the ISOCS Calibration Software. The data given in tab. 1 demonstrate good agreement between the referent and our results.

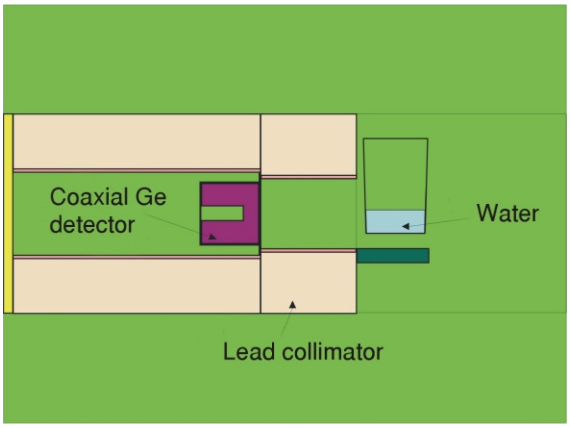

Figure 12. The MCNP geometry of germanium detector used to model the response of the water bottle (vertical cross-section)

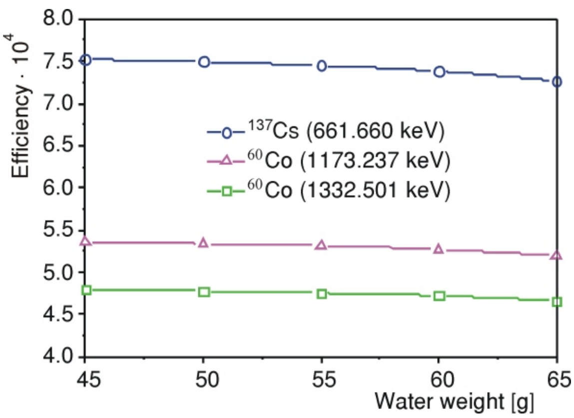

Figure 13. Efficiency of coaxial Ge detector given as function of water weight in the sample, placed from the detector base at 10.9 cm

Table 1. Results of measured and calculated water specific activity in the samples

Sample taken from	Activity [Bq/ml]	
	Referent Ge detector	Our results
Pool 1 Pool 2 Pool 3 Pool 4 Channel in room 141 Channel in reactor hall	114.8	116.3

The differences are within the statistical uncertainty indicating that the characterization of our detector and its numerical calibration by the MCNP code were carried out in a correct way.

The MCNP-5.0 simulations in this case, using 2 10^9 histories per run, were carried out at the Linux cluster of California University at Berkeley.

CONCLUSIONS

In accordance to the contemporary tendencies to calibrate detectors without the usage of radioactive sources, we have described a procedure for achieving this goal in the case of a coaxial (HPGe) detector. The modeling of the detector, being the initial step of the procedure, assumes the estimation of the detector dimensions, which was preformed by scanning the system with ^{137}Cs gamma source. It should be noted that this approach allows the dimensions to be assessed only to a certain degree of precision, which was further improved by their variations in Monte Carlo simulations.

Calibration of the detector was performed by MCNP-5.0 code. Numerically calculated efficiencies for the set of multi-nuclide standard sources were obtained and the results compared with the measurements. The differences were less than 5% within the full energy range from 0.1 MeV to 1.7 MeV and even smaller if we restrict to the energies higher than 1 MeV. Moreover, the calculations of the standard source energy spectra were performed. This type of calculations is considered to be far more demanding with respect to achieving acceptable statistical uncertainties in every single energy channel. Even in this case the calculations showed only ±3% discrepancies to the measured ones within the full energy range, while below the peaks it was only 0.3%.

The next step in our extensive checking of the adopted detector model was the calculation of the detector response to radiation from radioactive samples with unknown activities and non-standard shapes and positions. In all the cases the simulated results have shown excellent agreement with the measurements, confirming that the procedure of sourceless calibration was correctly preformed and that the detector may be successfully applied for *in situ* measurements.

Comparing the suggested procedure to the systems equipped with LabSOCS and/or ISOCS software, one can find it advantageous with respect to the range of shapes and positions that can be treated. This advantage comes from the superiority of the MCNP-5.0 code. On the other hand, the simulations of complex geometrical configurations with the MCNP-5.0 code with statistical uncertainties below few percents very often take several days of CPU time, thus making the usage of computer cluster unavoidable.

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Милијана СТЕЉИЋ, Миодраг МИЛОШЕВИЋ, Петар БЕЛИЧЕВ

МОДЕЛОВАЊЕ ГЕРМАНИЈУМСКОГ ДЕТЕКТОРА И ЊЕГОВА КАЛИБРАЦИЈА БЕЗ ПРИМЕНЕ ИЗВОРА

У раду је описана процедура адаптације коаксијалног германијумског детектора високе прецизности (HPGe) у направу која се нумерички калибрише. Процедура укључује одређивање димензије детектора и успостављање одговарајућег модела система. Да би се постигла успешна калибрација система без коришћења стандардних извора изведене су Монте Карло симулације ради одређивања ефикасности и функције одзива. Детаљан Монте Карло модел развијен је коришћењем MCNP-5.0 кода. Извршена анализа је показала да овај метод представља користан алат за квантитативну процену неодређености радијационих спектрометара и калибрацију детектора гама зрачења, минимализујући тако потребу за применом радиоактивних извора.

Кључне речи: спектрометрија гама зрачења, моделовање германијумског детектора, нумеричка калибрација, Монте Карло метода