MONTE CARLO SIMULATIONS OF A LARGE VOLUME HPGE DETECTOR

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The Gamma Beam System diagnostics of ELI-NP requires a precise determination of the gamma beam parameters up to 19.5 MeV. Part of the diagnostics involves the use of a high efficiency HPGe detector for in-beam measurements. Knowing the detector full peak absolute efficiency over the 0.2-19.5 MeV range is of utmost importance. Given the energy limit imposed by standard gamma-ray sources and nuclear reactions, simulations are a good way of estimating the detector efficiency for the full energy interval. In this work, data obtained from simulation were compared with experimental data in the 100 to 1400 keV energy range. Absolute efficiency has been extrapolated from the simulation up to 15 MeV.

Keywords: HPGe detector, absolute efficiency, Geant4, Monte Carlo simulation

1. Introduction

The Extreme Light Infrastructure-Nuclear Physics (ELI-NP) under construction in Magurele will become one of the most important scientific institutions in Romania and Europe. The research center will host two major facilities. The first one, the High Power Laser System will produce twin beams of 10 PW lasers while the second one will produce a high-intensity, continuously tunable gamma beam. The gamma beam system will deliver beams that are two orders of magnitude higher in intensity than any other facility currently in use, with unprecedented bandwidth. While the beam parameters are clearly defined [1] there is a great need to continuously monitor them during the experiment to ensure the quality of the nuclear data taken. One of the proposed gamma beam diagnostics [2] for the ELI-NP facility is the continuous monitoring of the beam energy using a high efficiency germanium detector (with anti-Compton shield) which is placed directly in the beam. The high intensity of the ELI-NP gamma beam system makes it impossible to do this kind of measurements without previously using an attenuator to reduce the incoming photon flux to measurable levels. Due to the fact that the incoming photon energy can vary over a very broad energy range (0.2-20

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MeV), it is of the utmost importance to understand the behavior of the detectors used for the diagnosis of the beam over the full energy range.

Usually, the absolute efficiency of the detectors is assessed by making well controlled measurements of standard gamma-ray sources with known activity. In this way, the efficiency of the detector can be measured up to 2-4 MeV, depending on the availability of short lived calibrated sources. To extend the energy range of the efficiency calibration, the IAEA proposes [3] a number of reactions that can extend the measurements up to 10 MeV. The most promising reactions to be used are the proton induced reactions which can be carried out at the Tandem accelerator of IFIN-HH. These reactions will allow measurement of the detector efficiency at a few well-defined energies but their precision will most likely be affected by additional uncertainties due to the complex experimental setup required.

Another accessible way of assessing the detector efficiency is to use Monte Carlo simulations. Monte Carlo simulations have the clear advantage that they can be used to obtain the absolute efficiency at any energy, provided that the model of the detector is appropriate. The quality of the detector modelling is checked by comparing the measured experimental efficiency with that obtained from simulations.

In this article we focus on the evaluation of the absolute detection efficiency from direct measurements using calibrated sources and from simulations. The second section describes the experimental setup and presents the results of the measurements. The third section focuses on the description of the Monte Carlo simulations. The forth section presents the simulation results and the comparison with the experiment. Section 5 contains a discussion on how the energy efficiency curve can be extended to the whole energy range of the ELI-NP facility.

2. Experimental detector efficiency

In order to limit the experimental uncertainties, a very simple experimental setup was used. The experimental setup consisted of a point-like ^{152}Eu calibration source placed in front of the detector at various distances. A standard spectroscopy chain made of a Canberra 2002C charge-sensitive preamplifier [4], a model 2026 Canberra amplifier [5] and an Ortec ASPEC-927 multi-channel analyser [6] were used to process the detector signals. A shaping time of 6 μs was used for the amplifier.

The activity of the ^{152}Eu calibration source at the start of the experiment was calculated from the source certificate information and was A_{152Eu}= 525(3) x 10^3 Bq.

Calibration spectra were taken at a few distances between the source and the detector, starting with 20 cm up to 150 cm. A typical energy spectrum is shown in figure 1 which shows the doublet at 1085.8 keV-1089.7 keV in the inset. The energy resolution was around 2.1 keV at 1408.01 keV, in accordance with the technical specifications of the detector.

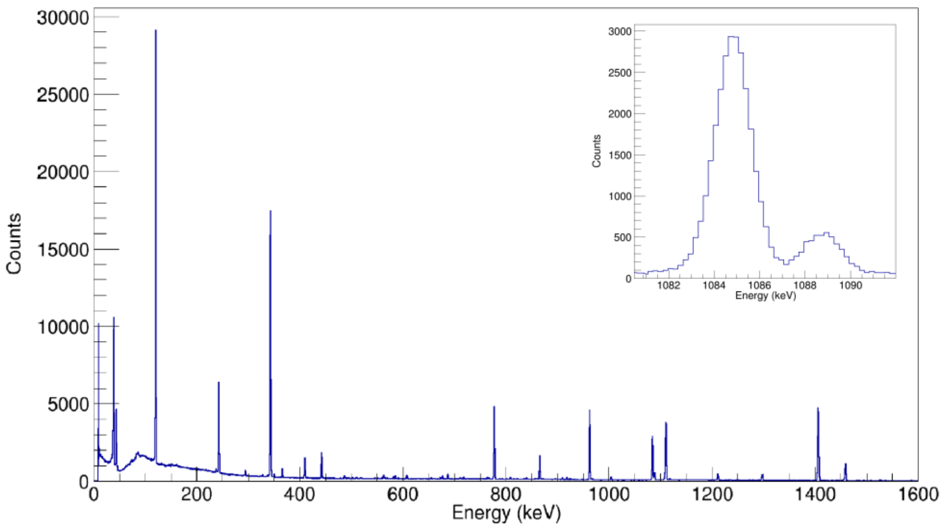

Fig. 1. Experimental ^{150}Eu spectrum measured with a 150 % HPGe detector.
The 1085.8 keV and 1089.7 keV doublet is presented in the inset.
Energy resolution was around 2.1 keV at 1408.01 keV.

The efficiency and the associated uncertainty of the detector was calculated using equation (1):

$$(\%) = \frac{N}{I_\gamma t_c A} \times 100 \qquad (1)$$

where N is the background corrected peak area, I_γ is the branching ratio [7], t_c is the measurement time and A is the source activity.

As the distance decreased the deadtime (reported by the MCA) continued to increase. This has a significant impact on the efficiency calculation since the acquisition time used in equation (1) is no longer a proper estimate of the real measurement time. While the MCA provides an estimate of the real measurement time, it does not provide an uncertainty for this value. As a result, a second set of data was taken by adding a 2 mm lead absorber in front of the detector. The spectra taken in this second experimental condition is no longer useful for a proper efficiency calibration but still provides valuable information for the comparison with simulations.

Two of the efficiency curves are shown in figure 2, where it can be seen that the impact of the lead shield is, as expected, much higher at low energies.

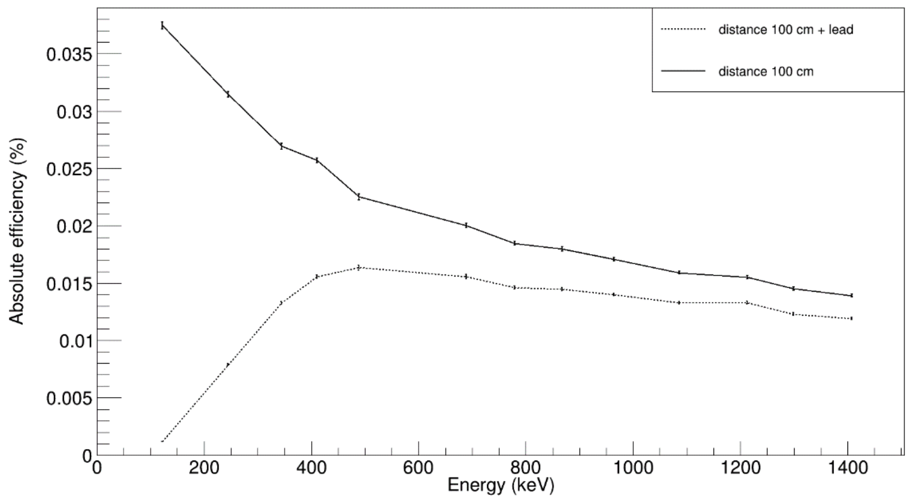

Fig. 2. Energy dependence of the detector's absolute efficiency. The distance between source and detector was 100 cm. The dotted line represents the data taken with a 2 mm lead shield in front of the detector.

3. Monte Carlo simulations

The simulation program used for this work is based on the Geant4 [8] package developed at CERN for studying the response of very complex detectors to high energy particles. Geant4 provides a consistent framework which allows almost any kind of simulation to be performed for almost any type of detector. In order to work, the user of the simulation needs to implement (or select from a few already implemented structures) four user classes, leaving the tedious Monte Carlo work like random number generation and particle propagation to the Geant4 engine. The four areas that need to be implemented by the user are: the source (telling Geant4 what are the properties of the particle source), the geometry (the materials that exist in the simulated space, their position, size, etc.), the physics packages and finally the analysis of the data (responsible for creating the measurement spectra).

The source used in the present simulation is a point like source emitting single energy photons isotropically, in a cone beam configuration. This is a simple variation on a complete isotropic source needed for the absolute efficiency measurements, improving the computation time. Single energy photons with energies similar to those in the ^{152}Eu spectrum were emitted from the source. Because of the large distance between the detector and the source the effect of coincidences and pile-up is deemed negligible.

The geometry implemented in the simulation is that of a single HPGe detector, without the LN2 dewar. This is due to the fact that the capsule of the detector is placed on a cooling arm, roughly 30 cm from the dewar (7905-30U/S cryostat [9]). The self-absorption of radiation in the source itself or in the materials supporting the source is neglected because the source was suspended at the proper height using very light and porous materials.

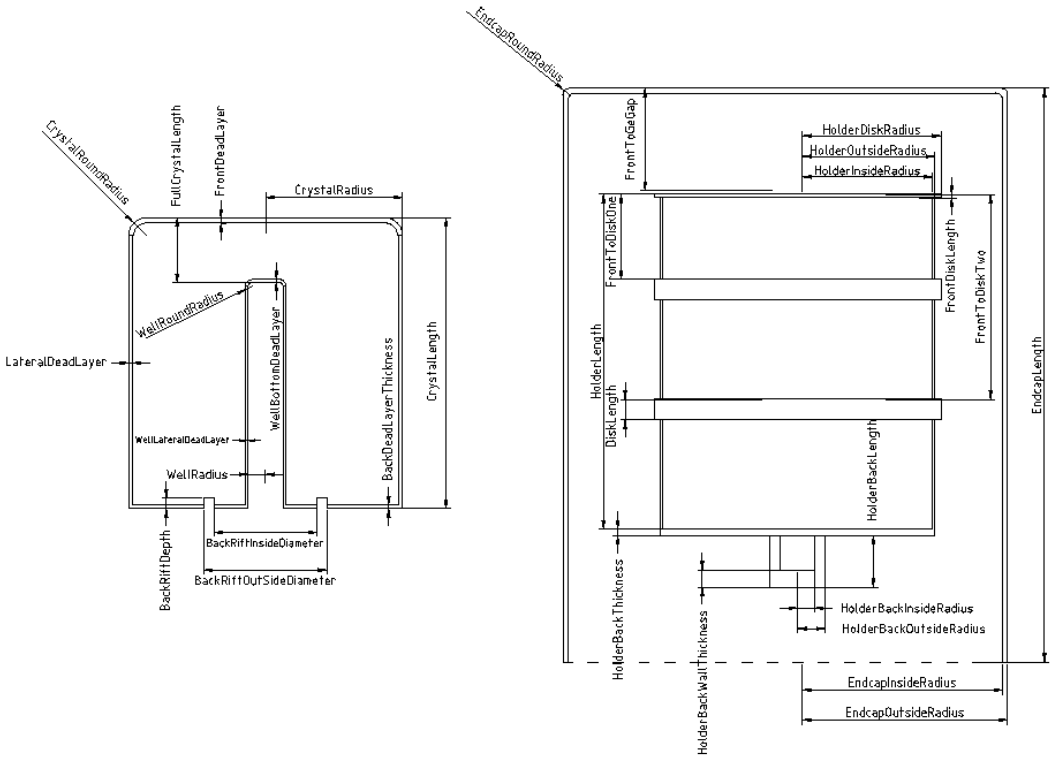

Fig. 3. Schematic representation of HPGe detector geometry. The picture shows on the left side the germanium crystal design, while the crystal holder and the end-cap are given on the right side

The detector is made of three main parts: the HPGe crystal, the crystal holder and the external end-cap as shown in Fig. 3 together with the parameters used for its description. Roughly 33 parameters were used for the geometrical description of the detector, most of them taken from the producer. Where the values were not available, some realistic assumptions were made. The crystal has a closed-ended bulletized [10] coaxial shape. The radius of the crystal is 45.25 mm and has a length of 91 mm. The well radius is about 0.5 cm with a depth of 63 mm. The crystal is a p-type with the n^+ outer contact of about 0.4 mm thick, and the inner p^+ contact thickness of about 0.3 μm. The crystal holder is an open ended cylinder made of aluminium, with three external cylindrical reinforcements. A smaller cylinder is attached at the back of the main shape. The end-cap is made of 1.5 mm thick aluminium and it has cylindrical shape with front rounded edges.

The physics packages used in this simulation are based on the implementation of the low energy photon interaction in Geant4. Two such implementations exist, one based on the one previously used for the Penelope code (G4EmPenelopePhysics) and one based on the Livermore models (G4EmLivermorePhysics). These two models are recommended to be used with photons in the range from a few keV up to a few MeV. The results obtained with both of them are identical (within simulation uncertainties) for the energies used in the comparison with the experiment.

The analysis used in the code is straightforward. The active area of the detector was defined using G4MultiFunctionalDetector. The energy deposited in the sensitive area of the HPGe detector is retrieved with the use of primitive scorer G4PSEnergyDeposit at the end of each event. The data was stored in histograms at 0.5 keV per channel using classes from the ROOT [11] framework.

4. Simulation results and comparison with experiment

The simulation package allows us to obtain an efficiency curve for each of the geometries used in the experiment. Nevertheless, the simulations only take into account the interaction between photons and the detector without any of the effects due to the electronics, signal processing or data acquisition. As a result, only the experimental data acquired under low dead time conditions can be directly compared with the simulations. The relative difference (R) was calculated using formula (2).

$$R = \frac{\varepsilon_{simulated}}{\varepsilon_{experimental}} - 1 \qquad (2)$$

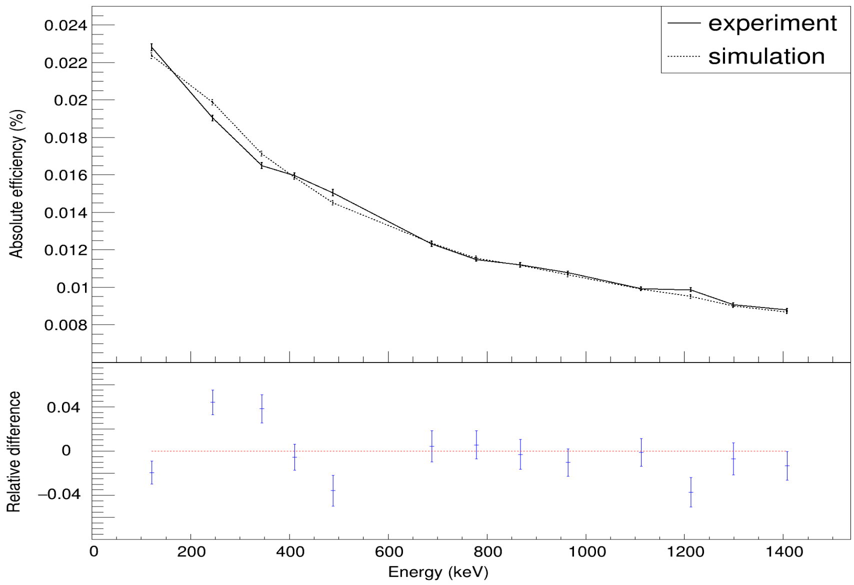

Fig. 4. The top part of the figure contains simulated and experimental absolute efficiency curves. The lower part shows the relative difference between simulation and experiment. The distance between source and detector was 130 cm.

Figure 4 shows the comparison between the experimental efficiency obtained with the source at 130 cm from the detector in the configuration where no lead shield is present, while figure 5 shows the same comparison between them for the distance of 80 cm, in the case where the lead shield is employed. The bottom graphs in each of the figures shows the relative difference between the measured efficiencies and those calculated from the simulations. It can be seen that the agreement is very good for the whole energy range. The uncertainties shown in the bottom graph are the cumulated uncertainties from both the experimental and simulated data.

The largest discrepancy between the simulated and experimental data is found for the 121.8 keV peak in the configuration where the lead shield is used. This discrepancy is most likely due to the fact that while we measured the average thickness of the lead shield to be 2 mm, at this low energy the detector response is sensitive to any irregularity in the thickness. As a result, the value at the 121.8 keV point is not presented in the comparison in the case where the lead shield is employed.

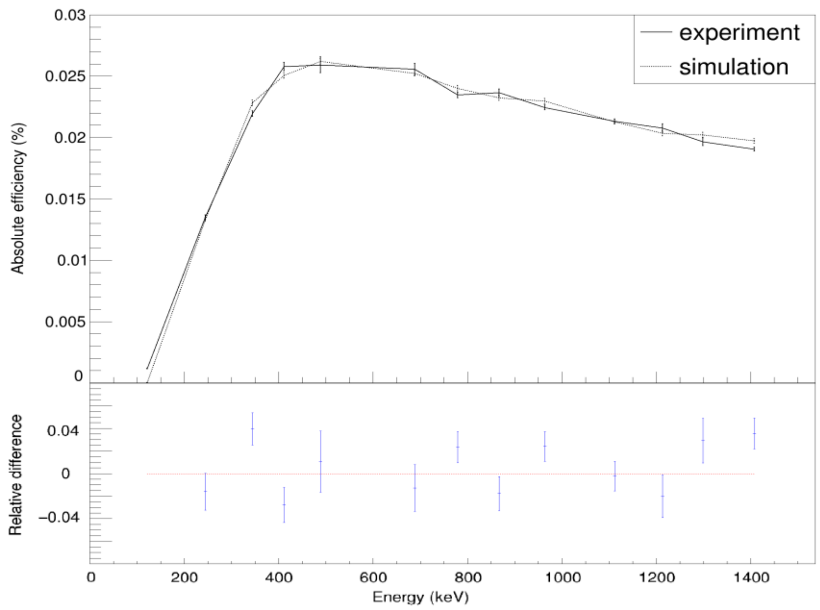

Fig. 5. The top part of the figure contains simulated and experimental absolute efficiency curves. The lower part shows the relative difference between simulation and experiment. The distance between source and detector was 80 cm. The data is taken with a 2 mm lead shield in front of the detector.

5. Extrapolation to high energies

While the goal of the present work is to understand the behavior of the detector for a broad energy range, it is clear that the simulations can't be used to assess the response of the detector over the whole energy range of the gamma beam system of ELI-NP without any high energy experimental efficiency points. Simulations using the configuration without any shielding were carried out up to 15 MeV, using both physics packages (Livermore and Penelope). The results of these simulations are shown in figure 6, where the bottom graph shows the relative difference between the values obtained with the two physics packages.

Note that both physics packages are giving similar results up to an energy of a few MeV, however at higher energies a clear discrepancy can be observed. To make the matters more problematic, the discrepancy is of the same order of magnitude (5%) with the desired efficiency calibration uncertainty. The results of this simulations clearly justify carrying out experimental efficiency measurements at high energies, and also set the limit for the desired precision of these measurements.

The obtained values of the efficiency at high energies can be used to estimate the required beam time for any of the (p,gamma) reactions that can be carried out.

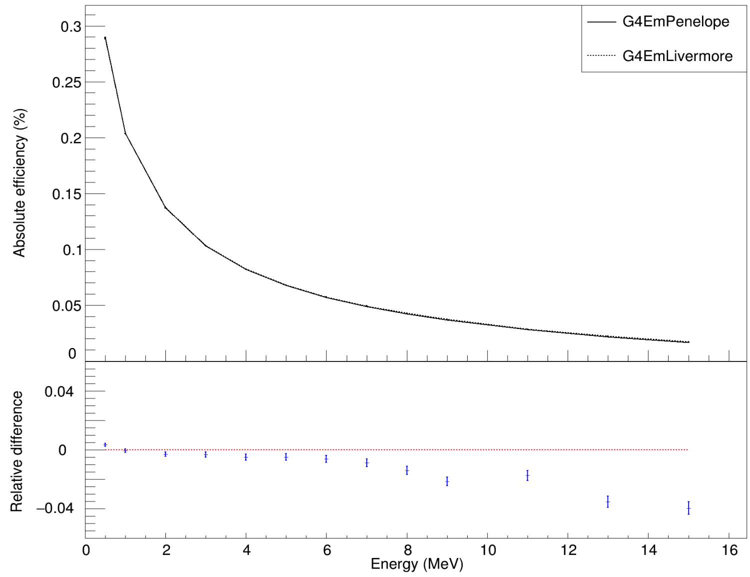

Fig. 7. Comparison of detector absolute efficiency using two physics models in the 0.5 MeV - 15 MeV range. Distance between the detector and the source was 25 cm.

The purpose of the work presented in this article is to lay the foundations for one of the gamma beam diagnostics of the Gamma Beam System under construction at ELI-NP. Experimental measurements using a large volume HPGe detector were performed and the results were compared with the simulations. The agreement between the simulation and the experiment is very good in both configurations that were used. The results of the simulations gives trust in the detector modelling but the extension to higher energies becomes troublesome due to the different simulated results obtained with two different physics packages. The simulation demonstrate the necessity to carry out experimental measurements at high photon energies and can be used to assess the requirements for the experimental design of these experiments.

REFERENCES

[1]. *O. Adriani et al.*, Technical Design Report; EuroGammaS proposal for the ELI–NP Gamma beam System, arXiv:1407.3669v1 [physics.acc-ph].
[2]. *H.R. Weller et al.*, Romanian Reports in Physics, Vol. 68 (2016), S447 - S481.
[3]. IAEA, Update of x-ray and gamma ray decay data standards for detector calibration and other applications, Volume 2, Vienna 2007.
[4]. Model 2002 Spectroscopy Preamplifier, User's Manual, 2004
[5]. Canberra, Model 2026 Spectroscopy Amplifier, 2010
[6]. Aspec-927 Dual Multichannel Buffer, User Manual, 2014
[7]. Nuclear Data Sheets 114, 1497, 2013.
[8]. *S. Agostinelli et al.*, Nucl. Inst. & Meth. in Phys. Res. A, Vol. 506 (2003), 250-300.
[9]. U-Style Cryostats. www.canberra.com. Web. 29 June 2016.
[10]. *G. Knoll*, Radiation Detection And Measurement, New York: Wiley, 1979.
[11]. *R. Brun, F. Rademakers*, ROOT - An Object Oriented Data Analysis Framework,
Proceedings AIHENP'96 Workshop, Lausanne, Sep. 1996, Nucl. Inst. & Meth. in Phys. Res. A 389 (1997) 81-86.