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Improving Simulations of the GRETINA Gamma-Ray Tracking Array

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1 Abstract

The GRETINA gamma-ray tracking array is an array of gamma-ray detectors used by the nuclear structure community to study properties of atomic nuclei. The simulation code toolkit used the build the code for GRETINA simulations is called Geant 4 and our research group developed and maintained code built from Geant 4 throughout the research time period. The problem is that when we compare measurements to simulations we see that the simulation is more efficient than the real array. This led us to investigate the size and shape of inactive volumes in the detectors by comparing our simulations with measurements made at Lawrence Berkeley National Laboratory with a pencil beam of gamma rays in order to improve our model of the detectors. The aim is to improve the simulations so that they match the real data and discover more about GRETINA as a whole.

2 Introduction

The GRETINA gamma-ray tracking array [2, 4] consists of 48 coaxial Ge detector crystals shaped like irregular hexagonal polyhedra that are packed together in groups of four called "quads". There are two crystal types, type A and type B, and these two crystals have slightly different geometrical shapes that fit nicely together. A quad consists of two A-type and two B-type crystals packed together and GRETINA has 12 quads total. The plan is to eventually build 30 quads to construct a full sphere of detectors. Each quad has a cylindrical hole cut out of the center of it that doesn't fully extend to the front of the crystal. This hole is where they put gamma ray source.

There are certain areas of the crystal that are inactive and they are called dead layers. Through experimental data, we see that GRETINA has certain dead layer thickness around the coaxial of each crystal called the coaxial dead layer (CDL) and at the back of each quad called the back dead layer (BDL). In the simulations, we try to improve the efficiency by finding the optimal the thickness of the CDL and BDL.

A photopeak is a peak that is formed in the energy spectrum by events in which the gamma ray deposits all of its energy in the detector. Photopeak efficiency is a performance parameter that we are most interested in when evaluating gamma-ray detectors because it is a measure of well a detector can see gamma rays. Photopeak efficiency is the ratio of the number of full energy events to the total number of γ-ray photons incident on the detector. The overall photopeak efficiency is especially important because it is an indicator of the accuracy of the simulation. This is the main tool.

3 Experiment

3.1 Pencil Beam Measurements

Pencil-beam measurements of GRETINA quad 4, crystal 4 were made at Lawrence Berkeley National Laboratory using the GRETINA scanning table. A 0.3 m Ci ^{137}Cs source encased in a Heavimet collimator was mounted on stepper-motor-driven stage that could be positioned in X and Y as shown in Figure 1. The collimator bore was 1 mm in diameter and 87.3 mm in length, giving a beam with an opening angle of 11.4 milliradians. Gamma-ray spectra were collected for 40 minutes at each position in a scanning pattern of four sets of 20 points in Y at X = 10.3, 5.3, 0.3, -4.7 mm and one set of 20 points in X at Y = -49.2 mm. The points were collected at a spacing of 4 mm outside of the region of the central contact and 2 mm near the central contact of the crystal.

4 Coaxial Dead Layer

4.1 Pencil Beam Simulations

4.1.1 Alignment of the Scanning Table Simulation

There was an offset in the y direction evident in Fig. 2 when $\psi = 165°$ in the pencil-beam scans that led us to believe that the cause of this shift was the angular orientation of the guard in the simulation was not right. Once we find the offset in ψ, then we can also look a possible for offset in the y position of the scanning table.

In order to test the different angles of the scanning table we had to first choose a range of angles to look at. The original angle for the scanning table was $\psi = 165°$ so we decided to look at the range between $161 - 166°$ in $1°$ steps. This angle ψ is the angular orientation of the quad about its central axis.

We developed, using Geant-4 [1], a code to find the best CDL thickness for each angle by scanning through CDL values that ranged from 1.5 mm to 3.5 mm and find the best one by finding the minimum χ^2 value.

Along with calculating the best CDL, we used the Minuit package [3] to find the best scale factor for the simmulations and the χ^2 values for each angle. The Minuit package performs a weighted least-squares χ^2 minimization to find the

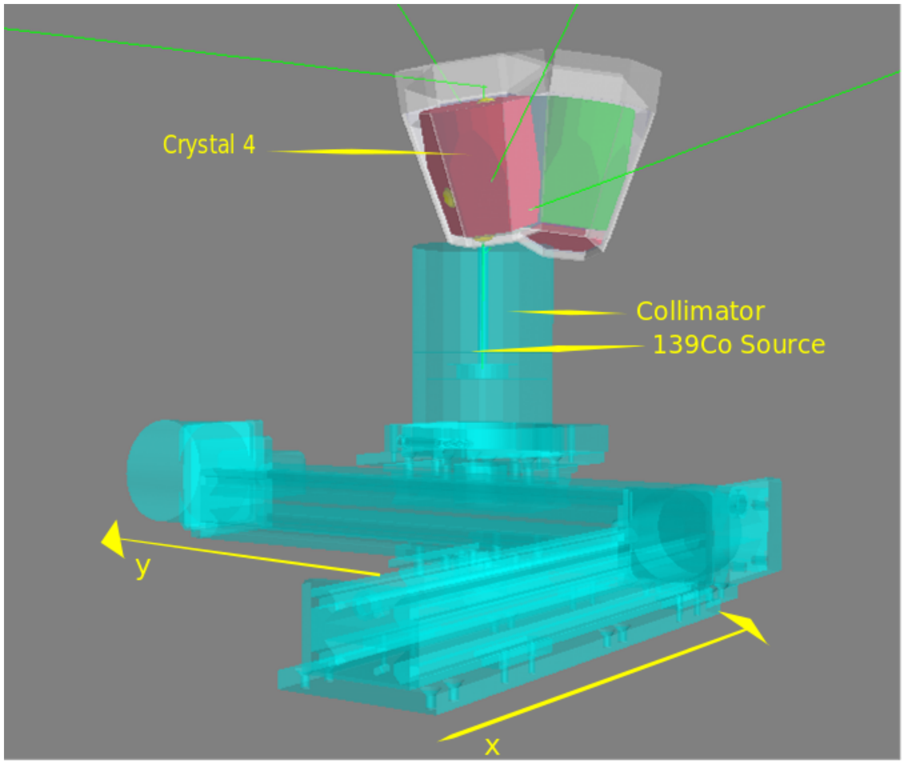

Figure 1: This is a visualization of the simmulation of the GRETINA scanning table. The controller x and y axes are shown.

best scaling of the simulations to the measurements. Minuit uses the following definition for χ^2

$$\chi^2 = \frac{(f(x_i, \alpha) - e_i)^2}{\sigma_i^2} \tag{1}$$

where α is the vector of free parameters being fitted, and σ_i are the uncertainties in the individual measurements e_i. The χ^2 values are values of χ^2 per degree of freedom. To find the best angle out of the range, we graphed the angle verses the χ^2 value with a cubic polynomial fit. The angle was calculated to be 163.328°. Then we repeated the process described above to find the best CDL, the best scale for the best CDL, and the χ^2 value for 163.3°. After finding ψ again, we discovered that the best angle was 163.337° and the best CDL for that angle was 2.14 mm. Refer to Figures 7-11.

We next investigated a potential Y shift in the simulations relative to the scanning table. We decided to use the best angle that we calculated above and change its Y shift. We predicted that the offset to the Y shift was not that large, so we investigated a range of -1 to +1 mm, increasing 0.5 mm increments.

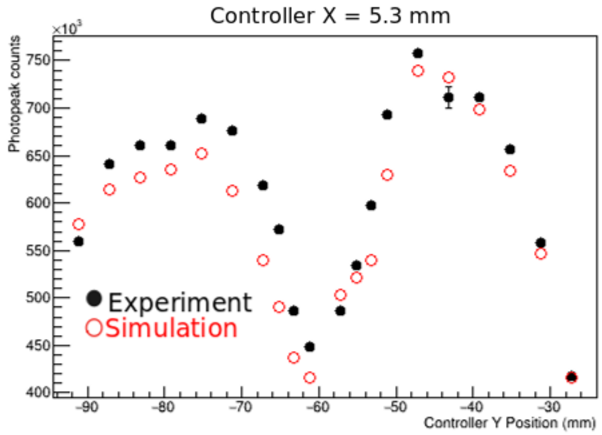

Figure 2: Measured and simulated photopeak efficiency vs. controller y at x = 5.3 mm with $\psi = 165°$.

The best scale and the Figure of Merit value was then found for the best CDL value using grutinizer. With this information, we created a graph of the Y shift increments vs the FCN values and discovered that the best value was 0 so there is no need to change the Y shift.

5 Back Dead Layer

5.1 Efficiency Measurements

Photopeak efficiency measurements were made of quad 4, crystal 4 while it was installed in the GRETINA array at the National Superconducting Cyclotron Laboratory. Here, we focus on comparing measured and simulated photopeak efficiencies at gamma-ray energies from ^{152}Eu and ^{56}Co gamma-ray calibration sources spanning the energy range 245 - 3451 keV. To optimize the BDL thickness, I used photopeak efficiencies for events that involve the back slice of the crystal.

5.2 Simulations

We created simulations where the BDL ranged from 1.5 mm to 5.0 mm increasing in 0.5 mm increments and for each simulation the χ^2 was calculated. Then we found the optimal BDL by graphing the BDL thickness vs the χ^2 value with a cubic polynomial fit to find the BDL thickness when the χ^2 value is at its lowest. The result we got was BDL thickness of 3.41 mm. We next had to check if the new BDL changed the CDL significantly and try to optimize the both of them. In order to do this, we had to find the best CDL when the BDL=3.41 mm for 163.337° which turned out to be 2.11 mm. We repeated the process of

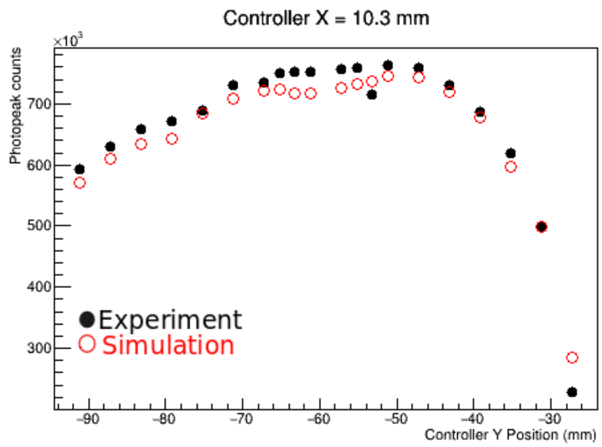

Figure 3: Measured and simulated photopeak efficiency vs. controller y at x = 10.3 mm with $\psi = 165°$.

finding a new optimal BDL thickness and find the best CDL thickness for that measurement. The final results were a BDL of 3.4 mm ±0.1 mm and a CDL of 2.12 mm ±0.01 mm.

6 Photopeak Efficiency of the Full Model

The photopeak efficiency of the full model is needed to see the performance of the simulation compared to the real data after careful calibrations. We used code to the create the graph and percent uncertainty of the overall photopeak efficiency. As a result we were able to produce the graph in Figure 12 and get the simulated photopeak efficiencies are 11% high on average. This result suggests that we way need to put dead layers on the outside of the detector in the simulations and see how that affects the efficiency. We plan to pursue this in future work.

References

[1] S. Agostinelli et al. Geant4â"a simulation toolkit. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 506(3):250–303, July 2003.

[2] Paul Fallon, Alexandra Gade, and I-Yang Lee. GRETINA and Its Early Science. *Annu. Rev. Nucl. Part. Sci.*, 66(1):321–339, October 2016.

[3] F. James. CERN Program Library Long Writeup D506 MINUIT, 1993.

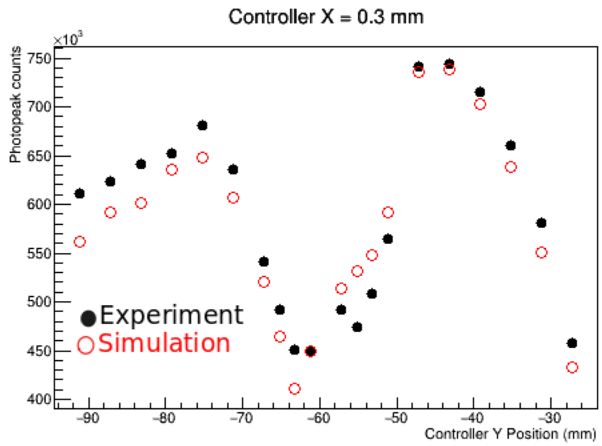

Figure 4: Measured and simulated photopeak efficiency vs. controller y at x = 0.3 mm with $\psi = 165°$.

[4] I.-Yang Lee. Gamma-ray energy tracking array: GRETINA. *J. Phys.: Conf. Ser.*, 420:012156, March 2013.

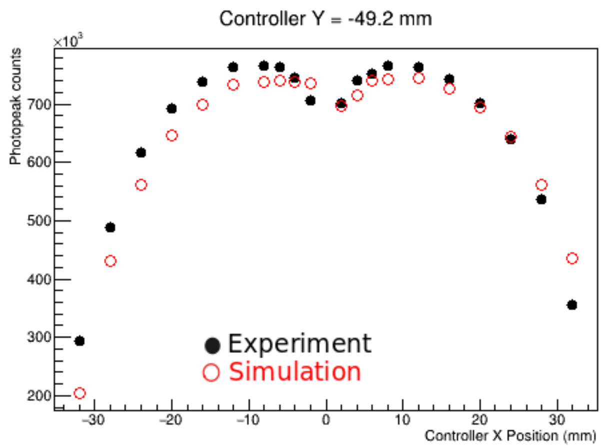

Figure 5: Measured and simulated photopeak efficiency vs. controller x at y = -49.2 mm with $\psi = 165°$.

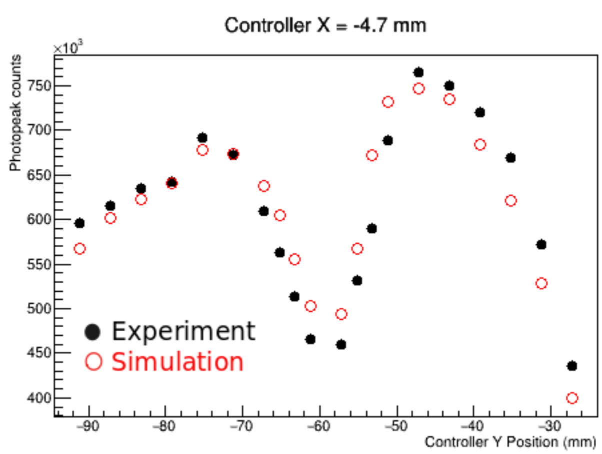

Figure 6: Measured and simulated photopeak efficiency vs. controller y at x = -4.7 mm with $\psi = 165°$.

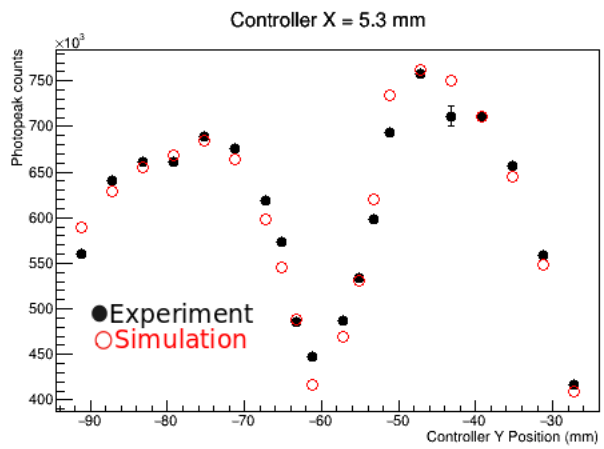

Figure 7: Measured and simulated photopeak efficiency vs. controller y at x = 5.3 mm with $\psi = 163.3°$.

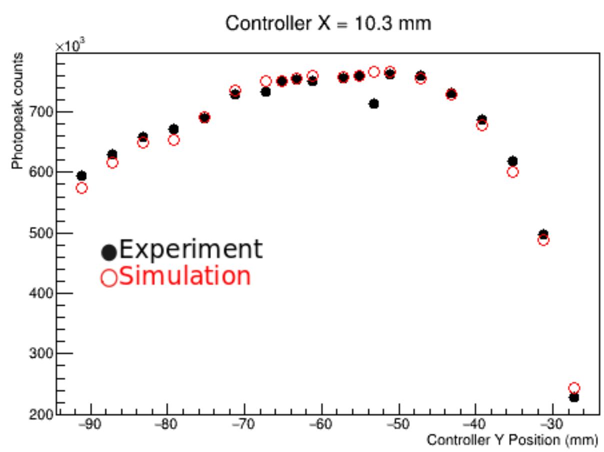

Figure 8: Measured and simulated photopeak efficiency vs. controller y at x = 10.3 mm with $\psi = 163.3°$.

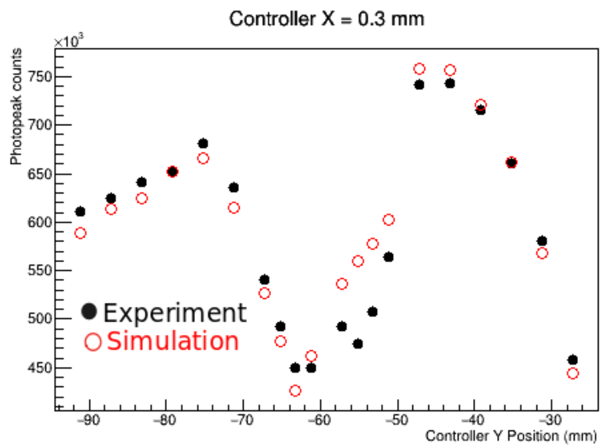

Figure 9: Measured and simulated photopeak efficiency vs. controller y at x = 0.3 mm with ψ = 163.3°.

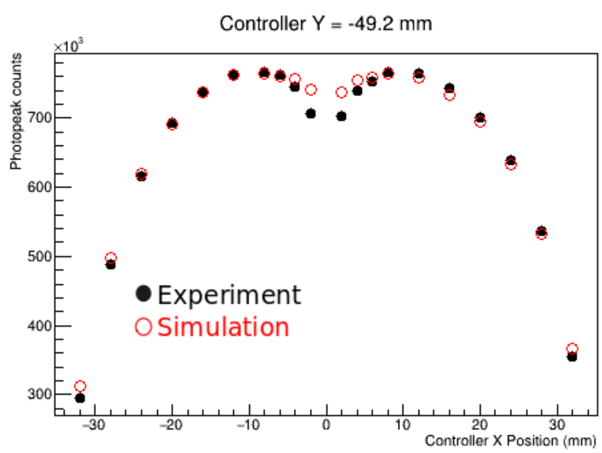

Figure 10: Measured and simulated photopeak efficiency vs. controller x at y = -49.2 mm with ψ = 163.3°.

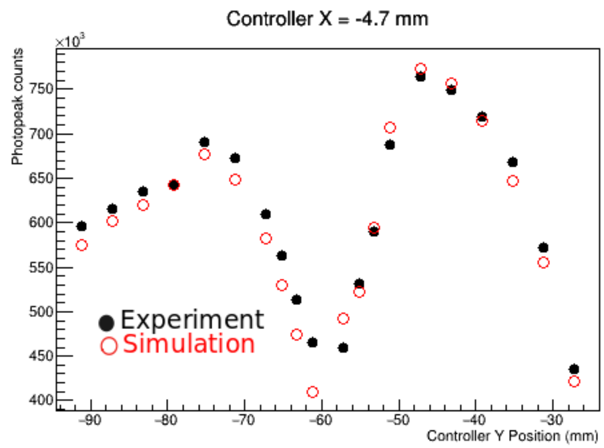

Figure 11: Measured and simulated photopeak efficiency vs. controller y at x = -4.7 mm with ψ = 163.3°.

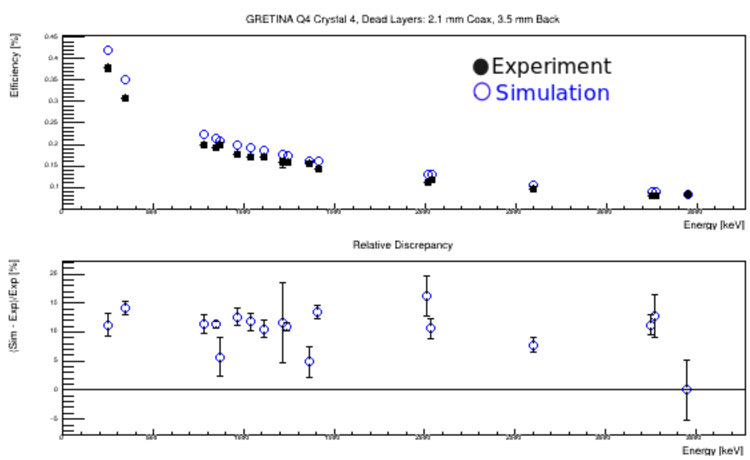

Figure 12: Measured and simulated photopeak efficiency of the whole crystal (top panel) and the relative discrepancy between simulations and measurements (bottom panel).