CHRISTOPHER NEWPORT UNIVERSITY

PHYS 498: CAPSTONE

FINAL REPORT

Further Modeling of PhytoPET Experiments using GATE

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Contents

1 Abstract

In modern experimental physics, simulations have become increasingly popular implementations to the research and design process. The Radiation Detector and Imaging Group (RDIG) at the Thomas Jefferson National Accelerator Facility (JLab) has expressed interest in the creation of a simulation for one of their projects which is known as PhytoPET. The PhytoPET project utilizes positron emission tomography to analyze the biodistributions of live plants via the use of positron-emitting radioactive tracers. This research provides key insight into how carbon is transported in plants and can lead to the optimization of plant productivity and bio-fuel development. To evaluate the feasibility of experiments, the RDIG wanted to incorporate the GEANT4 Application for Emission Tomography (GATE) into the PhytoPET project. A previous capstone project began the development of the simulation by building the framework needed to simulate different experiments. The goal of this project is to introduce new functionality into the PhytoPET GATE simulation that will allow the RDIG to simulate more complex experiments. This project simulates an in-lab PhytoPET experiment in which capillary tubes were filled with a radioactive tracer and inserted into different media, such as water and dirt. To accomplish this, this project defined new media in which the simulated environment can be filled with, created a macro file for the fluorine-18 radioactive tracer and a macro file that creates simulated capillary tubes to which the fluorine-18 source can be attached, and new physics processes. Python Jupyter Notebooks were used to analyze the energy deposition of the photons produced from the decay of the fluorine-18 source. This project proves that GATE is an effective simulation software to simulate more complex PhytoPET experiments. Using methods similar to the ones taken up in this project will allow the RDIG to test new experimental designs and verify the results of future and past experiments.

2 Introduction

For the last decade or so, the RDIG at Jefferson Lab has been working on the PhytoPET project. Their mission is to support the development of new detectors for the experimental nuclear physics program. In addition to the discoveries that have been produced from the PhytoPET project, the group has been instrumental in the development of clinical and pre-clinical imagining technology that is used for the treatment of diseases such as cancer. The PhytoPET project utilizes Positron Emission Tomography (PET) to develop images and models of the bio-distributions of positron emitting tracers, such as $^{11}CO_2$, that are injected into live plants. This research provides key insight into the process of photosynthesis. The $^{11}CO_2$ radioactive tracer in particular is used to facilitate research toward the optimization of plant productivity, biofuel development, and carbon sequestration in biomass [1]. The PhytoPET design utilizes positron-sensitive photomultiplier tubes (PSPMTs) and scintillators to create individual standalone modules that are used to detect positron emissions from the tracer. In order to further evaluate the feasibility of experiments, the RDIG wanted to incorporate the GEANT4 Application for Emission Tomography (GATE) into the PhytoPET project. GATE is a software tool that is commonly used to model nuclear medicine experiments using simulated environments. Last year, a former Christopher Newport University student, Carly Wever, began the integration and development of GATE software into the PhytoPET project [2]. Her project resulted in the successful simulation a simplified configuration of a well understood PhytoPET system in which two photons were emitted back-to-back with each other. Through her efforts, GATE was determined to be a sufficient tool to create simulations of the PhytoPET experiments that the RDIG wishes perform and further analyze. Her project serves as the groundwork that further implementations of the simulation can be built on.

This project set out to prove the capabilities of GATE to model a more complex PhytoPET experiment. The experiment in question involved the use of cylindrical capillary tubes that were filled with a radioactive tracer, fluorine-18 (^{18}F), and inserted into a cylindrical phantom environment that contained different media [3]. When the ^{18}F decayed, it produced a positron (beta-plus particle) which will annihilate with surrounding electrons and produce two photons with an energy of 511 keV. The RDIG found, through this experiment, the raw energy spectra versus detector counts at that energy level tend to attenuate when the capillary tubes were placed in media other than air. The other media that the group experimented with included water, dry-dirt, and wet-dirt to resemble common media that surround plants. Hence, the expectation of this project is to generate a simulation that will produce similar results to those obtained in the in-lab experiment. To achieve this goal, this project will create several new macro files which will add following:

1. New geometry what will simulated the used in-lab capillary tubes and phantom cylinder that held the different media.

2. New media in which the simulated environment can be filled with.

3. The radioactive tracer of choice which is fluorine-18.

4. New physics processes that will allow for a more accurate simulation. These include the radioactive decay process and positron-electron annihilation process.

These implementations will allow for the most accurate simulation of the phantom capillary experiment and should produce results similar to the in-lab experiment.

3 Theory

3.1 Mathematical Theory

The PhytoPET project that involves cylindrical capillaries revolves around the decay of the ^{18}F atom and the emission of positrons. Every radioactive isotope has a quantity called activity which is defined as the number of disintegration that takes place at its core at a given moment of time or number of decays per second. It is given as

$$A(t) = A_0 e^{-\lambda t} \tag{1}$$

where λ is the decay constant and A_0, the initial activity, is given as $A_0 = \lambda N_0$. N_0 is initial amount of atoms in a given sample of the radioactive isotope. Activity is measured is in both becquerel (Bq) and Curies (Ci). The conversion between the two is as follows:

$$1 \text{ Ci} = 37 \times 10^9 \text{ Bq} \tag{2}$$

In the phantom capillary experiment, the radioactive tracer, ^{18}F, has a value of 400 micro-curies which equals 14.8 mega-becquerel [3]. One other useful quantity when it comes to the analysis of radioactive isotopes is its half-life. It is defined as the amount of time it takes for the original amount of a specified quantity to be reduce by half. The formula for the half-life of an isotope is:

$$t_{1/2} = \frac{\ln 2}{\lambda} \tag{3}$$

The half-life of ^{18}F is approximately 6865 seconds.

Positrons are particles that are similar to the electron in mass, but have an opposite charge. Positrons are the antiparticle of the electron. Positrons are emitted through radioactive beta plus (β^+) decay. β^+ decay involves the decay of an atom that has an excess of protons. One of the protons decays into a neutron, neutrino, and a positron as described by the below equation:

$$p \rightarrow n + e^+ + \nu_e \tag{4}$$

Once emitted, the positron travels for a short period of time before it annihilates with a nearby electron. When the positron and electron annihilate, they produce two gamma particles (photons) via the electromagnetic interaction. This process is described by:

$$e^+ + e^- \rightarrow \gamma + \gamma \tag{5}$$

The two gamma particles produced then travel in opposite directions in order to conserve momentum within the system. The energies of the photons can be determined by the equation, $2m_e c^2 \approx h\nu_1 + h\nu_2$, which is derived from the conservation of four-momentum in the system. Since photons are massless particles, the frequencies of the two photons emitted, ν_1 and ν_2, will be equivalent. This leads to the result that each photon will have an energy of 0.511 MeV. These two gamma particles then travel away from the source of the annihilation within the plant and interact with one of the detectors. When the photons are produced inside different media, the amount of detector counts that readout a photon energy value of 0.511 MeV drastically decreases from the counts registered from air. Since other media, like water or dirt, have a larger density than air, it is expected that this attenuation should occur.

3.2 Data Analysis Procedure

In the in-lab experiment, the gamma rays travel away from the source of annihilation and interact with one of the PhytoPET detector modules. These detector modules utilize positron-sensitive photomultiplier tubes to collect the gamma rays and produce an electric signal which can then be interpreted by the RDIG. To simulate this process within GATE, this project makes use of a LYSO crystal array to simulate the positron sensitive photomultiplier tubes. The simulated gamma rays will collide with these LYSO crystal array blocks to mimic in-lab gamma rays colliding with the positron-sensitive photomultiplier tubes. Then, through the use of digitizer modules that are used to simulate the response of a physical photomultiplier tube, the signals produced from the simulated gamma rays are analyzed. In GATE, the collision of a particle with a simulated detector block is known as a Hit. Each Hit stores information on the position, time, momentum, interaction type, and energy deposition of each collision. The output of each digitizer module represented by a Pulse with the output of the final module being a Single. Singles represent the most accurate depiction of what an in-lab photomultiplier tube produces. The process of obtaining a Single within the simulation is shown below.

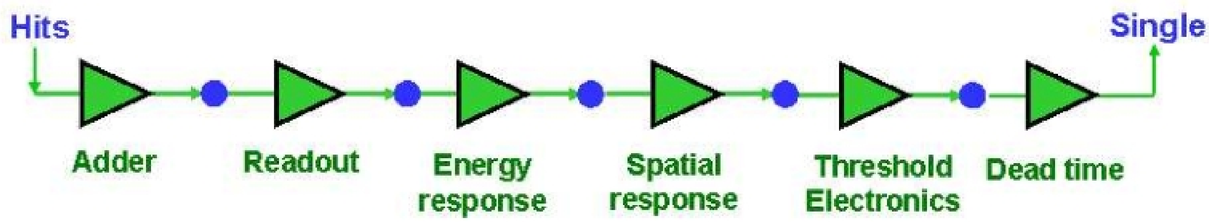

Figure 1: Digitizer chain of modules that begins with Hits and ends with a Single [4]

All of the data that is collected during each individual simulation run is outputted into a text file containing information on the number of events that took place as well as the elapsed simulation time and a .root data file that contains Hits, Coincidences, and Singles data. This project will primarily focus on the energy deposition of the simulated gamma rays. The simulation will be run four times, one for each media that is used in the in-lab experiment. These four media are air, water, dirt, and wet-dirt. To analyze the energy deposition of the photons produced within the four different media, the output .root file will be analyzed in python using Jupyter Notebooks and the uproot python library. The energy deposition data in the .root files are converted into numpy arrays which can then be visualized using the matplotlib python library. The objective is to produce plots of the energy deposition of each simulation run and see not only a defined peak around the 511 keV mark, but also attenuation in the peak for the different media. If the results from analyzing the Singles produced from each simulation run do not produce the desired results, Coincidence data may also be reviewed. Coincidences occur when two or more Singles are found within a coincidence window; the Singles are grouped together to form a Coincidence event [4].

4 Methods

4.1 vGATE

One of the primary differences of this project in comparison to the project compiled by Ms. Wever is the use of a new version of GATE on a new operating system, Virtual GATE (vGATE). This project is compiled in GATE version 9.1 which introduced new functionality based on updated to GEANT4 and depreciated some of the command lines used in the base project. Therefore, after pulling Ms. Wever's project from her GitHub repository, much of the macro files and commands had to be debugged or updated to satisfy the new version of GATE. In addition to adapting the project to a new version of GATE, a new operating system of GATE was used to compile this project which is known as vGATE. vGATE is a complete virtual machine that utilizes an Ubuntu 64bits operating system which can be run on the free software Virtual Box, made available by Oracle [4, 5]. Vir-

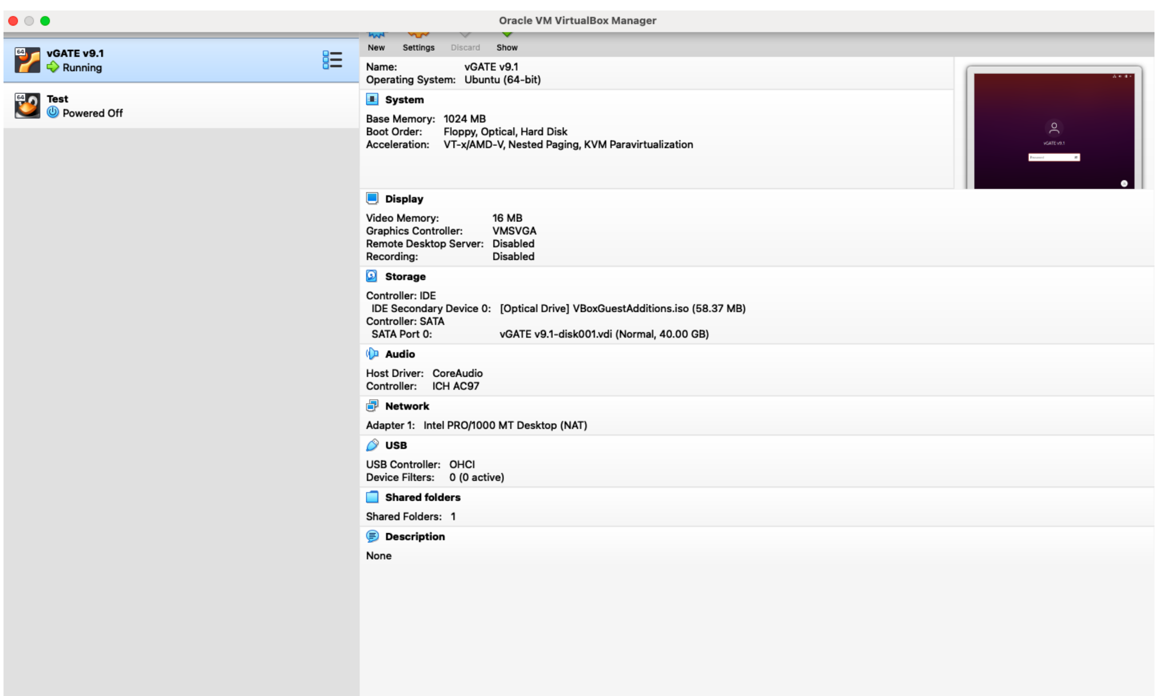

Figure 2: Image of the Virtual Box Manager that runs vGATE

tual Box and vGATE can be run on any host system. Downloading vGATE will provide the user with everything they need to successfully operate GATE as it includes the most current edition of GATE, GEANT4, and Root as well as many other software packages to make vGATE run efficiently. Once completely downloaded and set up in Virtual Box, to test that vGATE was working as intended, the base simulation was run. After debugging a few lines of code, the simulation that Ms. Wever created successfully ran. While there are several ways to run GATE simulations, this project utilized the command "GATE –qt" to run each simulation. Running this command creates a GUI in which simulations can be run by opening the appropriate file.

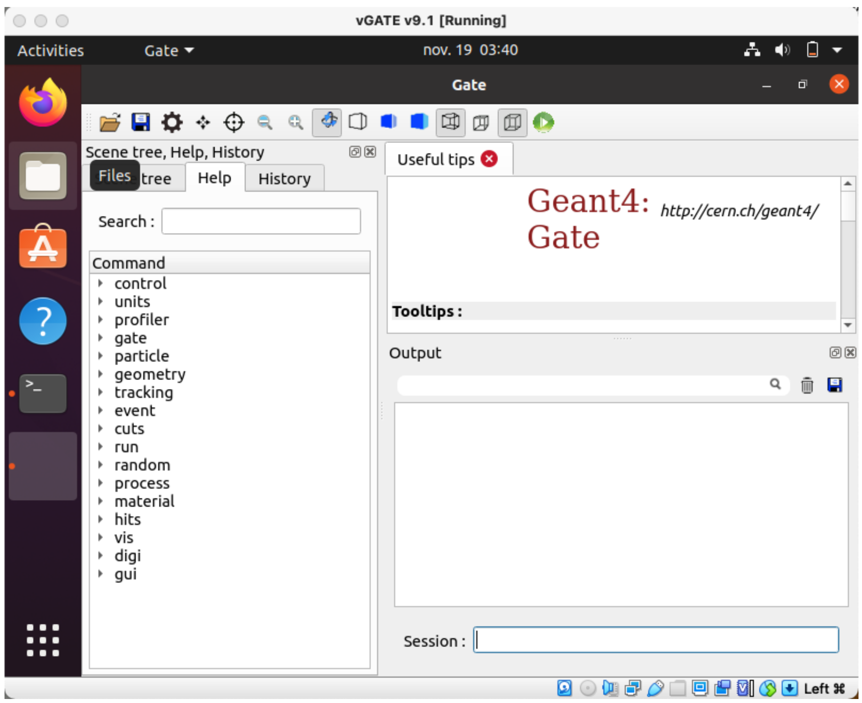

Figure 3: GUI produced when using the command "GATE –qt"

4.2 New Media

In order to simulate the energy deposition of gamma rays produced in different media, some of these new substances needed to be added to the generic GATE materials database. The generic GATE materials database (titled GateMaterials.db) already contains air and water, therefore, the only new materials that needed to be added were dirt and wet-dirt. Dirt is approximately 25% water, 25% air, 45% inorganic matter, and 5% organic matter. The GATE materials database does not contain a generic organic and inorganic substance, so they also needed be coded into the database. The generic organic substance used as apart of the simulated dirt was composed of 50% carbon, 45% oxygen, and 5% hydrogen as those three elements are the most prevalent in organic matter. As for inorganic matter, a combination of the most common elements that make up the Earth's crust was used to simulate a generic inorganic substance. These two generic substances were used in combination with the already existing air and water to create the simulated dirt. To create the wet-dirt, a combination of 65% water and 35% simulated dirt was used to create the simulated wet-dirt. Reference Appendix A to see code of simulated dirt and wet-dirt in full.

4.3 Summary of Existing Macro Files

The GATE simulation is compiled in a series of macros. Each play a particular role in making the simulation run. Ms. Wever's project successfully implemented the following macros to execute the simulation:

1. **mainRDG.mac** sets the simulation runtime and defines Monte Carlo random number generator seed.
2. **visuRDG.mac** opens a Graphical User Interface (GUI) which displays some of the visual components of the simulation.
3. **verboseRDG.mac** sets the verbosity of different elements of the simulation. This macro sets the print statements that are generated about the simulation's status as it runs.
4. **worldRDG.mac** sets up a three dimensional space in which the simulation will take place in.

5. **geoRDG.mac** sets up the different modeled detectors in the simulation.

6. **source_2gammasRDG.mac** implements the point source that emits two gamma rays in the simulation.

7. **physics.RDG.mac** adds the physical processes that mimic events that occur in the physical experiment. GATE uses the package emstandard_opt1 to simulate electromagnetic processes.

8. **petDigiRDG.mac** implements several digitizer modules that simulate what a photomultiplier tube produces. This macros is responsible for simulating Hits which occur when a particle interacts with matter; each Hit stores position, time, momentum, interaction type, and energy deposition of the interaction.

9. **outputRDG.mac** creates a .root that saves raw Hit information, Singles, Coincidences, and Delays in the experiment and .txt file saves information regarding number of events, physical processes, elapsed time, simulation time, and the start/end date. Both files are saved to an output folder.

This project makes use of all of these macro files with the exception of the source_2gammasRDG.mac file since the radioactive source in the experiment is no longer a point source. Some of the macro files were also changed or added onto so the new additions to the simulation would work properly. Some of these implementations include:

- mainRDG.mac: added new macro files to the list macro files in the order they needed to activate in the simulation.

- mainRDG.mac: disabled source_2gammasRDG.mac.

- physicsRDG.mac: enabled the processes of radioactive decay and positron-electron annihilation.

- outputRDG.mac: created new .root files for each of the four media used in the simulation.

4.4 cylindrical_phantom.mac

The first new macro file that was implemented into the simulation was the cylindrical_phantom.mac file. This macro generates a cylindrical phantom in the center of the simulation. This cylinder is named “phantom” and can be filled with any material. In this case: air, water, dirt, and wet-dirt. An image of the cylindrical phantom is depicted below (note: in future pictures, this cylinder will not be solid but instead a wired frame). This volume will also serve as the “mother volume” for the cylindrical capillary tubes that will be simulated next. For the complete code, see Appendix B.

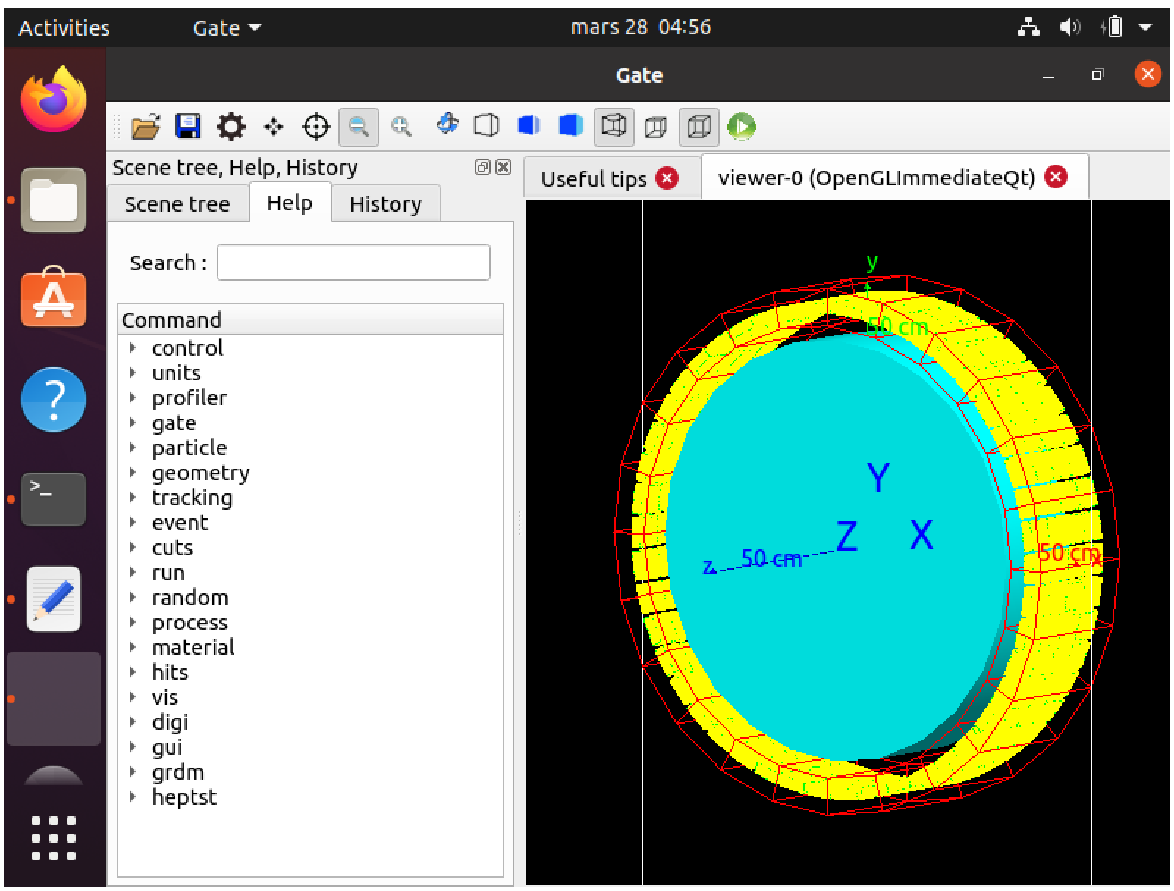

Figure 4: Simulated cylindrical phantom (solid light blue cylinder) containing wet-dirt

4.5 capillary_tubes.mac

The capillary_tubes.mac macro file contains the design and placements of all 12 cylindrical capillary tubes that are used in the simulation. In the in-lab experiment, the twelve capillary tubes are spaced out in different distances across four different directions (+x, +y, -x, -y). Because each capillary tube needs to have a source attached to it, each tube must be coded as its own individual volume. Each tube was implemented as a cylindrical hoop that is made out of glass to mimic as an in-lab capillary tube as closely as possible. These capillary tubes are placed in reference to the cylindrical phantom from the previous macro file and are known as "daughter" volumes. The below picture shows a zoomed in image of a single capillary tube. See Appendix C for the full code of the simulated capillary tubes.

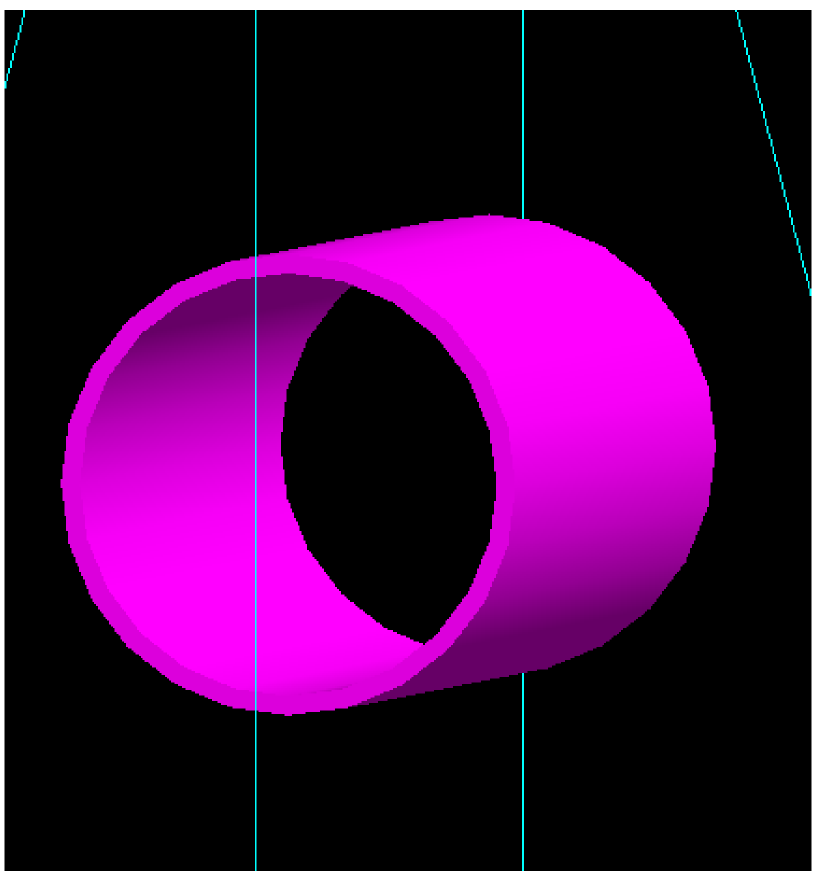

Figure 5: Zoomed in image of a single capillary tube

4.6 fluor18_source.mac and fluor18_source_backtoback.mac

These macro files introduce the radioactive source that is used in the experiment, fluorine-18 (^{18}F). The fluor18_source.mac generates positrons that annihilate with surrounding electrons which produce two photons, whereas the fluor18_source_backtoback.mac macro file generates two photons that travel back to back from each other when the ^{18}F source decays. Seeing that the in-lab experiment loaded a fluorine-18 solution into cylindrical tubes, the simulated ^{18}F source was coded in the shape of a volume which has a radius equivalent to the inner radius of the simulated capillary tubes. The ^{18}F source has an activity of 14.8 MBq and a half-life of 6865 s, however, lower values were used to test functionality throughout the experiment. One thing to note is that attempting to run the true values of ^{18}F's activity and half-life for all 12 capillary tubes at once can prove troublesome for the host machine. To counteract this, the simulation must be run for a very short amount of time. Similar to the capillary tubes, each ^{18}F source must be coded individually for each capillary tube. Once a source has been implemented, it is attached to one of the twelve capillary tubes. See the below images for an example of the ^{18}F source decaying to produce two photons. See Appendix D for an example of the code of the ^{18}F source for both the positron-electron annihilation version and the back to back photon version.

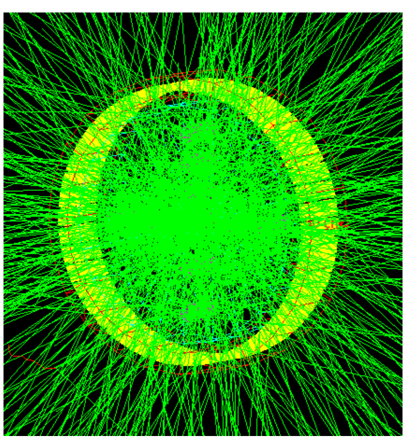

Figure 6: Image of multiple decays of ^{18}F

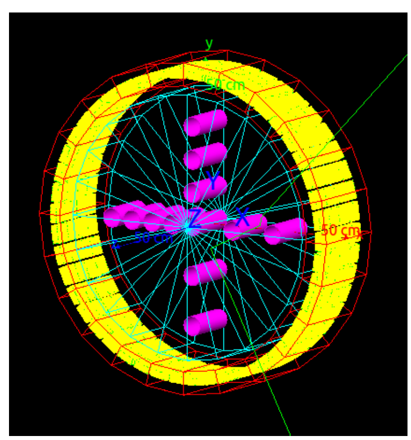

Figure 7: Image of a single decay of ^{18}F

5 Data

To analyze the data produced from the four simulations, Jupyter Notebooks coded in Python 3.7 were used. Using the Uproot library, the .root files were interpreted in the notebooks by translating the data from them into Numpy arrays. The data produced from the in-lab experiment depicts energy peaks around the 511 keV energy level, with attenuation of the peaks as they move towards more dense media. Reference "A Method for Characterization of PhytoPET in Plant Growth Media" for more details on the attenuation effect between the different media [3].

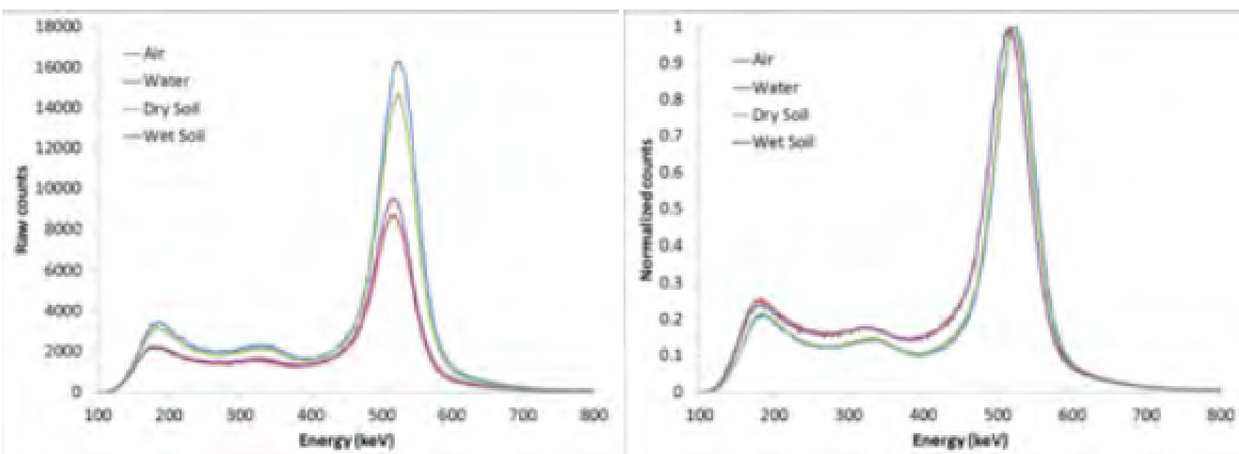

Figure 8: Energy distribution of in-lab experiment

For the simulated data, the energy spectra of the different media was interpreted using histograms to visualize the data. The data visualized in the following histograms was produced by running the simulation for one second for each of the different media. To be able to use the real values for the activity and half-life of ^{18}F, only one capillary tube could be "filled" with the radioactive source; if all twelve tubes were filled with the ^{18}F source, the simulation has shown to freeze and, eventually, crash. Thus, only one capillary tube, the one in the center of the simulation, is filled with ^{18}F. Drastically lowering the values of the activity and half-life of ^{18}F can allow the simulation to run all twelve filled capillary tubes at once. After analyzing data produced from both approaches, it was decided to focus on the data produced from one capillary tube filled with the real values for the activity and half-life of ^{18}F. For each media, 250,000 Singles were analyzed.

Starting with air, the energy distribution of the photons is represented in Figure 9.

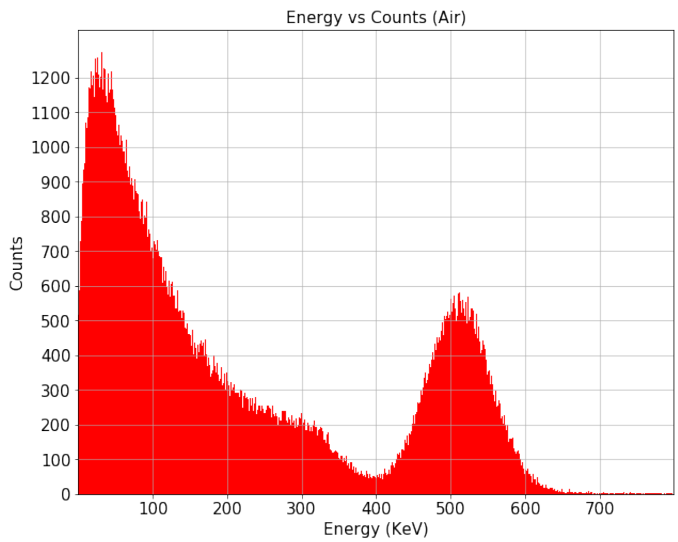

Figure 9: Simulated Energy Distribution of Photons Surrounded by Air (Singles)

The next media analyzed was water. Its energy distribution is shown in Figure 10.

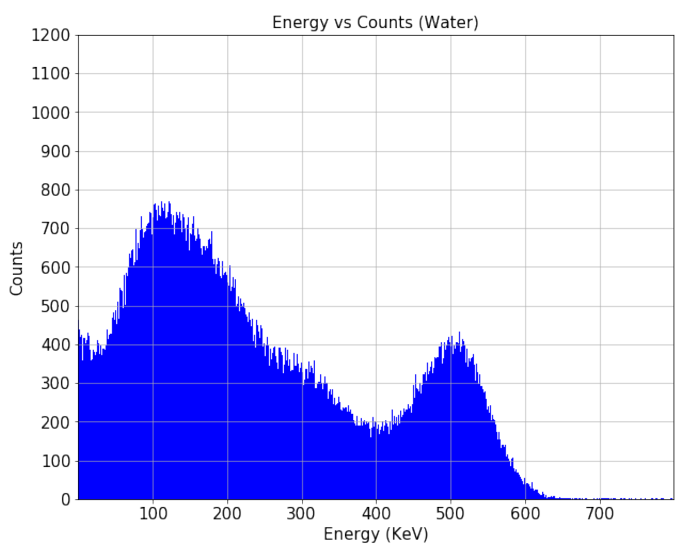

Figure 10: Simulated Energy Distribution of Photons Surrounded by Water (Singles)

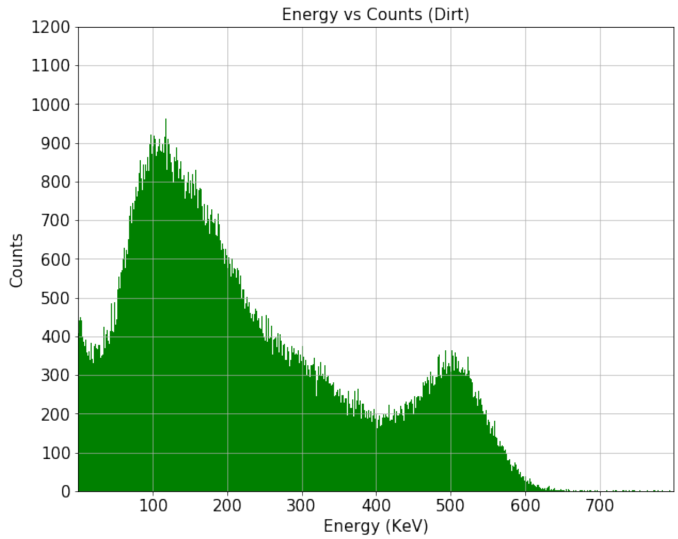

Figure 11: Simulated Energy Distribution of Photons Surrounded by Dirt (Singles)

After water, dirt was analyzed. One difficulty experienced while simulating dirt was that when the density of the dirt exceeded a certain amount, the simulation would produce little data. To counteract this, the density of dirt was lowered to 1.5 g/cm^3. The energy deposition of the capillary tube surrounded by dirt is shown in Figure 11.

Lastly, the wet dirt's energy spectra appears in Figure 12.

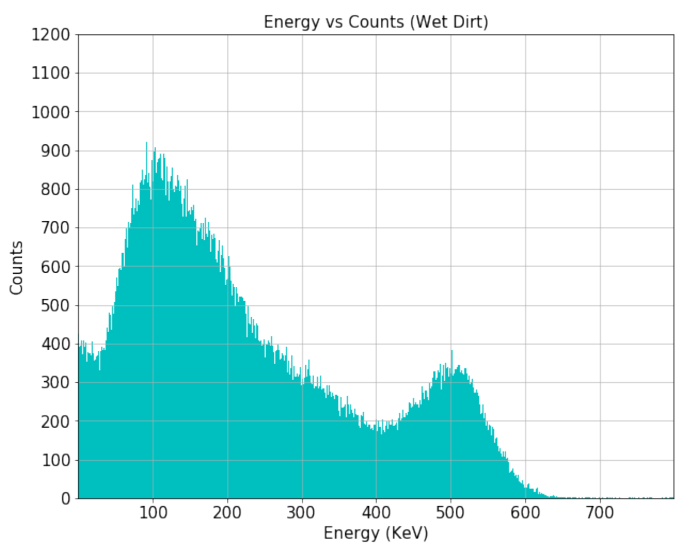

Figure 12: Simulated Energy Distribution of Photons Surrounded by Wet Dirt (Singles)

Fitting each of the above four graphs with a line instead of a histogram and then overlaying the results of each media yields the following graph which shows the attenuation between the different media more clearly.

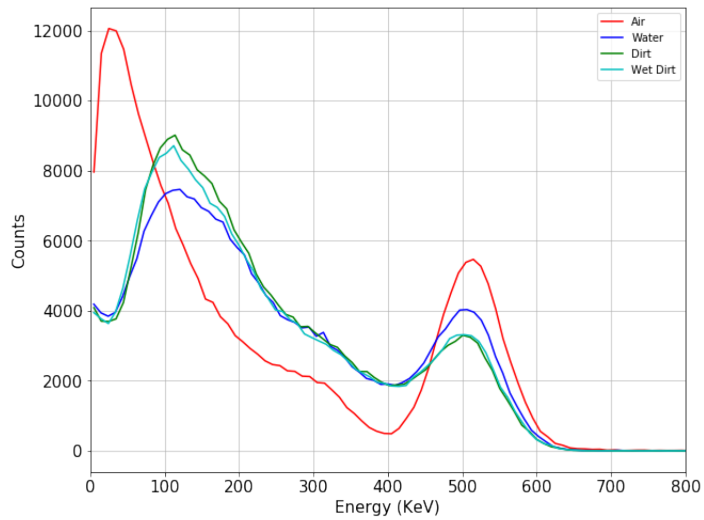

Figure 13: Energy distribution of simulated events (Singles)

Singles can further be categorized into Coincidence events. A Coincidence occurs when two or more Singles are found within a given coincidence window. The two or more Singles that are found within this window are then grouped together to form a coincidence event. The below image depicts the four different Cases for processing Coincidences. The numbers indicate the order in which Singles are detected in a coincidence

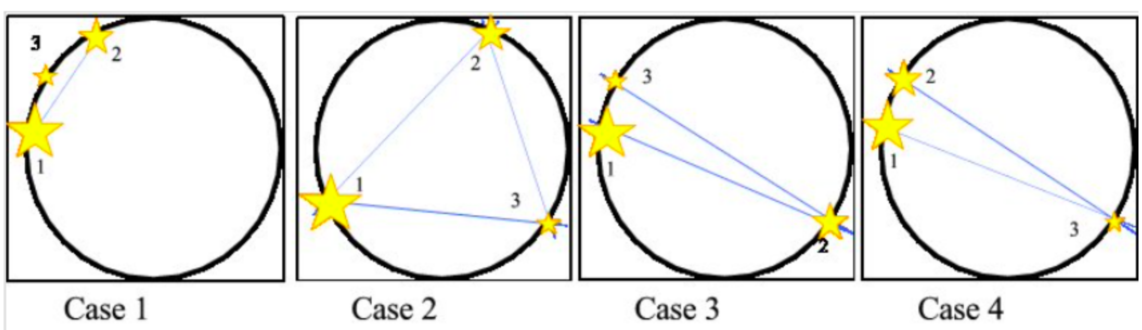

Figure 14: The four Cases that describe Coincidence events [4]

window and the size of the star indicates the amount of energy each Single has. GATE also has multiple options when it comes to determining which Coincidence events to take and which ones to terminate. This project utilizes the "takeWinnerIfIsGood" policy to determine which Coincidences to take. This method looks at events 1 and 2 from Cases 1, 2, and 3. If a Coincidence is detected that does not fit these parameters, this policy causes the simulation to discard the Coincidence. Analyzing the energy spectra for 40,000 Coincidences in each of the four media yields the following:

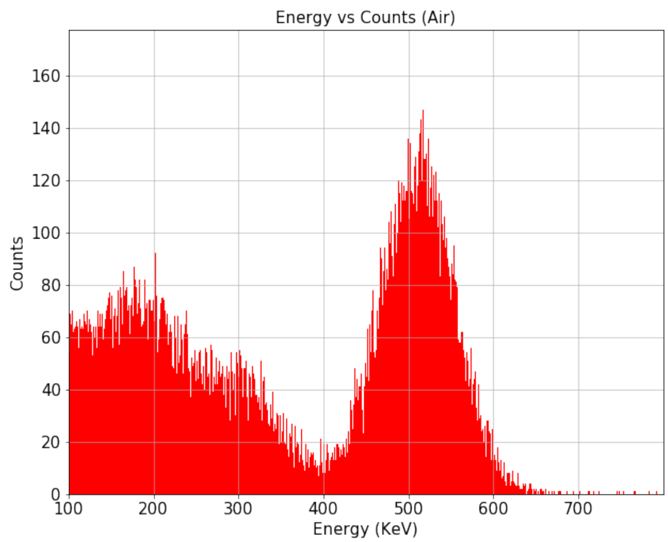

Figure 15: Simulated Energy Distribution of Photons Surrounded by Air (Coincidences)

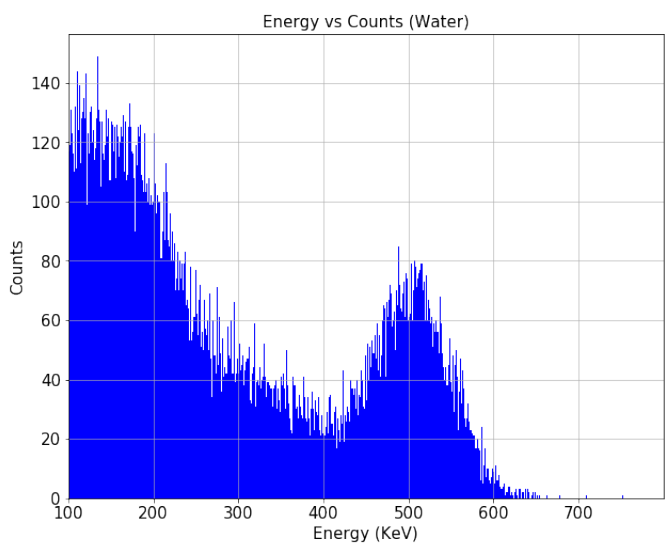

Figure 16: Simulated Energy Distribution of Photons Surrounded by Water (Coincidences)

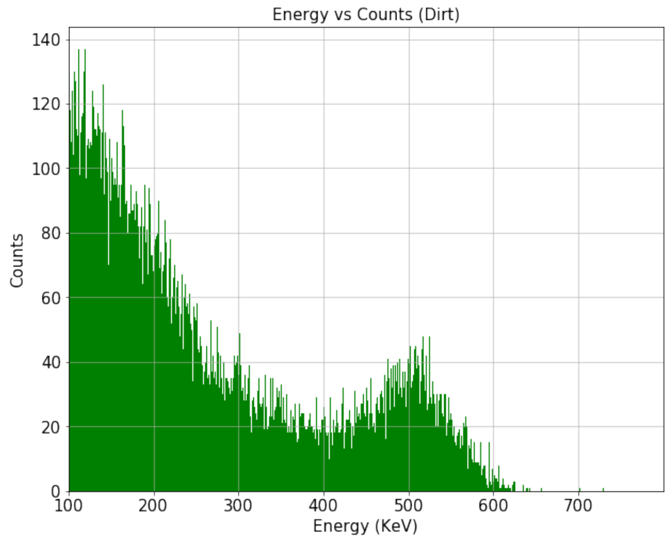

Figure 17: Simulated Energy Distribution of Photons Surrounded by Dirt (Coincidences)

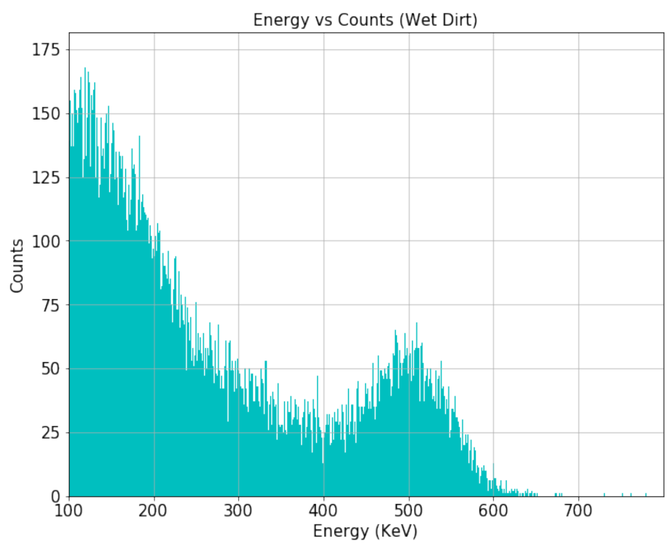

Figure 18: Simulated Energy Distribution of Photons Surrounded by Wet Dirt (Coincidences)

Similar to the Singles, converting these histograms to a wavefunction representation of the Coincidence data yields:

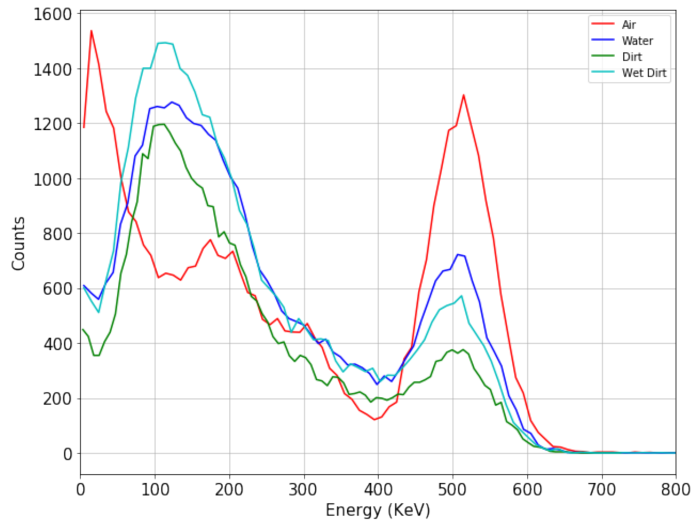

Figure 19: Energy distribution of simulated events (Coincidences)

6 Discussion

While all four energy deposition graphs exhibit a peak around the 511 keV mark, one common theme that appears in all four graphs is the large peak that appears around the 50 keV to 200 keV mark. The RDIG and Ms. Wever explained that this peak is the result of multiple different phenomena which includes "Compton noise" which is produced from scattered photons striking the detectors, background radiation from LYSO crystals, and simply the way GATE counts Singles, Coincidence, and threshold events. To obtain the 250,000 Singles, the simulation was run for one second for each media. When the simulated environment was filled with air, less Singles were produced in comparison to the other three media. This is due to the low density of air which does not annihilate every positron produced within the capillary tube. The same phenomena occurred when collecting and analyzing the 40,000 Coincidences. To collect this amount of Coincidences when the simulation media is air, the simulation needs to be run for at least five seconds if utilizing the "takeWinnerIfIsGood" policy. Those looking to utilize this simulation design in the future should take this into consideration and plan to run the simulation for longer periods of time. Note that when running the simulation in the GATE –qt GUI, if the simulation is running slow GATE will sometimes say that it is not responding and ask the user if they would like to force quit or wait. If the simulation is running correctly, simply quick wait and it will continue to collect data.

One of the other data analysis goals of this project was to analyze the attenuation of photon energy deposition for each media. While analyzing Singles showed some attenuation between the media, the effect was much more apparent when analyzing Coincidences. Analyzing the graph from Figure 19 showed a correlation between energy attenuation and density. As the density of the media increased, the amount of Coincidences registered at the 511 keV decreased. In the simulation, air has the lowest density, water has the second lowest, wet dirt the third lowest, and dirt has the highest density among the media. The graph shows dirt to have the biggest attenuation among the four media. While the attenuation effects of water and wet dirt match the experimental results, dirt was proven to have the smallest attenuation effect amongst the three media other than air. The reason why this simulation result does not match the experimental result needs to be researched further, perhaps knowing the true value for the density of dirt used in lab could correct this result.

In regards to the compiling of the simulation itself, this simulation is different than the in-lab experiment in that it does not have all twelve capillary tubes filled with ^{18}F at the same time. Perhaps if this project were run on a more powerful computer that is capable of handing the twelve radioactive sources at once, it would produce a more "realistic" output, however, the results obtained in this project would not differ very much from those theoretical results. Future use of this simulation could look into changing the capillary tube that is filled with the radioactive source to see if the results change in any way. The last design notes that make this simulation different from the in-lab experiment is that the dimensions of simulation are not exactly the same as the in-lab experiment. While this simulation does keep close to the true dimensions of the in-lab experiment, there were a few creative liberties employed throughout. Some of those include choosing an outer radius for the capillary tubes, choosing the height of the cylinder which contained the media, and adding four more detector blocks to reduce some of the gaps that photons could potentially exit out of.

In conclusion, this project has proved that GATE is a suitable tool for simulated more complex PhytoPET experiments. Each media produces an energy peak around the 511 keV mark and water, dirt, and wet dirt clearly show an attenuation effect from the results produced when the simulation media was air. This project successfully added new media and physics processes, the ^{18}F radioactive source, and new geometry into the simulation that was built by Ms. Wever. Future implementations to this project can be aimed at reducing the peak that occurs around the 150 keV mark and running the simulation with more capillary tubes filled with ^{18}F. This project also did not have time to create comparisons between the raw data produced in lab and the simulation data. If explored, this could more accurately confirm the simulation results. Another analysis that could be run on this project is utilizing laminography to produce an image of the simulated capillary tubes. In-lab results showed that images of the capillary tubes would become more blurry when placed inside different media. This could also be analyzed in GATE with the simulated capillary tubes to even further confirm the results of the simulation. Overall, this project allows the RDIG to confirm the results of the experiment involving phantom capillary tubes filled with ^{18}F as well as simulated new, more complex experiments and designs.

7 Appendices

7.1 Appendix A: New Additions to GATE Materials Database

GenOrgMatter: d=1.30 g/cm3 ; n=3 ; state=Solid
    +el: name=Carbon ; f=0.50
    +el: name=Oxygen ; f=0.45
    +el: name=Hydrogen ; f=0.05
Crust: d=2.70 g/cm3 ; n=10 ; state=Solid
    +el: name=Oxygen ; f=0.461
    +el: name=Silicon ; f=0.282
    +el: name=Aluminium ; f=0.082
    +el: name=Iron ; f=0.056
    +el: name=Calcium ; f=0.042
    +el: name=Sodium ; f=0.024
    +el: name=Magnesium ; f=0.023
    +el: name=Potassium ; f=0.021
    +el: name=Titanium ; f=0.006
    +el: name=Hydrogen ; f=0.003
Dirt: d=1.5 g/cm3 ; n=4 ; state=Solid
    +mat: name=Water ; f=0.25
    +mat: name=Air ; f=0.25
    +mat: name=GenOrgMatter ; f=0.05
    +mat: name=Crust ; f=0.45
WetDirt: d=1.298375 g/cm3 ; n=2 ; state=Solid
    +mat: name=Water ; f=0.65
    +mat: name=Dirt ; f=0.35

7.2 Appendix B: cylindrical_phantom.mac

```
# Define a cylindrical box
    /gate/world/daughters/name phantom
    /gate/world/daughters/insert cylinder
    /gate/phantom/geometry/setRmin 0.0 cm
    /gate/phantom/geometry/setRmax 10.0 cm
    /gate/phantom/geometry/setHeight 8. cm
    #/gate/phantom/setMaterial Air
    #/gate/phantom/vis/setColor white
    #/gate/phantom/setMaterial Water
    #/gate/phantom/vis/setColor cyan
    #/gate/phantom/setMaterial Dirt
    #/gate/phantom/vis/setColor gray
    /gate/phantom/setMaterial WetDirt
    /gate/phantom/vis/setColor red
    #/gate/phantom/vis/forceSolid
    # Define the sensitive detector
    /gate/phantom/attachPhantomSD
```

7.3 Appendix C: capillary_tubes.mac

```
### Define cylindrical capillary tubes
# Capillary Tube 1
    /gate/phantom/daughters/name capillary1
    /gate/phantom/daughters/insert cylinder
    /gate/capillary1/geometry/setRmin .55 mm
    /gate/capillary1/geometry/setRmax .85 mm
    /gate/capillary1/geometry/setHeight 30. mm
    /gate/capillary1/setMaterial Glass /gate/capillary1/vis/setColor magenta
    /gate/capillary1/placement/setTranslation 0 0 0 mm
    /gate/capillary1/vis/forceSolid
# Capillary Tube 2
    /gate/phantom/daughters/name capillary2
    /gate/phantom/daughters/insert cylinder
    /gate/capillary2/geometry/setRmin .55 mm
    /gate/capillary2/geometry/setRmax .85 mm
    /gate/capillary2/geometry/setHeight 30. mm
    /gate/capillary2/setMaterial Glass
    /gate/capillary2/vis/setColor magenta
    /gate/capillary2/placement/setTranslation -2.0 0 0 mm
    /gate/capillary2/vis/forceSolid
# Capillary Tube 3
    /gate/phantom/daughters/name capillary3
    /gate/phantom/daughters/insert cylinder
    /gate/capillary3/geometry/setRmin .55 mm
    /gate/capillary3/geometry/setRmax .85 mm
    /gate/capillary3/geometry/setHeight 30. mm
    /gate/capillary3/setMaterial Glass
    /gate/capillary3/vis/setColor magenta
    /gate/capillary3/placement/setTranslation -4.0 0 0 mm
    /gate/capillary3/vis/forceSolid
# Capillary Tube 4
    /gate/phantom/daughters/name capillary4
    /gate/phantom/daughters/insert cylinder
    /gate/capillary4/geometry/setRmin .55 mm
    /gate/capillary4/geometry/setRmax .85 mm
    /gate/capillary4/geometry/setHeight 30. mm
    /gate/capillary4/setMaterial Glass
    /gate/capillary4/vis/setColor magenta
    /gate/capillary4/placement/setTranslation -6.0 0 0 mm
    /gate/capillary4/vis/forceSolid
# Capillary Tube 5
    /gate/phantom/daughters/name capillary5
```

```
    /gate/phantom/daughters/insert cylinder
    /gate/capillary5/geometry/setRmin .55 mm
    /gate/capillary5/geometry/setRmax .85 mm
    /gate/capillary5/geometry/setHeight 30. mm
    /gate/capillary5/setMaterial Glass
    /gate/capillary5/vis/setColor magenta
    /gate/capillary5/placement/setTranslation -8.0 0 0 mm
    /gate/capillary5/vis/forceSolid
# Capillary Tube 6
    /gate/phantom/daughters/name capillary6
    /gate/phantom/daughters/insert cylinder
    /gate/capillary6/geometry/setRmin .55 mm
    /gate/capillary6/geometry/setRmax .85 mm
    /gate/capillary6/geometry/setHeight 30. mm
    /gate/capillary6/setMaterial Glass
    /gate/capillary6/vis/setColor magenta
    /gate/capillary6/placement/setTranslation 4.0 0 0 mm
    /gate/capillary6/vis/forceSolid
# Capillary Tube 7
    /gate/phantom/daughters/name capillary7
    /gate/phantom/daughters/insert cylinder
    /gate/capillary7/geometry/setRmin .55 mm
    /gate/capillary7/geometry/setRmax .85 mm
    /gate/capillary7/geometry/setHeight 30. mm
    /gate/capillary7/setMaterial Glass
    /gate/capillary7/vis/setColor magenta
    /gate/capillary7/placement/setTranslation 8.0 0 0 mm
    /gate/capillary7/vis/forceSolid
# Capillary Tube 8
    /gate/phantom/daughters/name capillary8
    /gate/phantom/daughters/insert cylinder
    /gate/capillary8/geometry/setRmin .55 mm
    /gate/capillary8/geometry/setRmax .85 mm
    /gate/capillary8/geometry/setHeight 30. mm
    /gate/capillary8/setMaterial Glass
    /gate/capillary8/vis/setColor magenta
    /gate/capillary8/placement/setTranslation 0 3.0 0 mm
    /gate/capillary8/vis/forceSolid
# Capillary Tube 9
    /gate/phantom/daughters/name capillary9
    /gate/phantom/daughters/insert cylinder
    /gate/capillary9/geometry/setRmin .55 mm
    /gate/capillary9/geometry/setRmax .85 mm
    /gate/capillary9/geometry/setHeight 30. mm
    /gate/capillary9/setMaterial Glass
```

```
    /gate/capillary9/vis/setColor magenta
    /gate/capillary9/placement/setTranslation 0 6.0 0 mm
    /gate/capillary9/vis/forceSolid
# Capillary Tube 10
    /gate/phantom/daughters/name capillary10
    /gate/phantom/daughters/insert cylinder
    /gate/capillary10/geometry/setRmin .55 mm
    /gate/capillary10/geometry/setRmax .85 mm
    /gate/capillary10/geometry/setHeight 30. mm
    /gate/capillary10/setMaterial Glass
    /gate/capillary10/vis/setColor magenta
    /gate/capillary10/placement/setTranslation 0 9.0 0 mm
    /gate/capillary10/vis/forceSolid
# Capillary Tube 11
    /gate/phantom/daughters/name capillary11
    /gate/phantom/daughters/insert cylinder
    /gate/capillary11/geometry/setRmin .55 mm
    /gate/capillary11/geometry/setRmax .85 mm
    /gate/capillary11/geometry/setHeight 30. mm
    /gate/capillary11/setMaterial Glass
    /gate/capillary11/vis/setColor magenta
    /gate/capillary11/placement/setTranslation 0 -5.0 0 mm
    /gate/capillary11/vis/forceSolid
# Capillary Tube 12
    /gate/phantom/daughters/name capillary12
    /gate/phantom/daughters/insert cylinder
    /gate/capillary12/geometry/setRmin .55 mm
    /gate/capillary12/geometry/setRmax .85 mm
    /gate/capillary12/geometry/setHeight 30. mm
    /gate/capillary12/setMaterial Glass
    /gate/capillary12/vis/setColor magenta
    /gate/capillary12/placement/setTranslation 0 -10.0 0 mm
    /gate/capillary12/vis/forceSolid
```

7.4 Appendix D: fluor18_source.mac and fluor18_source_backtoback.mac

fluor18_source.mac

```
# Define radioactive tracer Fluorine-18
    /gate/source/addSource fluor18
    /gate/source/fluor18/setActivity 14.8 megabecquerel
    /gate/source/fluor18/gps/particle e+
    /gate/source/fluor18/setForcedUnstableFlag true
    /gate/source/fluor18/gps/energytype Fluor18
    /gate/source/fluor18/setForcedHalfLife 6865 s
    /gate/source/fluor18/gps/type Volume
    /gate/source/fluor18/gps/shape Cylinder
    /gate/source/fluor18/gps/radius 0.55 mm
    /gate/source/fluor18/gps/halfz 30. mm
    /gate/source/fluor18/gps/centre 0. 0. 0. cm
    /gate/source/fluor18/visualize 5000 magenta 2
    /gate/source/fluor18/gps/confine NULL
    /gate/source/fluor18/gps/angtype iso
    /gate/source/fluor18/attachTo capillary1
    /gate/source/list
```

fluor18_source_backtoback.mac

```
### Define radioactive tracer Fluorine-18 for each capillary tube
    # Source for Capillary 1
    /gate/source/addSource fluor18
    /gate/source/fluor18/setActivity 14.8 megabecquerel
    /gate/source/fluor18/setType backtoback
    /gate/source/fluor18/gps/particle gamma
    /gate/source/fluor18/gps/monoenergy 511. keV
    /gate/source/fluor18/setForcedUnstableFlag true
    /gate/source/fluor18/setForcedHalfLife 6865 s
    /gate/source/fluor18/gps/type Volume
    /gate/source/fluor18/gps/shape Cylinder
    /gate/source/fluor18/gps/radius 0.55 mm
    /gate/source/fluor18/gps/halfz 30. mm
    /gate/source/fluor18/gps/centre 0. 0. 0. cm
    /gate/source/fluor18/visualize 5000 magenta 2
    /gate/source/fluor18/gps/confine NULL
    /gate/source/fluor18/gps/angtype iso
    /gate/source/fluor18/attachTo capillary1
    /gate/source/list
```

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