

# **Cloud Chamber, Simulation, and Particle Interaction**

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## **1 Abstract**

This paper develops appropriate techniques for manufacturing a thermoelectrically cooled cloud chamber system that allows for the visualization of high-energy cosmic rays and the observation of radioactive decay. While the use of dry ice remains the preferred technique for cooling cloud chambers, an electrically cooled chamber permits flexibility in scheduling its use and eliminates the need for purchasing and storing solid carbon dioxide. In addition to the engineering of the chamber, a computer simulation was built to test the proposed hypothesis that by placing a lead block above the cloud chamber, incident particles would be slowed forcing them to decay, which would increase the probability of seeing a larger number of particles inside of the chamber. By constructing a relatively low cost solution for a plug-and-play particle detector, CNU will have a demonstration device that allows observers to view radiation tracks in real time.



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## **2 Introduction**

Cosmic rays are highly energized charged particles that reach the Earth from outer space. As the particles pass through Earth's upper atmosphere, they collide with the air molecules producing a shower of secondary particles that continue towards the Earth's surface. These particles are so small and are moving at such high speeds that they cannot be seen with the naked eye. But a cloud chamber can detect and visualize these charged particles. Unstable radioactive elements can also be used, as they lose energy by giving off ionizing radiation not dissimilar from the cosmic rays. Photographs and video taken of the particle interactions allow me to analyse the particle tracks produced in the cloud chamber.

My expectation is to build a working cloud chamber without the use of dry ice and obtain video evidence of particle tracks being produced inside the chamber cavity. Investigations of particle physics usually involve sophisticated computerized data acquisition systems where a particle's energy or internal characteristics are examined. My goal of this project is to complement the particle investigations of a computerized system by enabling the added ability to see the radiation.

The two contemporary methods for visualizing these particles include a thermoelectric solution and a solid carbon dioxide method. The thermoelectric cloud chamber design I have chosen will provide me with the ability to reproduce many experimental trials both inexpensively and timely. Both types of cooling approaches rely on the same principle, to cool the bottom of a chamber to create a supersaturated solution of alcohol and air (Olson). When that unstable saturated layer is perturbed by incoming radiation, the air molecules ionize allowing small

nucleation pockets for the alcohol to condense along the path of the particle leaving behind a contrail. Part of my compact design choice is to allow future students to use the cloud chamber as a quick and easy experiment or demonstration tool, where particle tracks can be seen quickly with minimal setup.

### 3 Theory

#### a. Particle Interaction

Primary cosmic rays consist of the nuclei of elements produced by events like super novae and other high-energy cosmic activity. When these particles get close to the Earth they get trapped by its magnetic field, where these particles then hit the upper atmosphere and interact. The primary cosmic rays mainly consist of high-energy protons and helium nuclei, and when they come in contact with other nuclei and molecules in the air, they collide and experience very strong interactions. The high-energy protons and helium nuclei are broken into secondary particles, pions and kaons, all with different charges. Below, in process (1), a proton strongly interacts and produces a majority of pions. These secondary particles will continue to travel through the atmosphere and either decay or interact with molecules in the air.

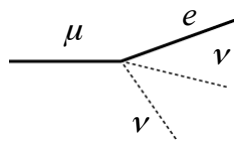
Muons are typically produced from the primary pions. Because muons have a very short lifetime ( $2.2\mu\text{s}$ ), a vast majority of them reach sea level due to their relativistic speeds.

$$p + p \rightarrow \pi^+ + \pi^- + \pi^0 + K^+ + K^- \quad (1)$$

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \quad (2)$$

$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu \quad (3)$$

At sea level, we expect to see a third chain of decay where a positive or negative muon decays into a positron (2) and an electron (3) respectively with a neutrino anti-neutrino pair (Beatty). This decay proceeds by the weak interaction, and the resulting three-particle system obeys the conservation of lepton number. The processes (2) and (3) described above will act as the basis for my simulation experiment. Below, are two pictures illustrating a muon interaction:



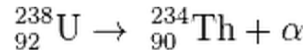
The simulation will promote the production of positrons and electrons in processes (2) and (3) by placing a lead block above the cloud chamber. The dense lead block will help slow down the incident muons, and if they release enough energy in the lead, they will decay into either a positron or electron dependent on the charge of the muon. By enabling this decay, the goal will be to capture a photograph of the muon-positron chain similar to the picture above (right).

## **b. Radioactive Decay**

For a higher concentration of ionizing radiation I have chosen to use Uranium as an alpha source inside of the cloud chamber. An alpha particle consists of two protons and two neutrons and is commonly known as a Helium nucleus. This radioactive decay occurs because the Uranium would like to be stable, so it constantly releases energy from its nucleus as it tries to stabilize. That energy comes

out in the form of an alpha particle. This particular Uranium isotope has an unstable nucleus that does not have enough binding energy to hold the nucleus together.

Below I have highlighted the process that is occurring:



During this decay, Uranium-238 is decaying into Thorium-234 and an alpha particle (Alpha). The energy required to break down a nucleus into its component nucleons is called the nuclear binding energy. This binding energy is usually measured in energy per nucleon (protons and neutrons only). So the goal in showing that this process will decay is by showing that the mass of the nucleons of Uranium is greater than the sum of the masses of the nucleons for Thorium and the alpha particle. This will indicate that the binding energy per nucleon for Uranium is not at a minimum and is therefore unstable.

$$\begin{aligned} m_{\text{UraniumNucleons}} &= [238.0508\text{amu} - 92e^-(0.000549\text{amu})] * [931.494\text{MeV}] \\ &= 221695.84 \text{ MeV} \end{aligned}$$

$$\begin{aligned} m_{\text{ThoriumNucleons}} &= [234.0436\text{amu} - 90e^-(0.000549\text{amu})] * [931.494\text{MeV}] \\ &= 217964.18 \text{ MeV} \end{aligned}$$

$$m_{\alpha} = 3727.38 \text{ MeV}$$

$$m_{\text{sum}} = m_{\text{ThoriumNucleons}} + m_{\alpha} = 221691.56 \text{ MeV}$$

$$m_{\text{UraniumNucleons}} - m_{\text{sum}} = 4.28 \text{ MeV}$$

This mass difference of 4.28 MeV indicates that the Uranium-238 will decay or lose energy leaving the resulting system with Thorium-234 and an alpha particle. These

alpha particles can be seen in the cloud chamber via their contrails. Below I have inserted an image illustrating what this decay looks like inside of a cloud chamber.



## **4 Methodology**

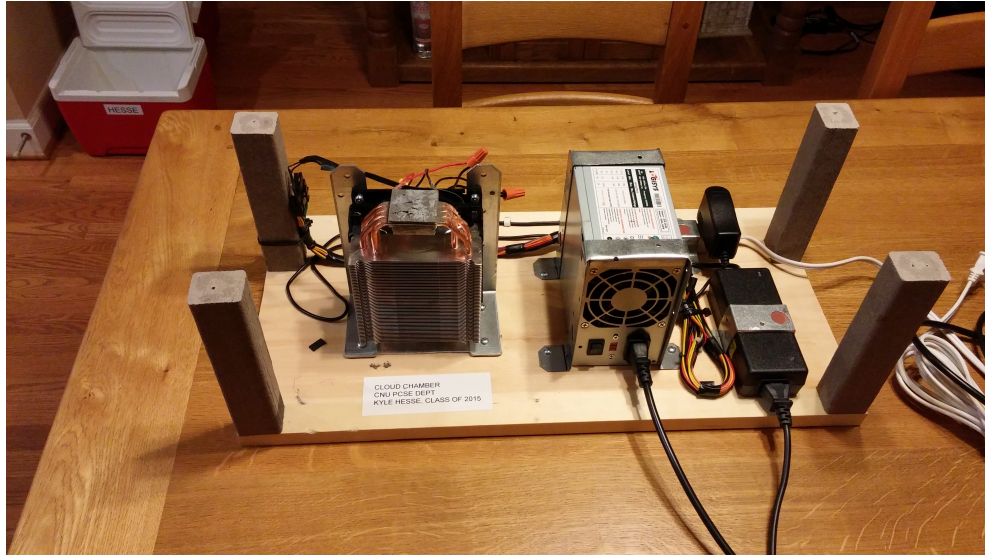
### **a. Cloud Chamber**

Fixed to the top of the cloud chamber is an absorbent material thoroughly soaked in 99% isopropyl alcohol. Making sure that the alcohol has high enough purity ( $>91\%$ ) is crucial to the success of the experiment. Otherwise the isopropyl will be too diluted with water and it will freeze near the coolers. The alcohol vapor then falls toward the cool bottom of the chamber where it mixes with the air creating a gaseous solution of air and alcohol. As the solution cools it becomes supersaturated. Supersaturation is an unstable state that occurs because the air-alcohol solution contains more alcohol than could normally be held in the air. For alcohol a minimum temperature of  $-26.1^{\circ}\text{C}$  needs to be maintained in order to achieve a continuous supersaturated state. This temperature is achieved by placing a thermoelectric cooling device in thermal contact with the cooling surface; in this case it would be the base of the chamber. The thermoelectric cooler works by placing a voltage across one positively doped and one negatively doped

semiconductor. This provides the impetus for the electrons to flow across the junction between the two semiconductors thus producing a temperature gradient (Thermoelectrics). Now, with a cool surface, when some ionizing radiation passing through the chamber disturbs this unstable supersaturated layer, the air leaves behind pockets of condensation nuclei for the alcohol to condense. These particles provide the “push” for the alcohol to condense into small liquid droplets, which can then be seen as a white cloudy contrail.

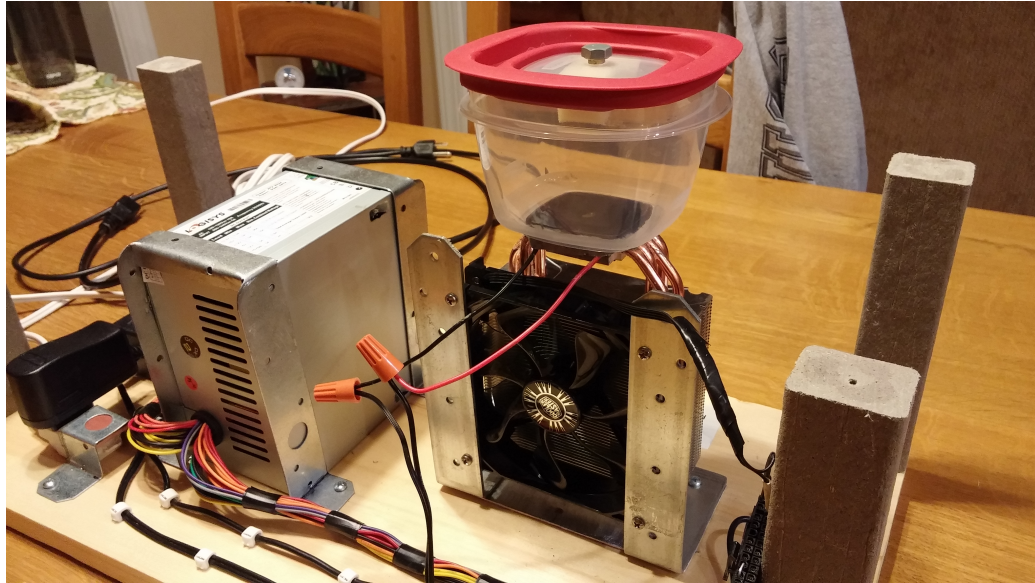
### **i. Design**

A plastic chamber is placed on top of a wooden unit that houses the coolers, a heat sink, and the power supplies. The container’s lid was cut so that a bolt could hold a kitchen sponge soaked in alcohol on the top portion of my container. The heat sink has a 120mm fan that is powered by a 12V line from the ATX power supply. This fan helps keep the heat sink cool as the coolers heat up. I have included a system of coolers (TEC-12709 and a TEC-12710) that are placed in thermal contact to cool my container (Olson). Since the bottom cooler needs to pump all the heat generated by the one above it in addition to any heat the upper cooler generated itself, the bottom cooler is attached to a more powerful 96W power supply while the upper cooler is connected to a 12.5W power supply. Below I have inserted a photo illustrating the positions of the three power supplies, the heat sink and the coolers.



A plastic Tupperware container is then placed in contact with the top cooler and a good seal is made using thermal compound. Once the coolers and the plastic container are secure, I then insulated the coolers from the air using pink insulation so that the top cooler and the bottom of the Tupperware container are not externally heated. The top lid containing the alcohol sponge can now be thoroughly soaked and the coolers and fans turned on. Using an infrared thermometer, the bottom of the container should read at least  $-26.1^{\circ}\text{C}$  before placing the lid on the container. Once sealed, after one to two minutes, tracks can be seen from a near by radiation source or if the alcohol mist is dense enough, cosmic rays can be seen. The final experimental setup is posted below.





## **b. Simulation**

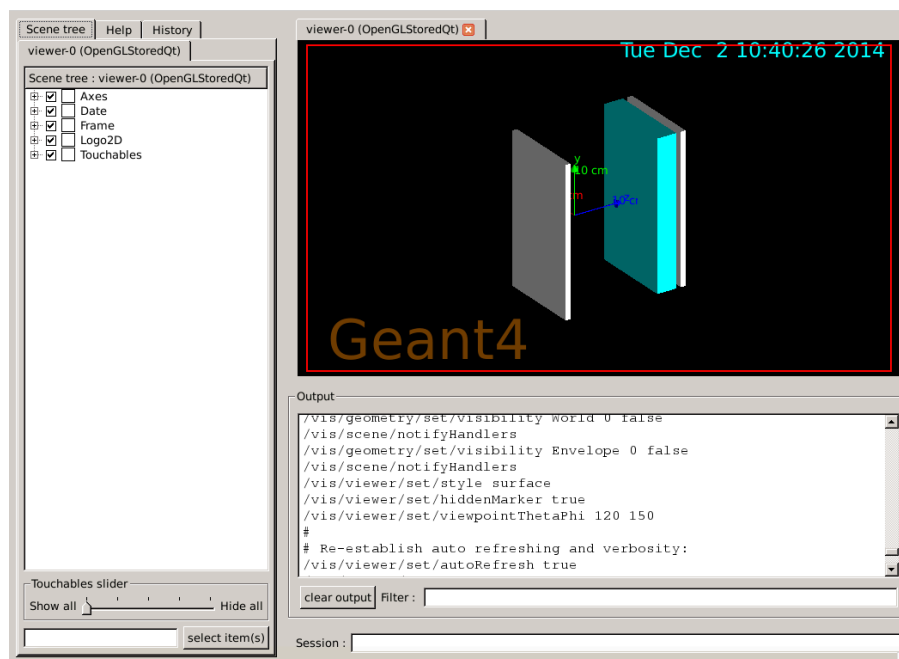
My simulation is designed to test the theory that by placing a stopping material above the cloud chamber, incident particles would be slowed forcing them to decay, which would increase the probability of seeing a larger number of particles inside of the chamber. To achieve this, Dr. Edward Brash proposed using a block of lead above the particle detector to test whether the dense material would successfully slow the higher energy particles to the point of decay. The primary objective of this simulation was to establish a relationship between the thickness of the lead block and the number of particles that decayed. A Monte Carlo simulation was devised using CERN's GEANT4 Simulation software in which an environment was created to vary the thickness of a lead block and measure the amount of positrons that are produced from the decaying muons.

GEANT4 is a software platform that is used to simulate particle interactions with matter. It allows me to create a simulation of cosmic rays passing through a stopping material like lead and examine the resulting data about the energy and

behavior of the of the incident particles. GEANT uses an object oriented C++ interpreter that includes physics' libraries that encompass the physical conditions and traits of high-energy particles. Having these physical phenomena already included in the design of the software makes simulating particle interactions much simpler. I have provided a computational overview on how my GEANT simulation was constructed and what file structures were needed to achieve a final result.

### **i. User Interface**

- The window below shows the visual interface for GEANT.
- The left side column allows for quick access to toggles and run types.
- The center console illustrates my simulation. The blue block is the lead stopping material.
- The two thin grey plates are scintillators, which are used in the detection of cosmic particles with the aid of a data acquisition system. They are also used to guide the particles path to ensure every incident particle hits the lead.
- The lower output section gives metrics on the outcome of the simulation.
- Once a session is started, particles are then shot into the blue lead block.
- For the experimental runs, the lead's thickness is incremented to test how many positrons are produced from the decaying muons.



## 5 Data

### a. Cloud Chamber

The two faint tracks seen in the picture below are alpha particles being ejected by the Uranium source in the upper left hand corner. Here, the cloud chamber was running at -28C, which is just below the condensation point for the supersaturated air-alcohol solution. Having two tracks present illustrates that thermoelectric cooling can achieve temperatures necessary for the proper use of a diffusion cloud chamber. However, the mist and track density is quite thin. Reaching colder temperatures would increase the density of the mist and make the tracks more pronounced. Where in the second picture below, there is a single alpha track that is more distinct and the condensation is far more visible.



The reason for the increased visibility in the second photo is directly related to the temperature of the chamber. Here the chamber is running at -32C and the vapor trails tend to have a thicker more milky white hue.

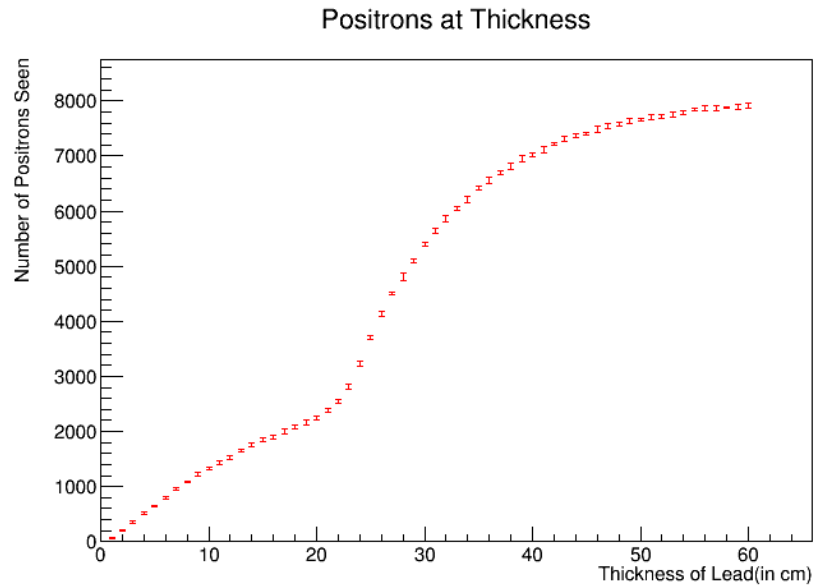


**b. Simulation**

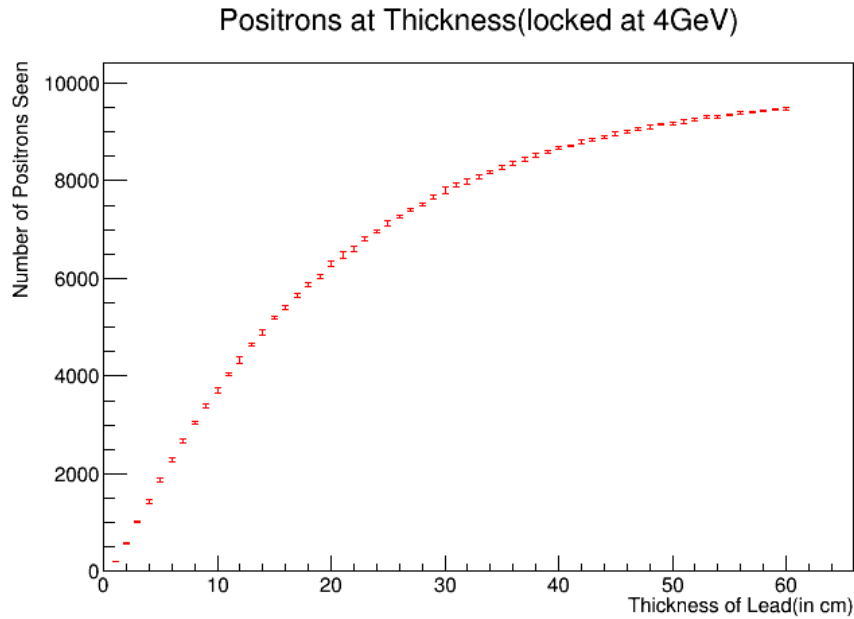
After assessing the simulated stopping material experiment, it was clear that muon decay and lead thickness have a positively correlating relationship. Below are two plots illustrating my data and demonstrating the increased promotion of positrons as the thickness of lead increased. The first plot was generated as a result of my first simulated experiment where the model of the energy distribution of muons was utilized. The distribution is given below where phi is the angle of trajectory measured from the vertical, and E is a particular energy of a particle (Beatty).

$$\frac{dN}{dE}(E, \varphi) = 0.14 * E^{-2.7} * \left[ \frac{1}{\left(1 + \frac{1.1 * E * \cos(\varphi)}{115}\right)} + \frac{0.054}{\left(1 + \frac{1.1 * E * \cos(\varphi)}{850}\right)} \right]$$

The second plot was generated by a second simulated experiment where the energy distribution was ignored and all particles were given a single energy of 4 GeV (average energy of muons at sea level).



The first data set demonstrates a positive relationship between muon decay and thickness, but it is slightly more complex than anticipated. The data appears to follow a compound exponential curve, where a sum of exponentials would fit the given data set. Figuring that the data's complex nature was caused in part by the energy distribution given above, it seemed reasonable to run a second experiment not using the distribution, but instead setting the starting energy of each particle to 4GeV.



As predicted, this data set shows a positive correlation between muon decay and lead thickness as well, but the relationship here does not appear to have a second exponential rise. Recognizing that the number of positrons increases as the thickness of lead increases is enough to claim that the use of lead while including the cloud chamber with CNU's cosmic ray telescope would most likely produce more events inside of the chamber.

## 6 Discussion and Conclusion

### a. First Build

The first cloud chamber design used a glass jar for the viewing chamber and an aluminum metal plate that would act as both the cooling surface and the bottom of the chamber. Upon initial testing, I was only achieving temperature at -6C to -8C, which is not cold enough for the saturation layer. I quickly found out that this was due to the metal plate that I was using. Most metals, including aluminum, have very high thermal conductivities, a property of materials relating to how well they



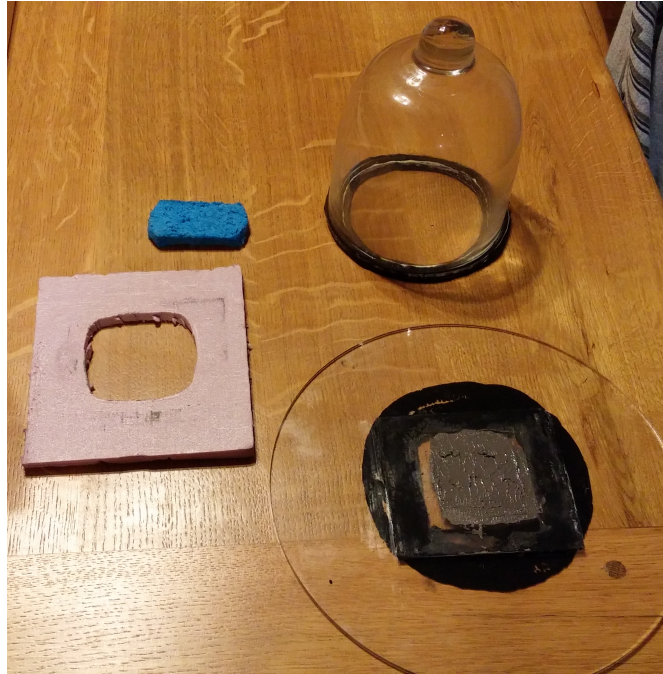
conduct heat. The higher one's thermal conductivity, the better that material will conduct heat. For aluminum, its thermal conductivity is  $167\text{W/m}\cdot\text{K}$  (Watts per meter Kelvin) which is extremely high. So even though the coolers were making the plate cold, the air was subsequently transferring heat into the plate. This ensured that my final temperature was reaching thermal equilibrium far above the point needed for the saturation layer. I decided insulating the aluminum from the air would help keep the plate cold. The expanding foam insulation did do its job well and I was able to achieve temperatures as low as  $-18.9\text{C}$ , but still not cold enough to see particles. Also the expanding insulation got in-between the coolers and created an air gap between them. A new build had to be made taking into consideration the effects of using metal and the use of insulation.





## **b. Second Build**

Learning from my mistakes in the first build allowed me to rethink how to approach the second. I started by removing the metal plate and switching to plastic for my contact surface. Even though the plastic has a relatively low thermal conductivity ( $0.2\text{W/m}\cdot\text{K}$ ), it is also much thinner and the air will not be able to heat the plastic as quickly as the coolers are cooling it. I tested this logic by cutting out the top of a Tupperware lid and gluing it with a silicon sealant to an acrylic plate seen in the picture below. The temperatures I achieved were at  $-31.6\text{C}$ , cold enough to get a saturation layer. In a hope to further insulate the system before running the experiment, I glued a rubber gasket to the bottom of the glass jar to act as an airtight seal and I purchased a pink insulation sheet to insulate the coolers from the air. After running a test, the plate was still cool at  $-30\text{C}$ , but the acrylic base had air pockets and small cracks that allow any sort of mist to escape from the bottom layer. Realizing the importance of an airtight system, I decided to get a completely closed system that would be in direct contact with the coolers. A Tupperware container is translucent enough for viewing purposes, seals with a lid to keep the mist from escaping, and is made out of a thin plastic, which I have previously tested.



### c. Third Build

After learning from the previous two setups, I now have a device that combines all of the most efficient components from each test. The plastic container needed to be blacked out with a permanent marker on its bottom side in order to limit the reflection of the container when shining a bright light inside of it. The lid of the container had a sponge fixed to the top for a place to hold the alcohol, and the coolers would be insulated from the outside air with the pink insulation. After adding alcohol to the sponge and turning on the coolers, the container's surface reached  $-28.9^{\circ}\text{C}$ . Just being below the threshold for saturation was not enough for the mist to form. So more alcohol was added to the bottom of the container to help supersaturate the air with alcohol. After two minutes of waiting, alpha tracks could be seen in the bottom 4mm of the chamber. Using the thermal coolers turned out to

be a success, as they could reach the temperatures needed and particle tracks could be seen. Please refer to the data section for the track pictures.



#### **d. Future**

With the ability to easily track particles in a working cloud chamber, the incorporation of this system with CNU's current cosmic ray telescope will greatly complement a high-energy particle detection setup. As seen from the data given from simulated experiments, using a lead stopping material will increase the probability of seeing more particles inside of the chamber. This stopping material could quite literally be a block of lead or a set of Shashlik calorimeters could be used, as they use absorbent slices of lead to help slow incoming particles.

While I was unable to capture a cosmic event on video, alpha particles are not too dissimilar from the cosmic radiation. Nevertheless, being able to see cosmic rays inside of this cloud chamber is a real possibility for the future. The main concern at the moment is that the mist layer is not thick enough to properly see

cosmic events. The density of this mist can be improved by lowering the temperature of the conducting surface. To do this, a better cooler will be needed. For instance, the TEC 12726 can be used as a single stage cooler running at a higher power rating than my two current coolers. Also increasing the power being provided to the current coolers could be examined, but the increase in heat and possibility of device failure would have to be considered. Once the chamber is made colder, further research can also be done concerning cosmic rays. Examinations of the number of expected particles could be done by counting the number of events seen in the chamber at a particular elevation, and the number of events seen can be statistically compared to experimentally accepted values in the field of particle physics.

## 7 Appendices

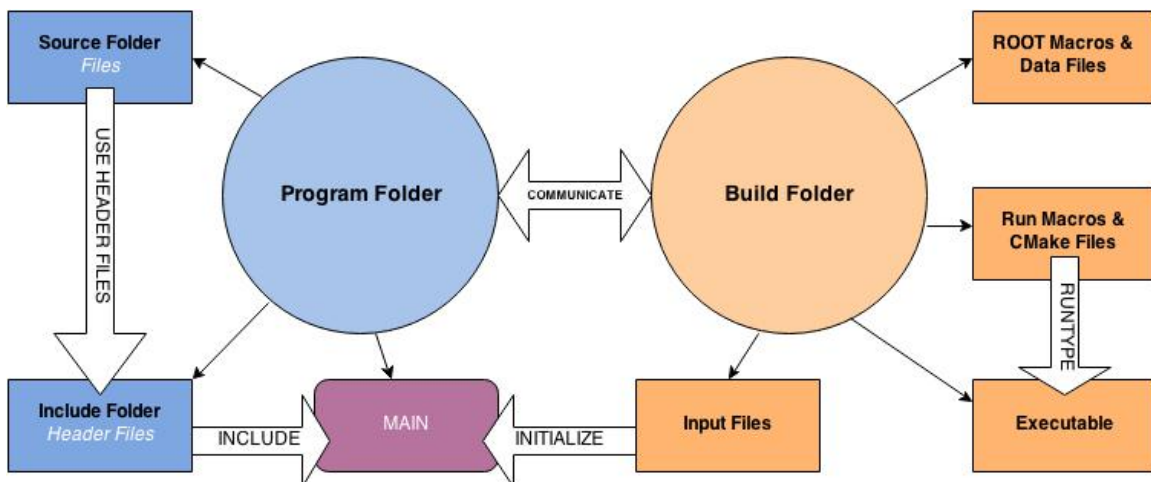
### a. List of Items Used

Item #	Name	Quantity/Description	Dimensions (L x W x H)
1	Tupperware Container	1 Small Rubbermaid Premium Container	129 x 129 x 86 mm
2	ATX Power Supply, 2 DC Power Supplies	1 480W PS 1 12V 8A 1 5V 2.5A	139.7 x 147.3 x 83.8 mm
3	CPU Cooler/Fan	1 Cooler Master 212	120 x 79.7 x 158.5 mm
4	2 Peltier Coolers	1 Model 12710 1 Model 12709	40x 40 x 3.4 mm
5	Thermal Paste	1 Arctic Silver	N/A
6	LED Flashlight	1 Single	N/A
7	Pink Insulation	1 Sqare	152.4 x 152.4 x 3 mm

8	Electric Tape	1 Roll	N/A
9	Black Silicon Caulk	Used as Sealant	N/A
10	Wood Glue	1 Bottle	N/A
11	99% Isopropyl Alcohol	1 Bottle	N/A
12	Sponge	1 Kitchen Sponge	4.7" x 3" x 3/5" inches
13	Camera	LG G3	N/A

## b. Simulation Overview

An understanding of the file system is essential to the creation of a GEANT simulation. In order to begin a simulation, certain directories are essential to the functionality of a working system. Below I have created a flow chart to help explain the critical files and folders and how the system interacts and communicates.



### The Program Folder

There are typically two sub folders called *Source* and *Include* as well as some additional files found in the program folder.

*Source Folder* - This folder contains all the class files for the program except the main class, which controls the entire program. The files inside of the source folder will control all of the inter-workings of the simulation. The essential files will include a Geometry Construction, an Event Action, a Run Action, and a Stepping Action all of which I will explain in another flow chart.

*Include Folder* - This folder contains all the header files for the classes in the source folder. There should be a header for each source file created. Inside of these header files are the initial values, objects, and methods that will be used in the class files within the *Source Folder*.

*Main Class* - This file is the main class for a simulation. It should have the same name as the project name, and will not have an associated header file. This file simply instantiates the entire simulation by calling all of the necessary classes and files that are going to be run for that specific simulation.

### **The Build Folder**

All files in this folder can be edited at any time without having to recompile. Any files not directly associated to the simulation (ROOT macros, data files, etc.) should be saved in this build folder. There is a sub folder called CMakeFiles that contains files necessary to the compiler.

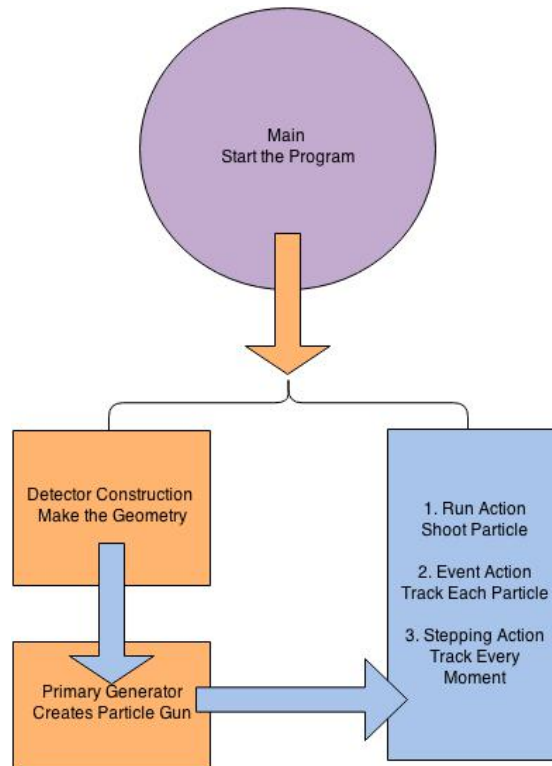
*The Executable File* - After compilation, this file is created in the build folder. It simply runs the simulation.

*Input Files* - These files can be used to manipulate variables between runs. For example, if I wanted to change the thickness of lead of the stopping material I would utilize the input file.

*Run Macros* – These files allow for quick simulated runs and are used in tandem with the executable file to run a simulation.

### **Required Files to Run a Simulation**

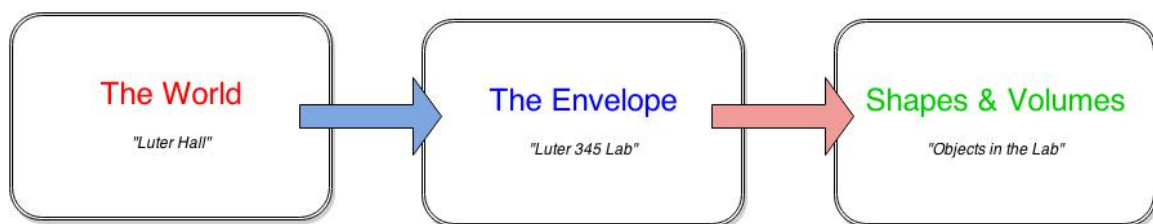
Now that the program structure is understood, there are several basic source files necessary to have a functional program. They should all be saved in the program folder within the source sub folder, with the exception of the main, which should be saved in the program folder. Below I listed these necessary files, with a brief description of their role to the program.



## The Main

This is the primary driver of the program. It will call the various other elements of the simulation.

## Detector Construction



This is where the environment and the objects in the simulation get defined. There are two required elements for any simulation: the world and the envelope. These two parts can be thought of as the containers that hold the detectors and devices of a particular simulation or to use an analogy the world can be thought of as Luter

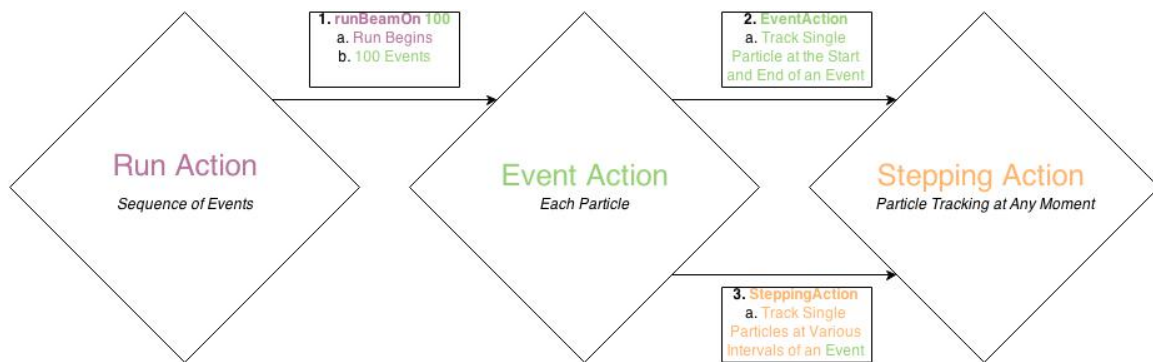


Hall where the envelope is a room within Luter where the experiment will take place. Inside the envelope one may place many different types of volumes to interact with. These volumes act as detectors or materials inside of our Lab in Luter 345. All of the geometry will be completed within this class.

### Primary Generator Action

This is where the particles that will be studied get defined. An analogy would be that a particle gun has now been created and is ready to fire.

### Run Action, Event Action & Stepping Action



GEANT simulations are broken into three levels: runs, events, and steps. A run is a complete simulation, as in each time you run the program. Tasks executed at this level happen once per execution of the program. An event is the level below a run. When one fires the particle gun, you are actually giving the program the number of events to execute after the command. An event is fairly flexible dependent on the simulation, but often it is a single particle being shot. The lowest level is a step. Each event is broken into a series of steps. Steps can be a certain amount of time passing,

entering or exiting a volume, or a particle decaying. It is important to note that variables created in one level must be included in the others to be seen so that these three classes can interact and simulated phenomena can be observed.

## 8 References

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