Measuring and Modeling the Energy Spectrum of Cosmic Ray Muons

Research Objective

Determine the energy distribution of cosmic ray muons and validate the results by simulating the experimental setup in Geant4.

Introduction

History

Cosmic rays were first observed in 1912 by a balloon flight made by Victor Hess[1]. Hess noticed that electroscopes had a much higher discharge rate as he rose in altitude. Studies on cosmic rays led to great development in the field of particle physics with the discovery of the positron, the muon, the pion, and the kaon being directly influenced from cosmic ray research.

The discovery of muons is attributed to Seth Neddermeyer and Carl Anderson in 1936 when they detected particles of greater mass than electrons, but retaining the same curvature in a magnetic field[2]. Their discovery was later confirmed by J.C. Street and Edgar Stevenson in 1937[3].

Cosmic Rays

Cosmic rays are high energy particles that are produced and accelerated by cosmic events such as supernovae. Cosmic ray nuclei collide with the nuclei of atoms in Earth's upper atmosphere, producing a shower of mostly pions[4]. These pions often decay into antimuons (μ^+) and muon neutrinos (ν_μ), which this experiment observes.

Muons

Muons are leptons most commonly produced from cosmic ray interaction in the atmosphere. Average muon count is $\approx$ 1 cm^{-2} min^{-1} and average muon energy at sea level is 4 GeV[5]. When the particles are created however, they have an average energy of 6 GeV.

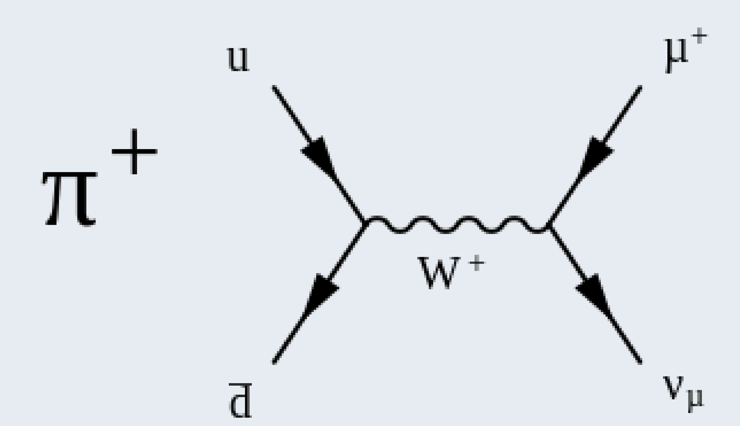

Figure 1: Pion decay mode[9]

Background

Evidence for Einstein's Theory of Relativity

Cosmic ray muons are generated about 15 kilometers above sea level and travel at speeds close to 99% the speed of light. At rest, a muon has a lifetime of 2.197 microseconds, meaning even traveling at such high speeds, it would only travel about 650 meters before decaying. However, muons are still observed by detectors even at sea level.

This is evidence for time dilation and length contraction as predicted by Einstein's theory of relativity. According to the theory, from the reference frame of an observer on Earth, time is dilated for the muon, lengthening its lifetime and allowing it to travel a greater distance before it decays. From the muonic reference frame, the length of the atmosphere is contracted so there is less distance that it must traverse before reaching the surface of the Earth.

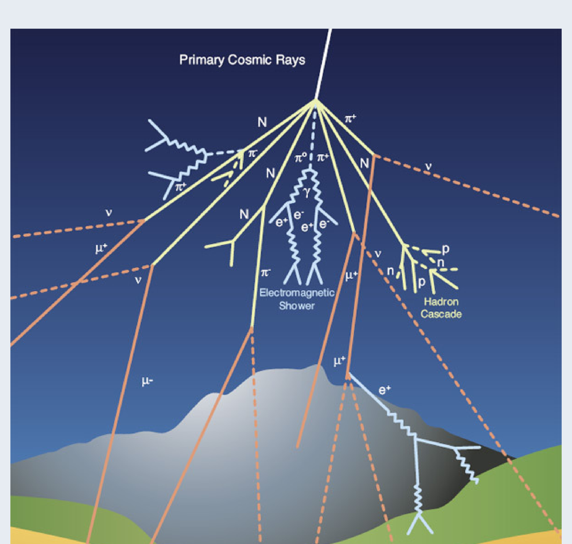

Figure 2: Cosmic ray particle shower[10]

An Approach to Modeling the Experiment

It is possible to model the data very accurately by making two assumptions:

1. The data falls into two components: a muonic component and a hadronic component
2. The number of muons seen stays constant and the hadronic component falls of by the following function:

$$C_{hp} = C_{hi} * e^{(-d/d_0)} \tag{1}$$

where C_{hp} is the predicted hadron count, C_{hi} is the initial hadron count, d is the distance of the lead between the detectors, and d_0 is the estimated nuclear interaction length of the hadronic component. We can predict the expected coincidences seen by the detectors using:

$$C_{total} = C_\mu + C_{hp} \tag{2}$$

where C_{total} is the expected number of total counts C_μ is the estimated muon count.

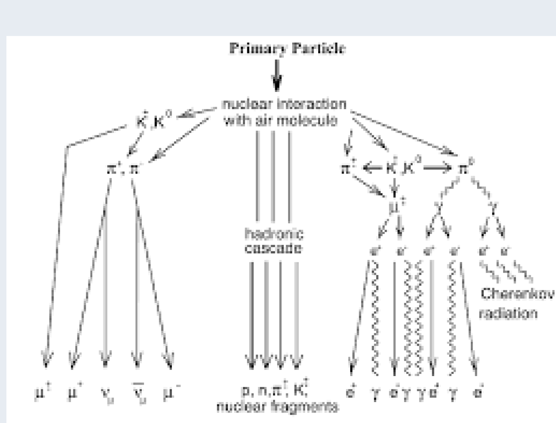

Figure 3: Cosmic ray air shower products[11]

The Physical Experiment

Objective

Observe the fall off of the hadronic component seen through coincidence detection.

Materials

- Two particle detectors
- 11 inches worth of lead
- Container/Shelf
- 3.5mm jack cables
- Raspberry Pi

Figure 4: Experimental setup

Approach

We varied the thickness of a shielding material (lead) placed between the particle detectors. The lead prevented the particles with energy below certain value to reach the second detector, making it observe only muons with energy above that value.

1. Set one detector above and below the container in a fixed position.
2. Set up the detectors in coincidence mode.
3. Allow the detectors to count for exactly 24 hours.
4. Place 1 inch of lead into the container.
5. Continue detecting for 24 hours and adding lead until all 11 inches have corresponding data.

Description

The detectors are placed $\approx$ 13.2 inches apart, lined up vertically so they form a line perpendicular to the ground. The top detector observes all particles that pass through the scintillator, but the bottom detector measures only coincidences between the two detectors. This ensures that the background radiation is ignored and only particles with approximately vertical trajectories (i.e. cosmic rays) are counted. Because the detectors are far apart from each other compared to scintillator size, the number of coincidences was low and the experiment had to be run for 24 hours. This minimized error by lessening the effect of outlier coincident particles on the total count.

The coincidence count can be compared to the total count to determine if an arbitrary fall of in counts can be explained by a decrease in overall particles.

Results

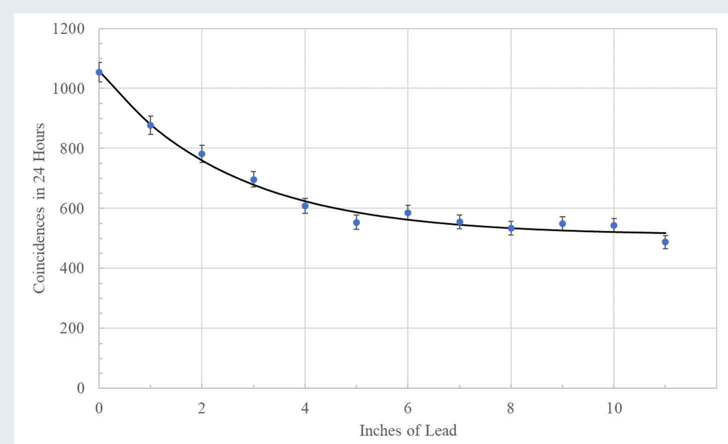

Figure 5: **Coincidences in 24 Hours as a Function of Lead Thickness** The amount of coincidences observed decreases as the amount of lead between the detectors increases. Equation (2) was used to generate the black curve.

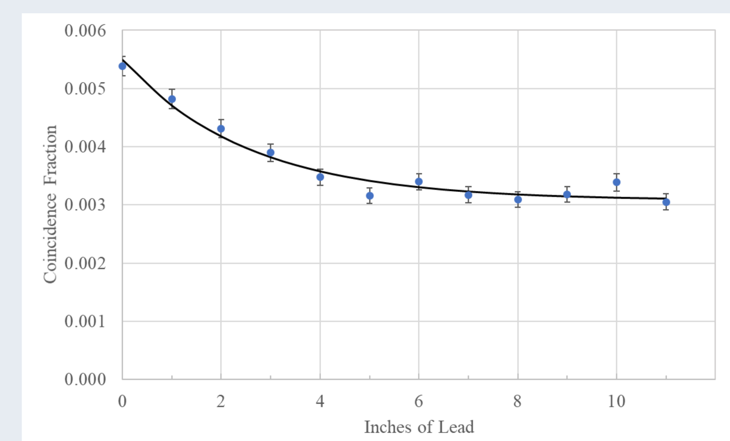

Figure 6: **Coincidence Fraction** Coincidence fraction is found by dividing the number of coincidences in 24 hours by the total number of counts seen by just the top detector. Equation (2) was used to produce the black curve, and C_{hi} and C_μ were calculated relative to the coincidence fraction values.

Data Analysis

The results showed that the number of coincidences observed decreased as the amount of lead increased. The model shown in Figure 6 is calculated using a nuclear interaction length of $\approx$ 72.9 g cm^{-2}, whereas the nuclear interaction length[5] of protons in lead is $\approx$ 199.6 g cm^{-2}. This implies either that some protons are being scattered out of the lead instead of being absorbed, or that the hadronic component in the model is composed of a mixture of particles, some of which have a small nuclear interaction length.

Geant4 Simulation

Objective

Create a simulation of the physical experiment using the Geant4 toolkit and observe the energy loss of μ^+ through lead.

Properties

- QBBC physics list
- 4 GeV μ^+ source
- 12 bricks of 1 inch lead
- 2 PVT scintillators

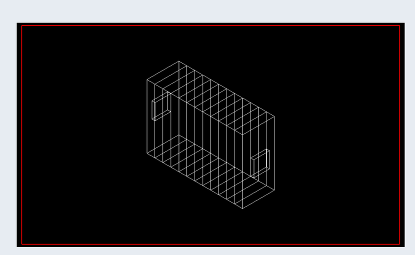

Figure 7: Experimental setup

Approach

Simulation software was created using the Geant4 toolkit. It was written in C++ and consists of approximately 1600 lines of code.

1. Create a source of 4 GeV μ^+.
2. Set the position above the lead and the trajectory down.
3. Construct the detector objects and register them as sensitive detectors.
4. Generate 1 μ^+ and detect it with both detectors and observe the energy loss through the lead bricks.
5. Run the experiment 1000 times to minimize outlier results.
6. Add 1 inch of lead and rerun the experiment and observations.
7. Continue to add lead until all 12 inches are used.

Description

Cosmic ray pions decay into μ^+ and ν_μ. Average energy of these muons at sea level is 4 GeV, therefore that is the logical energy to simulate first. When the simulation is run, every particle's movements, energy, and location are documented by Geant4. This allows one to track the movement and energy loss of a single muon.

The setup of the simulation includes 12 bricks of 1 inch lead stacked on top of each other with the PVT scintillators positioned directly above and beneath the lead bricks. This way the muon passes through the first detector, passes through the lead bricks, and then passes through the second detector.

The events of particles passing through the detectors are recorded. The particles that are result of interaction of the muons with the lead bricks (such as electrons, positrons, and gamma photons) are filtered out, since we are observing the energy loss by the muons only.

Results

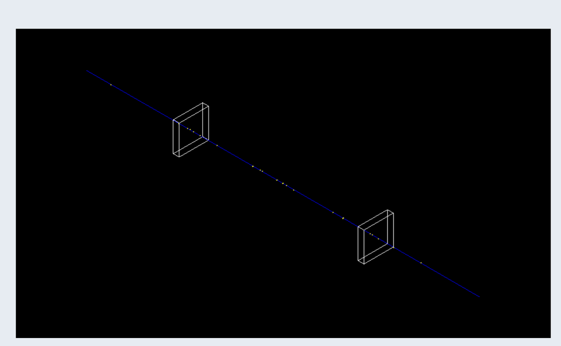

Figure 8: **Experiment run with 0 inches of lead.** A muon runs straight through the detector with no discernible changes.

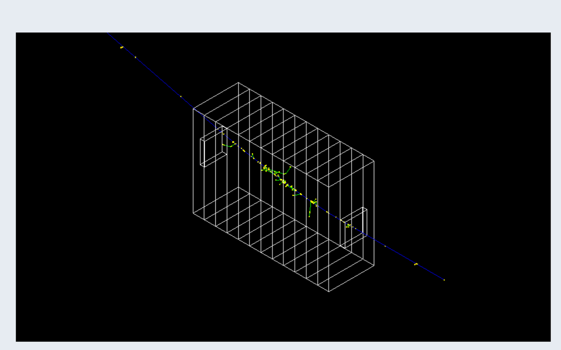

Figure 9: **Experiment run with 12 inches of lead.** The particle's path is noticeably diverted and a large number of particles are produced due to interaction between the muon and lead.

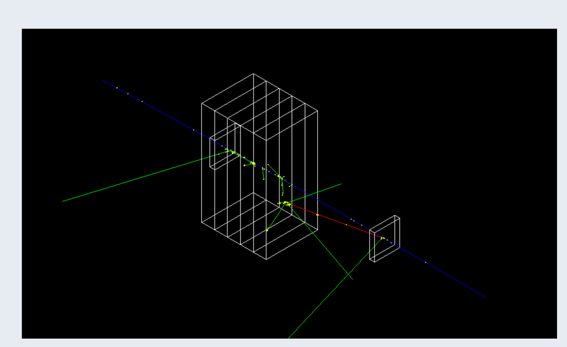

Figure 10: **Experiment run with 8 inches of lead.** The course of the muon is slightly diverted by the lead, as well as many electrons and gamma rays being produced through the particle's interaction with lead.

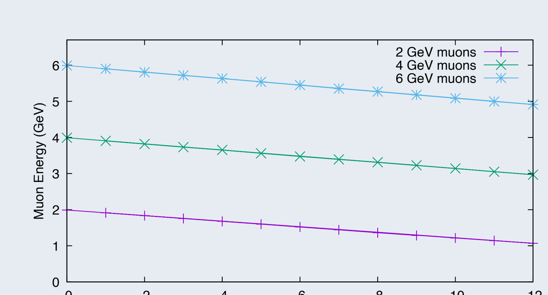

Figure 11: **Effect of lead thickness on μ^+ energy loss.** Average value of energy loss from different thicknesses of lead and muon energies of 2, 4, and 6 GeV.

Data Analysis

The simulations show that as lead thickness grows, the interactions between muons and lead also grows. This is indicative of loss of muon energy as it propagates through larger amounts of lead. After taking the average energy loss from 1000 runs of variable energy muons through different thicknesses of lead, a graph of the results can generate a line of best fit. We found these lines to be approximately linear. Interestingly, the results showed that higher muon energy also resulted in higher energy loss.

The current model doesn't completely simulate the real world. Unlike the cosmic muons, all muons in our simulation start from a single point in space and go downward. we also don't simulate the background radiation, such as that produced by the decay of radioactive isotopes

Learning a complex simulation toolkit like Geant4 proved a hard task that required many hours of reading tutorials and sample code. We are still learning and improving our model.

Geant4 Simulation Software

Background

Geant4 is a toolkit for the simulation of particle physics experiments. It was developed by CERN to design and replicate experiments conducted in large particle accelerators and detectors[6]. It has since been used in a number of fields, including high energy, nuclear, and accelerator physics, as well as medical and space science. It is written in C++ and provides implementation of various classes and concepts that can be used to create complex simulations of real-world experiments.

We used Geant4 to compare the experimental data we observe to the theoretical data that is produced from simulating similar conditions as the experiment. This comparison allows us to identify errors in our physical setup and detectors.

Steps to creating a Geant4 program

A Geant4 simulation is a C++ program that uses the Geant4 libraries. The users can describe the experimental setup, define particle sources, detectors and events.

1. Define different objects and specify their shapes, sizes, positions, and materials. Define some of them as the detectors.
2. Create the Geant4 particle gun, the source of particles.
3. Define the particle used, initial position of each particle, particle trajectory, and particle energy.
4. Specify the conditions necessary for the detector to acknowledge a particle hit.
5. Create and simulate the model of the whole setup using OpenGL and Qt5.

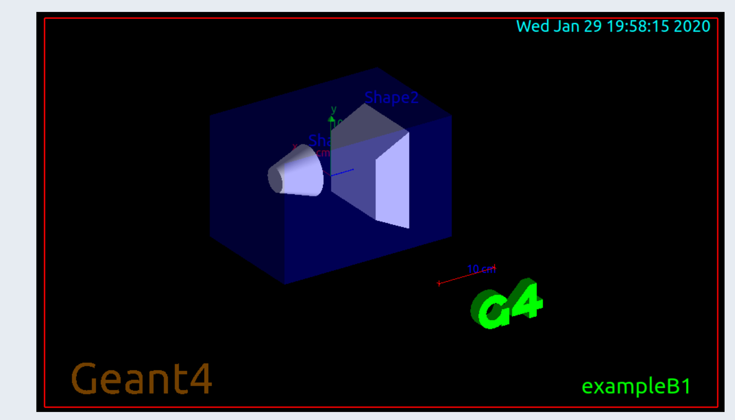

Figure 12: **First Basic Example:** This is the first basic example program provided by Geant4. This program demonstrates the capabilities of Geant4 through its construction of simple objects and particle generation.

Muon Detectors

- Designed by the CosmicWatch project[7].
- Offered a cheap solution to finding a detector capable of observing muons.
- Use plastic scintillators coupled with a silicon photomultiplier to detect incoming particles.
- Uses the detectors in coincidence mode to ensure the particle is produced by cosmic rays.

Figure 13: **Our Particle Detectors:** This is one of the detectors we are using, currently seen in coincidence mode.

Conclusions

- Muon counts were measured over 24 hours for varying thicknesses of lead.
- A model accurately predicted the fall off of the hadronic component.
- A Geant4 model of the physical experiment was created and showed a trend held true to our mathematical calculations.

Future Steps

- Create a map of the muon spectrum for the whole sky by varying the angle of the detectors and the shielding material.
- Conduct the physical experiment with more lead to further improve our curve estimate.
- Extend the Geant4 simulation so we can more accurately determine the energy loss of muons at different energies and different lead thickness. Add background radiation and simulate other particles that can trigger the particle detectors.

Acknowledgments

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