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Muon Radiography of the Pocono Mountains of Pennsylvania

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Abstract

The muon flux from cosmic ray interactions in the upper atmosphere is well understood theoretically and provides a fairly steady source of down going muons. The ways in which muons interact with matter such as water, rock, and metal have interesting applications. Particular to this project is muon radiography which uses the muon flux attenuation rate in matter as a way of determining the composition and amount of material in the muon's path. A low cost cosmic ray detector that uses plastic scintillators was built from scratch with designs from the Quarknet collaboration. Plans are now under way to use the muon flux attenuation rate measured by the detector to study the internal structure of hills and mountains in the Pocono region of Northeastern Pennsylvania. Various rocks and minerals consistent with the geology of these mountains will first be used to gauge the flux attenuation rate when exposed to the atmospheric muon flux from a variety of zenith angles. We anticipate that the attenuation rate is related not only to the composition of the material that the muons are traveling through but also to the zenith angle since the flux at larger angles is composed of a greater proportion of higher energy, deeper penetrating muons. These measured relationships will then be used to examine the internal structure of hills and mountains in the Pocono region with the goal of identifying caverns and areas of abnormally high density or unusual composition.

Keywords: Muon, Cosmic Ray, Matter Effects

1. Introduction

Cosmic rays are extraterrestrial particles which interact with Earth's atmosphere. They consist mostly (~85%) of hydrogen and other nuclei and can originate from the Sun, other stars, and other celestial bodies.[1] Cosmic rays bombard the atmosphere at a rate of 1000 collisions per square meter per second.[2] The original cosmic rays called primaries collide with particles in the atmosphere and form secondary particles such as pions and kaons through hadronic interactions. These then quickly decay into other particles.

About 80% of the secondary cosmic rays at sea level are muons. Muons are produced by pion decays and are of particular interest due to their long range and matter penetrating properties. Muons are charged, unstable leptons with lifespans of 2.2 μs and behave similarly to electrons, but are 207 times as massive. Due to their high speeds, close to the speed of light, relativistic effects allow the unstable muons which form in the upper atmosphere to travel around 15 km and reach the surface of the Earth.

On their way to the surface, muons may interact with different matter such as air, water and rock and undergo different types of energy loss such as electron-positron pair production, ionization, and bremsstrahlung effects. The energy loss of muons due to matter interactions is given by the equation,

$$-{}^{dE}/_{dx} = a + bE, \tag{1}$$

where a and b are constants accounting for different types of interactions, E is the muon's energy and x is the column depth.[3] For example, a 100 GeV muon traveling through standard rock has an a value of 2.44 MeV g^{-1} cm^2 and a b value of 3.04 g^{-1} cm^2.

Denser matter causes more energy loss slowing the muons and allowing them time to decay which also lowers the flux of muons that can reach the surface. The range of a muon with energy E can be found by solving equation (1) and is then expressed by[3]

$$R_\mu = {}^{1}/_{b} \ln(1 + {}^{b}/_{a} E). \tag{2}$$

For example, the range for 4 GeV muons (the average energy of cosmic ray muons reaching Earth's surface) traveling through standard rock (ρ = 2.65 g cm^{-3}) is about 16 meters. The flux of muons that are detected depends then on their original energy and the amount of material with which they interact. The zenith angle along which they travel also plays an important role in changing the expected muon flux since at big angles, muons must pass through more atmosphere which lowers the number of muons that can pass. The muons that are able to reach the Earth at larger angles are therefore higher energy particles which can pass through more matter than slower particles. Expected muon flux is well understood as are the effects of matter on the particles. These matter and relativistic effects while traveling through the atmosphere lead to a flux intensity, I, that depends on the zenith angle, θ, as

$$I(\theta) = I_0 \cos^2(\theta), \tag{3}$$

where I_0 is the energy-integrated flux intensity and has a generally accepted value of 0.0083 $cm^{-2}s^{-1}sr^{-1}$.[3] At angles larger than ~80°, however, the curvature of the Earth and exaggerated matter effects become large sources of error since the equation does not account for those changes.

Muon flux and matter effects are generally well studied and understood. Therefore, it is possible to measure the muon flux in order to accurately describe the amount of matter and the kind of matter that the particles have traveled through.

2. Experimental Design

The cosmic ray detector was constructed according to plans made available by the Quarknet Collaboration.[4] The detector consisted of two scintillators, attached photomultiplier tubes (PMTs), and a data acquisition (DAQ) board. The scintillators are organic (Anthracene) with a plastic base and were chosen for their fast timing. When a charged particle such as a muon collides with an electron in the Anthracene, the transfer of kinetic energy enables the electron to occupy a higher energy level. The subsequent decay back to its original orbital releases a photon. The photons which are given off by the scintillator in the presence of ionizing radiation such as muons are then picked up by the PMTs. In the PMT, a multiplication process magnifies the energy of the photon and converts the light into an electrical pulse which is then analyzed by the data acquisition board.

Two scintillator and PMT pairs were used in order to measure coincidence events and reduce the chance of detection of false events. An event was thus counted if both PMTs sent an electrical pulse within a window of 100 ns. This window was chosen because it was long enough to allow a muon to pass through both scintillators and be analyzed by the DAQ board while minimizing the window for random events. For the size of the scintillators used in the detector, 200 cm^2, high energy muons occur at about 2 per second so the chance of two different muons crossing the scintillators in a 100 ns window is quite low. Random events still occurred, however, at a rate of about one per minute due to background radiation and thermal electrons. The scintillators were placed 10 cm apart from each other in order to ensure that a muon was in fact passing through since other particles may decay between or even inside the scintillators. The DAQ board displayed a count of events on a triple digit LCD display during a set time period.

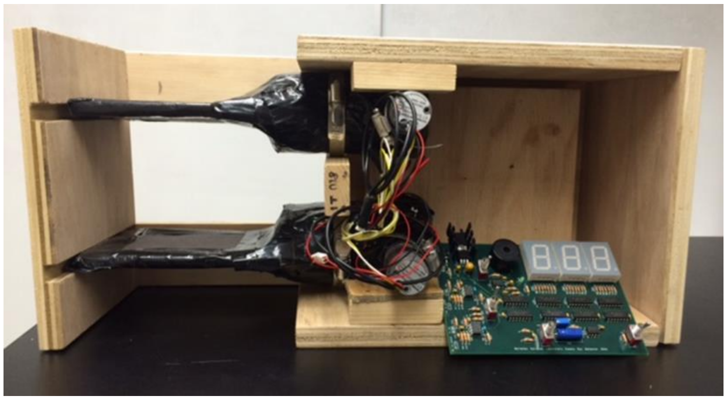

Figure 1. The cosmic ray detector

To test the cosmic ray detector, measurements were taken for one minute intervals at various zenith angles ranging from 0 to 90 degrees. The detector was angled at 0, 30, and 45 degrees, as well as 60 – 90 degrees with 10 degree intervals. Scintillator spacing, time, and all other variables were kept constant. The experimentally obtained results were compared to theoretical calculations to demonstrate the accuracy of the detector. Variation in cardinal direction measurements were also taken but did not show any statistically significant difference.

In order to compare matter effects to theoretical predictions, flux attenuation measurements were made with various amounts of material between the scintillators. The scintillators were placed 75 cm apart in order to limit the flux to muons that had passed through the matter. Detector orientation, time, scintillator placement and all other variables were kept constant with the exception of the amount of material between the scintillators.

After verifying the validity of the detector, it was used to measure the muon flux attenuation due to natural, geological structures such as hills and mountains. The detector was angled at 0, 30, and 45 degrees as well as 60 – 90 degrees with 10 degree intervals and was placed facing towards a local hill. This data was compared to data taken in the same way but without the hill in the way. Time, scintillator spacing, and other variables were kept constant.

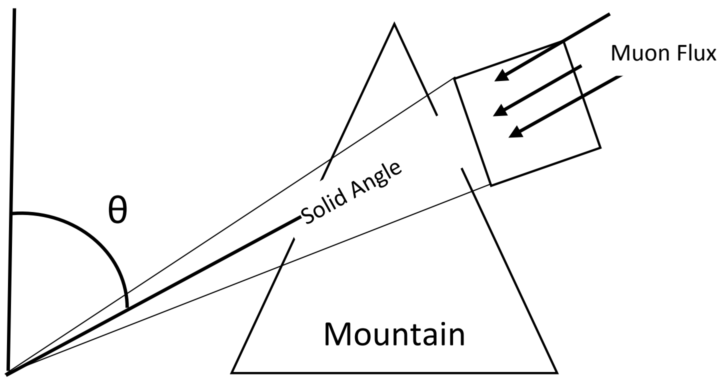

Figure 2. A diagram of the experimental setup. The cosmic ray detector is oriented so that it points along the desired zenith angle, θ, and detects muons entering through a solid angle of acceptance. In the displayed case, a mountain blocks the muon flux traveling toward the detector at the bottom left-hand corner.

3. Analysis

The measured zenith angle dependence and matter effects in a controlled setting were compared to theory to determine the accuracy of the detector response. As stated earlier in equation (3) the energy integrated flux has a squared cosine dependence on zenith angle. Furthermore, as the detector was rotated through the zenith angle, an additional cosine was picked up in the solid angle calculations leading to

$$\frac{dN}{dt} = \int I_0 \cos^2\theta (\cos\theta dA) d\Omega. \quad (4)$$

The final theoretical count rate was found by integrating the muon flux over the area of the scintillator pads and the solid angle subtended by the detector's design.

It should be noted that for large zenith angles greater than ~80°, the relationship used earlier in equation (3) becomes less accurate due to the curvature of the Earth and largely increased muon path through the atmosphere. In this case, interpolated data was used to accurately determine theoretical values.[4] Additionally, at large zenith angles, muons passing through the back of the detector were also taken into account, since the detector lacks directional discrimination.

Matter effects are taken into account by including an attenuation term in the flux integral as

$$\frac{dN}{dt} = \int I_0 e^{\left(\frac{X}{\Lambda}(1-\sec\theta)\right)} (\cos\theta dA) d\Omega, \quad (5)$$

where X is the column depth measured in g/cm^2 and Λ is the attenuation length.[5] The attenuated flux is again averaged over energy and depends on angle since this affects the amount of matter in the muon's path. For the material used, the density led to Λ = 1.92 g/cm^2.

4. Discussion

All of the experimental results matched theoretical predictions to within experimental error. Ranges an error bars include error from zenith angle measurement, thermal electron counts and statistical error.

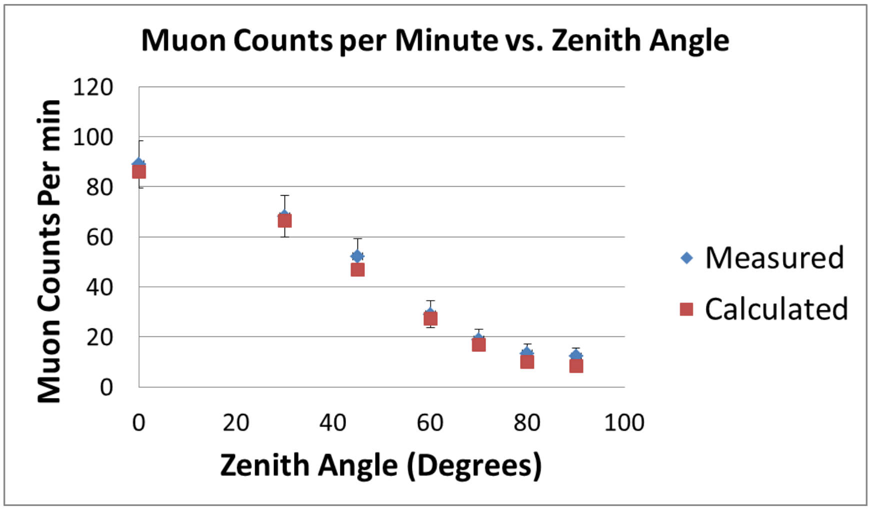

Figure 3. The number of muon counts per minute versus zenith angle (degrees)

When compared to the theoretical results, the measured results matched the expected pattern for the zenith angle dependence. Since the relationship between flux and zenith angle becomes complicated at large angles, a different, more complex analysis that incorporates using interpolated data to more accurately determine theoretical values is required.[4,6]

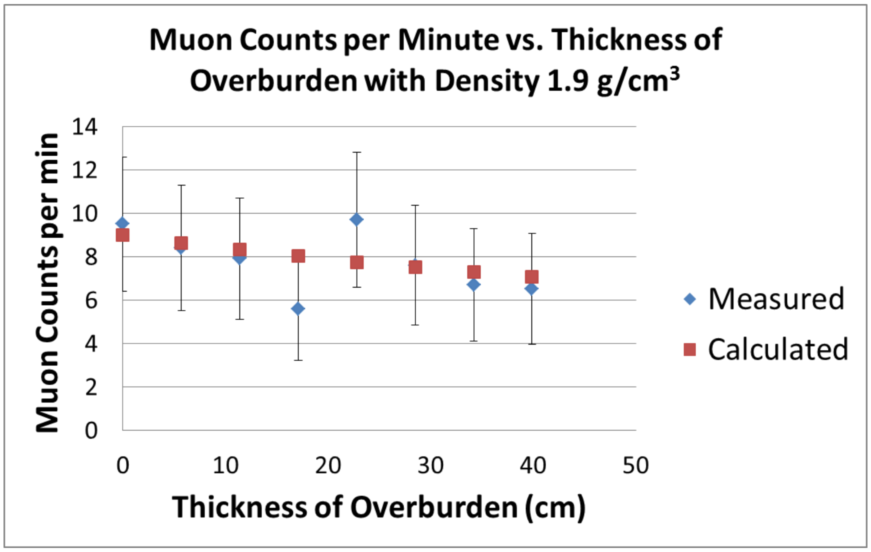

Figure 4. The number of muon counts per minute versus the thickness of the above overlying material with density of 1.9 g cm^{-3}

Experimental results matched theoretical predictions within error. A clear decrease in the muon flux with the increase of overburden was seen and can be concluded as an obvious relationship since more matter is able to stop more muons. Data was taken with the detector oriented in the vertical direction where the average muon energy was assumed to be 4 GeV.[3]

Table 1. Muons detected per minute with respect to zenith angle for an obstructed path and an unobstructed path

	Muon Counts per minute	
Zenith Angle (degrees)	Without Hill	With Hill
90	13 ± 3.6	14 ± 3.7
80	14 ± 3.8	19 ± 4.4
70	20 ± 4.4	22 ± 4.6
60	30 ± 5.5	24 ± 4.9
45	53 ± 7.3	45 ± 6.7
30	69 ± 8.3	58 ± 7.6
0	90 ± 9.5	84 ± 9.2

Preliminary data that was collected near a local geological structure is presented in Table 1. Although an overall clear pattern is not evident in the data collection so far, hints of a relationship present themselves between 30 and 60 degrees and are currently being studied. A theoretical comparison is also presently being calculated (see below for further details). It is worth noting that at larger angles, the expected relationship is less noticeable due to the presence of high energy, deeper penetrating muon which are less likely to be affected by the presence of the hill. At very small zenith angles, there was less of a matter effect since the geological structure was not tall enough to act as a large obscuring structure.

In order to compare the experimental hill data to theoretical values, the geometry of the hill must be used. The complicated layout of the hill makes the amount of matter in the muon's path difficult to calculate. In future research, a Monte Carlo simulation will be created in order to obtain theoretical values. This comparison will allow for the calculation of the amount and density of the material in the hill. Since geological structures mostly affect muon flux at large zenith angles and because matter effects depend greatly on the energy of the incoming muons, it becomes important to include energy spectrum information. The energy spectrum of the muon flux will also be incorporated into the rate integral in future research.

5. Conclusion

The research showed that it is possible to accurately measure muon flux with a low cost detector. Data taken revealed a flux dependence on zenith angle and matter, as predicted. Theoretical results also matched experimental data within statistical error. A Monte Carlo simulation will be utilized in the future to determine the full effect of the matter in the muons' path. The energy spectrum of the incident muons will also be added in order to obtain theoretical values for muon flux attenuation due to matter. A comparison of measured flux to the Monte Carlo simulation will then allow for the calculation of the amount and density of the overburden material.

6. Acknowledgements

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