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Article

Factors influencing muon flux and lifetime: An experimental analysis using cosmic ray detectors

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SUMMARY

Muons, one of the fundamental elementary particles, originate from the collision of cosmic rays with atmospheric particles and are also generated in particle accelerator collisions. Muon flux and lifetime are usually analyzed to obtain important insights regarding time dilation and to ascertain the characteristics of the particles and processes that occur during collision. In this study, we analyzed the factors that influence muon flux and lifetime using Cosmic Ray Muon Detectors (CRMDs). We hypothesized that the positioning of cosmic ray detector scintillator plates and depth of water above such scintillator plates would affect muon flux and lifetime. Muon flux and lifetime would be affected as an increase in matter in the path of a muon would slow or stop muons passing through it. Altering liquid shielding indicated that muon flux was inversely related to the depth of water that it passed through. Altering scintillator positioning indicated that detection rates of muon decay increased with the distance between the top and bottom of the scintillator plates resulting from the scintillator plate orientation. Unlike previous studies, the effects of the shielding were noticeable at smaller scales. Overall, this study suggests that water can be used to decrease muon flux and that the scintillator orientation is a potential determinant of the volume of data collected in muon decay studies.

INTRODUCTION

The Standard Model, a particulate model of how the universe works, purports the existence of two classes of elementary particles: fermions and bosons (1). Bosons include many of the force carrying particles in the universe, while fermions include leptons and quarks, which make up much of the matter in the universe. Leptons consist of three categories of particles with charge – the electron, the muon, and the tau, as well as particles with no charge – the neutrinos. Neutrinos are significantly smaller than electrons, and correspond to each charged lepton.

The Muon

The muon is a fundamental elementary particle that was discovered in 1937 by C.W. Anderson and S.H. Neddermeyer (2). The muon is about 207 times larger than an electron, and has the same charge as the electron, -1 e. Muons are unstable particles with a mean lifetime of 2.2 μs, after which they decay into lighter particles with the same net charge as the muon because charge must be conserved when decay occurs (3). Each muon decays into an electron (with the same charge as the muon), an electron antineutrino, and a muon neutrino. This is conserves charge. The mean-life of the muon is significantly longer than most other unstable elementary particles.

The Source of Muons on Earth

Muons are a product of the collision of cosmic rays with molecules in the upper atmosphere and other atmospheric particles (4). Cosmic rays are high-energy charged particles traveling near the speed of light, originating from supernovae and other sources beyond the solar system. When a cosmic ray proton hits Earth's upper atmosphere, it collides into a particle in the Earth's atmosphere. As this occurs, the cosmic ray forms a shower of various particles resulting from the collision. These new particles then travel and decay as well, cascading down through the atmosphere. Muons are generated when the cosmic ray proton collides with atoms in the atmosphere, creating short-lived pions. The pions soon decay into muons that travel towards the Earth's surface (**Figure 1**). Often, the muon, having a longer lifetime than many other unstable subatomic particles, reaches Earth's surface.

Cosmic Ray Muon Detectors

Cosmic Ray Muon Detectors (CRMDs) are devices that investigators use to study muons originating from cosmic rays. CRMDs use a set of counters, each comprised of a scintillator plate and a photomultiplier tube (PMT) (5). The scintillator plate luminesces when exposed to muons. This effect is amplified by the PMT, which allows for an electrical signal to be produced when a single muon passes through the plate. Photons can interfere with the signaling from scintillator counters, so each scintillator plate must be shielded from light.

CRMD signals can be read and analyzed by a specialized QuarkNet software (5). The software can characterize the

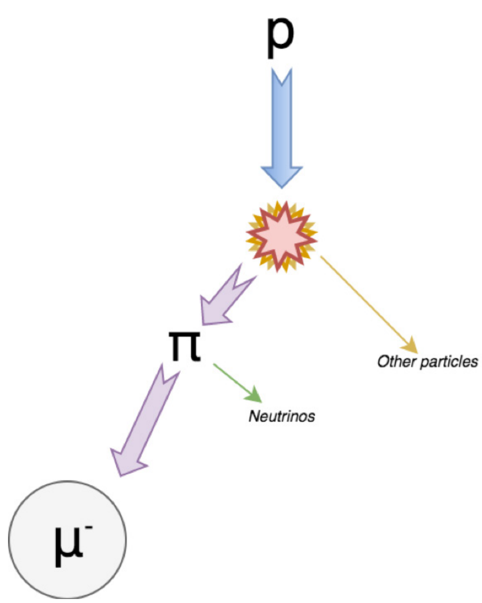

Figure 1. Cosmic ray showers. The collision of a cosmic ray proton (p) into an atmospheric nuclide produces pions (π). Pions, which are very unstable, quickly decay into muons (μ^-), which can be detected at the Earth's surface.

hits for single muons that have passed through two, three, or all four of the counters as two-fold, three-fold, or four-fold coincidences to allow for differential analysis of muons from specific directions or angles. It also allows for muon flux and lifetime data analysis. In a flux study, the rate of muon hits in a given area can be viewed over time, so that the effect of changes in the CRMD's surroundings can be detected. In a lifetime study, data on muons that decay within the scintillator plate is collected. Additionally, previously collected global data from other cosmic ray detectors can be accessed through the software. CRMD systems can have variations in their setup and hardware that result in inaccurate data, so calibration is required.

Purpose of this Study

Cosmic ray showers are often analyzed because they are natural examples of high-energy collisions often simulated in particle accelerators. Moreover, analysis of muon speed and lifetime gives researchers more evidence for the existence of time dilation, according to the theory of special relativity (6). Therefore, the purpose of this study was to identify and analyze the factors that influence muon flux and lifetime. We hypothesized that the positioning of scintillator plates and depth of water above such scintillator plates would affect muon flux and lifetime as an increase in matter in the path of a muon would slow or stop muons passing through it. In order to test this hypothesis, two experiments were conducted: 1) the liquid shielding flux experiment, and 2) the scintillator positioning lifetime experiment. CRMDs were used to conduct this study because these detectors enable the collection of data on muon presence and decay. The outcome of this research is significant because the information obtained from this experiment would enhance our understanding of the processes that can affect muon decay as well as detection. Additionally, this study aims to detect impacts of shielding at scales smaller than previous work. Understanding the path of muons after a collision allows researchers to ascertain the characteristics of these particles and processes that occur during the collision.

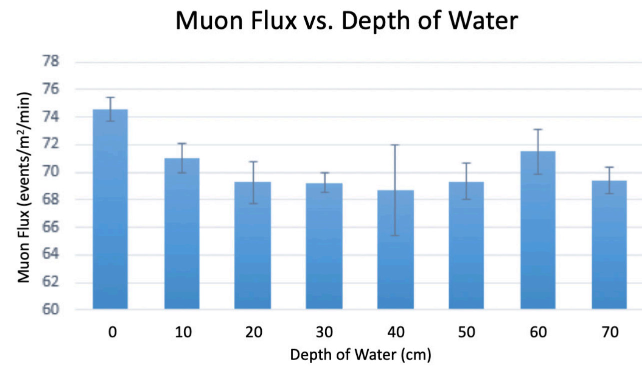

Figure 2. Liquid shielding flux experiment results. Muon flux measured as events/m^2/min was recorded for depths of water ranging from 0 to 70 cm. Error bars represent standard error of the mean.

RESULTS

Muon Flux Decreases with an Increased Depth of Water

To measure the effect of water depth on muon flux, flux data was collected at water depths from 0 to 70 cm. Muon flux decreased as the depth of the water in the bins increased, particularly when the depth was between 0 and 30 cm. However, higher variability in the latter half of the experiment (depths greater than 30 cm.) did not reflect the trend observed with lower depths of water. Nevertheless, a trend exists in the first 30 cm. of depth, implying muon flux decreases as water depth increases at this depth range (**Figure 2**).

Detection of Muon Decay Increases with Scintillator Plate Orientation Height

To determine the optimal orientation of scintillator plates for data collection, lifetime data at a one-fold coincidence was collected for each of three distinct orientations; the plates were set on their long edge, on their short edge, or flat (**Figure 3**). When the software collects lifetime data, it only counts

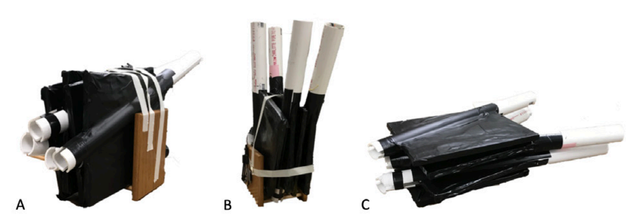

Figure 3. Scintillator positioning experimental setup. The three images present the actual orientations of the scintillator plates. It is important to note that position C has the shortest height, B the tallest, and A has an intermediate height.

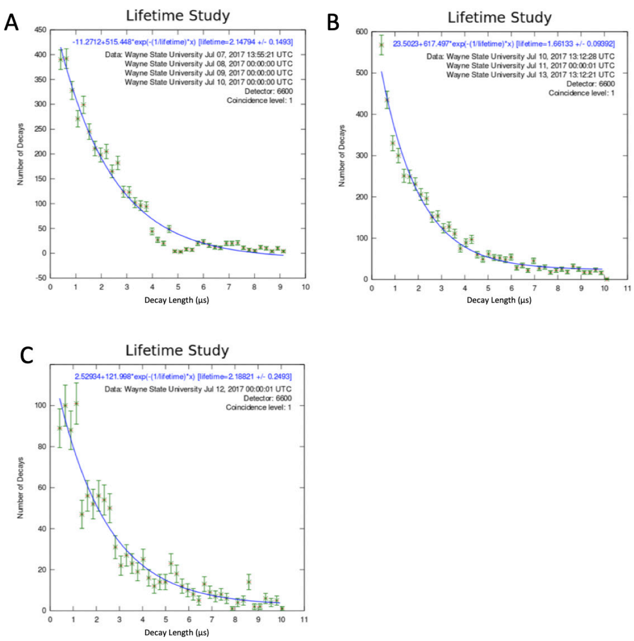

Figure 4. Scintillator positioning lifetime experiment results. Muon lifetime measured in µs was recorded for each scintillator plate orientation. Error bars represent standard error of the mean.

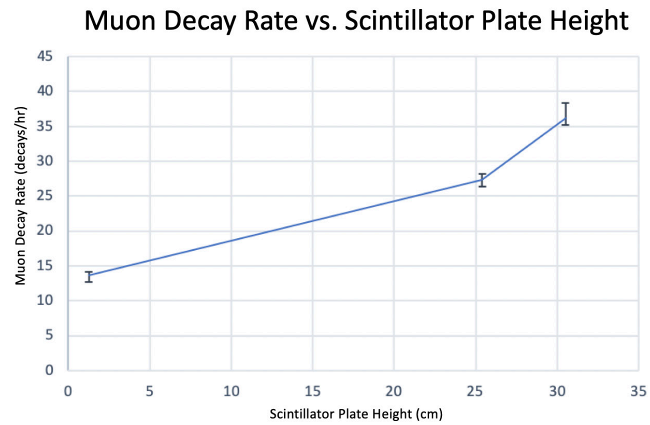

Figure 5. Scintillator positioning experiment synopsis. Muon decay rate in decays/hr. was calculated for each scintillator plate orientation corresponding to a vertical height in cm. Error bars represent standard error of the mean.

decay events that occur within a scintillator plate. The graph of lifetime data generated can then be integrated to provide a count of total hits during the data collection period for that orientation, and then a rate of hits for that orientation can be generated.

In the first, flat orientation of scintillator plates, we recorded 984 lifetime hits over a 72-hour timespan, so the rate of detected muon decay in this setup was 13.7 decays per hour. The standard error of the mean calculated for this position was 0.44 decays per hour (**Figure 4C**). In the second orientation, with the scintillator plates stacked on the long edge, we recorded 1258 lifetime hits over a 46-hour timespan, or 27.3 decays per hour, with a calculated standard error of the mean of 0.77 decays per hour (**Figure 4A**). In the final orientation, with the counters stacked on the short edge, we recorded 289 lifetime hits over a time span of 8 hours, so the rate of decay was 36.2 decays per hour. The calculated standard error of the mean in this orientation was 2.1 decays per hour (**Figure 4B**).

This data demonstrates an upward trend that corresponds to the vertical height of the scintillator plate orientations (**Figure 5**). When the orientation results in a greater distance between the top and the bottom of the scintillator plates, more muons can decay in the scintillator plates. Then, these decays can be measured.

DISCUSSION

We hypothesized that greater vertical height from scintillator positioning and less shielding would increase muon decay detection rate and muon flux.

In the liquid shielding flux experiment, we demonstrate a measurable effect of low-depth water shielding on muon flux. However, this relationship was not observed at depths greater than 30 cm. Confounding variables that may have led to this include power outage-associated voltage fluctuations that occurred on the day of data collection for the 40 cm depth, as well as on subsequent days, as changes in voltage affect the calibration and thus overall data collection integrity of the scintillator plates. Despite this potential inconsistency, the data in the initial periods of the experiment suggest measurable water shielding of muons. We know that this miscalibration was not present for the water depths below 40 cm because the data was collected sequentially; first 0 cm, then 10 cm, and so forth until 70 cm. However, if we presume that the calibration was unaffected by the power outage, our data suggests an initial decrease in muon flux when any depth of water is present but does not suggest a clear trend relating water depth and muon flux. Therefore, the shielding experiment should be repeated without confounding variables such as voltage fluctuations to ensure that the results are reproducible.

Researchers have analyzed muon flux, comparing seafloor readings underwater to surface readings (7). Additionally, the impact of shallower depths of water on muon flux have also been investigated (8). However, this present research shows that shielding from water can be detected at markedly smaller scales. Moreover, if water shielding could selectively block low-energy muons, our findings will be of value because researchers working on particle accelerators can selectively analyze high-energy muons, allowing for more specific insight during collisions and more specialized research into higher-energy particles because lower-energy muons may be shielded by water if implemented. Therefore, additional studies are needed to determine whether water shielding can selectively block lower-energy muons, or non-selectively blocks muons of any energy value.

In the scintillator positioning lifetime experiment, the observed rate of muon decay increased substantially when the vertical height of the scintillator plates increased. There was a 100% increase in the rate of muon decay when the scintillator plates were placed on their long edges, then an additional 32.2% increase as they were placed on their short edges. This is likely due to the fact that more muons approach Earth's surface vertically rather than horizontally (9). If a muon approaches horizontally, or at an angle, it has to travel through more atmospheric matter, which in turn slows down the muon, and therefore, it decays before reaching the surface (10). When muons descend vertically, they travel through less atmosphere, and therefore they maintain more of their velocity. As a result, incoming muons would be most likely to enter a scintillator plate from the top, vertically. Because of this, scintillator plates with an orientation that lends to a larger vertical height will provide denser matter for muons to decay in. Understanding this concept, based on our experimental results, provides new insights for better design of future muon lifetime detectors, and other future applications of muons.

Future studies can build on the research conducted in this study. For example, more data is necessary for depths of 40 cm and greater in the water shielding flux experiment to analyze the impact of greater depths. Additionally, liquids other than water or solids could be analyzed using a similar experimental design. Factors such as density could be analyzed to further confirm the theorized factors that affect muon velocity through matter. Furthermore, setting up additional quantitative heights in the scintillator positioning experiment would benefit future studies. The conducted study compared the heights of the scintillator plates in reference to each other, in three distinct heights. The scintillator positioning experiment can also be further expanded by incorporating new angles and setting up coincidences so that muon flux and lifetime can be analyzed from the zenith to the horizon, and possible cosmic ray muon generation in the water can also be accounted for.

The findings of this study confirmed our hypothesis that muons either slow down or remain in the detector for longer periods and decay when they have more matter to travel through. This study is novel because the effects of the shielding are noticeable at much smaller scales than those applied in previous studies. The results of the water shielding experiment suggested that water can be used to decrease the muon flux by allowing for greater decay. The results of the scintillator positioning lifetime experiment suggested that the height of the scintillator in its orientation is a potential determinant of the volume of data collected for muon decay studies.

METHODS

Cosmic Ray Muon Detector Setup

This study used the QuarkNet Model 6000 Cosmic Ray Muon Detector and was conducted in a university physics research laboratory (5). Four counters, each comprised of a scintillator plate and a photomultiplier tube (PMT), were used in the setup of the detector for both experiments. Black tape was used to fully cover each scintillator plate. The orientation and position of the counters varied depending on the specific needs of the study. Each of the four counters were wired to a data acquisition (DAQ) board. This board registered and counted all the data incoming from the four counters that were set up. The information was sent to a connected computer, in which the data was analyzed using specialized software from QuarkNet, generating readable flux and lifetime data (5).

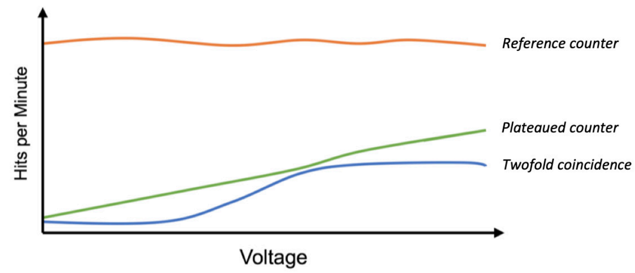

Figure 6. Plateauing graph. This graph shows, theoretically, how a typical plateauing curve should appear. The orange trace represents the reference counter. The green trace represents the counter being plateaued, which increases with voltage, while the reference counter remains at the same level. The blue trace represents the twofold coincidence consisting of the two aforementioned counters.

Cosmic Ray Muon Detector Calibration

Appropriate calibration of the CRMD was conducted so that a hit from a muon was neither over-represented nor under-represented in the generated electrical signal. The optimal voltage applied to each counter was determined by graphing the hits per minute of each counter versus a reference counter.

The PMTs were linked to a device known as the power distribution unit (PDU). The PDU allowed users to check the voltage of a counter with a voltmeter and alter the voltage if need be.

A plateauing method was used to calibrate each counter. One reference counter was set to a voltage that generated about 40-60 hits per second. The counter to be calibrated was stacked under the reference counter, and a two-fold coincidence was set. Data was then collected for about two minutes at a time, with a gradually increasing voltage in each period. The hit rates of the individual counters and the two-fold coincidence rates were graphed against voltage. In the graph, the reference rate stayed constant, much higher the other two traces in the graph. The two-fold coincidence trace produced a logistic function, and eventually plateaued. The individual trace of the counter being calibrated rose linearly, similar to the rate of the two-fold coincidence, until the two-fold coincidence graph plateaued. The voltage where the plateaued counter's graph diverged from the two-fold coincidence graph is the optimal voltage for the counter (**Figure 6**).

Plateauing was completed for the calibration of all four counters in this study. For counters 0, 1, 2, and 3, the values of optimal voltage were 770, 850, 820, and 910 mV, respectively. Counters 0, 1, 2, and 3 in the QuarkNet hardware correspond to counters 1, 2, 3, and 4 in the QuarkNet software, respectively.

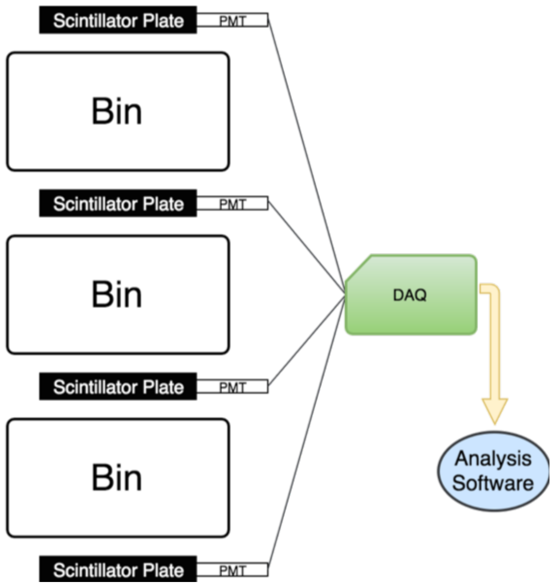

Figure 7. Liquid shielding flux experiment schematic. This diagram shows the setup of the counters and bins used to hold the water in the experiment. The counters were wired to the DAQ, which registered muon hits and compiled the raw data. That data was then uploaded and analyzed by QuarkNet data analysis softwares.

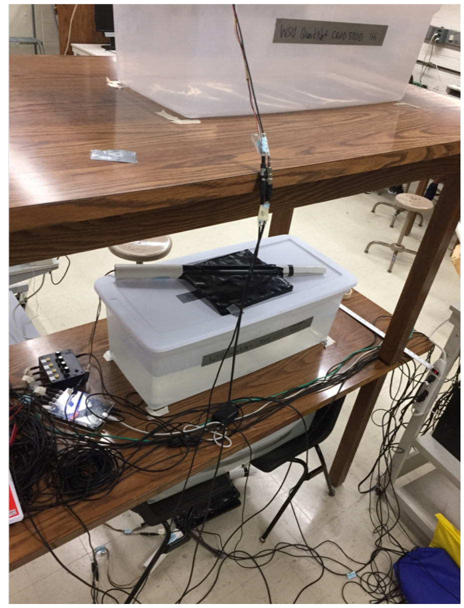

Figure 8. Detector positioning for shielding experiment. The image illustrates the actual setup of the liquid shielding flux experiment. Wire lengths and GPS positioning of each counter is entered into the data analysis software, as they affect the timing of signal reception from counter to DAQ.

Liquid Shielding Flux Experiment

The flux study was set up with four counters in a stacked configuration (11), with bins to hold water between each of them (**Figures 7 and 8**). First, a scintillator plate (counter) was placed flat on the ground. A bin that can hold a depth of up to 26 cm of water was placed 20 cm above the counter. This was repeated to have three bins, with four counters; one above the bins, one below the bins, and two in between the bins. As such, the bins can be filled to a total depth of 78 cm. As this study was set to a four-fold coincidence, only muons that passed through all four counters were counted during each data collection period. This was so that any detected muons are muons that have passed through the designated water depth, ensuring the validity of data collected in this study.

Control runs were conducted using the same configuration with no water. Data was collected for 0, 10, 20, 30, 40, 50, 60, and 70 cm of cumulative water depth. For each depth, data was collected for at least four hours.

Scintillator Positioning Lifetime Experiment

Muon lifetime data was collected when the paddles were positioned flat, in a stacked orientation (**Figure 3C**). A one-fold coincidence was applied to this setup. Data was collected for 72 hours. The length of time for which the data was collected does not impact the quantitative values of the muon lifetime data.

Muon lifetime data was then collected when the paddles were positioned at the longer edge, stacked side-by-side (**Figure 3A**). A one-fold coincidence was applied to this setup. Data was collected for 46 hours.

In the final orientation of the counters, the paddles were positioned on the shorter edge, stacked side-by-side, when the muon flux data was collected (**Figure 3B**). A one-fold coincidence was also applied to this configuration. Data was collected for eight hours.

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