Angular Dependence of Cosmic Ray Muon Flux

Stephen L. Eltinge and Jay M. Lawhorn*
MIT Department of Physics
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We will measure the zenith angle dependence of the cosmic ray muon flux using a pair of scintillator counters with photomultiplier tube readouts on opposing ends and the coincidence method. The angular dependence is known to go approximately with $\cos^2(\theta)$, where θ is measured from the zenith angle. We will test this prediction and make a measurement of the total cosmic ray muon rate.

1. SCIENTIFIC MOTIVATION

The interaction of cosmic rays with particles in the upper atmosphere produces secondary showers of highly energetic particles, including neutrons, charged pions, and kaons. As shown in Figure **??**, the pions can then decay into muons. The muon's mean lifetime is approximately 2.2 μs in its rest frame, but relativistic effects on high energy muons such as those produced by cosmic rays allow them to easily penetrate the atmosphere and some distance into the earth.

The Cosmic Ray Muon experiment in 8.13 measures the velocity of cosmic ray muons via time of flight measurements and their mean lifetime. The combination of these two measurements provide evidence for relativistic time dilation. The apparatus for that experiment consists of two large rectangular scintillating paddles with photomultiplier tube (PMT) read out on each.

It has extremely poor resolution for the point of interaction, so the acceptance calculation is generally made over the expected zenith angle distribution of the cosmic ray muons, which is given as a $\cos^2(\theta)$ dependence. This dependence is generally accepted by sources such as [**?**], but we intend to verify it experimentally.

2. HYPOTHESIS

This problem was previously tackled in an undergraduate thesis by MIT student Yi-Hong Kyo.[**?**] Kuo's thesis cites the following formula for the angular dependence of muon flux:

$$I(\theta, X_h, E) = I(0^\circ)\cos^{n(E,X_h)}(\theta), \tag{1}$$

where X_h is the vertical depth. Like Kuo, we expect to confirm the result that $n(E, X_h) = 2$ for the muons that interest us (*i.e.*, those with energies on the order of a few GeV). Kuo also found that the muon flux did not attenuate precisely to zero at angles of $\pm 90^\circ$, but rather exhibited small residual "tails." Since our experimental setup will be very similar to his, we anticipate finding this result as well.

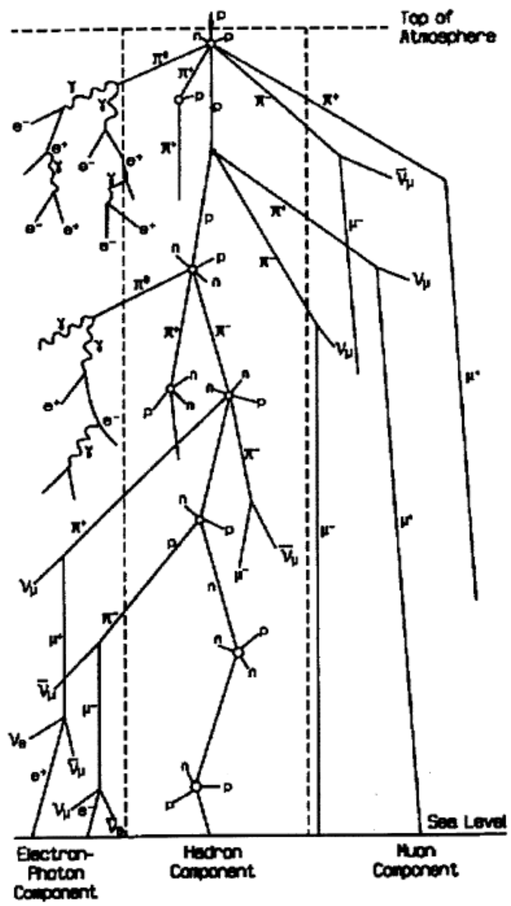

FIG. 1: Figure showing the production of muons and other particles from cosmic rays. From[**?**].

3. EXPERIMENT

3.1. Apparatus

We will use a pair of AMS scintillator counters, each of which consists of a long and narrow piece of scintillating material with a triad of PMTs at each end. We will read out each set of PMTs by oscilliscope. The apparatus itself is shown in Figure **??**.

The scintillation light produced by a muon interacting with the material will propagate and be detected at each end, and the time difference between detection at each

*Electronic address: seltinge@mit.edu; klawhorn@mit.edu

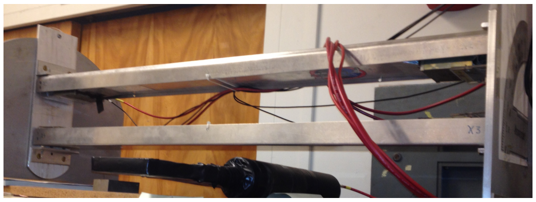

FIG. 2: The two vertical bars each enclose one scintillator counter, with four total PMT readouts located on each end of the vertical bars.

end allows reconstruction of the point of interaction. Using a pair of these counters will allow us to reconstruct a flight path for each muon and ultimately an angle of incidence.

3.2. Method

We will establish a working bias voltage for the PMTs by measuring the signal frequency as a function of bias voltage. If the bias voltage is too low, we will be losing events that we could otherwise detect. However, if the bias voltage is set too high, our signal will be dominated by amplified noise. We will set bias voltages for each PMT in the plateau between these two regimes.

We will measure the counter detection efficiency by placing two smaller scintillator paddles directly above and below one of the scintillator counters and looking at events where the two smaller paddles register a hit. The percentage of these events in which the middle counter also registers a hit will allow us to calculate the efficiency of the middle counter independently of the efficiencies of the smaller paddles. This setup will also allow us to validate our reconstruction of the point of interaction in the scintillator counter to a certain extent, although the expected precision in point of interaction will likely be much smaller than the additional paddles.

In order to find the angular dependence distribution, we will take data using the four PMT readouts in a series of long integration time runs, and reconstruct the flight path for each detected muon. The angle of incidence with respect to the azimuth can then be calculated. However, we will also need to take into account the geometric acceptance of the pair of scintillator counters, which we will model using a monte carlo simulation. If time permits, we will add detector effects and efficiencies to the simulation using either GEANT4 or a numerical integration scheme.

4. EXPECTED RESULTS

We expect to acquire an angular distribution of the incident muons in line with previous measurements going as $\cos^2(\theta)$ with some edge effects. We also expect to make a measurement of the detector efficiency of the scintillator paddles.

5. REQUIRED MATERIALS

We will require the pair of AMS scintillator counters, a four-channel USB-capable osciliscope, and if possible, two similarly sized scintillator paddles to be used for efficiency measurements. We hope to borrow the osciliscope from junior lab, and all scintillators from Prof. Becker.