Muon Decay Lifetime

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This study aimed to understand the ratio relationship between flux and solid angles of muon detectors, cardinal direction dependences for optimal flux acceptance, and the lifetime of a muon. Instruments used in the study included four varying muon detectors with corresponding coincidence parameters for detection. Increased solid angle proportionally increased flux, but the flux to solid angle ratio was independent of separation between detectors. Changes to the cardinal directions of the muon detector array showed a westward bias of muon flux with (708 ± 27) counts contrary to the other three cardinal directions, which all supported approximately 50 counts less on average. A timed detector array test resulted in an experimental muon lifetime of $(2.259 \pm 0.163)\,\mu$s. Compared to the actual muon lifetime of $2.197\,\mu$s, the run yielded a variance of 0.38σ.

Background and Significance

The Sun is the most efficient particle accelerator in the solar system. High energy particles are emitted from the depths of the Sun through fusion processes, and these cosmic rays bombard the Earth almost daily. Primary cosmic rays interact with the atmosphere and create air-showers of secondary and tertiary particles, invoking muon generation, illustrated in figure 1. The muon is a lepton like the electron, but much heavier and decays into two neutrinos to conserve the lepton number, specifically one electron neutrino and one muon neutrino. Muons differ from electrons due to their mass of $105.6\,\mathrm{MeV/c^2}$ [1].

Studies of muon generation during significant air-showers attempt to analyze the radiation factors that the particles pose to life on Earth. Although the lifetime of a muon is approximately $2.2\,\mu$s, ultimately, the significant mass, speed, and energy is concerning. Muon studies help to understand, track, and catalog these radioactive particles. With muon detectors, scientists are able to determine the flux and anisotropy of particles with shielding of different material or thicknesses.

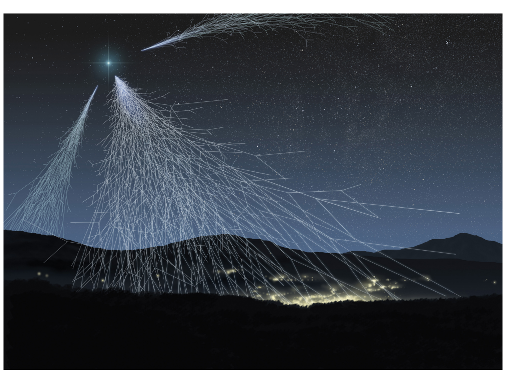

Figure 1. *Graphic of a cosmic ray shower bombarding the surface of the Earth. More rays are created as primary cosmic rays interact and create secondary/tertiary rays. [2]*

Apparatus

The apparatus included up to four muon photomultiplier tube (PMT) detectors that contained plastic scintillators. The detectors were adjustable to include less detector layers and manipulate the spacing/solid angle measurements. Each muon detection was discriminated at defined voltages and time intervals. The coincidence unit (scaler) was set up to count the amount of times that a muon was detected that triggered two or more detectors. The coincidence unit was also arranged to reject vetoed muon detections from the bottom detector at ascertained times.

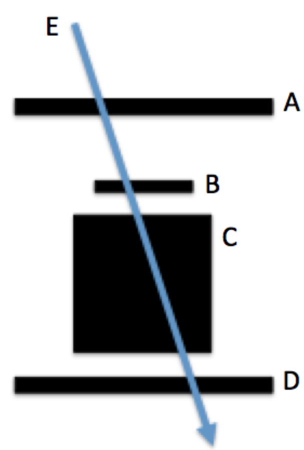

Figure 2. *The detector set up with a diverse range of height separations between the PMTs. A) PMT A B) PMT B C) PMT C D) PMT D E) Cosmic Ray Muon*

Procedure

The four muon detectors were plateaued before any data collection was done. Detectors A, B, C, and D were calibrated at 1750 V, 1550 V, 1400 V, and 1600 V, respectively.

To measure the vertical muon flux, two detectors were gradually separated by defined heights. A set time interval was specified, and the counts were measured for each height identity. The solid angle was derived from equation 1 using measured parameters of the detectors.

The directionality was determined by shifting the apparatus detectors parallel to the ground. The apparatus was rotated to represent muon flux in the north, south, east, and west cardinal directions.

$$\Omega = 4\left[\arccos\left(-\frac{\omega^2/4}{h^2} + \frac{\omega^2}{4}\right)\right] - 2\pi \tag{1}$$

$$VerticalMuonFlux = \frac{Flux}{\Omega} \tag{2}$$

The muon lifetime was found by triggering on muons that pass through the top two counters but stop in the large block of scintillator [1]. The counting timer elapsed a total of 510840 seconds or 5.91 days. Any signal that passed through detector D in figure 2 were vetoed and rejected from counting. Before data collection, a calibration curve was generated from 0.5 μs to 3.5 μs against channel numbers of the Multi-Channel Analyzer (MCA) [3]. Using the calibration and the measured flux of muons, the fit parameters of the resulting plot yielded the muon lifetime.

Calculation of Results and Errors

Flux against Solid Angle and Spacing between Detectors

Equation 1 states that increased solid angles increases the flux. Figure 4 shows the aforementioned statement as the flux proportionally increased as the solid angle was increased.

The muon vertical flux exhibited a converse behavior to the solid angle flux. Figure 2 showed increasing detector separation versus the ratio of flux and solid angle. Vertical muon flux is practically constant within the flux error, which shows the relation between flux and solid angle is independent of the separation distance.

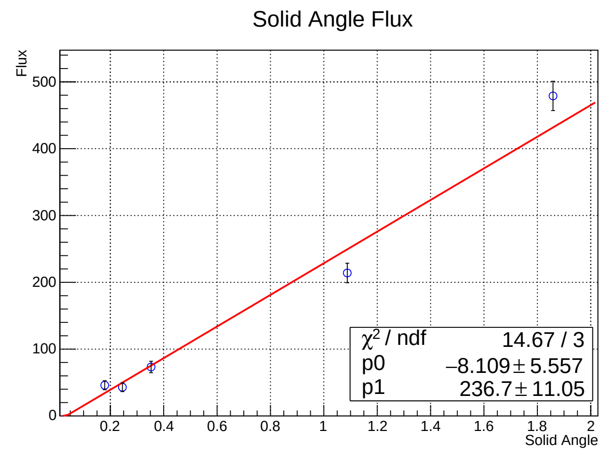

Figure 3. *Solid angle against flux with a linear relationship between the two parameters.*

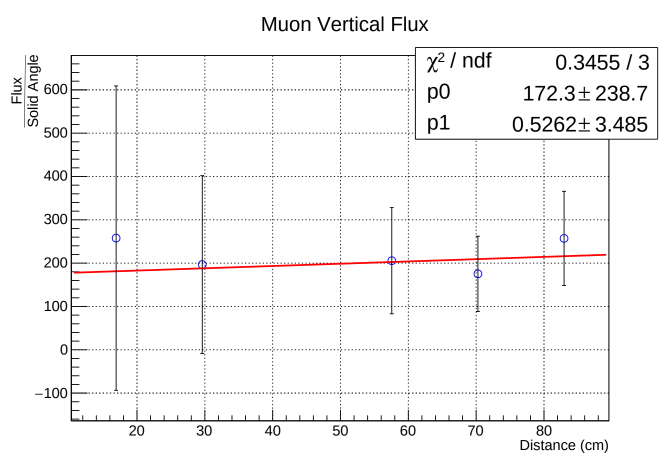

Figure 4. *Muon vertical flux relationship between the solid angle, flux, and the separation between detectors. The flux and solid angle ratio is constant with deviating detector separation.*

Cardinal Direction

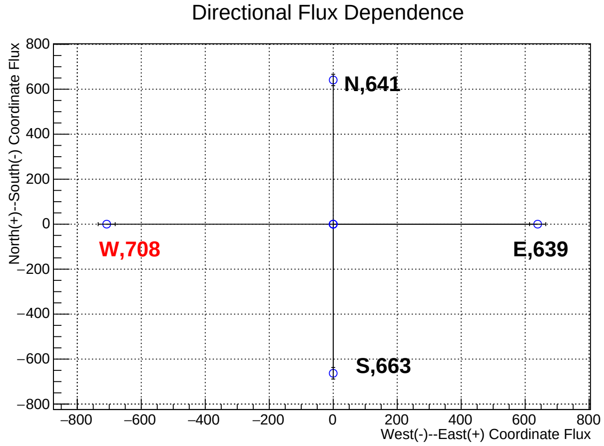

Figure 5. *A directionality map that illustrates the directional bias in the westward cardinal direction with approximately 708 counts.*

The muon directionality had an extreme westward bias of (708±27) counts. Conversely, the north, east, and southward flux were (641±25) counts, (639±25) counts, and (663±26) counts, respectively. The cardinal direction bias was attributed to the geomagnetic cutoff of the Earth's magnetic field, which allows only certain directions and rigidities of cosmic ray flux at equatorial latitudes.

Muon Lifetime

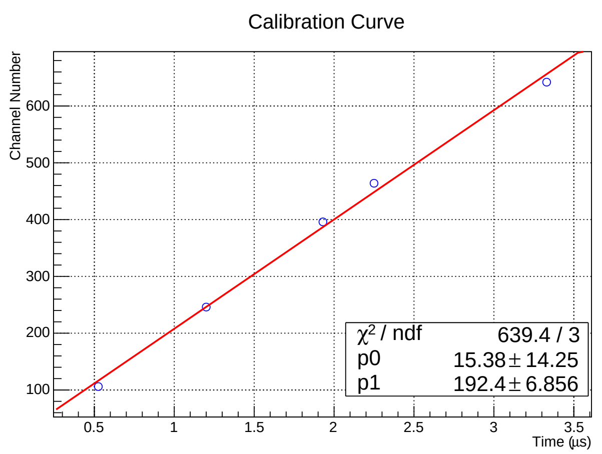

Figure 6. *Calibration curve with a linear fit used to convert MCA channel numbers into respective and proportional time.*

The calibration curve yielded a linear fit that included parameters to convert channel numbers into a time axis. The axis was converted from seconds to microseconds. The conversion parameters were used to manipulate the muon lifetime channel numbers into microseconds in figure 7.

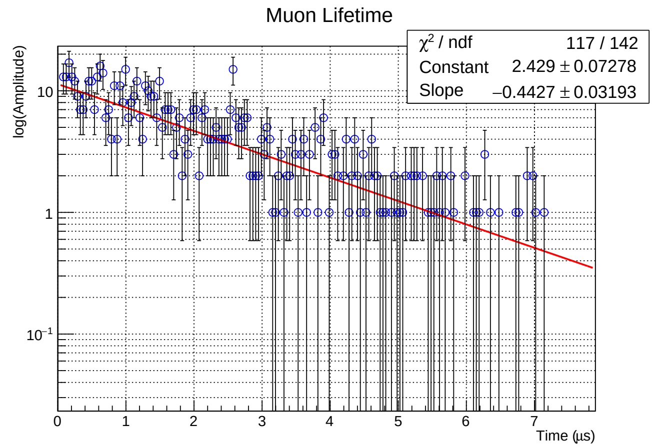

Figure 7. *Binned values of the muon lifetime portion of the study. A exponential fit is linearly placed to signify the regression as time elapses.*

Table I. *Experimental muon lifetime versus the actual lifetime*

Counting Time (days)	Experimental Muon Lifetime (μs)	Actual Mean Muon Lifetime (μs)	Error
5.91	2.259±0.163	2.197	0.38σ

$$ae^{-t/\tau} = e^{p_0 x + p_1} \tag{3}$$

$$-\frac{1}{p_0} = \tau \tag{4}$$

Muon lifetime, τ, was determined by the slope in figure 7. As time elapsed, the flux of muons decreased causing the regression originally in the MCA bins. The parameters of the slope were determined with an exponential fit in equation 3. A derived muon lifetime expression inverse to the slope, resulted in an experimental muon lifetime of (2.259±0.163) μs. The actual mean lifetime of a muon is 2.197 μs, therefore the experimental lifetime had a discrepancy of 0.38σ [4].

Discussion

A deviation of 0.38σ showed that the experiment was relatively accurate in determining the lifetime of a muon. The muon flux with solid angles exhibited the desired qualities, but there were large statistical errors when deriving the flux and solid angle ratio. Westward bias for muon flux was also accurate qualitatively, but the result was hindered as the southward cardinal direction is similar to the western flux within the error. The largest source of statistical error of calculations involved in this study were attributed to the Poisson error derived from the flux of muons.

[1] http://www.phys.hawaii.edu/~shige/phys481L/MuonDecay.txt
[2] http://www.geek.com/wp-content/uploads/2014/10/cosmicrays2.jpg
[3] "Multichannel Analyzer (MCA) Application Software." Nuclear Applications Software—ORTEC Scientific Equipment. ORTEC. Web. 5 Nov. 2015.
[4] http://pdg.lbl.gov/2012/tables/rpp2012-sum-leptons.pdf