Angular and Altitude Dependence of Cosmic Ray Muons

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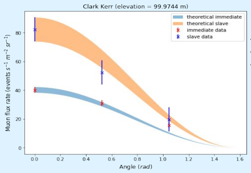
Background

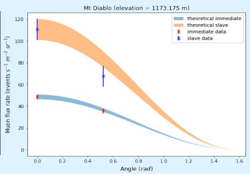
Muons are a second generation leptonic elementary particle, similar in most properties to an electron. While they have a charge(-1) and spin (½) that are identical to that of an electron, they are significantly more massive - approx. 207 times that of an electron. Being leptons, muons do not have a substructure. Their half life is 1.523 microseconds[1].

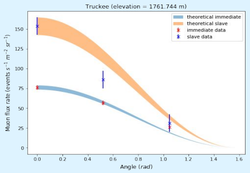
Muons are most commonly found as a consequence of cosmic rays -- high energy particles (mostly protons and alpha particles) colliding with Earth's upper atmosphere at altitudes between 10 and 15 kilometers[2]. Due to this process imparting relativistic velocity to each muon (characteristically 0.9995c)[4], we can observe these muons at sea level despite their short lifetime as a direct consequence of special relativity -- one of the strongest experimental confirmations we have of special relativity.

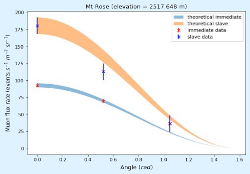
Abstract

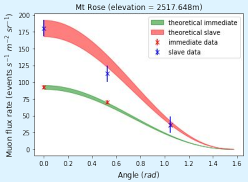
Using plastic scintillation detectors, our group produced data to measure the muon flux as a function of altitude, angle, and solid angle subtended by our detectors. This allowed us to compare our data to literature models[2]. Our data showed a high degree of convergence with existing literature models, even those lacking in technical rigour. Improvements could be made by surveying the energy distribution of muons at different altitudes[3], allowing us to use more robust modeling techniques and fit our data more closely.

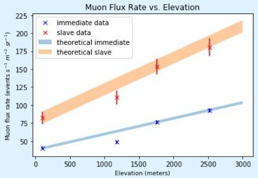












Data Analysis

Overall, we found a high degree of convergence between our measured data and a naive literature model. Especially poignant, given the structural limitations of our apparatus, is the confirmation of their efficiency: the literature [2] states that at Sea Level the integrated flux would be 72.5 normalized events per second, with a value of 98.8 at 600m. Our data reads at 82.25 normalized events at 100m, an error of 6.9% to the predicted model.

However, it might be noted that we consistently see too few events at $\theta \neq 0$. Part of this can be accounted for by using a more robust model. Shukla, et al. suggest that the power of the distribution grows as altitude does. Taking their projected value for a 2500m altitude, our data for Mt.Rose more accurately fits the projection [see left, graph with different color scheme]. Suppressing all other curves similarly yields a clear result: the more robust literature model more accurately reflects reality. This model of the shift in energy distribution is reflected in direct measurement experiments, such as McNichols.

As for flux as a function of elevation, we found a remarkable degree of convergence between the model proposed by the literature [2] and our data [see left]. The second data point is strongly divergent from the overall trend, perhaps as a consequence of a difference of overburden: the measurement was taken indoors, in a thick-roofed building.

Oddly, our regularized data seems to lack a scale factor of exactly 2 -- even when accounting for all other factors, the regularized flux is different by a scale of 2 under different detector alignments

Experimental Design

The angular, altitude, and displacement dependence of muon detection was determined by constructing four "Cosmic Watch" muon scintillation detectors. Each scintillation detector utilizes a silicon photomultiplier (SiPM) placed under a 5x5x1 cm BC408 scintillation block. Muons passing through the scintillation block excite electrons, which subsequently return to ground states and release photons in the process. These photons are then received by the SiPM and the signal is processed by an Arduino microcontroller. The voltage produced by the SiPM, muon count number, Arduino uptime/downtime, and analog-to-digital converter are all read to an SD card as a text file (or alternatively displayed on an OLED). Using the 3 mm audio jack of the Cosmic Watch, two muon detectors may be placed in "coincidence mode," wherein one detector (dubbed "slave") counts all muons passing through both the second detector (dubbed "master") and itself. The solid angle subtended by two detectors in coincidence mode may then be manipulated by varying the displacement between them, thereby increasing the accuracy and decreasing precision of the incident angle measurement as displacement is increased.

To vary altitude heights, data was collected at different locations (in the Bay Area) with significant and measurable differences in heights. 4 data collection points were ultimately chosen; Mount Rose (2517m), Truckee (1762m), Mount Diablo (1173m) and Clark Kerr UC Berkeley (100m). To vary angular dependance, a precisely calibrated mechanical device was constructed to accurately position detectors at the desired angles of 0°, 30°, 60°. Accurate incisions were cut into two perpendicular wooden struts, and a supporting beam, such that the angle of a supporting wooden beam, upon which the detectors were mounted, could be varied. The distance between detectors was varied by stacking four 1.570 inch detectors and connecting the first detector as the master for the fourth, and the second as the master for the third. This way, the distance between the pairs of detectors are 4.710 inches and 1.570 inches respectively.

Given data of muon counts/sec at each altitude at varying angles, we convert this muon rate to muon count/(m**2)(sec)(steradian) by factoring in the area of the detector interface and the solid angle carved out by the line defining the muon path between two detectors in coincident mode. We calculate two solid angles, with 'near' defined as the setup with two adjacent detectors, and 'far' defined as two detectors with a detector in between them (see right). The requisite normalization factors were either measured directly or taken from literature[5]. The muon rate, with desired units, is also illustrated to the right.

$$\omega_{near} = 1.6977sr$$

$$\omega_{far} = 0.1977sr$$

$$[\mu] = \frac{N}{m^2 * s * sr}$$

Conclusion and Further Work

Additional work is necessary to resolve the aforementioned co-factor of two -- further theoretical exploration would be necessary.

As our experiment has demonstrated, cosmic ray muon flux is robustly understood by extant literature models, and even naive models bear a high degree of convergence with real-world measurement. Further development of nascent techniques incorporating cosmic ray muon data is promising, such as the use of cosmic ray muon tomography to reveal previously unseen chambers in Egyptian pyramids [6]. And the use of muon imaging techniques to gauge record-breaking thundercloud voltages [7]. The precision of existing literature models for muon flux is vital to the development and reliability of such techniques

Citations

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