Angular and Altitude Dependence of Cosmic Ray Muons

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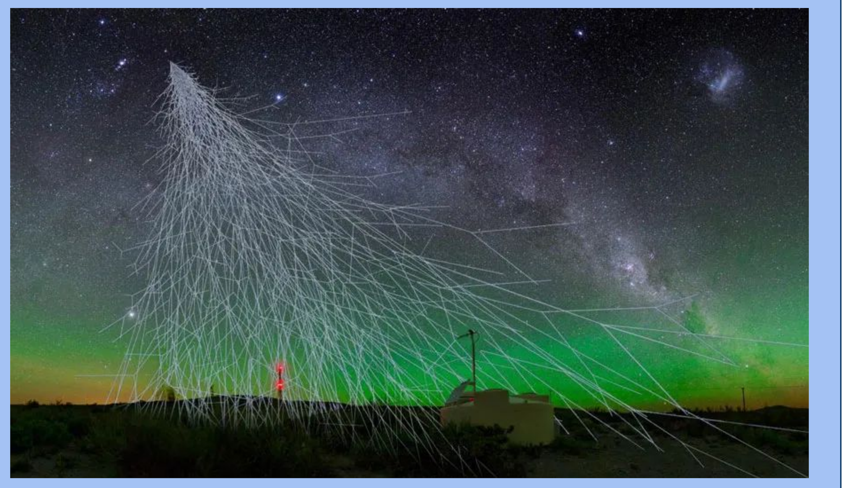
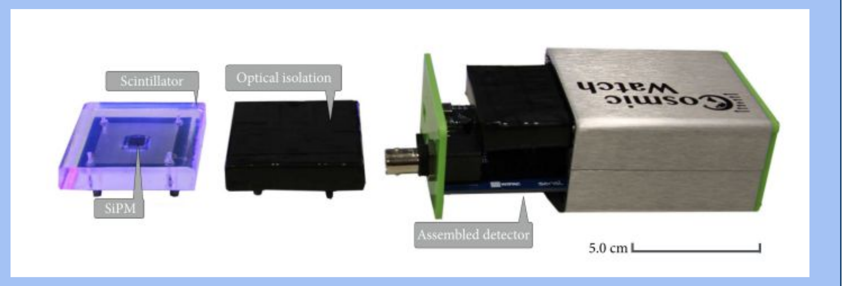
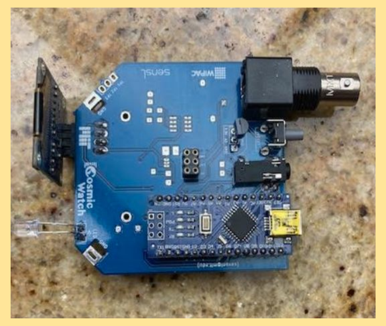
INTRODUCTION

Cosmic rays consist of high energy charged particles that travel through space at nearly the speed of light and bombard Earth from every direction. The interaction of cosmic rays with molecules in Earth's atmosphere produces a shower of many secondary high energy particles. One of which is a muon, a particle with similar properties to an electron but with a much greater mass. Muons, produced from the nuclear reactions of cosmic rays in the atmosphere, are able to reach sea level, and even penetrate a few kilometers into the Earth, despite their extremely short lifetime. This research aims to examine the angular dependence of cosmic ray muons and the effects of altitude on muon count rates.

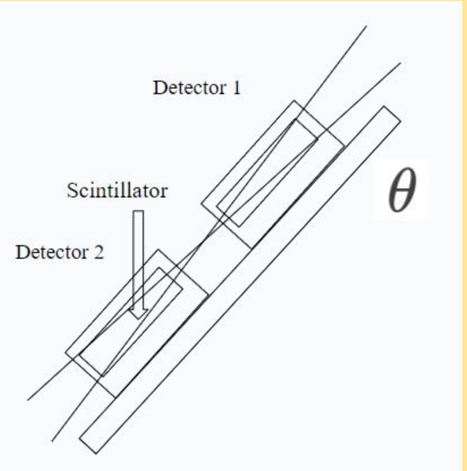


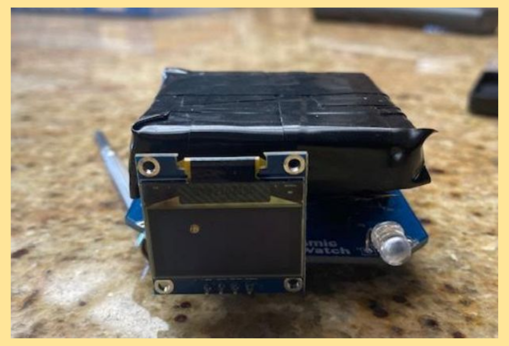


RESEARCH METHODOLOGIES



- In order to study the parameters affecting muons, I have constructed two small cosmic ray muon detectors (http://www.cosmicwatch.lns.mit.edu/detector). The heart of the detectors are a small piece of plastic scintillator and a silicon photomultiplier. Muons traveling through the scintillator produce photons that interact with the photosensitive SiPM and produce a measurable current.
- Angular Dependence Experiment
  - To test the angular dependence of muons, the two detectors were mounted 5 cm apart on a support pointed upwards. The support, held by a clamp, was adjusted to angles of 30, 60, 75, and 90 degrees.
- Altitude Experiment
  - To test the effect of altitude on muon flux, measurements were made by the CosmicWatch muon detectors close to sea level (166 ft +/- 10 ft) in Laguna Beach, CA and at an altitude of 8250 ft (+/- 10 feet) on Mount San Antonio in the San Gabriel Mountains.





DATA AND FINDINGS

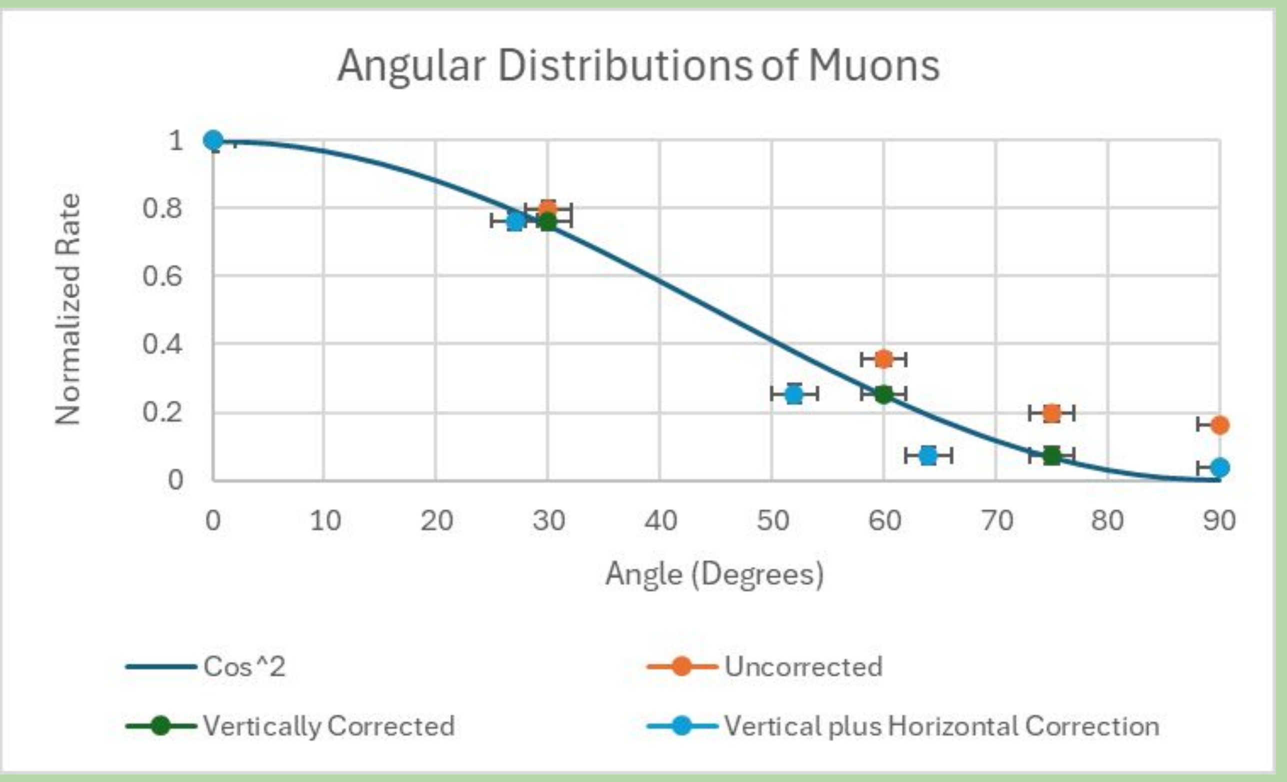


Figure 1: Measured angular distribution from the coincidence detector. Predicted cos^2 distribution is shown by solid blue curve.

Figure 2: Detectors running on Mount San Antonio

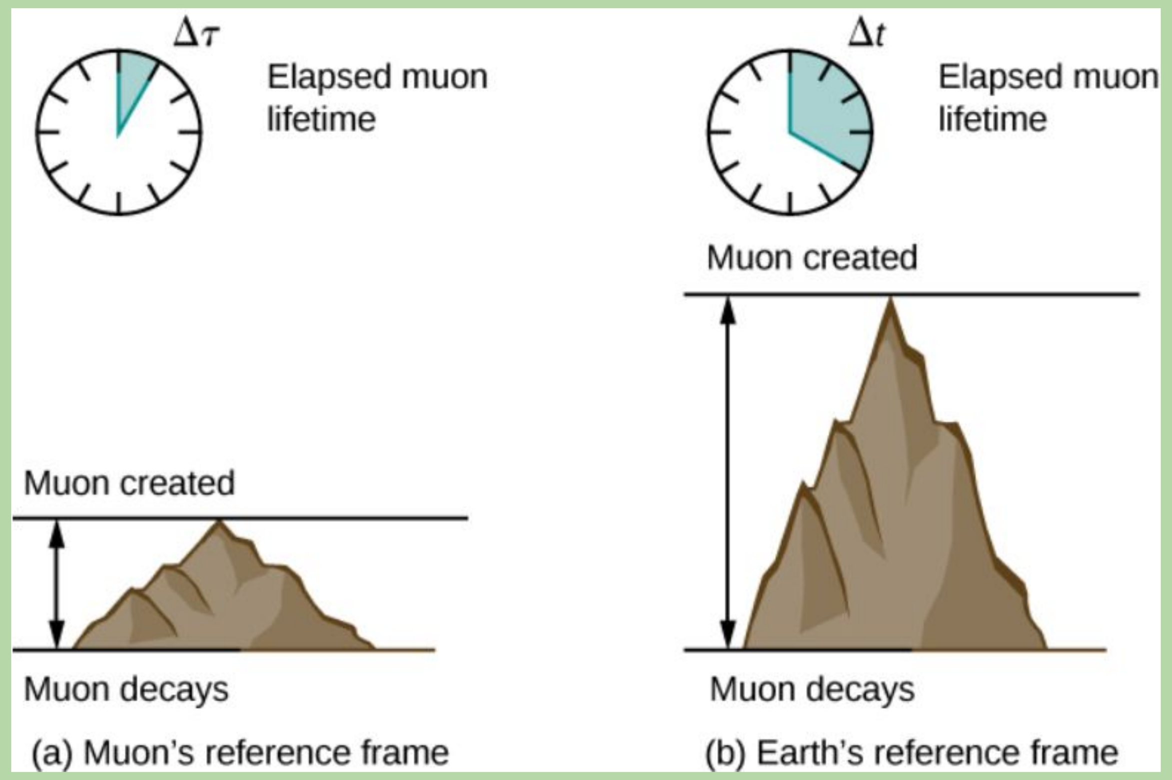


Figure 3: Diagram depicting the two reference frames of the muon and observer on Earth. Special relativity was used along with the difference in rates at altitude and sea level to calculate the average speed of muons of 98.52% the speed of light.

DISCUSSION, ANALYSIS, AND EVALUATION

Angular Distribution Experiment: As demonstrated by the graph, the raw data agrees relatively well with the predicted cosine squared distribution. However, rates do not fall off to zero as the angle approaches 90 degrees. This is expected to be due to air showers, a cascade of particles that are capable of triggering both detectors such that the event is recorded as if it were a true muon coincidence event. In order to get a better indication of the true distribution of muon rates, each data point is corrected for the effects of air showers by subtracting the measured rates from the rate of muon triggers at 90 degrees. Data points are also horizontally corrected to take into account the net effect on angle of higher rates closer to 0 degrees.

Altitude Experiment: Muon count rates at an altitude of 8250 ft on Mount San Antonio were close to double that at sea level. Even if the muon is traveling at the velocity of light, we would estimate it would take about 8 microseconds to reach our detector at sea level, about four times longer than the known mean lifetime of the muon, 2.2 microseconds. This means that about 97% of the muons should have decayed before reaching our sea-level detector. We would then expect the count rate at elevation to be about 40 times that at sea level, not just a factor of 2. We must invoke Special Relativity to explain what is happening. Figure 3 shows that in the moving frame of the muon its clock is running more slowly than in ours, so the elapsed time in the muon frame is only about 2 microseconds. From this we can calculate with Einstein's formulas the speed of the muon, about 98.5% of the speed of light.

ACKNOWLEDGEMENTS / REFERENCES

Special thanks to my mentor Dr. Jose Alonso as well as Prof. Spencer Axani, author of the CosmicWatch Program.

Link to Paper/References:

CONCLUSIONS, IMPLICATIONS, AND NEXT STEPS

The results of the angular distribution and altitude experiments to a strong degree followed expected hypotheses. However, in both experiments the orientation of the detectors allowed for large error. In the angular distribution experiment, the slightly separated detectors still allowed for muons coming in at angles plus minus 17 degrees from which it was set leading to a significant horizontal correction. However, at the same time, the assumptions used to make the horizontal corrections may turn out to not be very accurate either. In this case, it is necessary to understand the efficiency for detecting coincidences across all acceptance angles. Nevertheless, if repeated, the detectors should be oriented to minimize the error in angle so one is truly testing rates at an exact angle.

In the altitude experiment, the stacked orientation allowed for the collection of many nonvertical muons which complicate the interpretation of the data. This experiment could be redone with the scintillators held farther apart to reduce the solid angle. For example, the detectors could be taped around a low density material (wood) separated by 5 to 10 centimeters.