A Novel Method of Determining Air Shower Muon Half-Life Using Time-of-Flight

Introduction and Objectives

Air showers are events in Earth's atmosphere caused by incident cosmic rays created by events such as supernova of distant stars.

One of the main decay products of air showers and the particles created are muons. Muons have a half-life of about 1.56µs and are created predominantly at an altitude of 15km, assuming a speed of 0.994c, they would not be able to travel to the ground before almost all particles decay.

The muon's high speed causes this half-life to be dilated to an outside observer to 14.26µs. This brings the count rate from a miniscule non-zero value to around 1 count/minute/cm^2.

Objective: Gather data at varying altitudes and use the collected data to accurately determine the half-life of muons.

Materials and Methods

Determine a method of creating simple, cost-effective particle detectors that exclude background radiation.

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Source most efficient parts for this task and construct detectors with said parts.

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Ensuring proper functionality by comparing results to established values of count rate and hardware efficiency.

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Derive method and equation to directly calculate the half-life of the muon using large changes in altitude.

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Run detectors over the course of a commercial plane flight, and record the data collected across altitude.

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Process raw data from detectors and apply the derived equation to the processed data.

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Use Poisson statistics to ensure that count rate discrepancies are not caused by random gamma events.

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Determine cause of calculated half-life discrepancy and apply theoretical correction to demonstrate viability.

Assumptions & Limitations

- Pressure and temperature differential at high altitudes attenuates muon count due to atmospheric density.
- Due to limited resources, atmospheric noise has a larger effect on results due to small detector size and amateur quality equipment.
- Processors become more inefficient as count rate increases due to processing inefficiencies.
- Particles that decay faster in external reference frame due to speed loss cannot be accounted for with limited sophistication of detectors.

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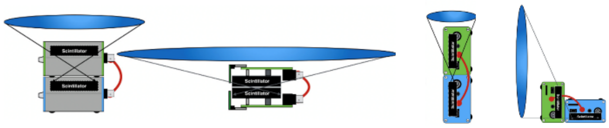
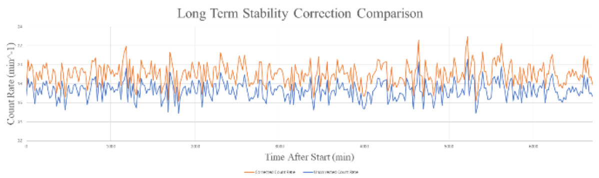
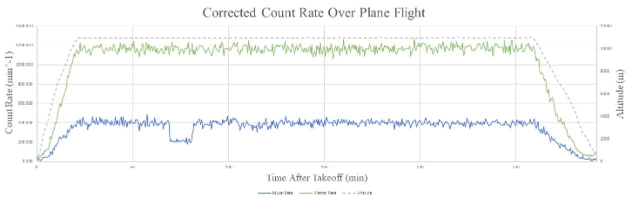


Derived Time of Flight Halving Equation

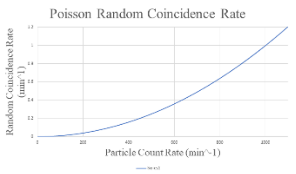
$$t_{1/2} = \left(\frac{h_{j_\mu}}{u_{j_\mu}} * \frac{1}{\gamma_{j_\mu}}\right) - \left(\frac{h_{1/2 j_\mu}}{u_{1/2 j_\mu}} * \frac{1}{\gamma_{1/2 j_\mu}}\right)$$

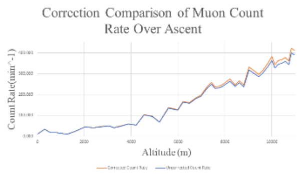


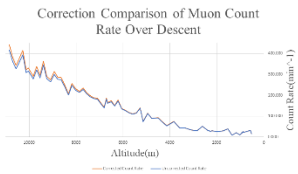


$$f(n, u) = \frac{u^n e^{-\mu}}{n!}$$

$$R_p(q) = \binom{q}{p} p N^p \tau^{p-1}$$







Results

Grouping #	Upper Altitude (m)	Upper Speed (c)	Lower Altitude (m)	Lower Speed (c)
1	7799	0.99300	5564	0.99370
2	8201	0.99285	5714	0.99350
3	9492	0.99275	6243	0.99325
4	10397	0.99269	6765	0.99315

Grouping #	Expected Half Life (µs)	Uncorrected Half Life (.994c, µs)	Corrected Half Life(µs)
1	1.560	0.820	1.001
2	1.560	0.913	1.105
3	1.560	1.193	1.402
4	1.560	1.333	1.560
P-Value		0.012	0.065

This shows that muon speed is most likely inconsistent across altitude, and that a theoretical calculated half-life scenario with changing muon speed has a p-value over 0.05, showing statistical significance over the original fixed speed calculation.

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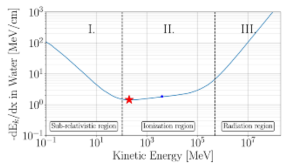

Conclusions

- Coincident, SiPM based scintillating detectors can detect muons with high purity of sample.
- At higher altitudes, half-life can be measured with reasonable accuracy, but as altitude decreases, so does the observed half-life.
- This inconsistency is likely due to the anisotropic nature of muon energy at a given altitude, and the mode of which high energy particles lose energy at different energy levels.
- This anisotropic nature of decay causes lower energy particles to almost immediately come to a stop at a certain energy level, causing lower energy particles to decay at much greater rates.
- The large effect that speed has on the half-life of the particles demonstrates the theory of special relativity, as well as showing that the slightly lower half-life measured at maximum altitudes is very likely to be the half-life of the muon.

References

1.) Axani, Spencer. "The Physics Behind the CosmicWatch Desktop Muon Detectors." *Arxiv*, July 2019. *Michigan Institute of Technology*, https://arxiv.org/pdf/1908.00146.pdf.

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