Building a Muon Detector: How these Invisible Particles are Detected and What We Can Learn From Them

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Introduction

Muons are elementary particles. They are similar to electrons, but about 200 times the mass. They are everywhere; approximately one muon passes through the palm of your hand every second [3], although you cannot feel them.

When cosmic rays (~ 89% protons), strike a nucleus in an air molecule in the Earth's atmosphere, a shower of particles are produced *(Figure 1)* [1]. Many will scatter, decay, or be absorbed. However, some muons survive to reach us on the ground, where we can detect them.

Without accounting for the time dilation and length contraction effects of Einstein's Special Theory of Relativity (STR), nearly all muons would decay before reaching ground level [2]. Muons and antimuons decay in the following ways:

$$\mu^- \longrightarrow e^- + \bar{\nu}_e + \nu_\mu$$
$$\mu^+ \longrightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

However, we detect many more than are predicted nonrelativistically. Muon detections at ground-level are evidence of the STR.

I plan to gather data at ground-level in Grand Forks, and from that, predict relative count rates at different altitudes, using the STR. I will then gather data for these higher altitudes to test the STR.

Methods

I am currently building two muon detectors, which I will use to gather count rate data at different altitudes.

The muon detector has a plastic scintillator (*Figure 2*) which is used to detect the muons. When high energy particles pass through the scintillator, they lose energy as they create electronic excitations (electron holes) in the atoms in the scintillator. When these excitations decay, they re-emit the energy as photons, which are detected. I am using a silicon photomultiplier (SiPM) to detect these photons, and I am soldering parts onto a board (*Figure 3*) for the detection.

I plan to record data in the basement and top floors of UND's Witmer hall, along with taking the detectors on a high-altitude flight up to about 30,000 ft thanks to help from the UND Aerospace department. I can also launch the detectors in one of our UND Advanced Rocketry Club rockets for further high-altitude detection.

Results

Although I do not yet have the muon detectors fully assembled, I have begun calculating the length contraction and time dilation of the STR for muons produced in the upper atmosphere (at an altitude of 15,000 m). Using *eqn. 1*, I can investigate the effects of time dilation, where $\Delta\tau_p$ is the proper time (from the muons frame of reference), Δt_i is improper time (our frame of reference), v is the velocity of the muons, and c is the speed of light.

$$\Delta t_i = \frac{\Delta\tau_p}{\sqrt{1-\frac{v^2}{c^2}}} \qquad (eqn.\ 1)$$

I can do the same for length contraction, using *eqn. 2*. In this case, L_p is the distance in the muons frame of reference, while L is the distance we observe it traveling.

$$L = L_p\sqrt{1-\frac{v^2}{c^2}} \qquad (eqn.\ 2)$$

The speed of muons are listed between 0.994c and 0.998c depending on the source [4], so using this range for v and the average lifetime of a muon, 2.2 μs, as $\Delta\tau_p$, I can calculate Δt_i as being between 20. μs and 35. μs. In other words, although a muon may 'feel' as if only 2.2 μs has gone by, while as the observer in the nonrelativistic frame, we will see 20-35 μs go by. Within this amount of time, a muon can travel between 6,000 and 10,000 m.

I can do the same sort of calculations for the length contraction. For example, if a muon is produced at an altitude of 15 km and travels to the ground, it will only feel as though it has traveled between 950 and 1600 m.

Along with the length contraction and time dilation effects, we have to consider that not all muons will decay after 2.2 μs; that is just the average lifetime. Using *eqn. 3*, the rate equation,

$$\frac{dN}{dt} = -\lambda N(t) \qquad (eqn.\ 3)$$

where λ is the decay constant, N is the number of particles, and t is the time, I can get *eqn. 4*.

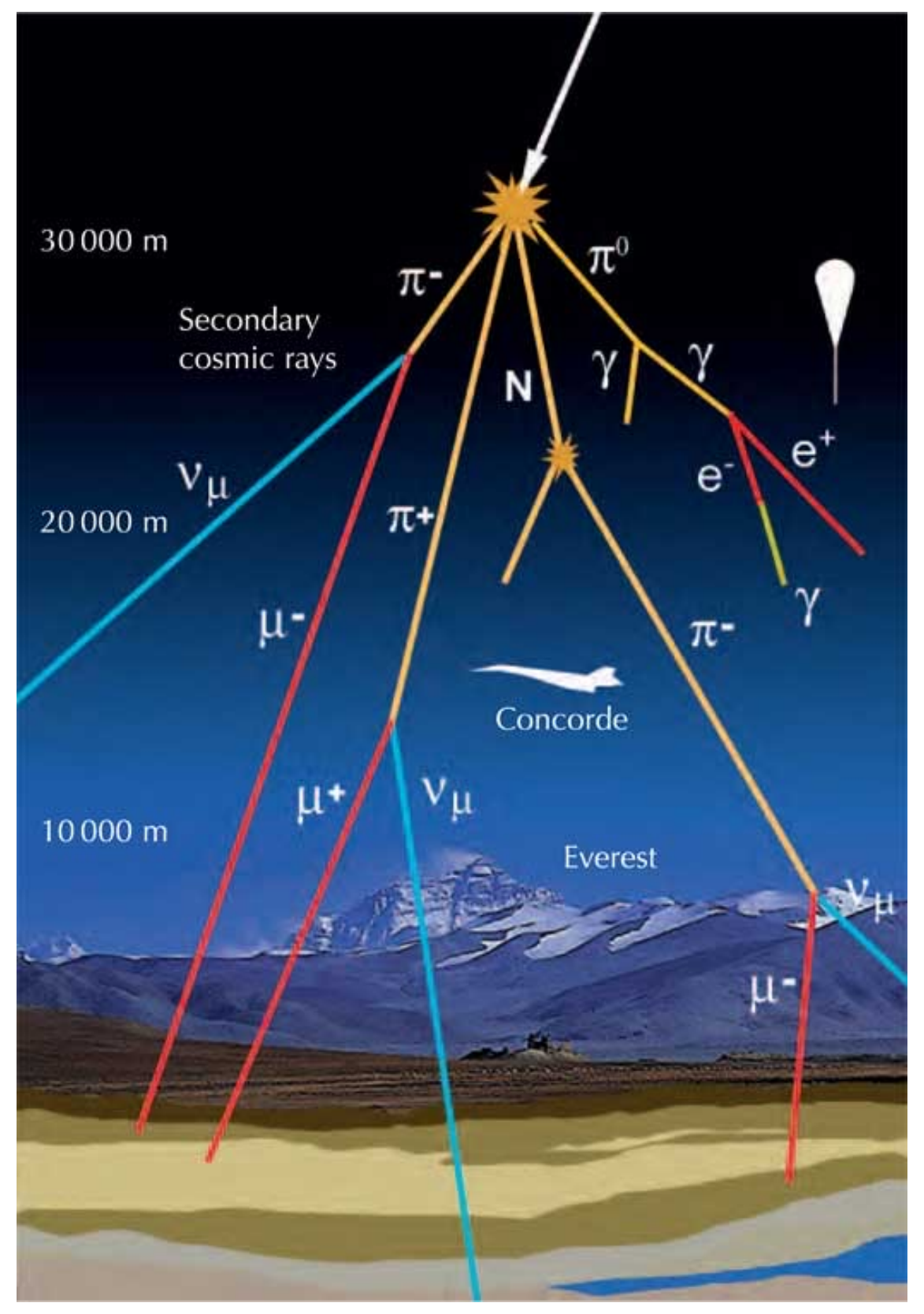
$$N(t) = N_0 e^{-\lambda t} \qquad (eqn.\ 4)$$

This equation shows that the number of particles as a function of time is an exponential function, telling me that even at further distances, there will be a more consistent number of muons that haven't yet decayed.

Using these equations, I can predict what percent of muons we will observe at various altitudes both accounting for and not accounting for Einstein's STR (*Table 1*).

As I gather data on muon detection count rates both for ground level and higher altitudes, I can compare them to my predictions.

Ionizing radiation such as beta rays, gamma rays, and neutrons, can penetrate into the detector along with the muons, affecting the count rates. I have also soldered a Geiger counter (*Figure 4*), which can detect gamma and beta radiation. I can use data from the Geiger counter to ensure I am not getting extra counts on the muon detectors due to unwanted ionizing radiation.



(Figure 1)

(Figure 2)

(Figure 3)

(Figure 4)

Conclusions

This research project is testing Einstein's STR. Based off my predicted muon percentages at each altitude, without the STR almost no muons would reach ground level.

If my predicted high-altitude count rates I get using the time dilation and length contraction equations match the measured data, it will support the STR.

Bibliography

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Table 1

	At ground level	At 7,500m (~25,000ft)
Accounting for Einstein's STR	~ 8.2 – 24 %	~ 29 – 49 %
Not accounting for Einstein's STR	~ 0.000000012 – 0.0000000013 %	~ 0.001 %