Cosmic Ray Predictions With a Homemade Muon Detector

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Introduction

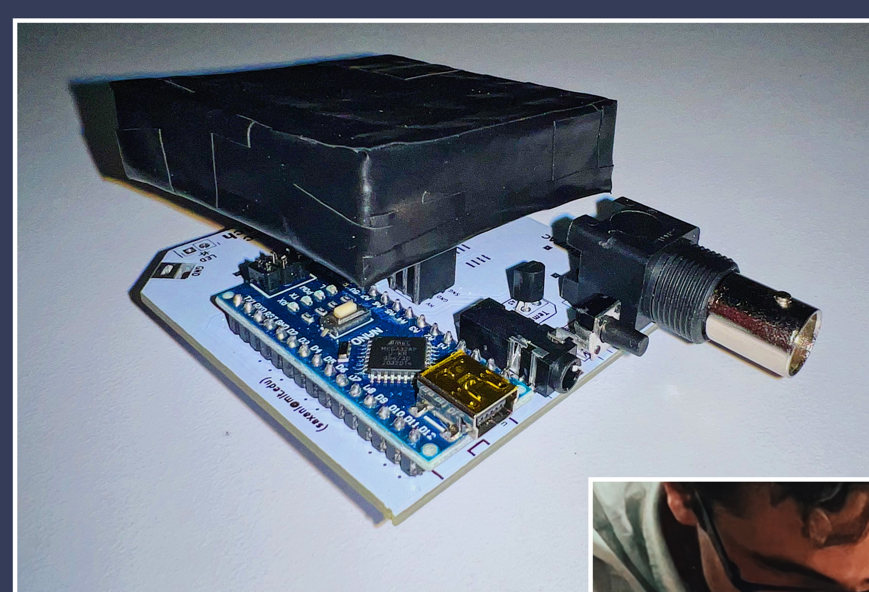
Muons: Every second, the Earth's atmosphere is bombarded with high energy cosmic rays from the sun and other celestial objects, which decay upon impact into millions of subatomic particles These "cosmic ray showers" create muons – our primary interest. Our project sought to a) successfully build a small, portable muon detector using the guide published by the MIT CosmicWatch team, and b) using a Monte Carlo simulation, study and model this atomic shower phenomenon so that we could independently analyze our own measures of muon flux at ground level. We used a Monte Carlo simulation to predict the quantity of muons created by a single proton's collision with the atmosphere. With data we collected from our own detector, we are able to extrapolate a ground-level muon count-rate to estimate the amount of high energy protons hitting Earth's atmosphere above Berkeley each second. Background: A muon (μ) is a subatomic particle called a "lepton," part of the family of "fundamental particles" that have no known substructures. Muons have the same electrical charge as an electron (-e), but are 200 times as massive. When high-energy streams of (mainly) protons, called "cosmic rays," collide with the earth's atmosphere, the protons decay into other subatomic particles, one being the muon – of which millions subsequently shower down at all possible angles, traveling close to the speed of light (its ground energy is roughly 3.5 GeV, which corresponds to about 0.99c). Despite its high speed, the muon has an average lifetime of t = 2.2 μs, and classically shouldn't be able to reach the ground before it decays – it only should be able to travel less than half a mile before ceasing to exist. But, thanks to Einstein's relativity and due to the muons' almost light-speed, a ground-bound muon's travel distance "contracts" and its time "slows," both by a factor known as "gamma," equal to 1 over the square root of 1 minus the known velocity squared over the speed of light squared. Due to this application of relativity, we can actually detect muons at sea level with our homemade detectors; current research estimates they hit the ground once per minute, per one square centimeter. Muon detectors can be built in many ways, but most measure a light pulse produced by radiation when a muon passes through a particular medium. We chose ours because there was already a design published, and because we could maximize affordability, compactness and portability.

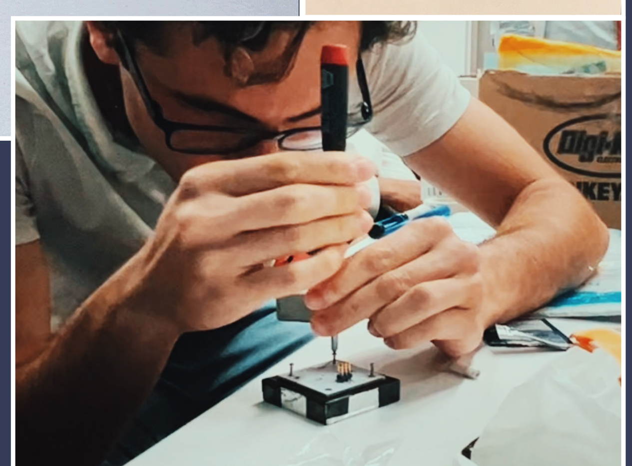
CONSTRUCTION

Detector Overview: We built our detector based on the instructions published by MIT's CosmicWatch program. Generally, we can simplify the muon-detection process into four main steps: 1) a muon enters the scintillator, a thick, rectangular piece of special plastic, 2) the scintillator absorbs the high-energy radiation of the muon and re-emits this energy as a pulse of light, 3) the silicon photomultiplier (SiPM) detects a photon with its thousands of single-photon diode-cells (only a few micrometers wide) connected in parallel, which generate and sends out a large electrical pulse, which 4) our electronics then process and filter to record as the passage of a muon.

Assembly: Our detector required over 50 different components, between the two main groups – the scintillator and silicon photomultiplier (SiPM), and the electronics. We worked for months researching the extremely subtle differences between types of components we needed, and worked with ULAB to order what we needed through BearBuy from around six different companies. Many times, we had to re-order parts either due to damage or subtly errant orders.

Building: First, we populated our printed circuit boards (PCBs), (see diagram in Figure 1). We soldered every piece by hand, which presented difficulties due to inexperience with soldering as well as the fragility and volatility of our materials. We then constructed our scintillator; with help from the machine shop, we drilled super-fine holes in the scintillator, wrapped it in a light-tight layer of aluminum foil, screwed the SiPM's PCB on top, and wrapped it all in electrical tape. We then connected our detecting components to the electronics, which concluded the main assembly.





(Above) Our working muon detector. (Top Right) Corina wrapping the drilled scintillator in aluminum foil. (Right) Alex screwing the SiPM into the scintillator.

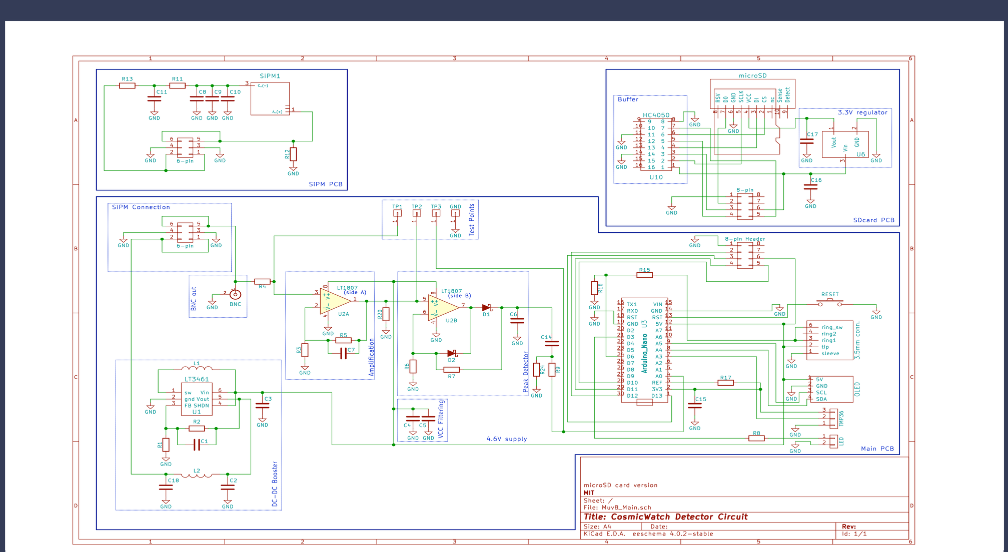
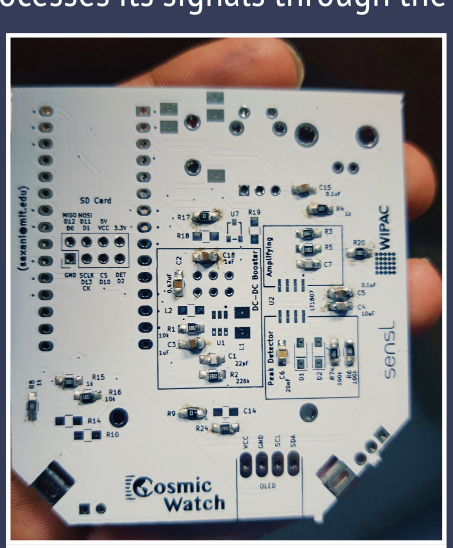


Figure 1: PCB Circuitry Map

DIAGRAM: Above are MIT's provided diagrams for the Main PCB, the SiPM PCB, and an SDcard PCB. The Main PCB provides the correct input voltage for the SiPM board and processes its signals through the Arduino, our microprocessor. We unknowingly received the wrong operational amplifier (pictured as LT1807), and have been unable to find a correct one, rendering the amplification circuit unusable – the Arduino cannot process signals from the SiPM. Although we still hope to complete the detector so that we can store pulse amplitude, get significantly better time estimates for muon events, and operate the detector unmanned, we were able to effectively circumvent the issue by reading the SiPM pulses from an oscilloscope.



Our main PCB in its beginning stages of soldering.

DATA COLLECTION

After building the detector but being unable to take data from it directly, we calibrated it using a SIGLENT Super Phosphor Oscilloscope (the PNG it gave us at right) to measure pulses sent through the main PCB directly by the SiPM. Varying the machine's trigger level using the "Normal" mode limits the number of voltage peaks detected, which is how we were able to distinguish between larger and smaller high-energy interaction events. The oscilloscope is connected to BNC out, which outputs the raw SiPM pulse. Using the history function, we were able to recall trigger events (i.e. peaks with a value higher than the trigger level) over a certain period of time as represented in frames. By dividing the number of frames over the time duration, the count rate was obtained. Then, a characteristic peak value was chosen to become the threshold for muon detection. We can thus obtain the muon flux by dividing by the surface area of the scintillator 25 cm^2.

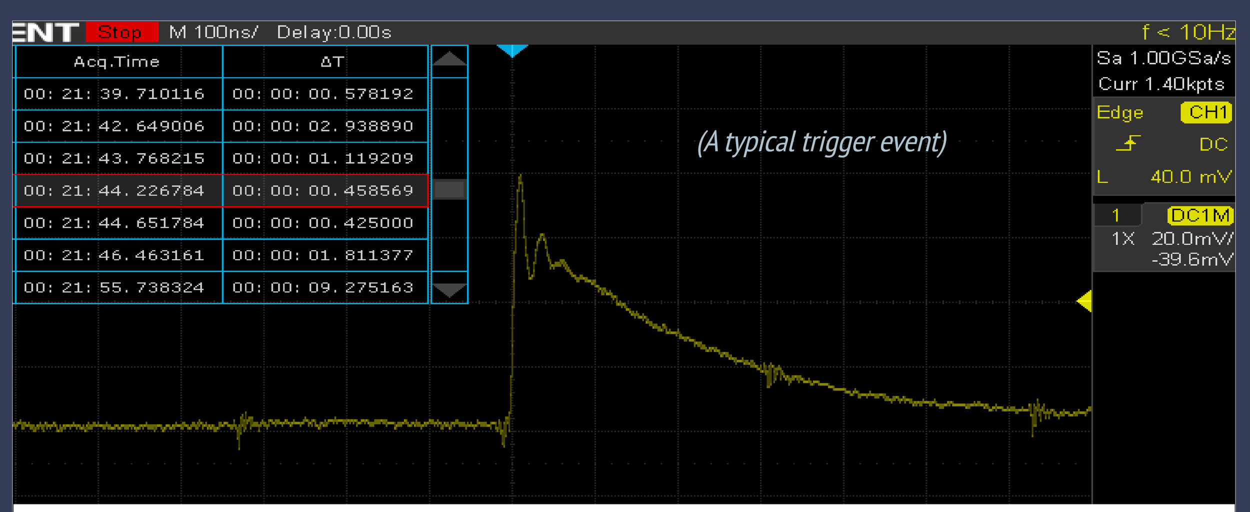


Figure 4: A freeze-frame recorded by the Oscilloscope at the moment a muons passes through the detector.

Trigger level (mV)	Average Count Rate (min-1)
20	94.92
40	32.57
50	32.18
60	23.19

Trigger Level (mV)	Average Count Rate (min-1)
20-40	62.35
40-50	0.39
50-60	8.99
60 and above	23.19

Figure 3: Average count rates for particular values (left) and for ranging values (right), with trigger levels varying from 20mV to 60mV

RESULTS

From literature, a 10-100 mV peak qualifies as a muon detection event. However, factoring in our specific circumstances, a trigger level lower than 40 mV would include too many events that are exceedingly common. Those events are highly due not to muon detection. Hence, we determined that a 50-60 mV trigger level is appropriate for muon detection for our detector.

ANALYSIS

After selecting the appropriate threshold, we were able to detect muons at a rate of 0.38 ± 0.12 muons/sec. In order to determine the number of high-energy protons striking the top of the Earth's atmosphere above the region around Berkeley, we first had to determine the rate at which we would observe muons with our detector if there was only 1 high-energy proton striking the top of the Earth's atmosphere. Since this is exactly what our simulation does, we were able to use the output from the simulation to determine that at sea level 1 high energy proton above Berkeley would produce 1,248 muons in the entire region specified by the NKG radius of 200 meters. This would mean that our detector which has an area of 25 cm^2 would detect muons at a rate of 2.5 • 10^{-3} muons/sec. Given this information, we could then determine that our detector must be interacting with 15,000 high energy protons each second. Assuming that the rate at which high energy protons collide with the Earth's atmosphere is homogeneous in space and time, we can then determine that there are about 6 x 10^{13} high energy protons colliding with the Earth's atmosphere each second.

SIMULATIONS

CORSIKA Background: CORSIKA is a software created by researchers at the Max Planck Institute for Nuclear Physics (Institut für Kernphysik), which simulates behavior of high-energy particles as they undergo reactions and decay in earth's atmosphere – most importantly, including muons. CORSIKA allows for its users to specify various parameters and then provides the requested output information. CORSIKA is run on the compiler.

Relevant Parameters and Steering: Many parameters we could control in our CORSIKA simulation were irrelevant and left in default mode. However there were a few parameters that we had to select at runtime to afford us more information about the muons – specifically the information necessary to plot the muon vs. depth graph as seen on this poster. CORSIKA also allows users to create a steering file, which saves these important necessary input values so we do not have to repetitively input them.

Model: The constructed graph to the left uses data which we generated with our CORSIKA simulation. Here we display the quantity of muons, antimuons, and hadrons per unit of atmospheric density by CORSIKA for the production of particles from a single proton colliding with the atmosphere above Berkeley. "Depth" is in units of grams per square centimeters, used specifically for low-pressure measurements (like high in the atmosphere), a similar metric to the SI unit of pascals. The graph describes the amount of particles present based on increasing air pressure above the muon observation point (one can read the graph as though the origin is the point where the proton hits the atmosphere; going from left to right, we are observing data closer and closer to earth's surface.)

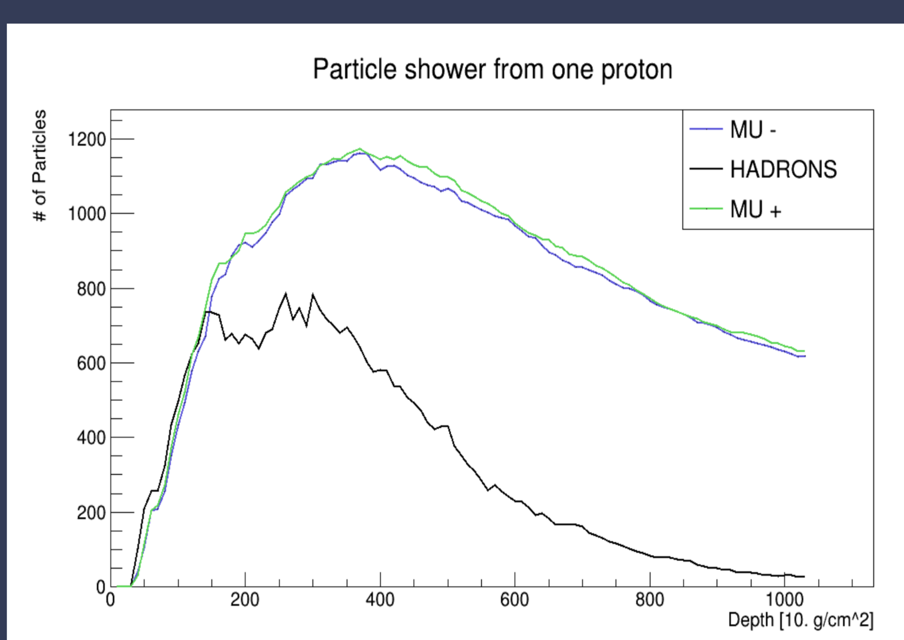


Figure 2: Simulation model of the number of muons falling given air pressure.

CONCLUSIONS

Despite the many obstacles, from soldering mistakes to parts ceasing to exist, we were able to detect muons and successfully determine muon flux. Furthermore, we were able to connect this data with a CORSIKA simulation to determine the number of high energy protons interacting with the Earth's atmosphere. While there do exist errors stemming from assumptions we had to make due to a lack of time, we are confident in the accuracy of our procedure. Therefore, we can consider our result [6 x 10^{13}] to be an order of magnitude estimation.

ACKNOWLEDGEMENTS

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