Inexpensive scintillation-based muon counting apparatus

Ryan J. Schlimme[1]

[1] *PHY 353L Modern Laboratory, Department of Physics, The University of Texas at Austin, Austin, TX 78712*

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We built a simple muon counting apparatus using a plastic scintillator, a silicon photo-multiplier (SiPM), an Arduino Nano microcontroller, and control electronics following the instructions developed by a group of MIT scientists. Unfortunately, we were unable to detect muons due to a malfunctioning SiPM. Instead, we document our procedure in depth for continuation by future students.

I. INTRODUCTION

A. What are muons?

Muons are elementary leptons — particles unaffected by the strong nuclear force — with a lifetime of 2.2 μs before they decay into neutrinos. However, they travel at nearly the speed of light; therefore, their lifetime is extended in the reference frame of the observer [1]. Due to their short lifetime, the muons we observe are generated from the collision of cosmic rays (high-energy protons) with atomic nuclei of the elements in Earth's atmosphere [2].

Atmospheric muons, those generated in Earth's atmosphere, are characterized by a spread of energies. Those reaching sea level have a mean energy of 4 GeV with an energy loss of about 2 MeV per g/cm^2. Since the interaction depth of the atmosphere is approximately 1000 g/cm^2, we can approximate the energy of muons at generation to be 6 GeV [3]. Current setups in our lab have noticed occasional high energy events which we hypothesize are atmospheric muon detections. Therefore, we decided to investigate this phenomenon by building an apparatus specifically to detect muons. We then found the work of MIT scientists in development of an inexpensive and simple muon detector which they named CosmicWatch [4].

This simple device counts muons along with the time at which they are measured and the amplitude of the pulse from the SiPM. With only one device, the measurements we can make are limited; however, we wanted to test the dependence of altitude on observation rate. Since muons interact with particles throughout the atmosphere, one expects to observe fewer muons closer to sea level. While we would not be able to test our detector at extreme altitudes due to limited funds and time, we were going to use the PMA building at UT Austin to provide our difference in altitude. However, the building obstructs muons further, so one would expect to have a larger attenuation than expected with decreasing altitude.

B. How to detect muons?

Like other high energy particles, one can detect muons using a scintillator and photomultiplier. Scintillators are inorganic crystals or plastics in which a primary electron absorbs an energetic photon, recoiling nearby electrons. Some excited electrons spontaneously decay to their ground states, ejecting photons in all directions. The primary photon, having lost energy to the recoiled electrons, enters the photomultiplier, passing through a photo-cathode, releasing an electron and directing it toward a series of dynodes, each of which have a high potential difference placed across them. As the "primary electron" collides with the dynodes, secondary electrons are released. As the electrons travel through the photomultiplier, the dynodes amplify them until they collide with the anode, resulting in a detectable electrical pulse [5]. A schematic of a scintillator and photomultiplier detection system is shown in Figure 1. Compared to a traditionally-used vacuum photomultiplier tube (PMT), the SiPM we use allows for detection with low offset voltage and small form factor [6].

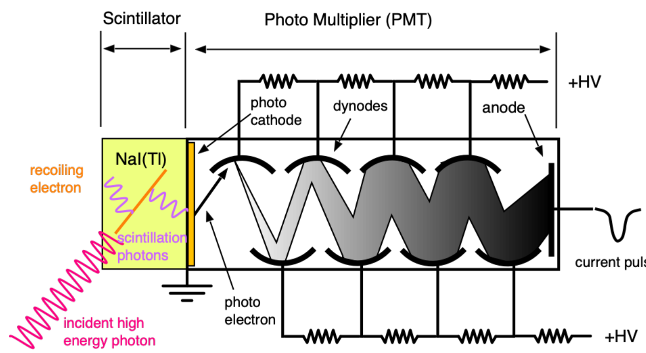

FIG. 1: Schematic of a scintillator and photo-multiplier tube (PMT) [7]

C. CosmicWatch Detection

The output current from the SiPM is amplified by an operational amplifier and then fed through a peak detection circuit before being read by an Arduino Nano. The microcontroller allows for collection of the pulse amplitude, count number, time of event, temperature, detector dead time, and a rate calculation. The threshold for which the detector counts a signal as an event can be adjusted via the provided Arduino processing code under the variable `SIGNAL_THRESHOLD`.

To read data from the detector, one can use the OLED screen, a microSD card, or a supplied Python program to read data directly from the USB port powering the detector.

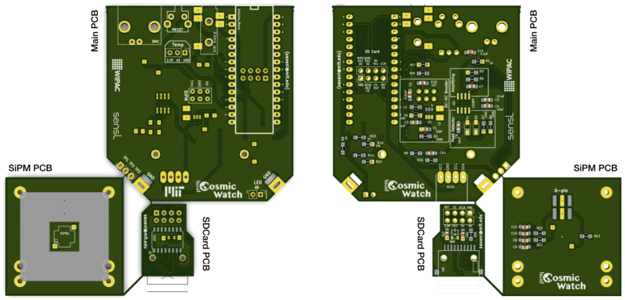

FIG. 2: Rendering of the three unpopulated PCBs [4]

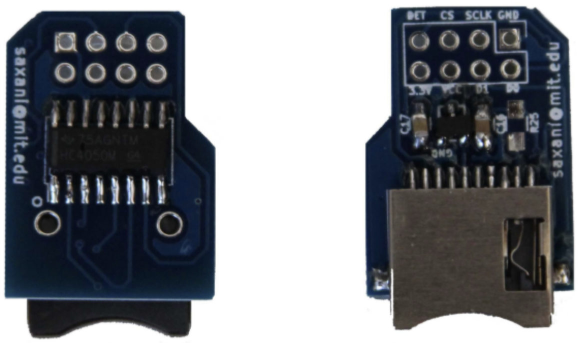

FIG. 3: Picture of the top and bottom of the populated SD PCB [4]

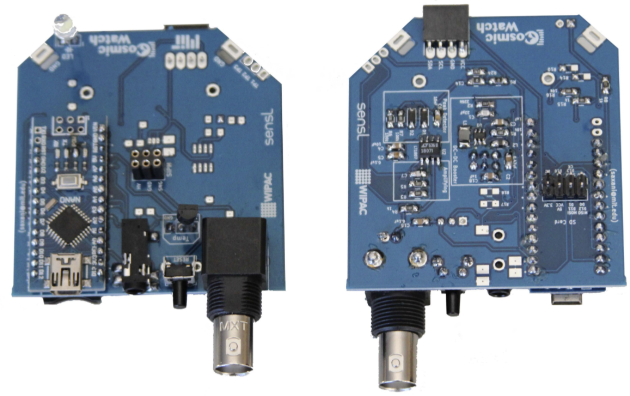

FIG. 4: Picture of the top and bottom of the populated main PCB [4]

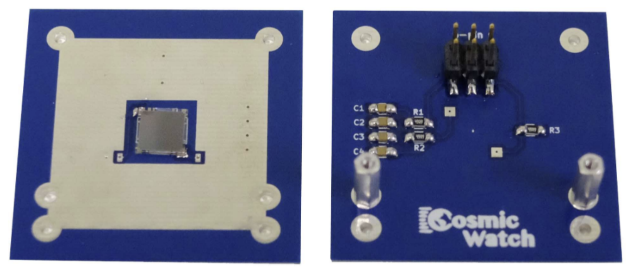

FIG. 5: Picture of the top and bottom of the SiPM PCB [4]

II. BUILDING THE DETECTOR

A. Populating the PCBs

To build a small muon detector, we first supplied the necessary components listed in [4]. Due to the high cost of the SiPM, we only sourced one while we sourced several units of the other products on the list.

Once all necessary components were sourced, we soldered the necessary surface mount electronics onto the three separate boards. We found the soldering tip in the lab too large for the precision we demanded, so if you can find a smaller tip to use, that would expedite the process. Ensure that no connections are shorted to each other, especially for the small integrated circuits, like the operational amplifier. We found the videos provided by Spencer Axani on his YouTube channel very helpful to determine which components to insert and where. Figure 2 shows a rendering of the three unpopulated PCBs where Figures 3, 4, 5 show the populated PCBs for the SD card, main board, and SiPM respectively.

B. Programming the Arduino

To program the Arduino, first install the Arduino IDE onto your laptop. Then, install the necessary libraries by clicking Sketch → Include Library → Manage Libraries. Then, you must install the following libraries.

- Adafruit_SSD1306 - by Adafruit Version 1.0.1
- Adafruit_GFX - by Adafruit Version 1.0.2
- TimerOne - by Jesse Tane et al. Version 1.1.0
- EEPROM
- SD
- Wire
- SPI

You may find that several of these libraries are pre-installed or have newer versions. To ensure consistency with the dependencies of the supplied INO files, I downloaded the exact versions they requested.

When uploading code to the Arduino Nano, you must ensure that you select the proper board in the IDE by clicking Tool → Board → Arduino Nano. Additionally, ensure that the IDE recognizes which port the Arduino is connected to by clicking Tool → Port.

Unfortunately, you can only run either the OLED or the SD script. The Arduino does not have the capacity to have both programs running simultaneously. We used the OLED script for testing and debugging and the SD script for collecting data. When running the SD script with the OLED plugged in, you may notice that the OLED displays the same information but does not update; we determined this to be normal behavior.

C. Machining the Scintillator

The instructions provided by CosmicWatch instruct students to machine the scintillator by cutting it to a precise size and treating it with heat polishing. We believed that these treatments would reduce the quality of our scintillator, so we skipped these steps.

In order to mount the scintillator to the SiPM PCB, we needed to drill four precise holes with a number 54 drill bit (1.397 mm) which will accommodate the four 5/16" Number 0 screws. We used a portable drill to complete this step, but we would have preferred to use the Student Machine Shop, but neither of us had the necessary training which would have taken several weeks.

We found that when drilling, the small drill would often get stuck in the melted plastic due to the high RPM, but without a high RPM, the drill would not have enough torque to remove plastic. We highly recommend seeking a more professional drill to complete the job at a low RPM and using the procedure documented in the instructions. We did not have any issues with cracking or chipping as they claimed to experience.

After drilling the four holes, we wrapped the scintillator in reflective foil that we flattened using the roll of electrical tape to try to remove any creases; this allows for a more even reflective surface. Leaving a 2 by 2 cm hole opening, and ensuring we still had access to the four holes we drilled, we finished wrapping the scintillator.

We then used a small amount of optical gel between the SiPM and the scintillator and mounted the two together. Ensuring a good fit, we then wrapped the entire device in electrical tape to ensure a light tight seal.

D. Troubleshooting

To assemble the device, we connected all three PCBs as instructed and placed it into a 3D printed housing since the proper housing had not yet arrived. However, when we plugged the device into the computer, we did not observe any counts. Theoretically, you expect one every 2 seconds or so. Therefore, we began the process of troubleshooting.

First, we plugged the powered device into an oscilloscope using the BNC port on the back of the device. We did not observe any waveform, indicating that there was potentially an issue with our SiPM board. We unwrapped the scintillator carefully as not to damage the reflective foil and inspected it for shorted components, bad solder connections, or any other obvious defects. However, we were unsuccessful in determining the cause of the issue.

Next, we tested that the SiPM board was receiving the proper +29.5 V DC of power through the high voltage pin of the main PCB. Once this was confirmed, we transferred the SiPM board to a breadboard and manually powered it using a DC voltage supply. We then read the signal to an oscilloscope. We observed a noise-dominated trace with no dependence on light intensity to the SiPM, indicating that there was potentially something wrong with the component itself.

We checked that the SiPM was mounted properly by checking for the presence of the Pin 1 indicator. Since the indicator was extremely small, we used a magnifying glass and a microscope to ensure it was mounted correctly. Additionally, we checked that the SiPM behaved as a diode: when testing its resistance, in one polarity you should see infinite resistance and in the other some high, finite number.

If we had mounted the SiPM backwards, it is very likely we fried the device; however, my lab partner, Dr Sitz, and I all agreed that it was mounted properly, leaving us unsure as to the cause of the failure. With a lead time of 52 weeks to receive another SiPM, we had no choice but to abandon the project for now, leaving it to a future group to pick up.

III. PROPOSED EXPERIMENTS

A. Altitude Dependence

With a single functioning detector, there are few experiments that one can perform. We originally wanted to measure the dependence of count rate on altitude, but after a brief literature review, we noticed that only at differences of thousands of meters can one observe a sizeable effect. Should a future group have the opportunity to take the detector on an airplane, we found the following Palmer model formulation for expected counts as a function of altitude [8]. Since this formulation relies upon a density formula — and since we expected only to collect data at low altitudes — we used the density of the troposphere as calculated by the Glenn Research Center at NASA [9].

$$
\begin{gathered}
\frac{\mathrm{d}\Phi}{\mathrm{d}h} = -\mu\Phi \\
\Phi(h) = \Phi_0 \exp\left[-\mu h\right] \\
\mu(h) = \mu_0 + \mu_0 \rho(h)/\rho_0 \\
\frac{\mathrm{d}\Phi}{\mathrm{d}h} = -\mu(h)\Phi \\
\Phi(h) = \Phi_0 \exp\left[-\mu_0 (h - h_{\max})\right] * \exp\left[-\mu_0/\rho_0 \int_{h_{\max}}^{h} \rho(h)\,\mathrm{d}h\right]
\end{gathered}
$$

$$
\begin{aligned}
\mathrm{counts}(h) = \Phi_{\max} * \rho(h) * \exp\left[-k_1 (h_{\max} - h)\right] * \\
\exp\left[-k_2 \int_{h_{\max}}^{h} \rho(h)\,\mathrm{d}h\right]
\end{aligned} \tag{1}
$$

$$\rho(h,T) = 101.29\left[\frac{T+273.1}{288.08}\right]^{5.256}$$
$$k_1 = 2.6\times10^{-5}\ \mathrm{ft}^{-1} = 8.5\times10^{-5}\ \mathrm{m}^{-1}$$
$$k_2 = 8.5\times10^{-2}\ \mathrm{ft}^2/\mathrm{slug} = 5.4\times10^{-4}\ \mathrm{m}^2/\mathrm{kg}$$
$$\Phi_{\max} = 8.5\times10^{6}\ \text{counts}$$

Equation 1 is the final result from which we would compare our data to. All that would need to be done is to insert the results of the density function and the fitted parameters discussed in the Palmer model [8].

B. Other Experiments

Since it is difficult to test altitude without means to ascend several thousand meters, we next thought of trying to include an attenuation factor from concrete as a exponential decay factor. One paper found decay factor of $k = 0.97cm^{-1}$ when adding decay factor e^{-kx} to Equation 1, where x is the thickness of concrete in cm [10]. We then could collect muon count rates using the detector at different altitudes as afforded by the height of the PMA, measuring the altitude from the reading on the Compass app of our iPhone.

We recommend building more copies of the same apparatus to allow for coincidence measurements. By using two detectors, you can check that both detectors see the same event, further verifying the validity of the event as a muon detection. Additionally, you can perform angular distribution measurements by inclining one of the detectors by some angle and observing the effect on the count rate.

IV. CONCLUSIONS

After observing several high energy particles in our gamma ray detectors which we hypothesized as muons, our group sought to make an inexpensive muon detector. We found the work of CosmicWatch at MIT and started building a copy of their apparatus. While we were ultimately unsuccessful due to a faulty SiPM, we documented our work to aid in future attempts by students who wish to finish the detector. We additionally provided the theoretical background necessary for performing altitude measurements.

I would like to thank my lab partner, Adrian, for his invaluable assistance during the experiment, especially with soldering the components. Additionally, I would like to thank Dr Greg Sitz for assisting our efforts in and outside of the lab and for making us aware of the work of CosmicWatch. This paper was written and compiled in LaTeX using the Overleaf online editor.

[1] K. Nagamine, *Introductory Muon Science* (Cambridge University Press, 2003).

[2] Office of Science, DOE Explains...Muons, `https://www.energy.gov/science/doe-explainsmuons` (2024), Accessed: 27 March 2024.

[3] D. Griffiths, *Introduction to Elementary Particles*, 2nd ed. (Wiley, 2008).

[4] S. Axani, K. Frankiewicz, and J. Conrad, CosmicWatch muon detector, `http://www.cosmicwatch.lns.mit.edu/` (2024), Accessed: 26 March 2024.

[5] G. O. Sitz (2024), background knowledge on Cobalt-60 decay basics, scintillator and photomultiplier tube design.

[6] R. Georgel, K. Grygoryev, S. Sorensen, H. Lu, S. Andersson-Engels, R. Burke, and D. O'Hare, Biosensors (Basel) (2022).

[7] W. U. Boeglin, Modern lab manual: Scintillation detector, `https://wanda.fiu.edu/boeglinw/courses/Modern_lab_manual3/scintillator.html` (2024), Accessed: 05 February 2024.

[8] J. H. Brewer III, N. J. Hansford, J. C. Hill, G. M. Palmer, and J. M. Kulman, *High Altitude Cosmic Radiation Detector Payload Summary and Flight Science Report*, Tech. Rep. (West Virginia University, 2007).

[9] N. Hall, Earth atmosphere model, `https://www.grc.nasa.gov/www/k-12/airplane/atmosmet.html` (2021), Accessed: 28 March 2024.

[10] W.-L. Chen and R.-J. Sheu, Radiation Protection Dosimetry (2017).