BUILDING A POCKET-SIZED MUON DETECTOR AND STARTING A COSMIC RAY RESEARCH GROUP

by

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ABSTRACT

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A pocket-sized muon detector was built to start a cosmic ray research opportunity for students at Brigham Young University - Idaho. The detector is one designed by the CosmicWatch Project at the Massachusetts Institute of Technology. This paper will provide an introduction to muons and cosmic rays and instructions to build and run the detector.

ACKNOWLEDGMENTS

I would like to thank my friends and peers for putting up with me for so long, specifically Aileen Godfrey and Kristen Hawkins who have let me vent to them so much these last few years. I would also like to thank those friends that stayed up with me until 4AM to keep me company while I soldered tiny components. Thank you to the physics faculty at Brigham Young University - Idaho for having (slightly misplaced) faith in me. My physics family has been the support I didn't know I needed, and I could not have asked for anything better.

Contents

List of Figures

Chapter 1

Introduction

1.1 The particle of interest

1.1.1 What are muons

The Standard Model lists and categorizes the elementary particles that make up everything in the known universe. The particles are categorized into elementary fermions and bosons, which are sub-categorized into leptons and quarks and into gauge bosons and scalar bosons respectively. (See Figure 1.1.) There are three generations of leptons, generation meaning each has the same properties as the others except for mass. There are also three generations of quarks which are also numbered by increasing mass.

The leptons consist of electrons, muons, tauons, and their respective neutrinos. The electron is the lightest charged particle and is stable (it does not decay nor does it have a lifetime restriction), while the muon and the tauon are more massive and have short lifetimes. The muon is considered a second generation charged lepton, it being more massive than the electron (first generation) but less massive than the tauon (third generation). The mass of the muon is about $207m_e$ and is sometimes

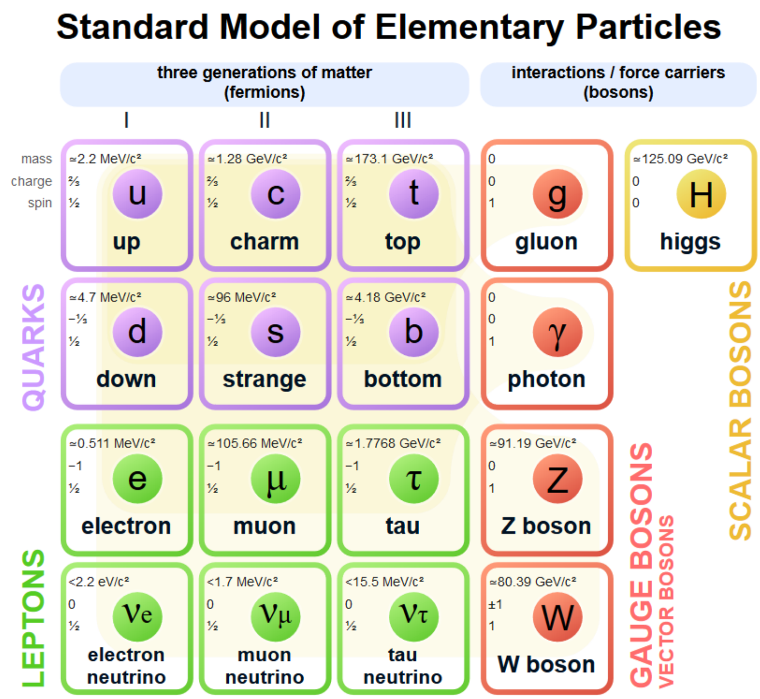

Figure 1.1 The Standard Model of elementary particle physics consists of fermions and bosons. The fermions are subcategorized into quarks and leptons, and the bosons are subcategorized into gauge bosons and scalar bosons. Source: Fermilab

referred to as a heavy or fat electron.

Since its discovery, the muon has been a major contributer to physics research. Muons are a common occurrence in astrophysics and solar physics as they are found in cosmic rays. The muon has helped physicists refine particle classification and develop a better understanding of special relativity. Muons are not as affected as electrons in electromagnetic fields due to the high mass of the muon, which allows it to penetrate deeper into matter.

1.1.2 Sources of muons

A common decay product of a pi meson is a muon, so most experiments or interactions that produce pi mesons will likely result in muons. These can include high energy interactions with normal matter and some particle accelerator experiments that use hadrons, both of which can be very expensive to run. Muons also come from cosmic rays which are a free source of the particle.

The most natural form in which muons come is that of cosmic rays, which is the high energy radiation from the universe (the rays mostly come from outside of our solar system). As the rays interact with earth's atmosphere, pi mesons are produced which, in turn, decay into muons. These muons are still carrying that high energy and are traveling at relativistic speeds, hence their relativistic behavior.

Being relatively massive particles, muons are not stable particles. Their average lifetime is approximately $2.2\mu s$, which is quite long in subatomic terms. When traveling with a velocity near the speed of light, there are two concepts that affect the muon's lifetime and travel: time dilation and length contraction. With time dilation, the muon relative to the Earth has a longer lifetime than in non relativistic circumstances. Length contraction can make the path to Earth's surface and beyond seem shorter to the muon. Both of these concepts can explain the ability of the muon to travel a great distance, even with such a short lifetime.

1.1.3 Importance of muons in nuclear and particle physics research

The muon contributed to the refinement of particle classification, specifically with mesons. When the muon was first detected, it was thought to be the predicted pi meson, but scientists realized that the particle they had detected did not fit all the predicted parameters. The mass of the muon led scientists to classify it as a meson, because at the time, if a particle was classified as a meson, it was because of its massiveness. With the inconsistency of the properties of the muon compared to the predicted pi meson, it was determined that the defining characteristic of mesons was that they were made of quark-anitquark pairs, unlike the muon.

The muon played a significant role in the experimental testing of time dilation. At the time of the Rossi-Hall experiment[10], muons were still known as mesons. Rossi and Hall used the high speed muons in the atmosphere (traveling at about $0.99c$) to qualitatively confirm time dilation and relativistic momentum. It was the first time that special relativity's time dilation was observed.

Muonic atoms, which consist of a muon replacing an electron in an atom, have been studied for a few decades. Some isotopes that replace an electron with a muon have an increase in mass which effects how it interacts with other atoms or particles. Positive muons, though much harder to capture, have been used in experimentation as well. The lightest hydrogen isotope is known as muonium[5], and it consists of an electron orbiting a positive muon, making the muon the nucleus.

One interesting use for electron-positron annihilation in accelerators is in quantum chromodynamics[7] (a theory in particle physics that discusses the strong interaction between quarks and gluons). The annihilation can produce muons and the relationship between that interaction and the electron-positron interaction that produces quark jets has been used to learn more about quark flavor and behavior.

Tracking muons through material can help map the internal configuration of rocky or dangerous structures. Muon transmission imaging has helped discover hidden chambers in the pyramids of Egypt [8] and determine depths of underground tunnels [6] that need addressing but may be too sensitive for invasive measurement. Magma chambers are mapped as well using muon transmission imaging. Mapping the magma chambers aids in predicting volcanic eruptions. A notable project is the Mu-Ray project by the Italian National Institute for Nuclear Physics, which is dedicated to mapping the chambers inside Mount Vesuvius in the hopes of predicting its next eruption.[3]

1.2 Methods and use of detection

One form of particle detection involves a scintillator with an electronic light sensor. A scintillator is a material that exhibits scintillation (a luminescent property) when hit with radiation, or in other words, a material that can glow when hit with ionizing radiation. An electronic light sensor is placed near the scintillator to detect the scintillation and absorb and re-emit it as electrons by way of the photoelectric effect. The electrons create an electrical pulse from which useful information about the radiation energy can be obtained.

There are several different types of scintillators that include crystals, liquids, and plastics. The demand for plastic scintillators is increasing due to their relatively cheap cost and ability to be shaped. Crystal scintillators are difficult to grow and machine, while liquid scintillators do not keep their shape and therefore can yield inconsistent results.

For electronic light sensors, photomultiplier tubes (PMTs) are known for their use in particle detection, however they are large and expensive. Photodiodes are similar to PMTs but are much smaller and silicon photodiodes are good for detecting excitation energies of charged particles. Silicon photomultipliers are made up of many silicon photodiodes to increase detection accuracy.

Particle accelerators like the Large Hadron Collider (LHC) or the Tevatron have a series of detectors surrounding the particle beam line that filter through the products from the collision. In Figure 1.2, a wedge of a cross-section of the Compact Muon Solenoid (CMS) detector at the LHC can be seen that shows the layers of detectors. The muon detector is the outermost layer shown. As mentioned before, the mass of

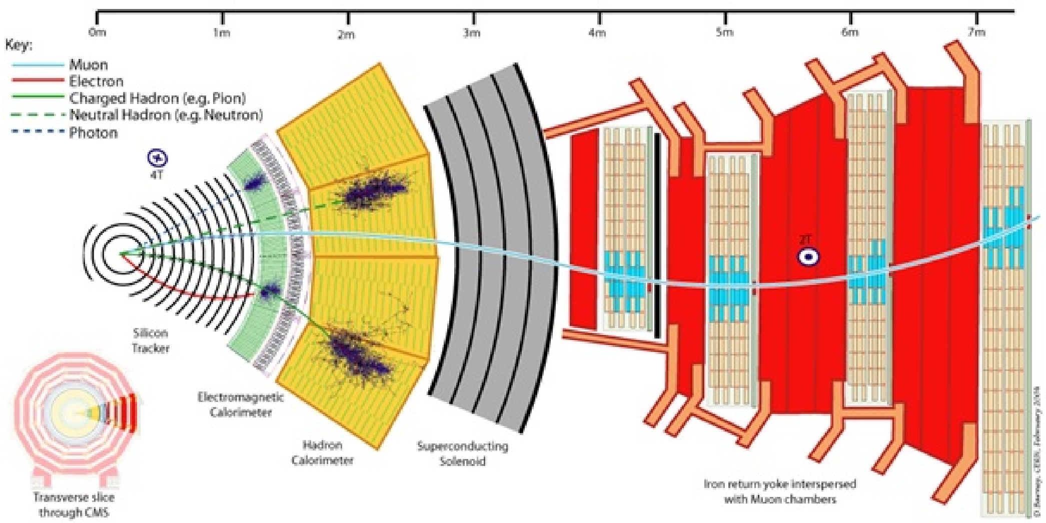

Figure 1.2 A wedge of a cross-section of the Compact Muon Solenoid (CMS) that shows the layers of detectors used in experiments. The first layer outside the beam line is the silicon tracker, followed by the electromagnetic calorimeter which detects photons and electrons. The hadron calorimeter is the next layer which detects hadrons like pions or neutrons. The superconducting solenoid is part of the accelerator design needed to keep the beam on the right path. A series of muon detectors makes up the final layer called muon chambers. Source: CERN

the muon allows it to travel further into material without interacting as much as an electron might. Given this, any signal picked up outside of the magnet must be a muon. The detector consists of iron return yokes and muon chambers.

1.3 The CosmicWatch Project

1.3.1 What is CosmicWatch?

With muon detection being so prevalent to particle physics research, it is important for undergraduate students to be exposed to it as early as possible. Hands-on experience with detectors would be an ideal scenario, but that could be expensive and take up a lot of lab room. Students, particularly those at non-research institutions where funding is more limited, could benefit greatly from the experience gained through building a low-cost compact muon detector.

The CosmicWatch Project was started by Spencer Axani[9], a PhD student at the Massachusetts Institute of Technology (MIT), to provide an inexpensive research opportunity with cosmic ray detection. The device is made to detect muons in cosmic rays, which can appeal to students interested in astrophysics or particle physics. The project is in collaboration with the National Centre of Nuclear Research in Warsaw, Poland.

Building the muon detector, which is about the size of a standard box of matches[9], consists of populating circuit boards, programming an Arduino Nano, and collecting and analyzing data. It can also include machining and polishing material that requires a smooth reflective surface, but that was not performed for this work and is only mentioned as a possible side project for any future work.

CosmicWatch was created as a way to get university students excited about research and to explore a variety of different skills. The cost per detector is estimated at 100 U.S. dollars[2], a cost determined by buying supplies in bulk. The design of the detector made it vastly less expensive than typical particle or muon detectors. A big part of the cost difference was in the use of a silicon photomultiplier instead of a photomultiplier tube, which are often large and expensive.

1.3.2 Notable measurements

The detector was not originally going to be mass marketed as an educational tool.[1] It started off as a project for the IceCube neutrino experiment. Fermilab's MiniBooNE neutrino experiment uses similar devices, but in their case they are calibration scintillator cubes.

To demonstrate the detector's ability to discern between radiogenic backgrounds

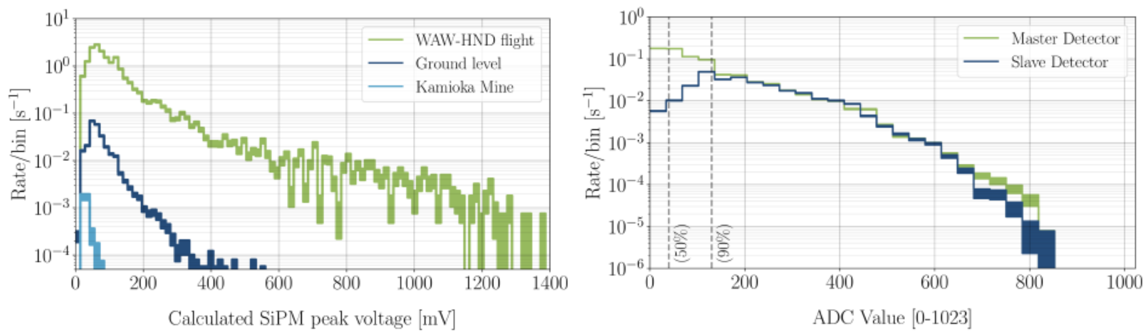

Figure 1.3 (Left) Data collected from three different locations in and around the Super-Kamiokande detector. (Right) The ACD value for the master and the slave.[1]

and cosmic ray muons, two detectors were taken to the Super-Kamiokande detector to collect SiPM voltage measurements. The detectors were used in a master-slave configuration (which will be explained in a later chapter) and data was collected in three locations: underground in the mine near the large detector, outside of the mine, and in an airplane. Figure 1.3 shows the data collected.

Two detectors were used to measure and test muon angular distribution. The angular distribution is said to obey a cosine squared dependence[4]. The detectors were put in coincidence (connected through the audio jack) and placed back-to-back on a meter long bar which was then placed at different angles to the wall. Figure 1.4 shows the data collected for the configuration. The data from the detectors fit the cosine squared curve fairly well.

1.3.3 Goals of this project

The goal for the project discussed in this paper is to get students at Brigham Young University - Idaho (BYU-Idaho) involved in the CosmicWatch collaboration. There is an ever increasing demand for affordable research projects at BYU-Idaho, and particle research is underrepresented. Starting a cosmic ray research group at BYU-

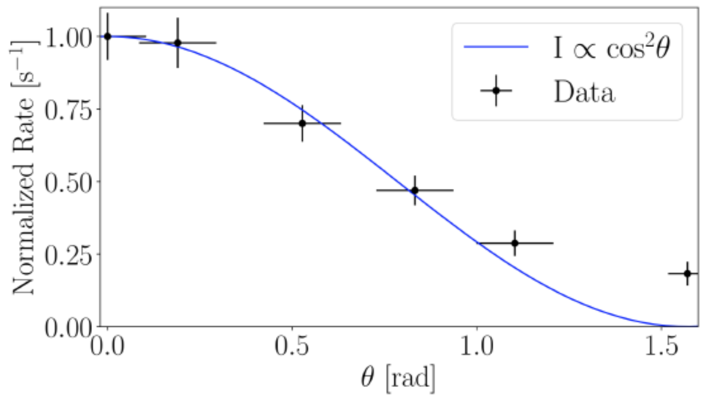

Figure 1.4 Data collected from testing the muon detector by measuring the muon angular distribution shown against the known dependence of $cos^2\theta$.

Idaho would provide an opportunity for students to learn and develop new skills and to be a part of something bigger.

To accomplish this goal, I built a muon detector and compiled all information required to build it. The detector is available for use by any student interested in research experience pertaining to particle detection.

This paper only introduces the possibilities of the pocket-sized muon detector. It will act as an instruction guide for future students at BYU-Idaho, especially those interested in particle and astroparticle physics. They can build upon this work which will introduce the university's first working muon detector.

Chapter 2

The detector

2.1 Supplies

The supplies to build the muon detector are listed on the CosmicWatch website[9] and also mentioned in papers published pertaining to the project. The detector consists of three PCB (polychlorinated biphenyl) circuit boards, a silicon photomultiplier (SiPM), plastic scintillator, the casing, and various electronic components. All the supplies needed for on detector are listed in Appendix A.

The PCB circuit boards are custom designed by the CosmicWatch project. The SiPM is the component that actually detects the energy of the muons. The plastic scintillator aids the SiPM by glowing in a certain range of wavelengths. (The light emitted from the scintillator is what the SiPM reads.)

All other components are used to make reference measurements, reduce background noise and combine and store all measurements made. Some of these include the temperature sensor, the SD card socket, the Arduino Nano, the OLED screen, and various resistors and capacitors. The Arduino Nano was chosen for the detector because it does a lot the conversions and measurements needed at an inexpensive cost

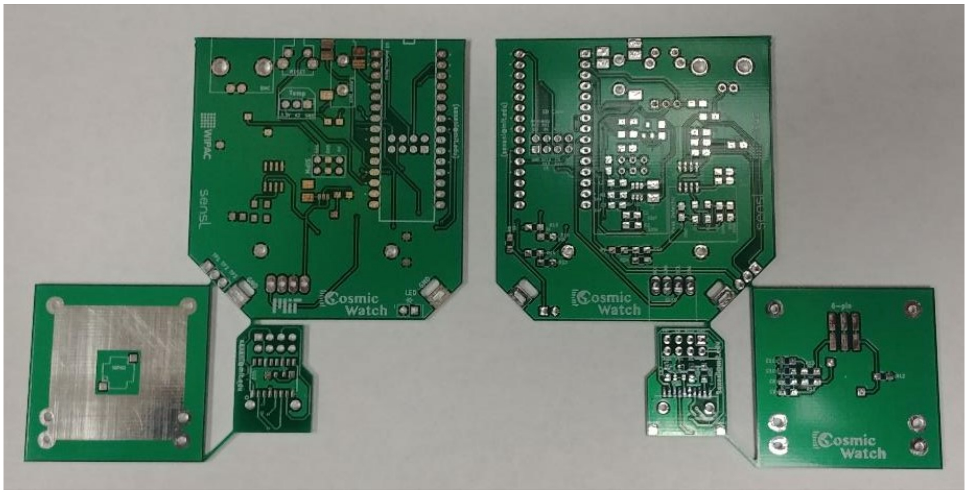

Figure 2.1 Unpopulated PCB boards showing silkscreens.

compared to building separate circuits to perform each individual function.

2.2 PCB Boards

There are three PCB boards: one for the SD card reader, one for the SiPM (explained further in Section 2.3), and the other is the main board with the Arduino Nano. The boards are purchased through Elecrow, which offers custom made PCB boards. The company uses Gerber files that the purchaser attaches to the order. The Gerber .zip file can be found on the CosmicWatch GitHub account.

The PCB for the SD card reader mainly consists of the SD card socket for micro SD cards, the non-inverting buffer, and the 3.3V regulator. The non-inverting buffer and the 3.3V regulator both help control the voltage in the circuit. The micro SD card socket writes the data onto the card. Writing to a micro SD card is optional. The Arduino code must allow for this option in order for the micro SD PCB to operate. The main way to record the data is to connect the detector directly to a computer, which was the method used for this project.

The main PCB connects the micro SD PCB and the SiPM PCB and contains the Arduino Nano, temperature sensor, OLED screen, and the external connector sockets. The BNC connection is for connecting the detector to an oscilloscope and the audio jack is to put two detectors in coincidence. The main PCB also contains the circuit components for data amplification, peak detection, and the VCC filtering (used to reduce data noise).

2.3 SiPM

The SiPM PCB is arguably the most important part of the muon detector since this PCB is what does the actual detecting. The SiPM is the device on the circuit that senses the light that will emanate from the plastic scintillator. The SiPM that was used was purchased from Sensl.

The SiPM is soldered to the PCB and the plastic scintillator is placed on top of the SiPM. It is very important that there is sufficient pressure between the plastic scintillator and the SiPM, but not too much pressure that would cause the SiPM to crack. The pressure is needed to help ensure that the SiPM does not pick up outside light sources.

To further ensure a light-tight enclosure, prior to being placed onto the SiPM, the plastic scintillator should be almost fully encased in aluminum foil (there should be as little crinkles as possible in the foil) which should be fixed with electrical tape. There should be a space in the foil wrapping larger than the SiPM so that the foil does not touch the SiPM (the actual component, not the PCB board). Once the foil is in place, the plastic scintillator can be placed onto the SiPM (optical gel or petroleum jelly can be used in between the two surfaces to further ensure connection). Electrical tape is then used to encase the entire SiPM PCB with the exception of the connection sites to mount the SiPM PCB to the main PCB.

2.4 Plastic Scintillator

A plastic scintillator is a special polymer that glows within a certain range of wavelengths. The glow range is also referred to as the peak range, as in the range within which the plastic shows a reaction. The ability for the plastic scintillator to reflect as much as possible is highly important. The sides of the scintillator must be smooth to ensure high reflection of the light so that the SiPM can sense it as accurately as possible.

Machining and polishing the plastic scintillator is a possible addition to the project, though it was not done during this experiment. The scintillator used for this detector (see Figure 2.2) was purchased from Eljen Technology and was from their EJ-200 line. The dimensions needed for the detector are 5cm $\times$ 5cm $\times$ 1cm and needs to be machined for four 18-8 5/16" screws. The scintillator then needs to be polished; there are many papers and videos demonstrating how to do this. Eljen Technology offers machining and polishing for extra costs and there are other companies that will make similar offers. Eljen is a popular choice especially among those that are building the CosmicWatch muon detectors; I found that Eljen already had scintillators machined and polished to the required specifications and were ready to ship.

In order for the detector to be sensitive to muons, the plastic scintillator needs to peak in the 400nm-430nm range. This range means the scintillator will emit a violet-blue glow. The light-tight enclosure of aluminum foil and electrical tape ensures the SiPM can pick up the the light emanating from the scintillator with minimal background noise.

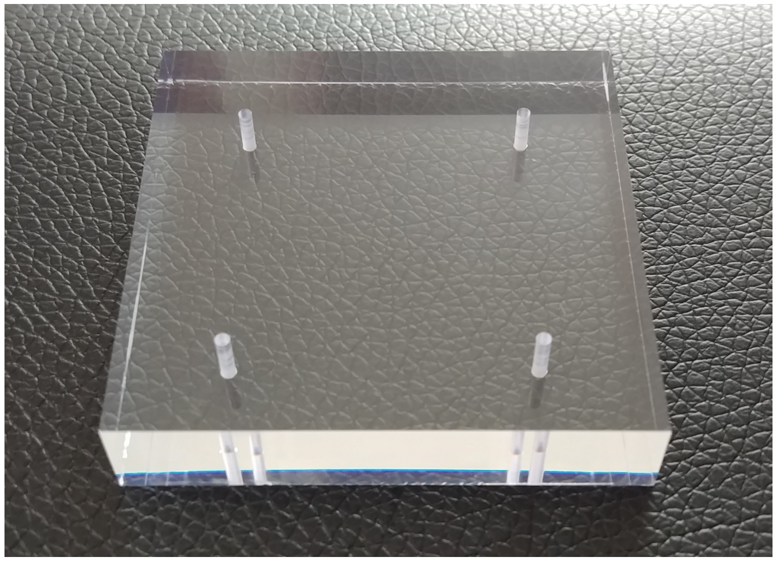

Figure 2.2 The plastic scintillator used and purchased from Eljen Technology's EJ-200 line of plastic scintillators. This scintillator's peak wavelength is 425nm.

2.5 Setup

Populating the PCB boards requires surface mount soldering of small components, some of which are expensive and caution should be used when soldering them. As with all soldering, a good connection of the solder between the component and the conductive spacing for the component on the board is important. The circuit schematic and the reference sheet for populating the boards can be found in Appendix A.

There are a couple of checks that can be made to ensure there are good connections. On the SiPM PCB board, a multimeter can be used to check that there is current one way but not the other, as the direction matters for the SiPM. On the main PCB board, there is a check for the voltage across the SiPM connection; the voltage should not exceed 29.4V. The voltage I was getting across was about 0.4V. I quadruple checked the connections and nothing changed. The voltage difference does not seem to make a difference in the data.

Connecting the three PCB boards is made easy by the silkscreens that are printed

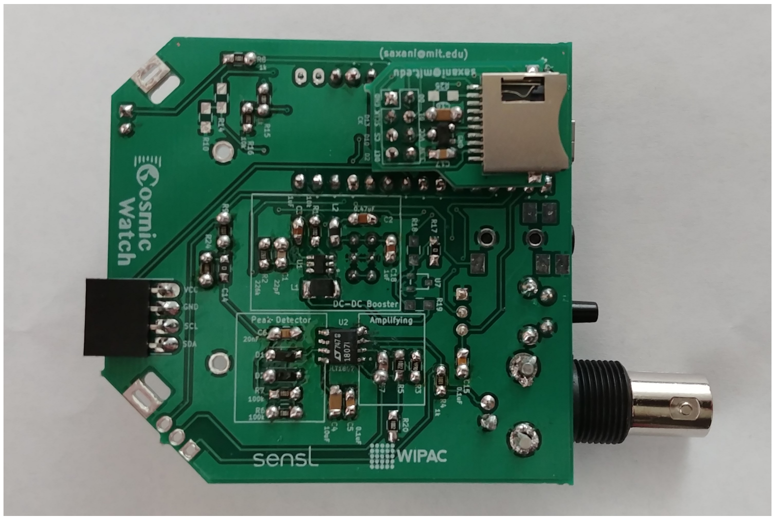

Figure 2.3 One side of the main PCB board that includes the OLED screen connection and the SD card PCB connection.

on the PCB boards (the silkscreens are part of the Gerber .zip file that is sent to the manufacturer). The micro SD card PCB connects to the side of the main PCB opposite the Arduino connection. (See Figure 2.3.) The SiPM PCB is connected on the same side as the Arduino and the standoffs on the SiPM PCB allow for clearance for all components. (See Figure 2.4.)

The SD card to Arduino connection comes from 2 multi-pin headers that should come with the Arduino Nano. For the connection, a 2x4 pin header is needed, but the Arduino Nano only comes with two 15x1 pin headers and one 2x3 pin header. Since not all of the pins on the 15x1 pin headers are used, two pins are cut off from one to create a 2x4 pin header with the 2x3 pin header.

A casing is included to protect the PCB boards and components. Figure 2.5 shows the detector without the casing while Figure 2.6 shows the enclosed detector. The casing body was purchased from Enclosures and Casings Inc. and it is from their split body line, size 2506H-2.9". The completed PCB board system slides into the slots on the inside of the aluminum casing. The end plates were purchased from Elecrow (the

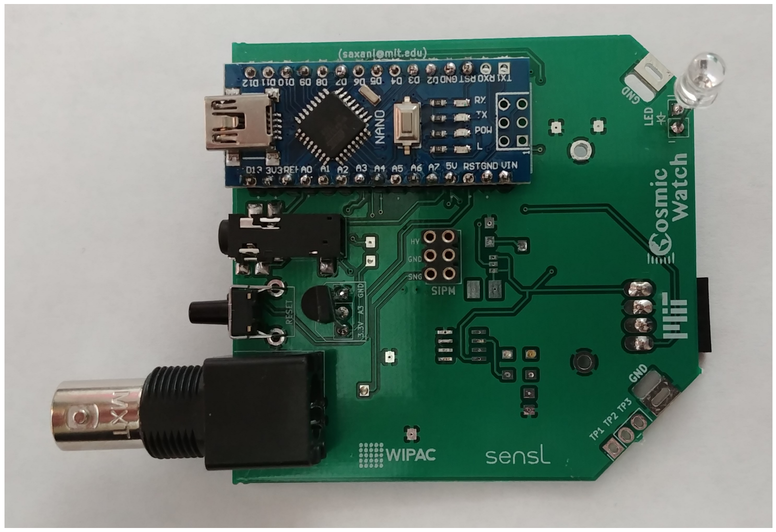

Figure 2.4 The other side of the main PCB that includes the Arduino Nano connection, temperature sensor, and the SiPM PCB board connection.

same company from which the PCB boards were purchased) and plates are secured into place with screws on either end of the aluminum body.

Depending on if the user wants to use the SD card for memory storage or saving directly to the computer, a different code would need to be uploaded to the Arduino. If the user wants to save directly to the computer, the OLED code would be better as the user can watch the detection live on the screen. The SD card code is needed for saving to a micro SD card, which is better for users who have remote experiment set-ups (example: on a weather balloon). A python code for collecting or retrieving data, provided by CosmicWatch, has a few options for the user: (1) record data to the computer which collects data live and creates and saves to a file, (2) copy data from the SD card, (3) remove data files from the SD card, or (4) connect to the CosmicWatch website to upload data to their database. (The upload to website option did not seem to work properly and caused python to crash. As this option did not pertain to this project, the decision was made to not use this option.)

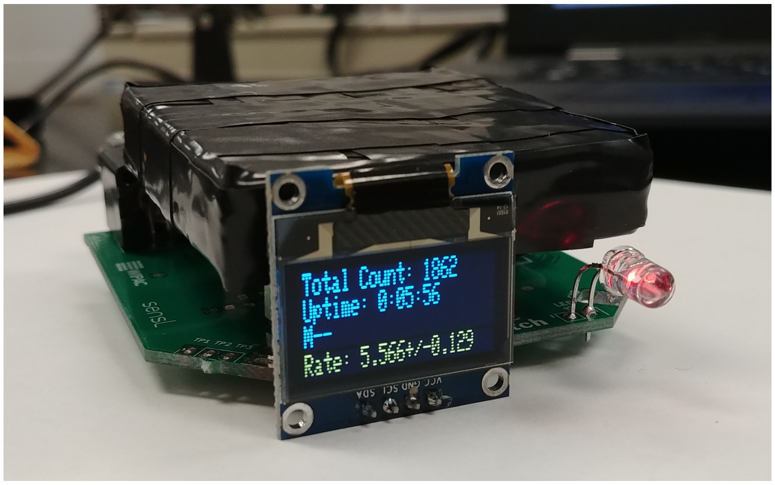

Figure 2.5 The detector without the aluminum casing.

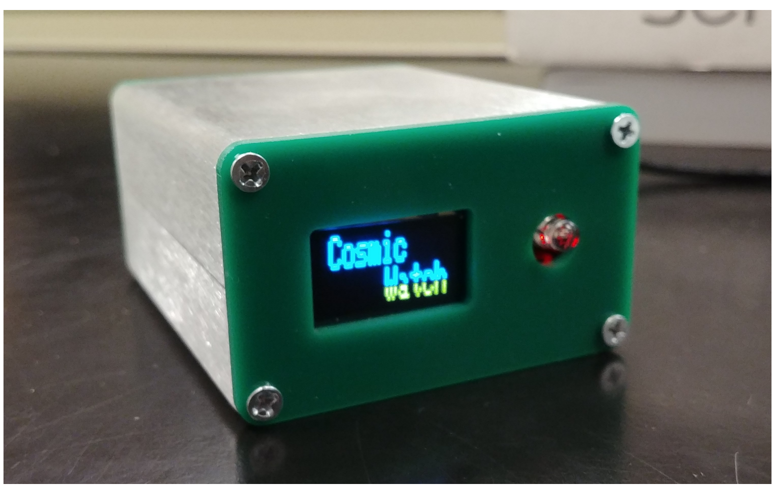

Figure 2.6 The finished detector in the aluminum casing.

Chapter 3

Results

The data files created by the Arduino code contain the count, time stamp, ADC (analog-to-digital conversion), SiPM voltage, and temperature. For each signal, the ADC, SiPM voltage and temperature are measured and recorded. There are two points of focus for the results; one is the counts per second and the SiPM voltage per count.

Finding the counts per second yields whether or not there is anything being detected. Figure 3.1 and Figure 3.2 show the number of counts per second for the first and second runs respectively. The detector is clearly getting something, and given the design of the detector, I would conclude that it is, in fact, muons.

The SiPM voltage is related to the radiation energy the scintillator absorbs. Figure 3.3 shows the SiPM voltage versus the count. There are a few peaks that imply that there was a high energy muon detected. For example, at around 13000 counts, there is a cluster of higher radiation which would mean higher energy muons. Figure 3.4 shows the SiPM voltage per count for the second run. The higher the SiPM voltage, the higher the energy of the muon.

Originally, the plan for the muon detector was to fly it in conjunction with BYU-

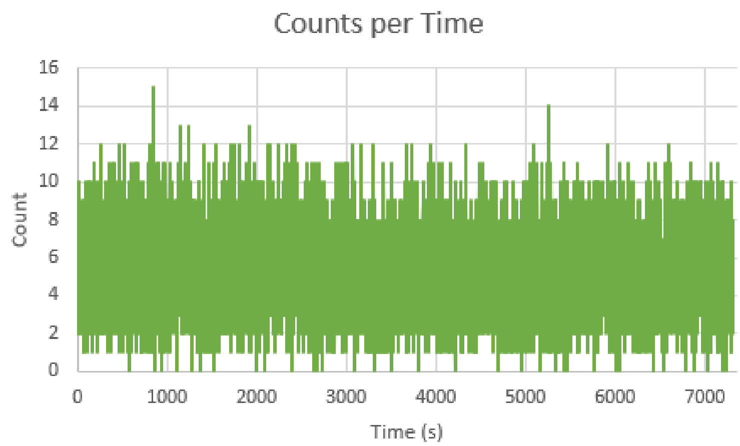

Figure 3.1 Counts per second for the first data run which lasted just over 2 hours. Time started at 13:27:10 MST.

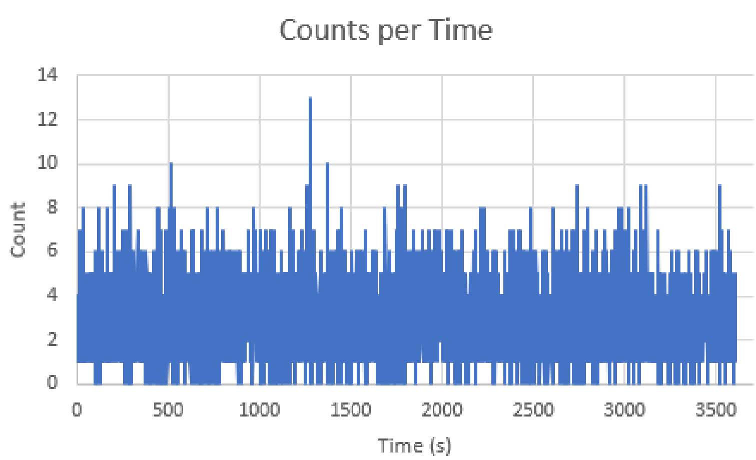

Figure 3.2 Counts per second for the second data run which lasted about 1 hour. Time started at 20:47:52 MST.

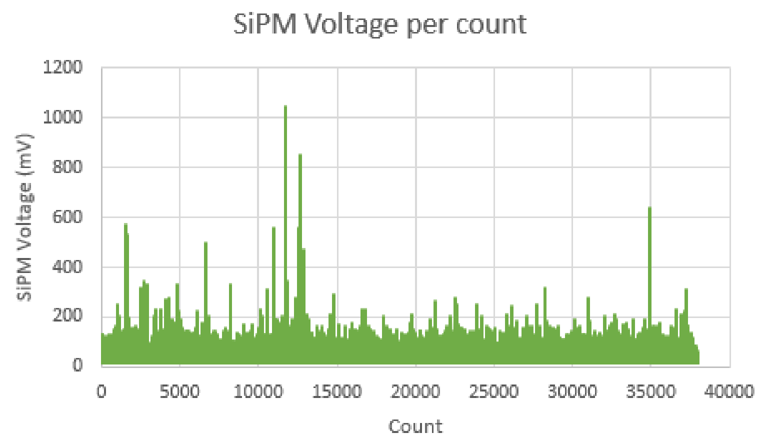

Figure 3.3 Plot of SiPM voltage per count for first run.

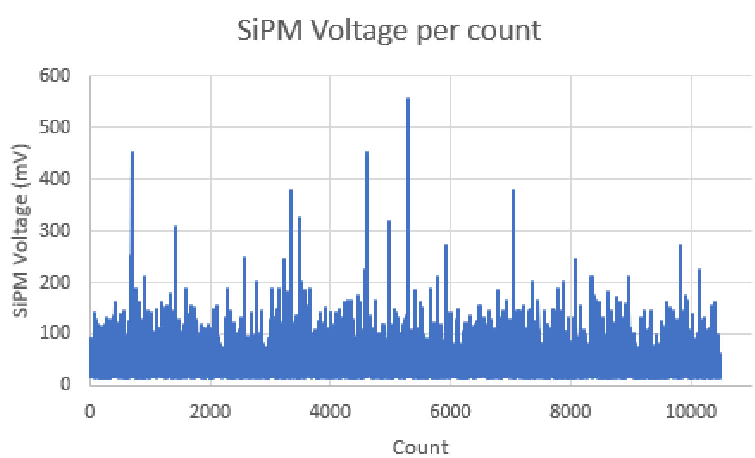

Figure 3.4 Plot of SiPM voltage per count for second run.

Idaho's High Altitude Research Team (HART). While testing the detector, the bench data was collected without problems and the both codes for the OLED and the SD card options operated as expected, however when connected to a battery power source, the detector would shut off after about 2 minutes. One possible explanation for this is that the detector was not designed with a voltage source regulator in mind, so when the source voltage drops below a certain threshold, the detector turns off. The detector needs a constant voltage source in order to operate. Another possible explanation for this is that the battery packs readily available turn off when they detect a full charge. The detector would appear to the battery pack as fully charged.

Chapter 4

Conclusion and Future Work

A muon detector was built to start a research opportunity, possibly even a team, at BYU-Idaho for students to gain more experience and interest in other areas of physics. Now that the school has a working muon detector, students have more research options. There are several ways that the muon project can continue at BYU-Idaho, including continued data collection, flying the detector with HART, and some modifications and configurations.

In order to send the detector as a payload with HART, the detector needs a constant voltage source. A modification to the circuit or a modified battery source could be a solution. A voltage regulator is a common electrical component that would be helpful for the modification. Another possibility to fix the voltage source problem is to find a battery pack that does not turn off after detecting a full charge and use that as the power source for the detector.

CosmicWatch used the Arduino Nano because it was cheaper and faster to buy it instead of building a similar board that would only do what is necessary. One potential downfall is that there is not enough memory on the Arduino Nano to a run a code that will both operate the OLED screen and write to the micro SD card. A possible project would be to modify the current design to accommodate a code that combines the two current codes. This could be done by upgrading the Arduino type or modifying the current codes to save space.

The CosmicWatch project designed the detector so that two detectors could be connected; they called this a Master-Slave setup. Two detectors are connected through the audio jack which is detected by the programmed Arduino. The connection makes one detector the master and the other detector the slave. When the master detects a specific energy, the slave is triggered to count. Essentially, the slave only counts when the master signals it to do so. More information on the Master-Slave setup can be found on the CosmicWatch website and also in the papers published by them.

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[10] Bruno Rossi and David B. Hall. Variation of te rate of deccay of mesotrons with momentum. *The Physical Review*, 59, December 1940.

Appendix A

Appendix A contains lists of supplies needed to build one detector, the circuit schematic for all three PCB boards, and the populating reference sheets to populate the PCB boards.

Component	Required Number	Description	Where to buy
10k Ohm Resistor	5	RES SMD 10K OHM 1% 1/8W 0805	Digikey Part Number: 311-10.0KCRCT-ND
226k Ohm Resistor	2	RES SMD 226K OHM 1% 1/8W 0805	Digikey Part Number: 311-226KCRCT-ND
249 Ohm Resistor	2	RES SMD 249 OHM 1% 1/4W 0805	Digikey Part Number: 311-249CRCT-ND
1k Ohm Resistor	4	RES SMD 1K OHM 1% 1/8W 0805	Digikey Part Number: 311-1.00KCRCT-ND
100k Ohm Resistor	3	RES SMD 100K OHM 1% 1/8W 0805	Digikey Part Number: 311-100KCRCT-ND
49.9 Ohm Resistor	4	RES SMD 49.9 OHM 1% 1/8W 0805	Digikey Part Number: 311-49.9CRCT-ND
24.9k Ohm Resistor	2	RES SMD 24.9K OHM 1% 1/8W 0805	Digikey Part Number: RMCF0805FT24K9CT-ND
0 Ohm Resistor	5	RES SMD 0 OHM JUMPER 1/8W 0805	Digikey Part Number: 311-0.0ARCT-ND
22pF Capacitor	2	CAP CER 22PF 50V NP0 0805	Digikey Part Number: 399-1113-1-ND
0.47uF Capacitor	2	CAP CER 0.47UF 50V X7R 0805	Digikey Part Number: 399-8100-1-ND
1uP Capacitor	3	CAP CER 1UF 50V Y5V 0805	Digikey Part Number: 587-1308-1-ND
10uF Capacitor	4	CAP CER 10UF 6.3V X5R 0805	Digikey Part Number: 490-1718-1-ND
0.1uF Capacitor	4	CAP CER 0.1UF 50V X7R 0805	Digikey Part Number: 399-1170-1-ND
20nF Capacitor	6	CAP CER 20nF 50V X7R 0805	Digikey Part Number: 1276-2472-1-ND
10pF Capacitor	2	CAP CER 10PF 50V C0G/NP0 0805	Digikey Part Number: 1276-1109-1-ND
10000pF Capacitor	4	CAP CER 10000PF 50V X7R 0805	Digikey Part Number: 311-1136-1-ND
47uH Inductor	1	FIXED IND 47UH 170MA 1.3 OHM SMD	Digikey Part Number: 490-4063-1-ND
2.5k Ferrite Bead	2	FERRITE BEAD 2.5 KOHM 0805 1LN	Digikey Part Number: 587-1919-1-ND
500ma diode	2	DIODE SCHOTTKY 40V 500MA SOD123	Digikey Part Number: MBR0540CT-ND
DC-DC Booster	1	3MHz Step-Up DC/DC Converters	Digikey part number: LT3461AES6#TRMPBFCT-ND
Op-Amp	1	325MHz, Dual, Rail-to-Rail Input and Output	Digikey part number: LT1807IS8#PBF-ND
3.3V regulator	1	IC REG LINEAR 3.3V 300MA SOT23-3	Digikey part number: AP2210N-3.3TRG1DICT-ND
Reset button	1	SWITCH TACTILE SPST-NO 0.02A 15V	Digikey part number: P12215S-ND
BNC header	1	CONN BNC JACK R/A 50 OHM PCB	Digikey part number: WM5514-ND
OLED header	1	4 pin header CONN FEMALE 4POS .100” R/A TIN	Digikey part number: S5440-ND
6-pin Header	1	SOCKET 7 MM SOLDER TAIL DOUBLE	Digikey Part Number: 1212-1229-ND
3.5 mm jack	1	CONN JACK 4COND 3.5MM SMD R/A	Digikey Part Number: CP-43515RSSJCT-ND
6-pin connector	1	6-pin connector for SiPM PCB	Digikey part number: WM17457-ND

Table A.1 List of supplies to be purchased from Digikey.

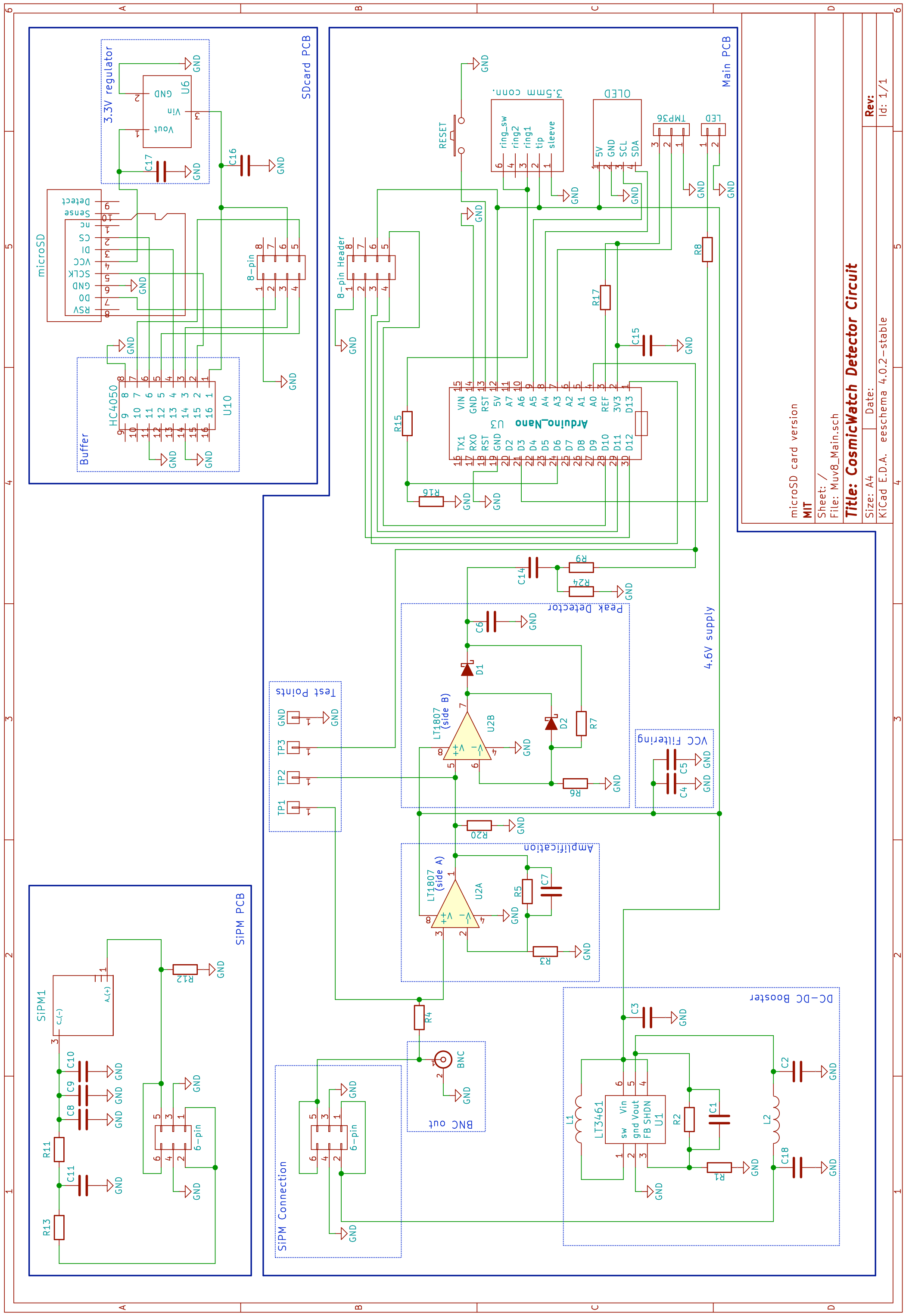

Figure A.1 The circuit schematic for all three PCBs.

Component	Required Number	Description	Where to buy
Standoff for SiPM PCB	2	1/8"HexSize,3/8"Length,0-80Thread Size	McMasterCarr part number: 91780A027
Standoff screws Main side	4	0-80ThreadSize,5/16"Long	McMasterCarr part number: 91771A056
Plastic scintillator screws	4	18-8StainlessSteel,Number 0Size,5/16"Long	McMasterCarr part number: 92470A024
Non-Inverting Buffer	1	High Speed CMOS Logic Hex Non-Inverting Buffers	Mouser Part Number: 595-CD74HC4050M96
LED light	1	Any color, 5 mm	Amazon
Temperature Sensor	1	TMP36 analog sensor	Amazon
SiPM	1	SiPM MicroFC-60035-SMT	SENSL
SD card socket	1	Micro SD Memory Card Slot Holder Sockets	Uxcell (Amazon or Ebay)
Plastic Scintillator	1	5x5x1 cm Plastic Scintillator (peak about 420nm)	Eljen ()
PCB boards	1	Main, SD card, and SiPM PCB	Elecrow
OLED Screen	1	OLED screen 4 pin	Amazon
Optical gel	¡1mL	Petroleum jelly works as well	Amazon
Black electrical tape	as needed	For wrapping scintillator	Amazon
Coincidence cable	as needed	For connecting two detectors	Amazon
BNC cable	as needed	For connecting detector to oscilloscope	Amazon
Tin or Aluminum Foil	about 100cm^2	For wrapping scintillator	local
Aluminum Case	1	Aluminum casing, split body, 2506-2.9"	Enclosures and Cases Inc.
Front and back plates	1 set	plastic end plates	Elecrow
LED holder	1	LED light mounting holder	Amazon
Arduino Nano	1	ATmega328 CH340G	Amazon
2x3 header	1	2x3 pin header	Comes with Arduino Nano
15x1 header	2	15x1 pin header	Comes with Arduino Nano

Table A.2 List of supplies that are to be purchased from other suppliers.

Component Code	What is it	Description	Comment
R1	10k	RES SMD 10K OHM 1% 1/8W 0805	
R2	226k	RES SMD 226K OHM 1% 1/8W 0805	
R3	249	RES SMD 249 OHM 1% 1/4W 0805	
R4	1k	RES SMD 1K OHM 1% 1/8W 0805	
R5	10k	RES SMD 10K OHM 1% 1/8W 0805	
R6	100k	RES SMD 100K OHM 1% 1/8W 0805	
R7	100k	RES SMD 100K OHM 1% 1/8W 0805	
R8	1k	RES SMD 1K OHM 1% 1/8W 0805	
R9	Short	RES SMD 0 OHM JUMPER 1/8W 0805	Short
R10	NS		
R11	49.9	RES SMD 49.9 OHM 1% 1/8W 0805	
R12	49.9	RES SMD 49.9 OHM 1% 1/8W 0805	
R13	49.9	RES SMD 49.9 OHM 1% 1/8W 0805	
R14	NS		
R15	1k	RES SMD 1K OHM 1% 1/8W 0805	
R16	10k	RES SMD 10K OHM 1% 1/8W 0805	
R17	Short	RES SMD 0 OHM JUMPER 1/8W 0805	Short
R18	NS		
R19	NS		
R20	10k	RES SMD 10K OHM 1% 1/8W 0805	
R24	24.9k	RES SMD 24.9K OHM 1% 1/8W 0805	
R25	NS		
D1	500ma diode	DIODE SCHOTTKY 40V 500MA SOD123	Has direction
D2	500ma diode	DIODE SCHOTTKY 40V 500MA SOD123	Has direction
L1	47uH	FIXED IND 47UH 170MA 1.3 OHM SMD	
L2	2.5k	Ferrite Bead FERRITE BEAD 2.5 KOHM 0805 1LN	
C1	22pF	CAP CER 22PF 50V NP0 0805	
C2	0.47uF	CAP CER 0.47UF 50V X7R 0805	
C3	1uF	CAP CER 1UF 50V Y5V 0805	
C4	10uF	CAP CER 10UF 6.3V X5R 0805	
C5	0.1uF	CAP CER 0.1UF 50V X7R 0805	
C6	20nF	CAP CER 20nF 50V X7R 0805	
C7	10.0pF	CAP CER 10PF 50V C0G/NP0 0805	
C8	10 nF	CAP CER 10000PF 50V X7R 0805	
C9	10 nF	CAP CER 10000PF 50V X7R 0806	
C10	10 nF	CAP CER 10000PF 50V X7R 0807	
C11	10 nF	CAP CER 10000PF 50V X7R 0808	
C14	Short	RES SMD 0 OHM JUMPER 1/8W 0805	Short
C15	0.1uF	CAP CER 0.1UF 50V X7R 0805	
C16	10uF	CAP CER 10UF 6.3V X5R 0805	
C17	0.1uF	CAP CER 0.1UF 50V X7R 0805	
C18	1uF	CAP CER 1UF 50V Y5V 0805	

Table A.3 The populating reference sheet to use as guide for the circuit schematic for the resistors and capacitors. The table lists the component label from the schematic, the value of the component, and the description of the component.

Component Code	**What is it**	**Description**	**Comment**
U1	LT3461	3MHz Step-Up DC/DC Converters	Has direction
U2	LT1807IS8#PBF	325MHz, Dual, Rail-to-Rail Input and Output, Precision Op Amps	Has direction
U7	NS		
U6	3.3V regulator	IC REG LINEAR 3.3V 300MA SOT23-3	Has direction
U8	SD card socket	SMT SMD Cell Phone TF Micro SD Memory Card Slot Holder Sockets	
U10	Non-Inverting Buffer	High Speed CMOS Logic Hex Non-Inverting Buffers	Has direction
Reset	Reset button	SWITCH TACTILE SPST-NO 0.02A 15V	
2x4 SD header	2x3 header +2x1	header for mounting SD card PCB. 2x3 + 1x2	
15x1 header	15x1 header	2x headers for mounting Arduino	
Arduino Nano	Arduino Nano	16 MHz CH340/ATmega328P Arduino Nano	
BNC receptacle	BNC header	CONN BNC JACK R/A 50 OHM PCB	
OLED header	4 pin header	CONN FEMALE 4POS .100” R/A TIN	Bottom
LED	LED light	Any color, 5mm	
6-pin Header	6-pin Header	SOCKET 7 MM SOLDER TAIL DOUBLE	
3.5 mm jack	3.5mm jack	CONN JACK 4COND 3.5MM SMD R/A	
Temp	TMP36	Temperature Sensors TMP36 Precision Linear Analog Output	
SiPM1	SiPM	SiPM MicroFC-60035-SMT	Has direction
SiPM PCB 6-Pin	6-pin Pins	WM17457-ND	

Table A.4 The populating reference sheet to use as guide for the circuit schematic for all other components. The table lists the component label from the schematic, the value of the component, and the description of the component.

Appendix B

With the way the data files are written from the detector, a code was needed to convert the data to counts per second from information per count. The following is the code to convert the raw data files.

```
#!/bin/python2
#
# Program to convert CosmicWatch output files to count rate per interval.
#
# This program requires two command line arguments:
#
# (1) The path/name of the CosmicWatch file to be converted, and
# (2) The time interval to use in the conversion, in ms.
#
# Output is written to the terminal.

import sys

# Check the command line arguments.
```

```
if len(sys.argv)<3:
sys.stderr.write("You must specify by command line arguments:\n")
sys.stderr.write("  (1) The path/name of the CosmicWatch file to be"
+"converted, and\n")
sys.stderr.write("  (2) The time interval to use in the conversion,"
+"in ms.\n")
sys.exit(1)

filename=sys.argv[1]
interval=int(sys.argv[2])

print "# \""+filename+"\" -> count rate per "+str(interval)+" ms."
print "# First column is the upper bound of the interval, in ms."
print "# Second column is the number of counts in the interval."

# Open the file and read the data (the arduino time).

try:
times=set()
datafile=open(filename,"r")
for i in range(6): datafile.readline() # Skip first five lines
line=datafile.readline()
while line: # Read line by line, storing the arduino time
times.add(int(line.split()[3]))
line=datafile.readline()
```

```
except:

sys.stderr.write("Error encountered reading file \""+filename+"\".\n")

sys.exit(2)

finally:

datafile.close()


# Now process the times array into the desired data format.


count=1

while len(times)>0:

tmax=count*interval

inthis=set([i for i in times if i<=tmax])

print "%15d %15d" % (tmax,len(inthis))

times=times-inthis

count=count+1
```