University of Washington

Interlake High School

Cosmic Ray Muons TeXtbook

Author:
Chunyang Ding

Supervisor:
Dr. Shih-Chieh Hsu

June 10, 2015

1 Introduction

Particle physics is a very exciting frontier of modern physics, as the instruments for measuring fundamental particles become cheaper and more available. Fermilab's excellent QuarkNet program has been providing high school and undergraduate students with a simple analysis tool. However, it is remarkably difficult to obtain a comprehensive narrative to explain the results. Instead, numerous papers published across a five decade span helps to slowly fill in the gaps of knowledge.

This mini TeXtbook on cosmic ray muons aims to educate the student on the basics of muon research, ranging from the fundamentals of modern particle physics to more complex analysis of the magnetic moment of the muon. All of these ideas are organized such that a student can understand with no prerequisite knowledge of particle physics.

In addition, a strong connection to the current Fermilab QuarkNet device is included throughout this text. Both the hardware and software for QuarkNet is analyzed and compared to modern particle physics collection tools. Understanding the data analysis methodology is as fundamental as understanding the physics ideas.

Although there are not any prompted problems in this text, there are certain derivations or concepts that are not fully elaborated. Instead, students can follow the references to uncover more depth of knowledge as they would like.

However, this text is not limited to students. Teachers and instructors are encouraged to use this text as instructional aids in any way that is useful. Hopefully, all QuarkNet high school groups would be able to gain a higher level of understanding through this text.

In short, this text should be an introduction for students and teachers to modern cosmic ray experiments. The text can be read in any format, although a sequential reading is not remarkably long and would likely make more sense.

Best wishes,

Chunny Ding

June 10, 2015

Contents

2 A Brief History of Particle Physics

Through the 20th century, it was evident that physics was incomplete. The original understanding of the atom as the smallest unit of matter was beginning to crack. JJ Thomson discovered the a negative particle in 1897 and Rutherford revealed the nucleus in his famous "gold foil" experiment. These particles, now known as the electron and proton, began to establish a new field of physics in understanding the reactions of the nucleus. However, as nuclear physics progressed, it became obvious that even this was insufficient explanation. How could the neutron become a proton in beta minus decay? What bound together the positively charged protons in a nucleus? Physics was in search of smaller particles.

Particle physics rapidly expanded in the 1950s, as cloud chambers and photographic plates began to track subatomic particles. The "particle zoo" began to rapidly grow from the two hadrons and lepton of the atom (proton, neutron, electron) to include roughly 20 fundamental particles. The properties of these particles are known through the Standard Model, which dictates the interactions of these particles through four fundamental forces.

Although the branch of particle physics is not suited to predict any macro events on human-sized scales, it is able to model very small interactions and their effect on important nuclear reactions. These interactions ultimately govern the basics of why our universe works, and are thus interesting not only for philosophical studies, but also for building up our knowledge for more complex simulations and models. Current studies seeks to formulate a better understanding of the interactions between all possible particles, and to eliminate any holes in understanding. The goal is to obtain a "Grand Unified Theory" to explain every aspect of our universe.

2.1 Introducing the Muon

The muon is one of the fundamental particles and is classified as part of the lepton group. The lepton family of particles can be defined as particles with spin of $\frac{1}{2}$ and that follows Pauli's Exclusion principle. Spin is an inherent quality of all fundamental particles, with $\pm\frac{1}{2}$ values, The best known lepton is the electron, which is typically found in atomic orbitals but also exists on its own. The properties of the muon are very similar to the properties of the electron. The muon has the same spin value as well as the same electric charge. However, the mass of the muon is 207 times greater than that of the electron [CITATION HERE]. In addition, the muon does not interact with normal matter, as all interactions of the muon are strictly with the weak force, not the strong force. This means that the muon is a particle that can pass through most solid objects without being deflected or losing energy.

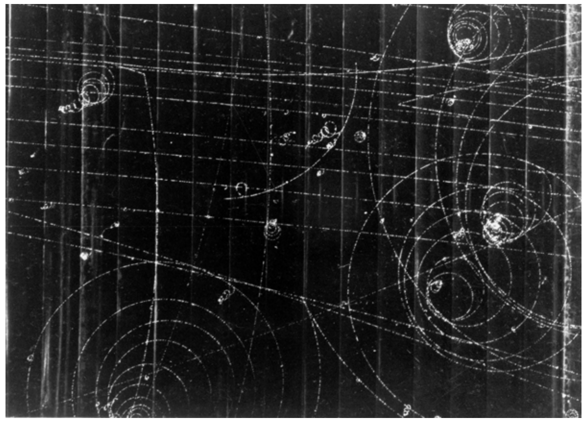


Figure 1: An old cloud chamber plate. The streaks are paths of particles

Muons were initially observed in cloud chambers, which are devices that show the traces of subatomic particles. Through a suspension of supersaturated alcohol, any moving charged particle will leave behind a trace of its path. The charged particle causes the alcohol to condense very rapidly to form those paths. Early particle physicists realized that even in dark, shielded rooms, particles were penetrating the ceiling and being captured in the cloud chamber. Further experiments allowed physicists to increase their knowledge of these mysterious particles. When physicists applied a known magnetic field to these cloud chambers, several curved paths showed up. The moving charges felt a electromagnetic force from the external field and curved appropriately, much like a satellite curves around the Earth's gravitational field. By measuring the radius of curvature, physicists were able to obtain better calculations for both the charge and the mass of these newly discovered particles. This allowed for better characterization of particles and subsequent discovery of new particles, including the muon.

In 1936, Carl Anderson and Seth Neddermeyer observed particle trails that curved less sharply than that of an electron. This particle tended not to decay as it passed through the cloud chamber, and there were consistently a large number of them despite any amount of shielding. These researchers hypothesized that the cloud chamber tracks revealed the existence of a new particle, which they called the "Mu Meson". At the time, mesons were new subatomic particles hypothesized by Hideki Yukawa to be a collection of quarks. However, further observation and testing revealed that this particle did not interact with the strong force. After the decay patterns to this particle were realized, emerging from pions and lambda baryons. As these were interactions that were not common to other mesons, the "mu meson", or "muon" was re-categorized to be a lepton.

What use is the muon to us? We know many of its fundamental properties, including the following:

Lifetime: $2.1969811(22) \cdot 10^6 s^{-1}$

Mass: $105.6583715(35)\ \frac{MeV}{c^2}$

Electric charge: 1 e

Color charge: None

Spin: $\frac{1}{2}$

Beyond these fundamental properties, there is not much more to understand about what the muon is. Any particle with these above properties would behave identical to a muon! However, do not be fooled. Looking at these properties could accurately describe the majority of particle physics. As long as a particle has the same fundamental properties as another particles, they would be the same. Particle physics is not so simple as to only searching for the fundamental properties of the particle. This would be like knowing exactly how large and how heavy a ball is, but have no clue how the ball bounces when dropped. While these properties characterize particles, the study of the interaction between particles and other particles or other fields is much more interesting to understand. The exploration of higher energy interactions and the search for more exotic fundamental particles[1] drives the field of particle physics as it moves forwards.

2.2 Cosmic Rays

So far, this has been a lengthy introduction to what particle physics and muons are. However, you are likely reading this document as part of a Cosmic Ray Research group, not as a particle physics research group. Therefore, what is the connection between cosmic rays and particle physics?

First, we must make some clarifying definitions. Cosmic ”Rays” are not rays like we think of in geometry or like rays of light, but are instead highly energized particles traveling through space. These particles are typically protons or alpha (α) particles (helium nuclei) that have been ejected by some cosmic event. They travel through the vacuum of space with very high energy, and because high energy is correlated to high velocities, these cosmic rays travel very close to the speed of light. Eventually, they will reach some observer after travelling through the vast expanses of space.

These cosmic rays travel an enormous distance in order to reach Earth. They need to weather through the solar wind and travel without disturbance in solar radiation. Many cosmic rays do not reach the Earth, whether because they are blown off course or because they hit some particle in the dust clouds. However, because of the extremely high flux[2] of cosmic rays, we still encounter a reasonably high flux of cosmic rays

[1]For a good example of why we call these things ”fundamental particles”, see this SMBC comic
[2]rate of particles per unit area

on Earth. However, once these primary cosmic rays encounter Earth's atmosphere, they are no longer able to travel in an unimpeded environment. Instead, they hit and interact with the ozone molecules and other molecules that constitute the Earth's atmosphere. Due to the high energy of these primary cosmic rays, they can often break apart other molecules, giving up a fraction of their original energy. These decay particles[3] are often also very highly energetic, and could continue to decay. With an extremely highly energetic particle, a chain reaction of particles can be found, a "shower" of cosmic events.

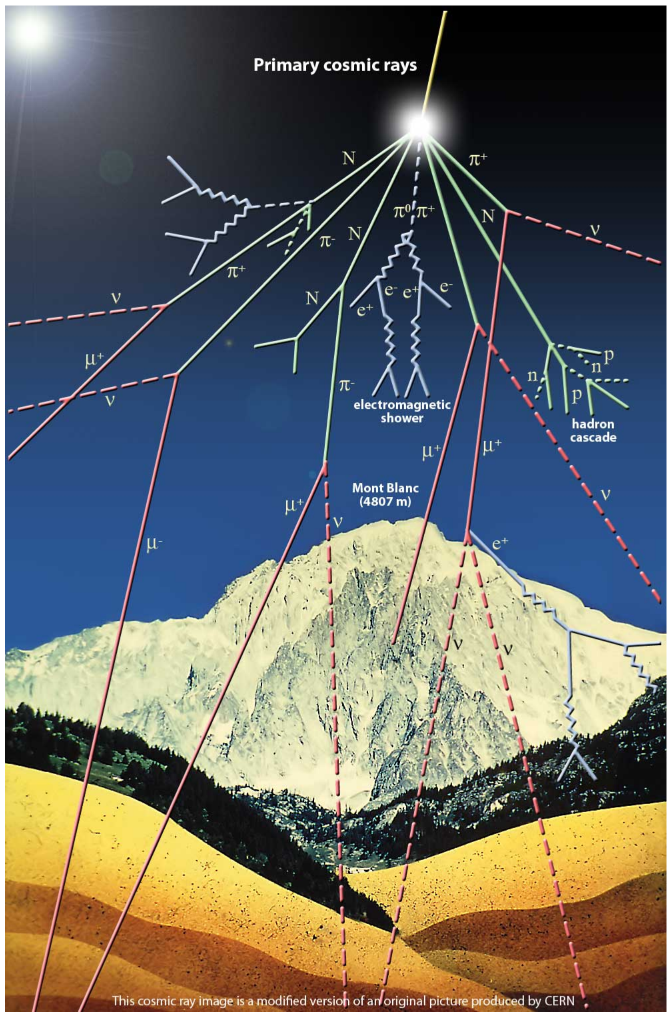


Figure 2: A graphic of a cosmic ray shower. This simplified illustration shows some subatomic decay particles. The study of how these particles decay will be a large portion of our investigation. From Zach Williams

To give a better sense of the energy magnitude of cosmic rays, consider this: The Large Hadron Collider[4], the world's most powerful particle accelerator, is able to accelerate particles up to several terra-electron Volt,

[3]many subatomic particles can be broken apart into smaller particles. These particles are referred to as "decay particles", and there is a set number of probabilities for the creation of some decay particles.
[4]http://home.web.cern.ch/topics/large-hadron-collider

or 10^15 eV. [5] (TeV). Not every cosmic ray has the same amount of energy. Instead, cosmic rays have a wide range of different energies, depending on how that particle was created and what interfering forces acted upon it as it was traveling through space. Through rigorous detection methods, scientists have determined a plot that relates flux with cosmic ray energies. See Figure 3 for full details.

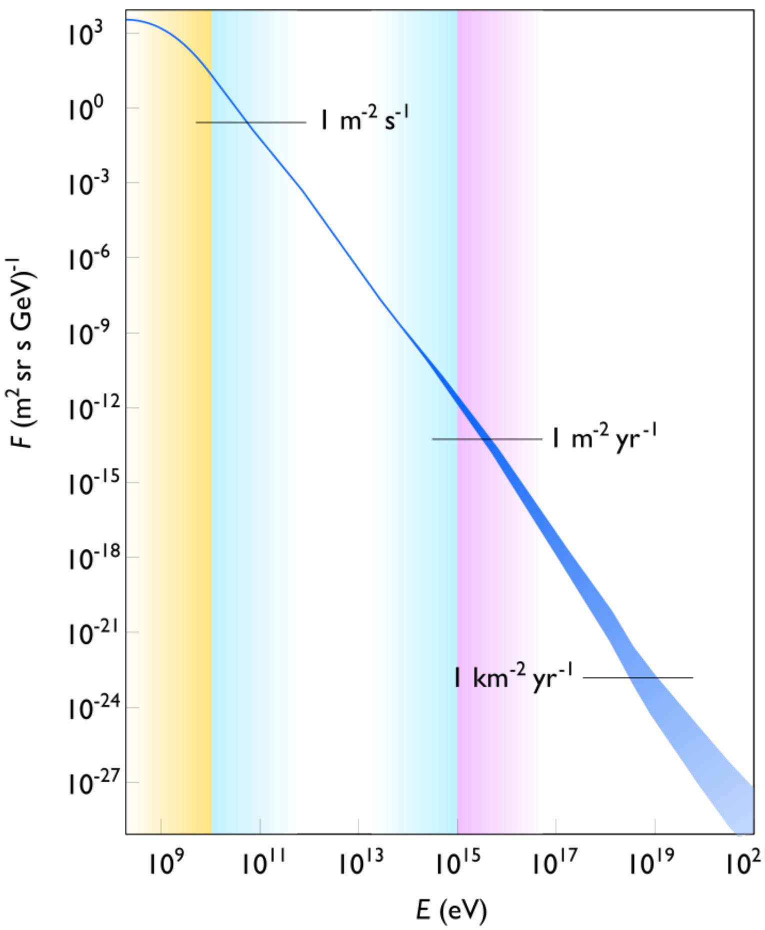


Figure 3: A graph of the cosmic ray energy scale. Notice that even at 1 TeV of energy, the flux is relatively high. From Wikimedia - Sven Lafebre

One of the many decay particles of cosmic rays is the muon, as previously discussed. It is particularly interesting to study as it it has a (comparatively) long lifetime, and typically reaches the surface of the Earth. In the next subsection, we will explore why the muon in particular is interesting to study with these detectors.

Even though our awareness of cosmic rays predate the first particle accelerators by almost a century,

[5]One electron volt is the energy equivalent of an electron passing through one Volt of electric potential difference. $6.24x10^18$ eV is one Joule, and 4181 joules are in one kilo-Calorie. The next time you are eating a 100 calorie snack, think that you are consuming 6.2 Yotta-electronVots ($6.2x10^24$)!!

we still do not fully comprehend the mechanism of cosmic ray production. Oddly, cosmic rays seem to be isomorphic[6]. Extragalactic cosmic rays are very poorly understood, although new research suggests that they are products of supernova events. Modern research at the Auger observatory[7] is still exploring if cosmic rays have a maximum energy, or if they just slowly increase towards infinite energy. However, as revealed by Figure 3, these events occur very rarely, at a rate of perhaps one particle per square kilometer per *century*. Let the waiting game commence!

As we expand our knowledge of cosmic rays, we are able to use the incidental decay products in our basic research. The state of the art particle physics research currently uses controlled particle beams in order to conduct high level precision readings. Those scientists have the advantage of knowing the properties of each muon that they study and to turn the beam on and off at will. However, as it is not likely that you have access to a particle accelerator, we are able to "mooch" off of the free muons created by cosmic rays. In comparison to particle accelerator muons, the muons created by cosmic rays have a wide range of energies and do not arrive at our detectors at an entirely consistent rate. Still, a muon is a muon, right?

2.3 Muon Investigations

Previously, we discussed the basic properties of the muon. However, we did leave one section out: How does the muon interact with other particles? Or for that matter, how does any particle interact with any other particle? In order to understand this concept, an understanding of the fundamental particles and forces is in order. See the following figure (Figure 4) for more information.

Do not worry if you see particles that you don't recognize! Many of these fundamental particles are not typically found in regular matter and have no significant impact on the everyday world - the neutrino is so unreactive to regular matter that scientists use giant underground caves to try to capture one of the trillions of neutrinos that pass through every second, and they still only get a few hundred interactions - per year! On the other hand, don't worry if you don't see particles you think *should* be on this list. For instance, where is the proton and neutron? What is a gluon? Why are there three different particles labeled as neutrinos?

The common conception of a "fundamental particle" is mostly limited to what is found in atoms[8], ie, the proton and neutron. However, these are not fundamental particles by themselves. Instead, both of them are made up of three even smaller particles called quarks. The six quarks labeled on the above diagram make up most of what we consider to be "matter" - quarks tend to interact with the strong nuclear force

[6] a scientific term meaning that the flux of cosmic rays is symmetric, regardless of where in the universe you look towards
[7] For more information about the research at the Auger observatory, click here
[8] Of course, "atom" comes from the Greek word *attomos*, meaning "uncuttable" - and now, not only have we cut it up into protons and neutrons, we've cut those up into smaller bits too.

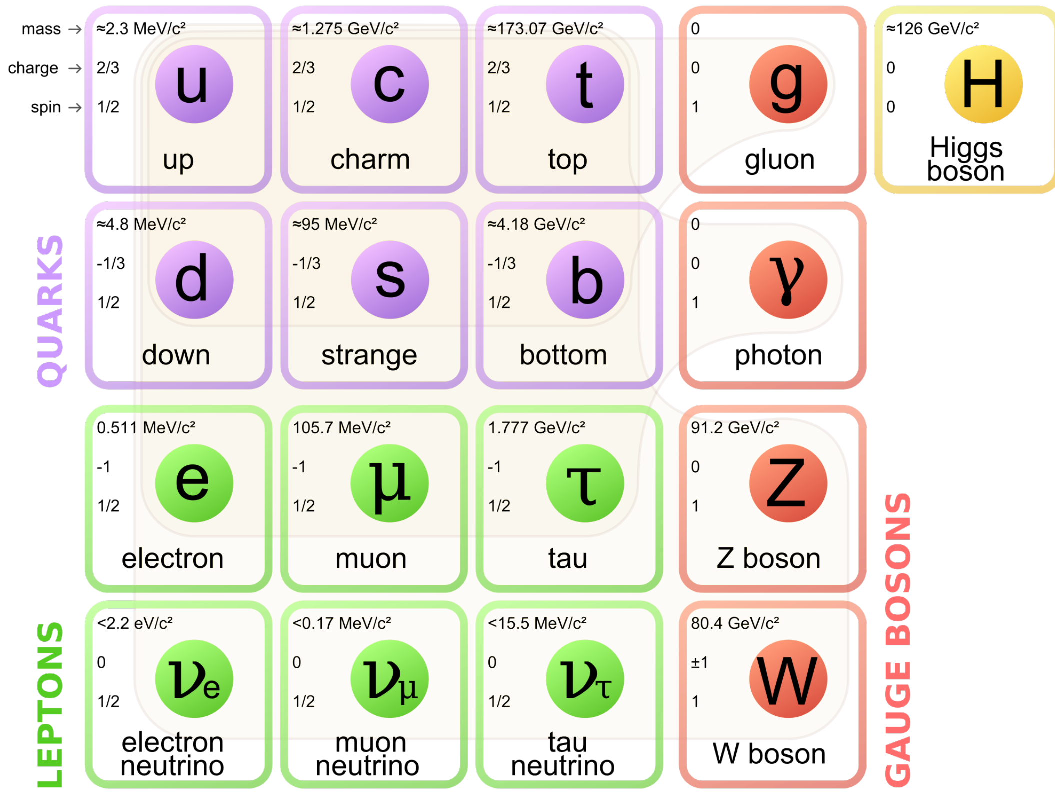


Figure 4: A nice graphic of the fundamental particles

and have large masses, as compared to particles from the lepton family. Quarks also have a spin value and an electric charge. The proton is made up of two up quarks, each with a $+\frac{2}{3}$ charge, and one down quark, with a $-\frac{1}{3}$ charge. Summing up all three charges gives the net charge of +1 that we all know. The neutron, on the other hand, is made of two down quarks and one up quark. Using the fractional charges we learned about above, we quickly realize that the neutron comes to a net charge of 0, as expected. These quarks work together to give the proton and neutron their fundamental properties.

Merely knowing the different particles is not sufficient for particle physics. This is perhaps analogous to knowing what kinds of Lego pieces you can use, but not knowing how to put anything together. The four fundamental forces are needed to understand the interactions between fundamental particles. Unfortunately, it is rather tricky to explain... (See Figure 5)

However, we can show how some of these nuclear forces work through example. All of the quarks are able to interact with other quarks using the strong force. This dictates the way that quarks are able to be bound together without breaking apart. In addition, the strong force is able to hold together the nucleus of the atom together, keeping the positive protons from expelling outwards. The strong force, in general, allows

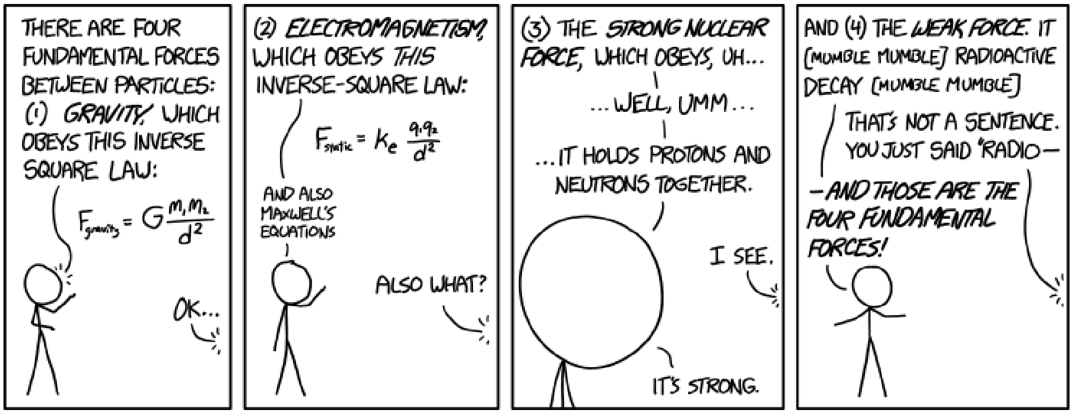


Figure 5: Credits: Randall Monroe, xkcd.com

for particles to not simply pass through each other. On the other hand, the weak force typically mediates the transformations between one quark to another, allowing nuclear decay to occur. The weak force is only able to act over small distances and has very low coherence beyond this small length scale. Both of these forces have bosons that mediate the way that particles interact - the strong force uses the gluon, while the weak force is mediated by the $\exp W+-$ and Z bosons.

The muon is rather interesting because it does not interact with the strong force and primarily has weak and electromagnetic force interactions. The lack of strong force interactions allows the muon to pass through what we consider to be "solid material" without simply ricocheting off. The muon's operations under the weak force primarily govern the mechanisms of which the muon decays.

Given these facts, how are we able to detect the muon? It does not interact with regular matter, which seems like both a blessing and a curse. However, the muon does interact with the electromagnetic force, and we can use that electrical signal to our advantage. This force is well known by most physics students, as it allows for electricity to be passed through circuits. Because the muon is a charged particle, any detector that can be triggered[9] with the passing of a charged particle can be used to detect the muon. If you recall, this is the same principle used in the cloud chambers mentioned earlier. Any charged particle passing through would trigger the supercooled alcohol solution to condense, leaving behind a visible trace. In fact, we can further use the fact that the muon has no strong force interaction to heighten our detection mechanisms. As the muon is moving very rapidly and does not interact with regular matter, if we obtain multiple detectors and stack them on top of each other, we can configure the logic of the plates to only detect signals that

[9]Triggering a detector will be a common theme in this investigation. It simply refers to the detection of some signal that notifies the computer microchips that an event has begun

trigger multiple plates at coincidence timing[10]. These exact mechanisms will be elaborated, in reference to the Fermilab CRMD panels, later on.

[10]The more precise definition of "coincidence" will be defined later on. This typically is a variable that can be manually set, depending on the experiment that is being conducted

3 Fermilab QuarkNet

So, what exactly is the Fermilab QuarkNet project? If you are reading this manual, it is likely that you have the QuarkNet detector and at your high school or undergraduate college. Perhaps you are trying to find a research topic for ISEF, or perhaps you are just trying to get some extra credit for school. In any case, QuarkNet is an educational outreach program developed by the scientists at Fermilab, a large national laboratory in Illinois that operates the TeVatron[11] from 1983 to 2011. Today, they continue to host both theoretical and experimental fundamental physics research. QuarkNet was created to provide training for young physicists, getting a hands on experience into the esoteric world of particle physics. By providing a basic particle detector and resources (like this one!) for students to access, they hope that more students will become attracted towards this world and continue the legacy of scientific excellence. Through this program, thousands of young people have been trained with top notch equipment on real research questions.

Unfortunately[12], it is rather intimidating to begin research into as foreign of a field as particle physics. While many research papers and graduate level textbooks help illuminate these topics, it is quite difficult for students to understand the key ideas behind current fundamental particle physics research, and even harder to propose interesting research ideas. That is why this text is created - to help students figure out where to investigate!

QuarkNet tends to provide several major pieces of equipment: A muon detector with Data Acquisition Board (DAQ Board), the EQUIP software for data gathering, and the eLAB interface for processing data. By itself, these three items can provide weeks of research opportunities as you explore what each component means. However, there are additional materials that you can use the detector for, such as homebrew code for data analysis and revolving mechanisms in order to do additional analysis.

3.1 Hardware Setup

As previously mentioned, muons do not interact with the strong force, and can generally not be seen. Therefore, the detector exploits the fact that muons are charged particles. Charged particles can be detected using scintillator plates, which are specially treated plates that generate a photon when a charged particle passes through it. This photon scatters throughout the plate and reaches a Photomultiplier Tube (PMT), a special signal-amplification device for photons. Using the principle of electrophotons and magnetic fields,

[11]The TeVatron was one of the world's leading particle accelerators, the first to have reached energies of 1 TeV. After 2011, it was stopped due to budget cuts and the completion of the Large Hadron Collider in Switzerland, an accelerator that reached up to seven times the energy

[12]as the author of this TeXtbook realized when he was trying to get a handle on it - there's so much to learn!!

the PMT amplifies the original photon signal into a cascade of electrons, generating a spike in voltage, or an electric signal. That electric signal can be interpreted by the DAQ board and then sent to a computer for further analysis.

This section will seek to understand the physics behind how each component of the Quarknet setup works. For actual setup instructions, please refer to the actual Fermilab guide, published and accessible through the ELAB page.

There are two lines that are connected to the scintillator plates: one of these is a black 35mm cable that connects power, and another cable that connects signal. We will first attempt to understand the power generation of the PMT and how it works, before moving onwards to the signal generation aspect.

3.1.1 Photomultiplier Tubes

The physics of the photomultiplier tubes is especially interesting and relevant for this investigation, as well as for many introductory detector mechanisms. The photomultiplier tube was a great innovation that allows for detection of very small signals. Even a single photon can trigger a substantial signal output. This makes it very useful in this cosmic ray muon detector, as each passing muon may only excite one or two photons. For a detailed view of these electronics, please see Figure 6. The cascading electrons create a noticeable signal that is sent through the BNC cable. This cable is connected to the DAQ board, which receives the signal.

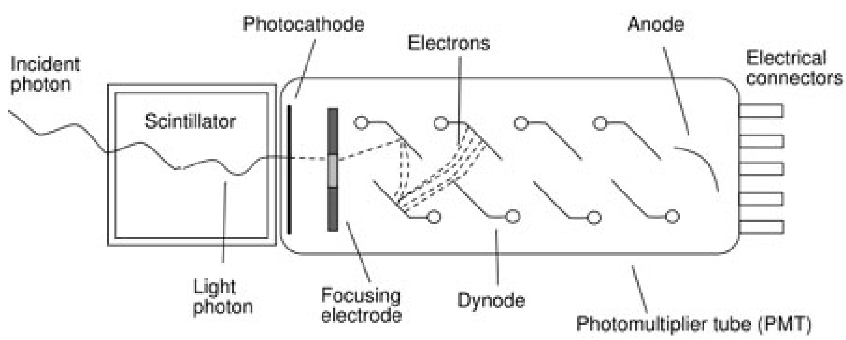


Figure 6: Schematic of the insides of a PMT. The diodes show where the photoelectrons bounce and cascade.

However, the photomultiplier tube has one dangerous drawback. In order to generate the proper signal, a very large voltage difference needs to be generated across the PMT. These high voltage lines can often be dangerous, and in older models of the PMTs, this voltage needs to be generated from an external source. This involved hooking up a high voltage generator to the scintillator plates using special cables. However, the Fermilab board is special in having the high voltage built into the PMT. Therefore, we only supply a nominally small voltage (¡3 volts) to the PMT, and the internal amplification of the PMT creates the necessary field. Because there is a linear correlation between the nominal voltage that is supplied by this small black box with the high voltage generated inside the PMT, we can substitute the two terms quite conveniently. In addition, a large benefit of Fermilab's design is that their PMT is inherently more safe than older models. There is less of a risk for electrocution, although students should still remain cautious when operating equipment.

If you have taken Electricity and Magnetism, you may notice something interesting about the design of the PMT. Most of the electrons that bounce between the dynodes are going through a vacuum, and are susceptible to magnetic fields. In fact, even a field as small as the Earth's natural magnetic field can have a significant effect on the flow of electrons. Given the remarkably small initial signal, we can see how the PMT needs to guard against external magnetic fields. The PMTs provided by Fermilab, as well as most other PMTs, use a clever material in order to solve this problem.

μ-Metal is a specialized metallic material that allows for conduction of magnetic field lines. PMTs are lined with μ-metal in order to allow magnetic field lines to be rerouted. This could be analogous to setting up a detour for magnetic field lines to follow around the sensitive measurement areas of the PMT. Further reading about μ metal can be found at Section 7.2

When designing any experiment, the integrity of the PMT must be taken into account, as it is a vital part of how data is properly collected. Many different kinds of calibrations can be done to ensure that the PMTs are receiving the correct signals. In addition, any experiment regarding strong magnetic fields should be closely modeled and analyzed before the experiment takes place.

3.1.2 Data Acquisition Board

The Data Acquisition Board (DAQ) is the brain of the Fermilab Quarknet project, as it does all of the initial processing of data before it is sent to the computers. Here, the inputs from the four PMTs are taken in and basic logic is applied. By using the software on the computer, the onboard DAQ can process the thousands of data signals before they reach the computer in order to rule out junk data and to synchronize data in a useful fashion. In addition, the DAQ board coordinates with a small GPS tracker and an extremely fast on-board clock in order to measure a very precise time. This is crucial for measuring accurate information about each pulse.

One of the primary functions of the DAQ board is to check for event triggers. For instance, the DAQ board can recognize if the experimenter wants all four plates to be simultaneously triggered in order for a valid event to be sent to the computer. In addition, the DAQ board can be programmed to understand what time window is valid for a real trigger. True coincident events are not very precise, as it is impossible for a particle to be in more than one place at the exact same time. However, because the muon is travelling close to the speed of light, and because the plates are set up with less than a foot between the top plate and the bottom plate, the muon is theorized to be able to pass through the plates in less than a nanosecond. Therefore, a useful time window would be one nanosecond - when events are detected on all four plates within the same nanosecond, then it would be a valid event. The experimenter may need to manually change the time window to be larger, especially for shower experiments. In addition, the DAQ board recognizes how many nanoseconds it should wait before closing off an event, and what to do if there are multiple events[13] Most of the preproccessing of data is done on the DAQ board, but the remaining raw data is then sent to the computer for full analysis.

The clock on the DAQ board is very important to understand, as it dictates the numbers that come out. For most new models, this clock ticks once per 1.25 nanoseconds. Therefore, any counter found in the data should be multiplied by 1.25 in order to get the proper time in nanoseconds. This is especially important in setting the gate window and TMC delay to be correct.

3.2 Software Settings

Most students will be working with EQUIP as they get to know the DAQ board and Quarknet equipment. This java file is created by M Jones of Purdue University, F Roetker of Jefferson High School, and E Peronja from Fermilab and is very useful for gathering information from the board. It provides a graphical interface for how the board properly works. In addition, it allows users to send commands telling the board what to do in different situations.

To get started with this software, using the README file is very useful. There are clear, step-by-step instructions on how to setup the software to do what you want it to do. Some key points to keep in mind: Make sure you know what version of Windows you run, and if you are using 32 bit or 64 bit windows. This will make a big difference, especially with the rxtxSerial.dll file. In addition, ensure that you have the latest Java installed on your computer[14] before running the program.

I advise you become familiar with the Command Prompt in using EQUIP, as it allows a more comprehensive idea of where you are running files from and where the data is being saved to. Some of the basic

[13] In the EQUIP file, the time window is labeled as gate window, or w, and the second variable is labeled as "TMC delay", or d. The EQUIP files are somewhat confusing, as using manual input of variables is in clock ticks while the java file uses real time signals.

[14] Fair warning, Java tries to install Yahoo toolbars, so be on the watch for that

commands like `dir` and `cd` will definitely be needed. Use tab for autocompleting long variable names! When you are navigated to the correct folder, run the command "java -jar EQUIP-[VERSION]" to start the program.

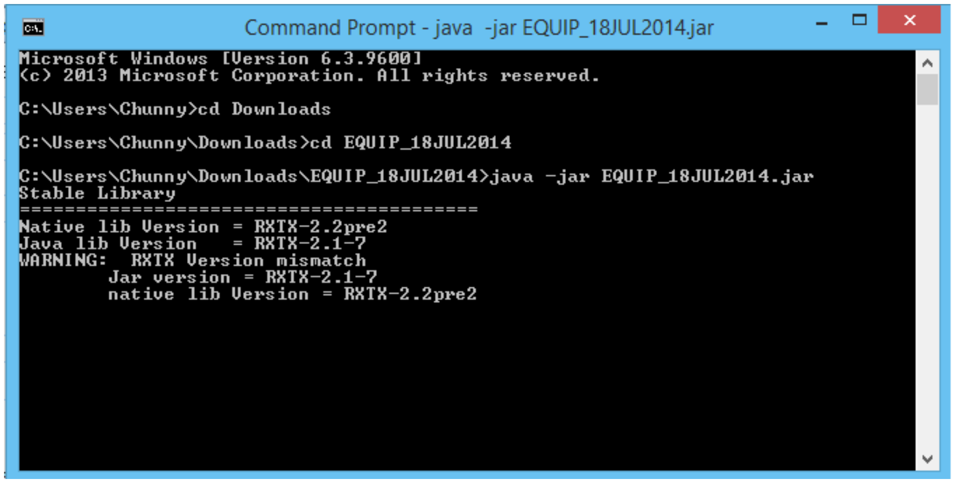


Figure 7: A sample of the commands required to start the EQUIP file. Here, my EQUIP folder is under the Downloads folder, which I switch to by using the "CD" command.

First time startup information: Ensure that you are saving the file to an appropriate location with an appropriate file name by editing the "Log File" box, and select the Serial Port that is correspondent to the USB port you plugged the DAQ board into[15]. Most of the basic startup information is preset, but ensure that all four boxes under "trigger" are checked and that the coincidence level is set to 4. Click the "Enable(CE)" button and immediately, you will begin to see data come into the file to the right.

When first starting to use EQUIP, explore some of the many functions. Note that the most important ideas come from the first tab, labeled as the "Control Panel". Here, you can set variables and input specific commands to collect data. Some of the other tabs, such as TOT monitor and Rate Monitor, provide instantaneous visualization of the data and is very useful in debugging. It is not particularly useful for conducting research, but it allows immediate feedback so that the experimenter can recognize errors.

Another very useful aspect of the EQUIP program is the live text readout panel found on the control panel. This occupies the right half of the screen and has live updates from the data output file. As the EQUIP file is run, the data is automatically saved to the DATA folder[16], but the EQUIP file also instantaneously reads out everything. This allows you to review the data that is being collected. For instance, if you are expecting a very high rate of data coming in but the data stream is not updating, it is likely that some wire

[15] Trial and error is pretty useful here - once you get it once, the serial port should not change.
[16] or another folder, if you chose to respecify the save link earlier

is disconnected or a setting is incorrect. If you are expecting a data point only once every few minutes and are instead getting a constant stream of data, perhaps your coincidence levels are incorrectly set or your voltages are incorrect. In any case, all recorded data, including commands sent to the box, are recorded in the data files and are mirrored on the display.

3.3 Data Output

The data output generated by EQUIP is somewhat difficult to understand, but if you invest time, you can definitely make the effort to do so. Most people will choose to simply allow the computer to process the data, and subsequently interpret the graphs that are generated. However, if you understand the meaning of each data word, then you can work towards writing your own analysis code for creating more interesting graphs[17].

When looking at the data output, go to the DATA folder and open any of the files saved there. While the files do not have an extension by default, they can be opened by any text processor. Notepad and Wordpad are both valid programs, but I recommend using Notepad Plus Plus or Sublime Text, as these text processors have several advanced features that makes interpretation faster and easier.

The CRMDManual, published by Fermilab and found on the ELAB page, has specific instructions for the interpretation of these data words. However, there are several aspects that warrant additional explanation.

```
80EE0049 80 01 00 01 38 01 3C 01 7EB7491F 202133.242 080803 A 04 2 -0389
80EE004A 24 3D 25 01 00 01 00 01 7EB7491F 202133.242 080803 A 04 2 -0389
80EE004B 21 01 00 23 00 01 00 01 7EB7491F 202133.242 080803 A 04 2 -0389
80EE004C 01 2A 00 01 00 01 00 01 7EB7491F 202133.242 080803 A 04 2 -0389
80EE004D 00 01 00 01 00 39 32 2F 81331170 202133.242 080803 A 04 2 +0610
```

Figure 33. A sample event containing five lines of data. Each line is comprised of the same 16-word format with each word separated by a space.

Figure 8: A sample of some data from the EQUIP file. Taken directly from the CRMD Manual.

Word 1 is the exact clock trigger that was recorded at the instant of the event. This 32 bit hexadecimal[18] word encodes information about the exact time that the DAQ board is measuring. It is used in conjunction with word 10, which stores information about the relative time. That 32 bit hexadecimal data word is synchronized with the GPS signal, which delivers a highly accurate time signal from GPS satellites. To better understand how the DAQ board knows the exact time for each cosmic event, picture this. Every

[17]Also, it totally is a bragging right to look at seemingly random numbers and interpret real world events!
[18]If you are not familiar with the hexadecimal system, I highly recommend you get familiar. Now!

second, a referee starts a very highly accurate stopwatch that counts down to units of nanoseconds. The counting code is immediately saved to the accurate atomic clock that the referee has to the side. When a runner passes the finish line, the referee writes down the units that the stopwatch has recorded. Because the referee knows how much time passes for each unit on the stopwatch, the referee can compute how much time after the benchmark time did the runner make it in. You may wonder - well, why doesn't the referee use the atomic clock all the time instead of complicating matters? The truth is, it is inefficient to constantly rely on the GPS time, as disruptions in signal or micro-fluctuations may cause the clock to be off by several nanoseconds, a huge problem in measuring tiny time intervals. However, the on-board clock is very very accurate, so using this benchmark/synchronization method is better. It is important to note that the resolution for these triggers is at 10 nanoseconds.

Word 11 and Word 12 are both relevant in the above scenario - they are the recorded GPS time and date, respectively.

Words 2-9 are the most interesting data points, as they tell you specific information regarding the specific scintillator plates. They provide you with the Rising Edge and Falling Edge information, technical information regarding the detection of a signal. The short explanation of these terms is that a signal must rise and then fall, with some variable amount of time above the threshold, labeled as "Time over Threshold (TOT)". While computing the TOT is not always useful, seeing if a scintillator was triggered or not is.

Each of these 8 words are encoded in hexadecimal, meaning that they contain a letter from 0-F in base 16. However, it is possible to convert a hexadecimal number into a binary number, just as you would convert a hexadecimal number into a decimal number. For instance, the number AA would be 26 in decimal, but be 1010 1010 in binary. It is particularly convenient to perform this conversion because you can separate each individual hex character into four binary bits. Because B is 1011 in binary, BA would be 1011 1010, and you don't even have to convert to decimal. This makes hexadecimal a very compact manner to store information.

So, for each of these 2 character hexadecimal words, you essentially have 8 binary bits of information. The way that this information is encoded is as follows: Bits 0, 1, 2, 3, and 4 define an even more precise clock count on the board of 1.25 nanoseconds. Bit 5 should be 1 for every valid event, while bit 7 should ONLY be 1 for word 2 - it defines the start event of a cluster of events. Bits 6 and 7 are always 0. Therefore, the binary word `1011 0010` would mean that a new event in a new cluster has started at 22.5 nanoseconds after the initial time measurement.

Looking at one channel may require you to look between several lines in a cluster. The first line of the cluster is always indicated by the 1 in Word 2, and typically it is easy to follow along the cluster by looking at Word 1 and seeing when the hexadecimal stamps stop being consecutive. By getting the idea of easily understanding the data words, you can read the data like a pro.

When working on your own data analysis software, you would want to utilize all the data above in analysis. One way to do this is by reinterpreting each of those data words into specific variables to be stored in large arrays. You can use the `bitshift operatives << and >>` to easily convert hexadecimal values into binary values.

3.4 Data Processing

One of the most important aspects of this experiment is to properly process all of the data that is created. After the data is provided to the computer, we need to interpret the data for our experiment. This tends to be different from small scale data processing, as the data files produced through this experiment can range from several hundred megabytes to a couple gigabytes. It is utterly impossible to go in and sort out all of this data by hand.

However, computer programming provides a suitable alternative. By using code, we can command the computer to automatically process the data and make it into something more useful. Often times, this means making a graph or chart using the data points.

For those who are not interested in doing all of the programming by themselves, they can choose to use the free ELAB on-line tool, available here. This tool created by Fermilab automatically does many of the chart creations that are needed for a good experiment. In order to access these tools, you must have a teacher who had participated in the training sessions and has a registered class account that is matched with your specific DAQ board to receive data. However, a significant drawback of using this resource is that the user may not understand how the charts come to be. It is difficult to understand what happens in this black box.

In order to better understand these processes, we have created code that any individual can run and understand. The basic principals of this code is based on our understanding of what each data line means. Ultimately, it searches through each of the events and tries to identify only events that are within our parameters. Then, it adds that bit of data to a large file that knows everything about each significant event. Finally, it uses that file to create a histogram representing some crucial property of the muon. These histograms can have a matching curve fitted onto the data points, which will then reveal some intrinsic properties of the muon.

4 Muon Flux

Measuring the muon flux is one of the first things that any high school experimenter should do. As mentioned earlier, *flux* is defined as the rate of flow of an object through a unit area in some time. Determining the flux of muons would be equivalent to knowing how many muons are passing by us at any time. Knowing this information is especially significant when we are on the lookout for extremities in flux, either high or low, because they often tell us that some special event is happening.

The muon flux at sea level is a rather well known value of approximately 1 muon per square centimeter per minute, or 167 muons per square meter per minute. This value can be used as a quick result to see if your muon detectors function properly. Using the above interfaces, you can use the rate monitor tab to observe the average incidental flux. Remember to calculate the expected flux using the actual size of the paddles. The significance of running a muon flux chart is so that you can see any changes associated with cosmic ray production over either time, location, or angle. This would help our understanding of where cosmic rays come from.

The basic hypothesis in all of these experiments is that muons are uniformly generated across all space. If this is true, then regardless of what kinds of changes you have the detectors do, they will always return with the same flux. However, if you hypothesize that changing some factor changes the rate of muon detection, then you would be able to understand something about the origin of muons. If you could detect a statistically significant difference in muonic flux, then it would show that there may be a solution to understanding muon origins!

Here, we will discuss three different muon flux experiments that you can conduct. These are generally the easiest experiments and provide a good learning experience for newcomers to the equipment. We will first understand the rationale behind each experiment, and then guide you through the start of the analysis.

4.1 Time Experiment

Have you ever wondered about the origin of the muons? If we consider sources that are in the sky, the most obvious one seems to be the sun. Given the nuclear fusion that happens in this star, is it possible that it is also producing highly energetic cosmic rays, beaming it's way towards us? If we could detect cosmic rays from the sun, we would notice a significantly higher muon flux during the day as compared to during the night. This is because the cosmic rays produced at night, when the sun is on the opposite side of the Earth, would be observed by the Earth. Therefore, there would be a noticeable difference in cosmic rays, and consequentially, a noticeable difference in muon flux. Please see Figure 9 for illustration.

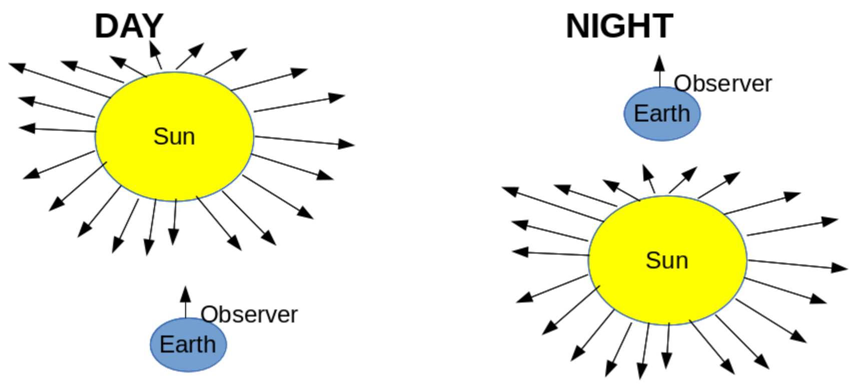


Figure 9: A cartoon of the cosmic rays hypothesised to be created by the sun. Note that the observer does not receive as many at night time.

In addition, as we previously discussed, cosmic rays can be stopped by solid material. Therefore, would other large heavenly bodies, such as the moon, have significant effect on whether cosmic rays arrive or not? If the moon was to stop a significant number of cosmic rays, then the flux observed on Earth of muons should be proportionally decreased.

Unfortunately, these two hypothesis conflict with each other. If there is a significant flux difference between night and day, it may be difficult to tell if it is due to the sun or due to the moon. **What solutions would you have to solve this problem?**

The best way to test these two hypothesis is to observe the muon flux over a very large time sample. Afterwards, by observing the graph of muon flux, it may be possible to see any periodic oscillations that may exist. For further analysis, it may be interesting to attempt to model it using a cyclical trigonometric function and determining the amplitude, if any.

On the other hand, if a time study does not show significant changes in muon flux, what does that tell us about the moon or the sun? What kind of variables are possibly messing up the experiment - can you control for them, or are some of them inherently bad?

4.2 Elevation Experiment

Another possible experiment to do with muon flux deals with elevation. As we rise into the higher parts of the atmosphere, we would expect to see changes in the observed muon flux for several, conflicting reasons. The wide array of confounding variables makes this a remarkably interesting, yet complex, experiment to be conducted.

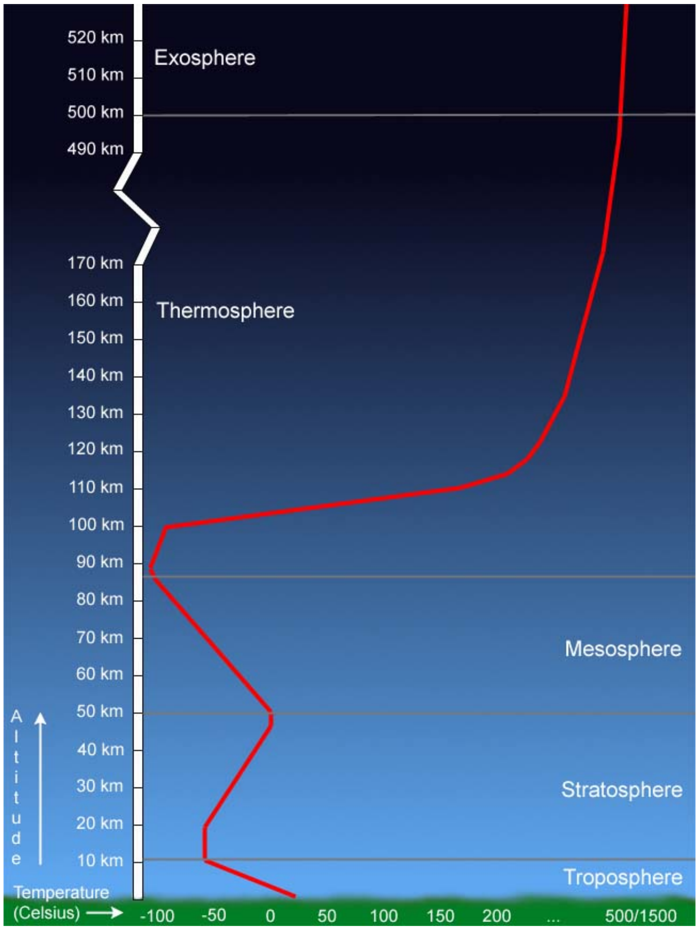


Figure 10: A figure of the layers of the atmosphere for reference.

As previously discussed, muons are created when a cosmic ray enters the atmosphere and hits a particle. In research conducted by Regener and Pftozer, the maximum cosmic ray flux is roughly 15 kilometers in the atmosphere, or in the low stratosphere. It would therefore be reasonable to say that above 15 kilometers, there would be few muon detections as there are few cosmic ray events. However, determining the muon flux from 0 to 15 kilometers is still difficult. While it is expected that the muon flux would be roughly equivalent to the cosmic ray flux, several factors present a linear correlation. As we rise in the atmosphere, it becomes less likely for a created muon to have spontaneously decayed via hitting too many atmospheric molecules, and the number of muonic atoms removing the regular muon decreases. However, it is also true that there are fewer cosmic events as we rise upwards, as many cosmic rays penetrate deep below 15 kilometers. Studying the many different effects would therefore provide a visualization of possible stratification of muons in the atmosphere.

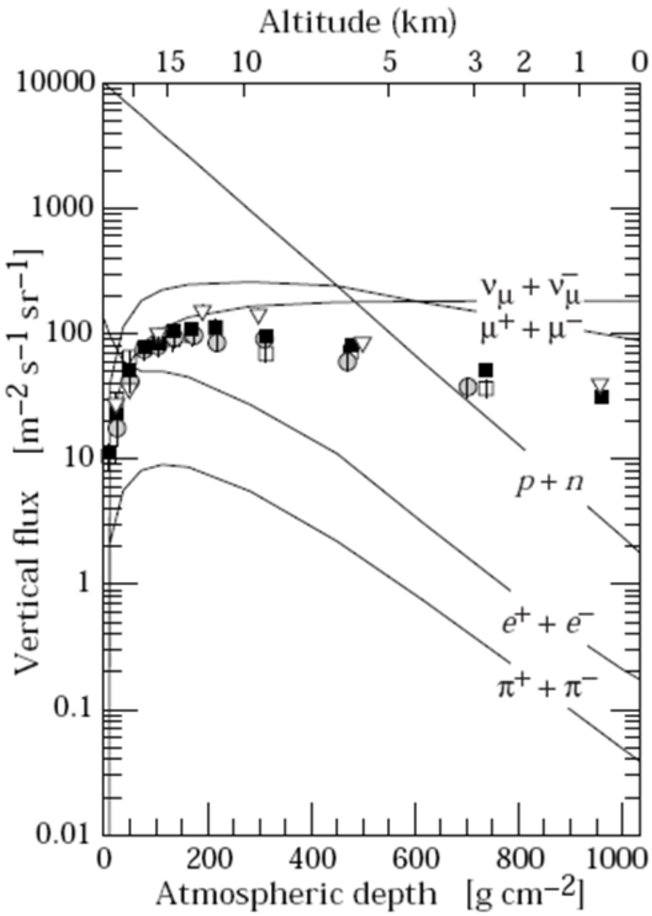


Figure 11: A graph showing some previously computed values for flux. Can you improve on them?

However, this experiment provides many different challenges. The original challenge would be in obtaining the appropriate weather balloon for encasing the cosmic ray equipment, complete with a power source, data collection mechanism, and GPS tracking device for balloon recovery. Coupled with legal issues regarding the Federal Aviation Administration regarding what can be legally flown in the United States, and you have several weeks of planning before the first data points can be collected. However, if you have friends or family who have had experience with weather balloons or amateur flying, then this is a great opportunity.

Beyond the basic logistics, there are several further physics challenges that a good experimenter should consider. For instance, the weather balloon is not going to be rising straight up for the entire duration of the flight. It is much more likely to be swaying in the wind as it ascends, to perhaps ± 30 degrees in any direction. This would potentially have a very large effect on the flux gathered, particularly because of the Earth's magnetic field. As is discussed in Subsection 4.3, the magnetic field causes the muons to fluctuate in a predictable pattern. Without tracking for this variable, it is unlikely that you would be able to gather workable data.

Another item to consider is the speed at which the hot air balloon rises. The balloon would rise at a roughly steady rate at all times, meaning that you cannot measure the long term flux at a specific altitude. Instead, you would have to define a range of altitudes, say 1200-1300 meters, and find the average flux for that region. The difficulty here would be to find ranges that are large enough to collect sufficient flux data, but still small enough to see a significant pattern emerge.

The elevation experiment is perhaps one of the most engineering focused experiments here, as it requires a high level of competence in actually constructing the hot air balloon. There, I cannot significantly help you. However, always try to think of the confounding variables in conducting this experiment and you will create an experiment to be proud of!

4.3 Zenith Angle Experiment

One final experiment to do deals with the angle to which the board is measuring. In the resting configuration as originally stated, the cosmic ray detectors are facing directly up. This implies that the majority of the muons that the detector receives originate from a location straight up. In addition, as outlined in section 6.4, in order for the detector to be triggered, multiple scintillators need to be triggered. Therefore, a muon that is coming in at a very low angle may not be recorded.

Given this information, we can determine that pointing the device at different angles would result in different measurements of the sky. While the detector typically points to the zenith, or the point in the sky directly above the observer, the experimenter can change the angle to the zenith in order to collect different data.

Why would someone be interested in the differing zenith angles? Consider the following. As previously mentioned, a significant aspect of the muon is the fact that it has an electromagnetic charge. In addition, we understand that the Earth generates a magnetic field through the shifting magnetic core. This background field is roughly 0.5 Gauss, which is rather small. However, it is significant enough to alter the path of the muons.

Testing to see the difference in flux as the detector is rotated along the East-West axis would thereby show evidence of the muons charge.

5 Cosmic Ray Showers

Muon flux is not the only thing that the QuarkNet equipment is suited to handle. Another interesting topic to study is a cosmic ray shower. These events are somewhat of a misnomer, but they are important in our understanding of how cosmic rays work. Study of this topic requires long BNC cables, power extensions, and lots and lots of patience.

5.1 Cosmic Events

As seen in Figure 3, we know that there are significant variations in the energy level of cosmic rays. We see that the correlation between frequency of cosmic rays with the energy of the initial cosmic event. As cosmic rays become more energetic, the number of muons that they excite become larger. If we visualize the shower event as a small pancake of muons flying towards the Earth from the atmosphere, a more energetic cosmic event would lead to a larger pancake.

Our plates can be configured in order to measure the approximate areas of showers, given several crucial assumptions. The four scintillator plates are able to be repositioned and separated over a very wide area, where the only constraint is the length of power and BNC cabling that is available. Therefore, it is reasonable to move the four plates to four separate corners of the room, but keep the coincidence trigger count to be at four. Clearly, under regular muon situations, the DAQ board would never be triggered. It is grossly unlikely that four simultaneous events would be detected so far away from each other within microseconds of each other. However, if we assume that there is a pancake of muons arriving at the same time at all four plates, we can understand how the plates came to be triggered.

While it is possible to use four completely discrete scintillator plates arranged in a circular fashion, I believe that one can get the best of both worlds by using a two-stack configuration. This would allow for a higher amount of certainty that each stack truly detected a muon, as the muon needs to have penetrated through two plates, and also allows for adjustment of the distance between the two stacks. This distance would be representative of the minimal radius of the pancake of muons that could reach the detectors.

An additional benefit of separating the plates is that we can accurately measure how large the minimal size of the shower is. As shown in Figure 12, by measuring the distance between stacks of plates, we can know the minimal radius of the shower that passed through. Therefore, a suitable experiment is to gradually increase the distance between the stacks in order to increase the minimum area of shower events.

Immediately, it is obvious that these setups will not detect all of the showers that are possible in the area.

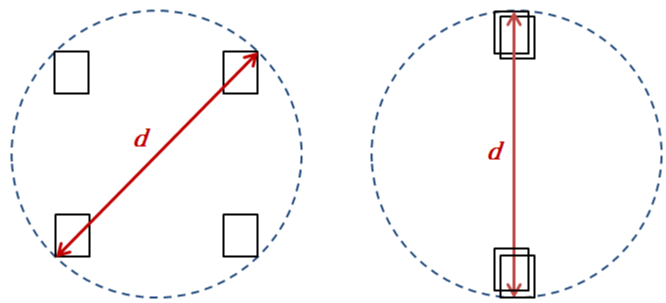


Figure 12: A cartoon that shows the way that the plates can be setup in the shower array.

Many showers may be positioned such that they do not go around both detectors in a perfect circle. Instead, they may only loop around 1 of the stacks, or perhaps just be a bit too low to be detected altogether. This is an unavoidable measure in this experiment, as there are insufficient resources to compile a huge array of scintillator stacks.

However, keen experimenters will notice a key flaw in the experiment. While expanding the radius of the detectors allows for the minimum pancake radius to be expanded, there is no limitation on the maximum pancake radius. To illustrate this problem, let us consider a problem. Suppose that a highly energetic event has created a pancake of muons that is 1.2 meters in radius. However, suppose that the setup radius is only 0.5 meters apart. Therefore, even if positioned in a optimal location, these highly energetic events would be mistakenly placed into a category of cosmic showers that is lower than expected.

While there is no perfect solution to this problem, there is a small workaround. Given enough concentric circles, you can determine the number of showers that fall within one specific band of radius by taking the difference between multiple conditions. Suppose that stack separations of 0.50, 0.55, and 0.60 meters were used. The difference between the count rates at 0.55 and 0.50 meters would be approximately an accurate count rate for the showers that truly had a radius of between 0.50 and 0.55 meters. For n measurements, it is therefore possible to get $n - 1$ useful data points. However, a key drawback of this workaround is time. With the exponential decrease of cosmic ray energy in relation to flux and the unpredictable and coincidental rays used for this experiment, it would take time scales of hours in order to collect valid data for shower experiments. Anything fewer than that may be simply attributed to the fact that one did not wait long enough. As running a single variable will take hours, the entire experiments can run for weeks on end, and still have kinks in the data shown.

5.2 Current Research

Currently, this research is being continued in professional arenas and most noticeably at the Pierre Auger Observatory in Argentina. This level of research is probing at the highest energies of cosmic rays that can be possibly discovered, thereby broadening human understanding of potential theoretical maximums of cosmic ray energy levels. If these are found, then it may give us increased insight as to the origin of cosmic rays as extragalactical sources.

However, note that the scale of the Auger experiment is considerably higher than what Quarknet allows us to do. Because the energy scales are in the $10^{1}8$ eV level, the distance for which the detectors span needs to be giant. Cosmic rays in this energy band are projected to only arrive at a rate of 1 per square kilometer per **century**. Therefore, the Auger experiment uses 1600 detectors to cover an area of over 3000 square kilometers. What the Auger experiment sacrifices in terms of resolution, it makes up for in terms of collecting power.

In addition, note that the Auger experiment does not run into the same ”minimum radius” problem that we do. This is because most cosmic rays would only trigger a subsection of the 1600 detectors in the Argentinian desert. Therefore, by looking at the circle of detectors that did not trigger, it is possible to determine an exact radius of the pancake, albeit a inprecise answer.

As the current research pushes the boundaries of what we understand about cosmic rays, we can still use the QuarkNet equipment to smartly analyze more plentiful cosmic rays at our energy level.

6 Muon Lifetime

Perhaps one of the most interesting experiments that can be done with the Quarknet Material is determining the lifetime of the muon through decay mechanisms. This is a typical experiment in the particle physics curriculum, and is often conducted in senior level laboratories on advanced physics. In order to grasp this concept, quite a bit of theory needs to be first understood. However, the theory is very rewarding, as it leads to several universal ideas within particle physics.

First, we must understand what it means for a muon to have a lifetime. It is simple to picture a living item as having a lifetime; eventually, all things that are living must also die. In addition, even inanimate objects can be pictured to have a lifetime. Eventually, they are no longer useful and must be thrown away, or they have broken down beyond repair. But what does it mean when the fundamental particles of the universe have a lifetime as well?

In the particle physics world, many composite particles also have a lifetime before they decay into more fundamental particles. For instance, the decay of the neutron into a proton and an electron is a well known process called beta decay, which plays a significant role in nuclear reactions. The mechanism for how such a basic particle can decompose even further can be predicted using Quantum Chromodynamics, Quantum Electrodynamics, and the study of the Weak Force. As mentioned in [CITE ABOVE], the Weak Force governs how many particles decay through the medium of the W and Z bosons. Using our current knowledge of this, physicists can predict what particles decay into over time. Sometimes, these decays require large amounts of initial energy. This is one of the motivations for why large particle colliders, like the Large Hadron Collider and the Fermilab collider, are used to study fundamental physics. They can help confirm the predictions made by theoretical physics.

Several things are required by fundamental laws and are very useful in predicting the outcomes of decay reactions. The conservation of energy-mass and the conservation of momentum are both useful tools to be applied. Note that the conservation of energy alone or mass alone is not necessarily followed. However, with Einstein's energy-mass equivalence, we can describe particles by their energy in Mega Electron Volts per C squared ($\frac{MeV}{c^2}$).

There is one specific reaction that we can use to predict the decay of the muon. This is listed below as

$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu \tag{1}$$

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu_\mu} \tag{2}$$

This odd formula is not very informative for people who do not understand the symbols, so let us break it apart and figure out what it means.

The μ is the standard symbol for the muon, the particle in motion. Obviously, the e^- is the electron, and less obviously, the ν is the neutrino, a massless particle that is emitted in this reaction. With this knowledge, we understand the basics, that a muon turns into three objects - an electron and two neutrinos.

However, there is more information in this statement. For instance, you may have noticed the superscripts in this statement - the minuses, plusses, and bars that float above the Greek characters. These symbols actually change the meaning of the particle that we are referring to, and are the reason for why we have two equations rather than one. The μ^- and e^- correspond to the standard muon and electron respectively, where the charge of the muon and electron is one minus. However, the antiparticles that correspond to the muon and electron are the anti muon and positron, respectively. The antiparticles are identical in all properties to their normal counterparts, but have an opposite charge. Therefore, the positron is represented as e^+ and the antimuon is represented as μ^+. For the muons, more slight differences dictate the creation of the antiparticles. In these cases, the antiparticle is represented as a bar written above the normal particle symbol.

In addition, note that there is significance to the subscripts attached to the neutrinos. You may notice that the subscripts, e and μ do correspond to the electron and muon. This is not an accident. It is because instead of there only being one type of neutrino, there is actually three "flavors" or neutrino, which correspond to one of the three leptons. (This can be seen with more clarity in Figure 4). Therefore, the subscripts are important to know in understanding the exact particles that are emitted. While neutrinos are not very significant for our use, as they are extremely weakly interacting and carry no charge, they are important in order for our many laws of conservation to work - in this case, they help satisfy the law of conservation of lepton number.

Another way of understanding this decay process is with a Feynamn diagram. Richard Feynman, the great particle physicist of the 20th century, created these simple diagrams in order to model how particles interacted with each other and ultimately decayed. They show a simplified model for how particles are able to decay, which allow physicists to infer different configurations for the process. See below for the standard decay of the muon.

However, the process of which the muon decays is not so simple. In fact, many different variables come into consideration when we probe the mechanics of decay. Understanding the exact methods that the W boson interacts with the muon allows us to ask interesting questions. The primary question that we must

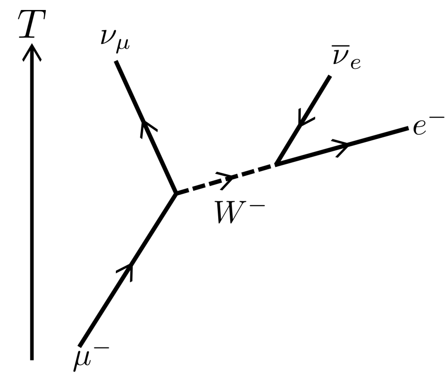


Figure 13: A Feynman Diagram of the decay of the Muon, as described in Equation 1.

consider in this experiment is the proposed lifetime of the muon, or in other words, how long it lives from creation to decay. In planning this experiment, note the many things we must consider - how to note the decay of the muon, how to calculate precise timings of the muon, and how we can even stop a muon in order for it to decay. These ideas will be discussed in more depth in the following subsections.

6.1 Creating of Cosmic Ray Muon

Before we go into how the muon decays, we must first understand how the muon is created. The reason we need to know this is to understand the starting properties of the muon as it comes through the atmosphere. They give us a good sense for why we are able to make the assumptions that lead to the calculation of the muon lifetime.

As discussed earlier in Section [INSERT REF HERE], muons are created as a byproduct of cosmic rays. Cosmic ray events lead to a multitude of several different reactions in the atmosphere, due to the nature of high energy collisions. Many primary products that are created as a result of the collision include pions, kaons, V-particles and other exotic entities. However, the majority of these particles have extremely short lifetimes. For example, the charged pion (π^+- has a lifetime of 26 nanoseconds ($2.6x10^-8$ seconds) and the neutral pion has a much shorter lifetime of only $8.4x10^-17$ seconds! These particles do not even experience sufficient relativistic effects to keep them living for a sufficiently long time to reach the surface of the Earth. However, some of their decay products do have sufficiently long lifetimes to reach Earth and be detected, namely, the muon.

An important characteristic to note is that both muons and pions are created at relativistic speeds. That is, they are born traveling very close to the speed of light, at approximately 99.97% of the speed of light. As we will discuss later, this is very significant for ensuring that the muon arrives on the Earth. In addition, the

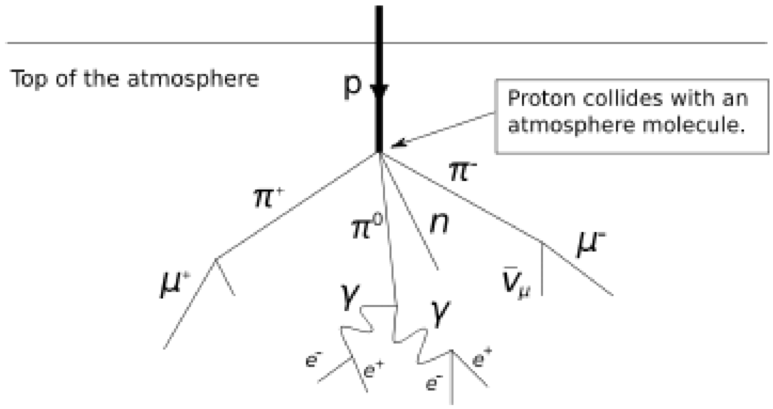


Figure 14: A Feynman diagram of some of the reactions that occur at a Cosmic Ray event.

original polarization of the pion leads to special effects regarding the rate of which the muon and antimuon reach the Earth. All of these characteristics are important in determining the lifetime. However, the first and most important of these is that we do not treat the muon's creation as happening at time zero. While it seems to make sense to measure the lifetime of a muon from the moment it is created to the moment it dies, it does not work in this scenario. This is primarily because we do not have detectors high up in the atmosphere to track the creation of every single muon. Thankfully, it does not significantly matter to our experiment, due to relativistic effects.

6.2 Relativistic Physics

Many people have heard of relativity as the genius idea that Einstein created in equating time and space together. In addition, a large number of people may have come to understand relativity through space travel, where people could live for decades traveling at high speeds while people on Earth would age faster. In movies like Interstellar, these plot lines would be used to emphasize the drama and tension of the moment. However, one of the first experiments that helped conclusively prove the workings of special relativity is the muon's travel time.

Consider the following: theoretical physics predicts the muon's lifetime at roughly 2.1 microseconds (μ seconds). If we do a quick calculation, we can compute the distance traveled by the muon at 99.97c under non-relativistic effects. This computes to be:

$$distance = velocity \cdot time$$

$$distance = (99.97 \cdot 3 \cdot 10^8 m/s) \cdot (2.1 \cdot 10^-9s)$$

$$distance = 629.811 meters$$

Clearly, 629.811 meters is much less than the projected distance of 50 kilometers that the muon spends through the atmosphere. If conventional physics was to be accepted, it is clear that we could not detect any muons at all. Yet, we do. The only explanation for this inconsistency must be that our current definitions for motion are not complete and must be updated.

Special Relativity introduces a new term to the classical Newtonian laws of motion. Rather than treating all time and distance as fixed, the two can change depending on the velocity that something is traveling at. As an object moves faster, an observer from the inertial frame (the frame that is not moving) will observe that object to be moving with a slower clock. In addition, that object that is moving will observe the distance in front of it contract at a equal rate. The conversion factor for this calculation is commonly referred to as the Lorentz factor, or γ. This is shown below as

$$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} \tag{3}$$

where v is the velocity of the traveling object and c is the speed of light. We can then use the Lorentz factor to adjust our laws of motion, as such:

$$\Delta t' = \gamma \Delta t \tag{4}$$

where $\Delta t'$ is the new time measurement and Δt is the old time measurement. An important aspect to note here - as velocity increases, you will notice that the Lorentz factor will increase as well. This will therefore always result in a new observed time that is longer than the old time. This makes sense because in relativistic physics, the shortest time frame occurs when the observer is at rest.

However, this poses a contradiction to us. If we find that the observed time of the muon is slower, could we not flip it around? Suppose that we were sitting on the muon, moving towards Earth. In this frame of reference, we would notice that we are standing still and the Earth is moving very rapidly towards us. As a result, we would "see" that the Earth is taking a long time to move towards us, thereby resulting in both the timeframes exaggerated. How do we reconcile this difference?

The important thing to keep in mind is that while we would perceive the muon to be experiencing time dillation, an observer on the muon would better be able to perceive distance dillation. That is,

$$\Delta L' = \frac{\Delta L}{\gamma} \tag{5}$$

Instead of seeing the world move in slow motion, they would see a shorter path distance to the surface of the Earth. Therefore, it's internal decay clock is still ticking away, but it only has to "travel" for a fraction of the distance and therefore a fraction of the time.

Calculation of the distance traveled, with the numbers used above, is left as an exercise to the reader.

When we take this into account, we can calculate a new maximum distance of the muon by special relativity effects. We can see how special relativity is a significant item to consider when interacting with particles that move close to the speed of light.

In summary, we have found that due to relativistic effects, the muon is able to reach the Earth in a time period that is insignificant according to it's own internal clock. Because that is the only clock to matter for it's decay, we can essentially treat the muon as not having moved in time during it's travel period. Instead, we can assume that the time that it starts living is the moment that it is put to rest.

6.3 Stopping of Muon

Given the above information, it is clear that we need to stop the muon somehow in order for it to decay. While the muon does not interact with the strong force, which allows it to penetrate most material, it does lose energy through electromagnetic interactions with the protons and electrons of a material. Each time the muon passes through an electron cloud, it has the capability to slightly interact with the electrons in the cloud, disturbing the stable orbitals. This interaction costs a little bit of energy currency, resulting in the electrons gaining a little bit of energy and the muon losing a little bit. Eventually, if the muon loses all of it's kinetic energy, it will be brought to a stop. This will likely happen in a material that is densely packed and has a large number of electrons and protons.

Materials that fit our bill are commonly heavy metals, such as copper, aluminum, or lead. These materials are often the most commercially available materials and allow for the most flexibility in understanding the mechanics of the material. By placing a large sheet of copper between the paddles, we can note that some number of muons will be stopped within the copper and subsequently decay, emitting electrons or positrons along the way.

At this point, we have described some of the basics of how the muon actually decays. However, we have so far omitted the topics regarding the user detection of the muon. How are we able to use QuarkNet in order to properly detect both the start and end results of the decay process?

6.4 Triggers

One of the exciting things about the QuarkNet interface is that you will be able to use the triggering to determine different setups for the device. Previously, we had changed the triggering in order to make more accurate determinations on whether the event we recorded was really a muon, as determined by if it passed through all four plates. Now, we can go further and analyze if the particle that passes through really is a muon that has been stopped by the copper, and if we can detect the decayed electron that should come out.

The first part of this to note is that the stopping material needs to be between the plates, not on top or below it. This is because while the muon would be stopped inside the copper, we need to know if a muon had even arrived to the copper plate before hand. Therefore, we tend to place one or two scintillator detectors on top of the copper. If these two plates fire at the same time, then we know that there was a muon that passed through.

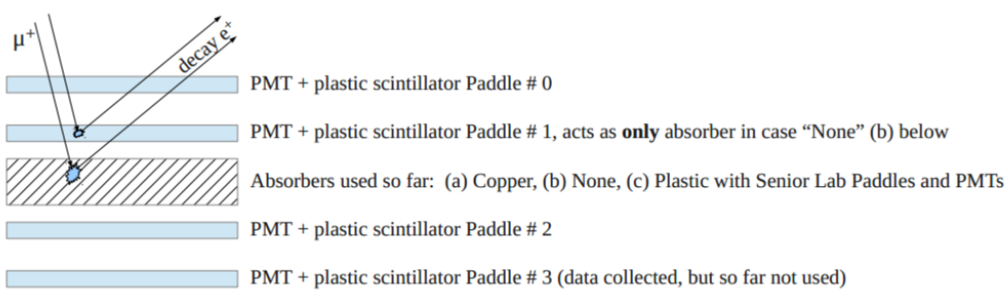


Figure 15: A diagram of the scintillators and the trigger logic that is used for detection of lifetime experiment.

However, the above information is insufficient for understanding the muons in depth. For instance, suppose that a muon passed through both of the two above plates but proceeded to pass through the shielding material as well without losing sufficient energy. If this happens, the muon would not have decayed and any subsequent collected data would not be so useful. Therefore, if we see that any plate below the stopping material is triggered within a short period of time immediately following the initial triggering, it would be a sign that this data event is not useful. Unfortunately, the ”veto” sign is not easily done using the DAQ settings, but we can do it during post-processing of data.

The next step would therefore be to determine when the muon has decayed. This can be done when the detectors detect a second signal, but at least greater than 20 or so nanoseconds after the initial signal. Most likely, this second signal would be a result of the decay electron or positron rebounding out from the copper sheet. This electron/positron has a significant amount of energy, as the rest energy of the muon has went into it's creation. Therefore, it has the capability to penetrate multiple scintillator plates. It is ultimately up to you to decide if you want for a single detection or two-fold coincidence to dictate the stopping signal. The primary differences between these choices would be the number of decays you will detect as well as the certainty that you have in actually detecting a decay. Keep this in mind when you are designing your lifetime experiment.

With this, you know how to compute the two triggers - both the start trigger and the end trigger. The difference between the time signals for these two triggers would be the time that the muon spent within the stopping material, before it decayed. This would compute to be the lifetime of the muon, which is what this experiment seeks to gain.

Given the data that you have collected with this setup, you can then begin to analyze to really understand the lifetime. However, with this preliminary information, you are set to begin experimenting. The next section will focus on some more advanced topics regarding polarization, exotic atoms, material differences, and counting statistics, and can be used to enhance your knowledge about the muon.

6.5 Muon Lifetime, Part 2

When analyzing the muon lifetime, there are many factors that need to be considered in the process. While the above section outlines the basic ideas used in the construction of the lifetime experiment, it skips over many of the physical aspects of the detection process. In addition, there are many specific corrections needed for full understanding of the experiment. This section will guide you through some of these advanced topics and lead you to a better understanding of the different components that physicist must go through.

6.6 Data Analysis

One of the first ideas that must be properly addressed is the analysis of the data that comes out of this project. First, an understanding of the scope of data collected in this experiment is needed. This experiment is designed to be collected over a period of several days or even weeks. This typically results in a very large pool of data and needs special analysis tools to get into it.

After collecting data for several weeks, you would want to analyze the data that the DAQ board outputs.

The raw text files are almost incomprehensible, but it is possible to create programs to reinterpret it. While this text will not guide you through writing your own programs, we will give you several ideas to keep in mind as you consider this endeavor.

First, be sure you fully understand the output that the text file outputs by reading the documentation and evaluating some sample events. Realize that a cosmic event is often distributed across several different lines and can sometimes take on odd forms in broken data streams. You must understand how to pre-process the data and put it into a consistent format that can be read by both humans and computers.

Afterwards, you need to determine what information is most important to you. In this case, the crucial information is the time difference between the initial trigger events and the final trigger events. Could you design some sort of discrimination to only attract the events that have start and end triggers? Could you find the difference in clock time between those events? These are some of the challenges that you will need to decode when gathering your final processed data file.

You need to create a graph for easily visualizing this information and for deriving useful information about how the muon is reacting in the stopping material. The best graph to use would be a histogram-type chart, where you could easily visualize the entire set of data. Many advanced physicists would use the MATLAB program and coding language, but as it costs money to purchase a license, a useful alternative to investigate would be the Octave program[19] This is a package within the Linux family of software that is open access and is relatively easy to begin working within. Links to sample code and coding environments are attached to the conclusion of this document.

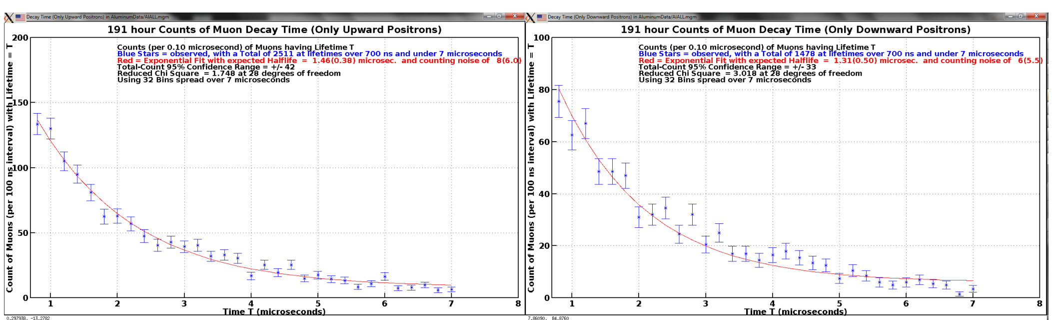


Figure 16: One of the graphs created for the muon lifetime experiment, using Aluminum as the stopping material

Creating your own data analysis software is very time consuming and difficult, but ultimately, it provides the most benefit in understanding where the data is going and how you are able to interpret it. Perhaps

[19]Some personal advice - try to find a mentor who is familiar in the Linux environment. It is difficult to keep up with the rapid development in software, and manuals very rapidly become out of date, sometimes even before they are published! Keep up to date with the latest by finding someone else who is up to date.

some of the best skills that you may learn through going through this project will be centered around data processing ideas.

6.7 Muonic Atoms

One significant aspect of the muons that we gather here is that we see more antimuons than regular muons. At sea level, we see a rate of roughly 1.8 antimuons for every 1 muon. Because we understand that charge should be symmetrical at the point of creation, there is clearly some function in the atmosphere that is intentionally removing regular muons[20]. We can therefore The significance of the antimuons is related to the muonic capture process and muonic atoms.

Considering that a muon is essentially a heavy electron, it is reasonable to expect that a muon has certain properties that allow it to interact with atoms. Rather than simply be slowed down in copper, regular muons can act as a electron substitute in both the atmosphere and in the copper sheet. As the muon passes through the atmosphere, the high energy of the muon allows it to potentially knock out some electrons in hydrogen and helium atoms. Due to the negative charge of the muon, it is possible for the atom to then capture the muon, preventing it from immediately passing along. This creates an *exotic atom*, or an atom that is not simply made up of protons, neutrons, and electrons. The specific name for this atom is the muonic atoms, and it was one of the first exotic atoms discovered.

Because of the muon's greater mass, the muonic atom is unstable and the muon tends to be drawn towards the nuclei of the atom. There, as it hits the protons in the nucleus, the muon undergoes a process called muonic capture, where the following reaction takes place:

$$\mu^- + p \rightarrow n + \nu_\mu \tag{6}$$

This process is significant for two main reasons. One, the timescale for the muonic capture is much faster than the muon decay. As it decays on the order of several nanoseconds instead of several microseconds, it is reasonable to infer that most muons will have undergone the muon capture process rather than the muon decay process. In addition, it is significant here that no charged particle is produced during the decay. Therefore, for a negatively-charged muon in a copper stopping material, it is reasonable to assume that they are severely discriminated against and that the signals we see from the decay events are primarily coming from the decay of anti-muons.

[20]Obviously, we understand that the function is removing regular muons and not creating additional antimuons, as the creation of new antimuons would be breaking symmetry

7 Muon Magnetic Moment

The Muon Magnetic Moment may be one of the most advanced experiments that can be done with the QuarkNet equipment. This is not only a significant experimenters for muon studies; it is also a pivotal experiment in modern particle physics. The ability for QuarkNet students to be doing the same experiments that are going on at Fermilab is quite amazing!

7.1 Meaning of Magnetic Moment

The Magnetic Moment of the muon hinges on several quantum mechanics and particle physics concepts that may be foreign to the regular reader. The magnetic moment relates the spin of the muon, an intrinsic property that all particles have, with it's oscillation frequency when subject to a magnetic field. As the muon operates in a magnetic field, the direction of its spin would precess along its axis at a rate correlated with the magnetic field exerted.

It is often difficult to imagine what the "spin" of a particle is, especially as we visualize the particle as a point in space with no volume. However, because we can experimentally notice that some quality of the particle seems to rotate under the influence of a magnetic field, we must conclude that the particle has some intrinsic property that is difficult to describe. One reason why we call this property spin is not because we visualize the particle as literally spinning like a top, but because we notice the precession effects of the spin axis as a magnetic field is applied. Like a spinning top that has a torque applied to it, the spin of the particle slowly moves in a circle that is proportional to the magnetic field applied.

We can understand the magnetic moment as a ratio of the oscillation frequency, as modeled by the following equation:

$$g = \frac{2m_\mu \omega}{eB} \tag{7}$$

where g is the magnetic moment, m_μ is the mass of the muon, ω is the precession frequency, e is the fundamental charge of the electron, and B is the external magnetic field applied. Using Dirac's theory for calcuation, we can find g to be equal to exactly 2.

The enigma of the magnetic moment is that the experimental conclusions do not agree with the theoretical assumptions. While g is predicted to be 2, the experimental value is slightly greater. This is most often represented in physics as

$$a = \frac{g-2}{2} = 0.00116592091 \tag{8}$$

which is a small but significant difference. Getting more precise digits on this constant is a main goal of experimental studies conducted at Fermilab.

At this point, you may ask the question of how scientists actually see the precession of the spin axis. After all, there is no real interpretation of the "spin" concept, right? However, we can see the effects of the spin axis, especially when coupled with the lifetime experiment. As it turns out, the spin of the muon is correlated with the direction that the emitted decay electron/positron. This can be more noticeable when you have muons that have polarized spin. And fortunately for us, as discussed in the previous sections, we find that there are polarized incidental muons to be used.

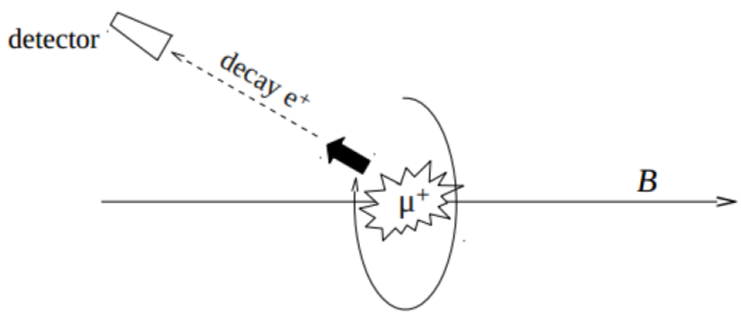


Figure 17: The precession of the spin axis results in a different direction that the decay positron is emitted towards

When the decay positron is emitted in a specified direction, we can see a signal in the lifetime curve. However, if we only observe the stop trigger signals in a specific direction, say only the up plates, we would ideally observe an oscillation in the number of signals. Instead of consistently receiving signal that is only proportional the lifetime of the muon, there would be a oscillating overlay created as the spin axis precesses.

If we properly measure the oscillation frequency by examining the best fit line, we can come up with an approximate measure of the ω for the muon. This requires some detailed knowledge regarding the counting statistics and regressions for modeling functions[21]. If possible, try to input the data into some other source for the statistical regression and analysis. It is also possible to use certain packages within the Octave database to conduct the statistical regression.

This has been a rather brief exploration of the magnetic moment experiment. If you would like to continue doing research, I would highly advise searching through some of the PhD thesis and disseratations. Having made it so far through this TeXtbook, it is likely that you have the prerequisite knowledge to begin

[21] This is rather difficult to explain - the majority of master's dissertations are dedicated towards explaining this portion.

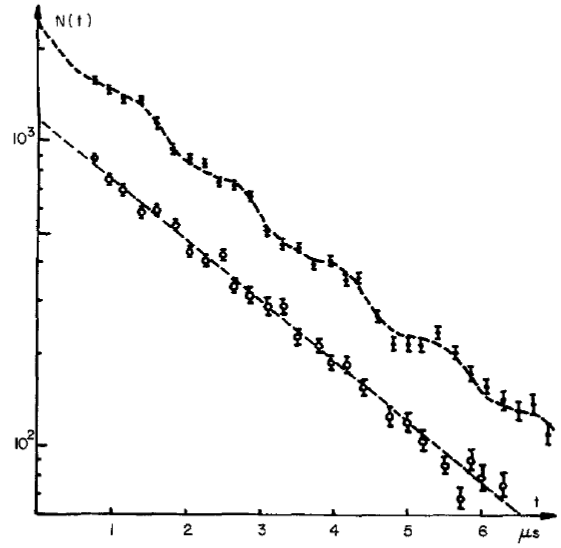


Figure 18: The original results from the Amsler experiment that investigated the muon's magnetic moment. Note the oscillation in the second best fit line.

understanding those concepts as well.

7.2 Appropriate PMT μ-Shielding

As mentioned previously, the Photomultiplier Tubes have several inherent safety characteristics in order to maintain the validity of the data. One of the biggest concerns is the effect of external magnetic fields on the ability to conduct proper data gathering. Even a small magnetic field could wreak havoc with the delicate diodes of the PMT, and unfortunately,the Earth does generate a small magnetic field of 0.55 Gauss.

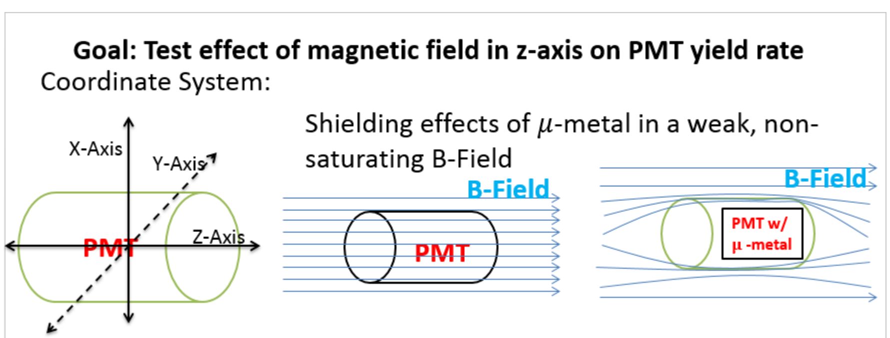
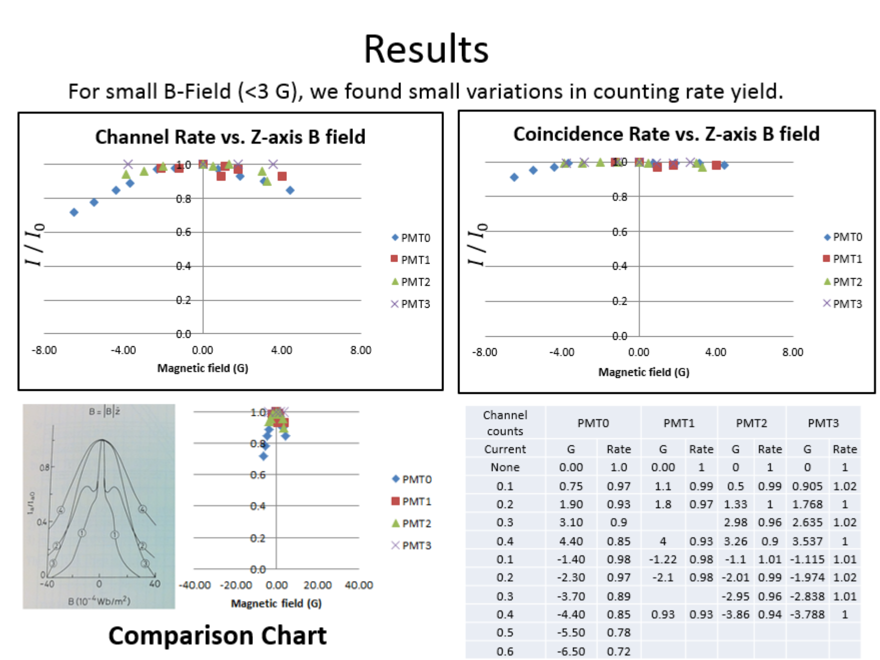


Figure 19: A cartoon of the PMT's shielding effects. Straight lines are magnetic field lines. Credits to Chunyang Ding

However, the creators of the PMTs are not silly enough to allow this well-known fact deride science!

The PMTs are therefore shielded using a special material known as Mu-Metal, a blend of copper and other metals that is particularly suited for allowing magnetic field lines to be channeled through[22]. When placed in a magnetic field, the cylinder of μ-metal acts like a lightning rod for magnetic field lines. Rather than passing through the delicate PMT instrumentation, it is absorbed and passed harmlessly through the device.

However, the μ metal is not a magic bullet. It also has drawbacks, particularly in the maximum amount of magnetic field that it can absorb. At some point, the ability of the mu metal to absorb excess B-field begins decreasing, and larger and larger fluctuations will begin showing up within the sensor. In order to verify the capacity of the mu-metal, especially for the magnetic moment experiment, I conducted my own calibration settings. Attached below is the results page.



Channel counts	PMT0		PMT1		PMT2		PMT3	
Current	G	Rate	G	Rate	G	Rate	G	Rate
None	0.00	1.0	0.00	1	0	1	0	1
0.1	0.75	0.97	1.1	0.99	0.5	0.99	0.905	1.02
0.2	1.90	0.93	1.8	0.97	1.33	1	1.768	1
0.3	3.10	0.9			2.98	0.96	2.635	1.02
0.4	4.40	0.85	4	0.93	3.26	0.9	3.537	1
0.1	-1.40	0.98	-1.22	0.98	-1.1	1.01	-1.115	1.01
0.2	-2.30	0.97	-2.1	0.98	-2.01	0.99	-1.974	1.02
0.3	-3.70	0.89			-2.95	0.96	-2.838	1.01
0.4	-4.40	0.85	0.93	0.93	-3.86	0.94	-3.788	1
0.5	-5.50	0.78						
0.6	-6.50	0.72						

Figure 20: Collected data on the efficiency and saturation point of the mu-metal found in QuarkNet PMTs. Credits to Chunyang Ding, Zhanpei Fang, and Nicholas Dreyer

From these results, it is clear that the mu-metal is rather efficient in keeping out the B-field for small fields of <3 Gauss. Above that, we rapidly see a sharp decrease in the counting rate yield, as is predicted by other respected sources like the Knoll textbook on radiation. As the expected maximum magnetic field near the region of the PMTs is closer to 1 Gauss, it is highly likely to not have significant negative effects on the collection of valid data.

For those who wish to conduct their own magnetic mu-metal shielding tests, please see the general

[22]It is somewhat difficult to get exact materials for the makeup of the mu-metal, as it is a proprietary set of information. All you really need to know is that it works!

experimental guidelines below.

The key concepts behind the mu-metal testing is remarkably similar to the plateau testing as covered in Section 8.1. We look at two PMTs receiving signals from incidental cosmic rays, where one of the PMTs is influenced by an external magnetic field generated by a solenoid. A solenoid, or a simple loop of wire connected to a power source. These circuit parts generate an exact amount of magnetic field within the loop of wire given a certain amount of current passed through the loop. By applying this magnetic field to one of the PMTs, one would expect to see a decrease in flux as the current through the solenoid increases. Measuring the normalized values of such PMT outputs[23] will be useful in understanding past what magnetic field strength causes a sharp drop in counting statistics.

[23]normalization can be completed by dividing the experimental PMT with the standard PMT that does not have a magnetic field. This is because we assume that both plates should be receiving the same signals.

8 Detailed Calibrations

When setting up the QuarkNet detectors, one of the most important things to confirm is that the detectors are functioning properly. This allows you to trust in the data that you collect. As covered previously, the QuarkNet data has potential to capture information down to the nanosecond. However, if all of the data was wrong due to a light leak, regardless of the precision of the data, it would be useless. Therefore, it is very important to check the detectors through a string of different calibrations.

8.1 Plateau Calibration

One of the first calibrations that all students should conduct is the Plateau calibration. This calibration deals with assigning the proper voltages to each of the PMTs/scintillator plates. Without proper voltages, the PMTs would not be able to detect the correct signals from the scintillator plates. It would be possible for the electrons to be accelerated too far, resulting in over-excited responses, or not enough, resulting in loss of signal. A plateau calibration is the first step to determine what settings is most suitable for the individual PMT device you have.

While it is a general rule of thumb that the voltages supplied to the PMTs should be in the 700-1200 mV range, the precise value varies greatly between different PMTs. As PMTs are very sensitive instruments, it is difficult for the manufacturer to create identical PMTs each time. Therefore, it is the resonsibility of the user to use the most optimal settings for operation.

After calibration is completed, it is very unlikely that the settings of the PMT will change significantly, barring any disastorous damage done to the PMT. Record the values for the PMT voltage levels in a safe place and ensure that you use the same voltage levels through all of your experiments. Differing voltages would lead to significantly altered results which may no longer be statistically significant.

In order to do a plateau calibration, follow the following steps:

1. Download the Plateauing Calibration spreadsheet from the ELAB platform. This spreadsheet will allow you to easily calculate and graph the counts of various voltages.

2. Set up two of the four scintillators on top of each other. Deactivate the other two scintillators.

3. Using EQUIP, configure the boards such that there is 2-fold triggering. This allows for data to be collected when both scintillators fire.

4. Using a multimeter, test the voltage in the small black box for the test channel and the control channel.

5. Set the voltage on the control channel to be around 1000 mV, or such that the individual 5 minute count rates are roughly 2500.

6. Set the voltage on the test channel to be 750 mV. Set the EQUIP program to get count rates every 5 minutes by either using "ST 5 1" or by typing it into EQUIP's java interface.

7. After collecting data for five minutes, EQUIP should spit out a line of data from the previous 5 minute period. Copy and paste the hexadecimal numbers into the Excel spreadsheet, as shown below. You should be inputing control channel, test channel, and coincidence level data.

8. Adjust the voltage on the test channel, increasing it by 25 mV. Ensure that you reset the count of the detector by reentering the command "ST 5 1", in order to clear out junk data that was collected as the test channel voltage was adjusted. Repeat step 7 up to test channel voltage of around 1200 mVs.

9. Repeat this process for every other scintillator plate. You can choose to use the same control plate in order for better quality data, but keep in mind that in the end you need to calibrate the control plate as well.

10. For each test plate, the proper voltage can be found by looking at the coincidence data on the graphs. The corresponding voltage where the coincidence levels begin to level off is where you should set the voltage for that specific plate.

After completing these steps, you should have a calibrated setup for future data collection. However, why does plateau calibration work? What is the theory behind it?

In this process, notice that we had a single variable: voltage across the test channel. As the voltage increased, we generally see a corresponding increase in the single count rate of that test channel. This matches our assumptions of what the voltage does to the PMT; it causes more signals to be detected. In addition, notice that the count rate for the control plate is constantly very very high. This is used as a control because it serves to be a very sensitive background muon detection. Recall that we only register muons when they pass through two separate plates at the same time. Therefore, because the control plate registers almost every single noise fluctuation, it would certainly capture every single real muon that passes through it.

The most significant portion on the graph is therefore the coincidence rate. At first, the coincidence rate rises at the same level as the test channel count rate, but at some point, this coincidence count levels off, or "plateaus". The plateau here means that even though our detectors are becoming more sensative to noise,

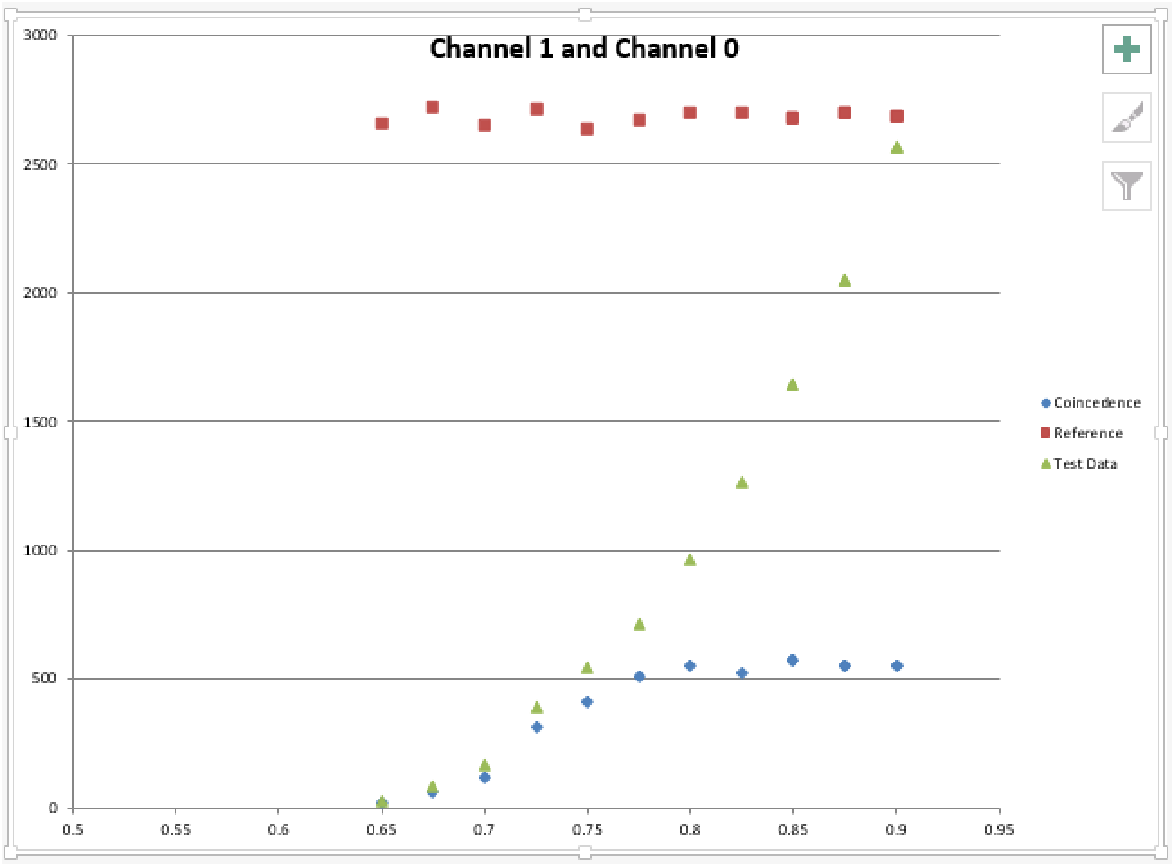


Figure 21: Collected data on calibration of QuarkNet platforms. Note the plateau shape of the blue diamonds as compared to the green triangles. Credits to Chunyang Ding and Zhanpei Fang

they are not detecting any more muons. Therefore, the region where the coincidence rate begins to plateau would be the optimal operating voltage for our plates.

Through all of this, recall that this process is not neccessarily perfect. Using only a five minute section to collect data is not optimal, as it typically only allows for 500 coincidence events to be detected. If the time period for each trial was extended, the data would be more validated. However, as we must take into account opportunity costs and the large time burden of this calibration, a five minute window allows for sufficient data to be collected. In addition, recall that the voltage read by the box through a multimeter is not actually the voltage across the PMT. Instead, the PMT voltage is much higher, as it is achieved through many voltage accelerators that have been designed into our PMTs. However, because we assume that there is a linear dependancy between the PMT actual voltage and the measured voltage in the box, we can equivocally substitute the two ideas together.

8.2 Time Calibration

The next major calibration scheme that we could use is a time calibration. This calibration would allow for us to verify the accuracy of the clock on the DAQ board. Most students will not require the use of this calibration, as the clock on the DAQ board is incredibly stable to be around 24 MHz[24], but it is a useful exercise to be done if the accuracy of the clock is a primary requirement in order for further experiments to take place.

In order to calibrate the DAQ board by time, it is require that a known time signal be brought in. The only way to calibrate the timing is to use some device that is known to be accurate. While this may raise philosophical questions about what the first timing calibration device was correct, let us not fall into a hole of epistemology and focus on the practical struggles time calibration brings in. Perhaps the most convenient device to be used for a time calibration would be a light pulsor. This device generates light signals that travel through BNC cables and can be directly connected onto the DAQ board. The setup would be bypassing the scintillators altogether, as they are not crucial for conducting the time calibration.

Before you conduct the time calibration, it may be helpful to get to know your pulsor better. This can be done through hooking it up with an oscilloscope[25] and understanding the many different settings that are possible with the pulsor. Optimally, you want a pulsor that can send out signals as short as a one onehundreth of a microsecond and as long 100 milliseconds. This allows you to test the DAQ board over a very large range, therefore justifying the validity of the board's clock. Be sure you understand how to set up your pulsor to be generating the signals that you want to use during the calibration. Typically, the pulsor works by sending out two signals that differ by some time interval as determined by the user.

Afterwards, the simplest method for checking the calibration is to plug the pulsor into the DAQ board and let it run for 2 minutes. Many pulsors allow for the user to select how many pulses per minute are wanted; a recommended number would be around 2000. This would allow 4000 individual events to be saved and then later used during analysis.

For a very brief analysis, simply look through the raw data and confirm that each of the hexadecimal values between the two test channels differ by the same amount each time. Recall that 1.25 nanoseconds is equivalent to one clock tick, so any multiple of 1.25 would result in another hexadecimal difference. Also, keep in mind that every microsecond is recorded in the large time counts as the first word, rather than the

[24]It is important to check on the actual frequency of your DAQ, as there are currently two versions of the DAQ board - the 5000 and 6000 series. They have different clock speeds, which MUST be corrected for

[25]In general, oscilloscopes are *really cool* and should be played with. Using a pulsor is perhaps the easiest manner to get to know your oscilloscope, as the signal output should be very steady and regular

individual channel counts. This is important to remember when testing for large intervals of greater than one microsecond.

For further analysis, you should create your own analysis software to collect all of the individual data points that are produced and create a histogram for visualizing the data. Ideally, you would see a histogram with all data in a single bin, but due to random variations in the board, there may be slightly different values. By looking at a histogram, you can see the magnitude of the variations and if they are within the appropriate range for your experiment.

8.3 Energy Calibration

The final possible calibration is to conduct an energy calibration. However, this is not necessarily needed, and is somewhat difficult to understand. If one studies the energy profiles of the muons that are passing through, it is unlikely that you will find anything interesting. This is because most muons pass all the way through and deposit the same amount of energy on each scintillator plate. In addition, the acrylic scintillator material is designed to allow most muons to pass through and is not a very good measure of energy readings. However, the theoretical ideas will be briefly discussed here.

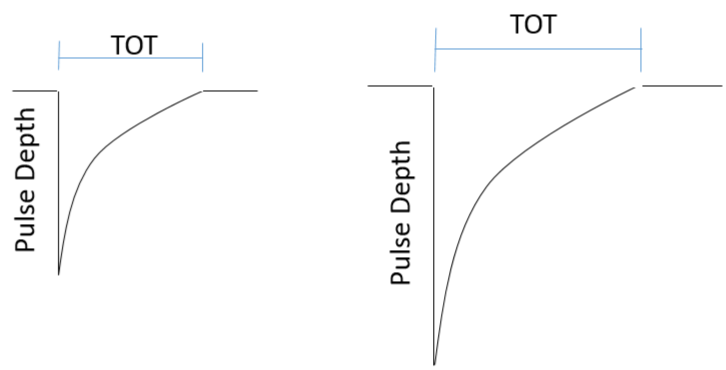


Figure 22: A cartoon of the relationship between the pulse height and the time over threshold.

Energy calibration is most closely related to the PMTs, as the passing of any charged particle through the scintillator generates incidental photons. The number of photons is correlated to the initial energy of the particle[26], and as the photons trigger the PMT, we can gather information. The quantity of photons passing into the PMT determines the voltage differential, and thus, the pulse height. However, the pulse height is not data that can be directly obtained from the DAQ board.

[26]Up to some maximum value, where no additional photons could be created based on constraints of the scintillator

A workaround this is to utilize the known correlation between the pulse height and the Time over Threshold - see Figure 22 Therefore, if we place a source of known energy near the scintillators and subsequently observe the time over threshold readings, we could correlate that energy level to a specific TOT and interpolate for other values.

Unfortunately, this would require obtaining a source of steady energy, and the best candidates for this would be radioactive materials. In addition, radioactive materials do not typically work well with acrylic scintilators, and have a tendancy of leaving behind unwanted energy levels. Therefore, conducting an energy calibration is a significantly difficult task with possibly small payouts.

9 Conclusion

Congratulations! You have suffered your way through 50+ pages of a high school senior's best attempt to put together the knowledge from a year of internship. Hopefully, you have learned about the fundamentals of particle physics through hands on experiments with the QuarkNet equipment, and is now ready to go the next step. Never stop pushing the boundaries of physics, even as a student, because there is always something more to be discovered! The future is in our hands, and I hope that you will always have an interesting thought to chew over, and to always keep learning.

10 A letter to the teacher

Dear teacher, Thank you for being invested in your students explorations for physics and engineering! As a high school senior myself, it has been the support of many teachers and professors that I was able to compile this resource that you have here today. I would definitely advise for you to allow your students to explore all the resources that are out there, but to help them narrow their focus and find a proper research question early on. I was so lost when I first began my research, and I do hope that this resource can synthesize many of the lost hours on Wikipedia and Hyperphysics that I aimlessly stumbled around on. It would mean that your students can much more rapidly get to the interesting technical discussions on how to formulate the best research questions and how to obtain suitable data analysis tools. Again, thank you for dedicating your time and energy towards helping your students explore this field! I hope it is as rewarding for you as it has been for me.

A Experiments

List of Experiments:

1. Time Experiment: Section 4.1
2. Elevation Experiment: Section 4.2
3. Zenith Angle Experiment: Section 4.3
4. Cosmic Shower Experiment: Section 5
5. Muon Lifetime Experiment: Section 6
6. Muon Magnetic Moment Experiment: Section 7

B Stand Blueprints

This is a particularly interesting technical report that I worked on with several of my high school classmates. Please see the end of this TeXtbook for the original technical report. Following those directions, a school can construct their own stand for the QuarkNet equipment in order to carry out the Zenith Angle experiment.

C Useful Formulas for Reference

C.1 Radioactive decay

$$\mu^- \to e^- + \bar{\nu}_e + \nu_\mu \tag{9}$$

C.2 Measurement of muon lifetime

$$t_{muon} = \frac{d}{v_{muon}} = \frac{30x10^3 m}{3x10^8 m/s} = 100\mu s \tag{10}$$

C.3 Special Relativity

$$t_{observed} = \frac{t_{actual}}{1 - \frac{v^2}{c^2}} \tag{11}$$

C.4 Magnetic Moment

$$g = \frac{2m_\mu \omega}{eB} a = \frac{g-2}{2} = 0.00116592091 \tag{12}$$

D Detailed References

1. Amsler, C. "The Determination of the Muon Magnetic Moment from Cosmic Rays." American Journal of Physics Am. J. Phys. 42.12 (1974): 1067. Web.

2. Argyropoulos, S., and J. Waechter. "Measurement of the Magnetic Moment of the Muon." Diss. Ed. A. Bravar. Universite De Geneve, 2011. Print.

3. Bernardini, Paolo, and Simona N. Sbano. "Evidence of Geomagnetic Effect on the Azimuthal Distribution of Extensive Air Showers." J. Phys.: Conf. Ser. Journal of Physics: Conference Series 409 (2013): 012229. Web.

4. Charpak, G., P. J. M. Farley, E. L. Garwin, T. Muller, J. C. Sens, and A. Zichichi. "The Anomalous Magnetic Moment of the Muon." Nuovo Cim Il Nuovo Cimento 37.4 (1965): 1241-363. Web.

5. Chatterjee, Animesh. Muon Lifetime Measurement Experiment. Mumbai: Tata Institute of Fundamental Research, n.d. PDF. Cosmic Ray Muons and the Muon Lifetime. N.p.: University of Florida, 2013. PDF.

6. Ding, Chunyang, and Zhanpei Fang. Effect of Small (2G) External B-Field on Standard PMT for Magnetic Moment Experiment. Seattle: University of Washington, 2015. PPT.

7. Ding, Chunyang, Zhanpei Fang, Nicholas Dreyer, Shih C. Hsu, and David Pengra. Step by Step Instruction for Muon Lifetime Experiment. Seattle: University of Washington, 2014. PDF.

8. Dolgoshein, B., B. Luchkov, and V. Ushakov. "Polarization of Low Energy Cosmic Ray Muons at Sea Level." J. Exptl. Theoret. Phys (U.S.S.R) 15.4 (1962): 945-55. Web.

9. Dreyer, Nicholas. Proposal for Using the QuarkNet Cosmic Ray Detector to Measure the Muon Magnetic Moment. Seattle: University of Washington, 2014. PDF.

10. Drielsma, F. "A Muon Magnetic Moment Measurement." Diss. Ed. A. Bravar and A. Haesler. U of Geneva DPNC, 2013. Print.

11. Egede, Ulrik, Gosta Gustafson, Christina Zacharatou Jarlskog, and Janus Schmidt-Sorensen. Parity Violation in Muon Decays. Lund: University of Lund, 3 Apr. 2000. PDF.

12. Ganai, Rajesh. "Muon Liftime Measurement Using Stopped Cosmic Muons in a Plastic Scintillator Detector." Diss. Tata Instituite of Fundamental Research, 2010. Print.

13. Hall, R. E. ”A Simplified Muon Lifetime Experiment for the Instructional Laboratory.” American Journal of Physics Am. J. Phys. 38.10 (1970): 1196. Web.

14. Hawley, Jim. The Magnetic Field in and around a Finite Cylindrical Air-core Solenoid. N.p.: n.p., 2011. PDF.

15. Hertzog, David. Cosmic Ray Muon Laboratory. N.p.: n.p., 2009. PDF.

16. Hoch, Richard Claude. ”Advances in Cosmic Ray Muon Tomography Reconstruction Algorithms.” Diss. Florida Instititue of Technology, 2009. Print.

17. Jergerlehner, Fred, and Andreas Nyffeler. ”The Muon G-2.” Physics Reports 477 (2009): 1-110. Web. Jergerlehner, Friedrich. The Anomalous Magnetic Moment of the Muon. Berlin: Springer, 2012. Print.

18. Johnson, C. Scott. ”Polarization of Cosmic-Ray Muons at Sea Level.” Physical Review Phys. Rev. 122.6 (1961): 1883-890. Web.

19. Kammel, Peter. ”Muon Capture.” The Workshop on Physics at the First Muon Collider and at the Front End of a Muon Collider (1998): n. pag. Web.

20. Liu, Lulu, and Pablo Solis. The Speed and Lifetime of Cosmic Ray Muons. Boston: MIT, 18 Nov. 2007. PDF.

21. Maleti, D., A. Dragi, R. Banjanac, D. Jokovi, N. Veselinovi, V. Udovii, M. Savi, J. Puzovi, and I. Aniin. ”Stopped Cosmic-ray Muons in Plastic Scintillators on the Surface and at the Depth of 25 M.w.e.” J. Phys.: Conf. Ser. Journal of Physics: Conference Series 409 (2013): 012142. Web.

22. Measday, D.f. ”The Nuclear Physics of Muon Capture.” Physics Reports 354.4-5 (2001): 243-409. Web.

E Acknowledgements

Thank you to the many teachers, advisers, labmates, and coworkers who have made this possible. I'm no more than a high school senior, but I'm seeing my dream of becoming a particle physicist slowly realized.

To Dr. Hsu, who started me on this entire path of research. Thank you for being patient and answering questions at all hours of the night, and for coordinating my stay at the University of Washington.

To Nicholas Dreyer, for supervising the CRMD project along with several others and for always providing valuable feedback and suggestions on all ideas. You have been the realist in our group, keeping the students in check and supplying us with all of the amazing analytical tools. Thank you for teaching me so much.

To David Pengra, for always being a steady source of detailed information on every detection mechanism. In between and after the advanced laboratory classes, you always had time to come and help high schoolers. From borrowing equipment and books to reconfiguring the logic on the large plates, your help accelerated our research to where it is today.

To Zhanpei Fang, a most amazing lab partner. Thanks for keeping the lab always interesting and always exciting. I have been so lucky to have learned so much with you together, and best wishes as you go off into your bright, bright future.

And finally: to my dad, Jun Ding, for forcing me to push ahead with research and studies in physics, and giving me that same love for understanding the world. And to my mom, Jing Xu, for always supporting me in every way, the tireless mom who wants her son to be happy. You two mean the world to me.

Muon Detector Rotational Device

Created by students of Mr. Milhollen's IB Design Technology Class
For Mr. Chunyang Ding
Authors: Jessica Zhang, Waylon Huang, Ty Foster,
Stuart Sutherland, and Amber Tavener
28 March 2015

Abstract

The Muon Detector Rotational Device (MDRD) is a carefully designed, mechanized product purposed to support an array of muon detectors in a variety of positions. The client of our product is Chunyang Ding, a high school intern working for the Fermi Labs at the University of Washington. The MDRD will host four detectors, stacked together parallel in a wooden clamp. The MDRD will rotate vertically 45 degrees in both directions, and 360 degrees in the horizontal plane. The minimal accuracy of the horizontal and vertical rotation is 1 degrees. The entire device will weigh an approximate 200 pounds, depending on materials used. The MDRD will be allowed to rotate vertically through a rack and pinion system: gear wheel, gear rack, and linear actuator. The MDRD will be able to rotate horizontally through the combined use of a turntable and wheels along a track support. The main materials used are steel and plywood due to their cost, weight, durability, and stability. Overall, the MDRD serves to increase efficiency in subatomic particle research: a rising field in physics and technology research.

Table of Contents

Executive Summary

The Muon Detector Rotational Device (MDRD) is an effective solution to a delicate problem for our client, Chunyang Ding, a University of Washington physics department intern. Mr. Ding requested a machine that can rotate a set of four muon (subatomic particles) detectors 360 degrees on the horizontal plane and 90 degrees on the vertical plane as the logistics that went into turning the detectors by hand was inefficient and unreliable for academic research.

Our MDRD is divided into three main sections: the clamping system, vertical rotation system, and horizontal rotation system (with the support system integrated throughout).

The clamping system is a wooden shelving unit that keeps the muon detectors stacked in a parallel fashion. The purpose of the clamping system is to prevent shifting of the muon detectors (keeping them overlapped), safeguard against any damage that might be done during rotation, and keep the wires that protrude from the detectors from tangling. As such, the clamping system hosts the detectors which are held together securely by shelf clamps on both sides. PVC pipes face the same direction as the detectors so that the wires come out together and remain undeterred by rotation. Finally, a pillow block bracket at both ends holds together the shelves and prevents shifting of the detectors.

The vertical rotation system consists of the rack and pinion system. The gear wheel surrounds the clamping system and holds the shelving unit and detectors together. The gear contains 360 teeth (one for each degree), and rotates when pushed by a gear rack.. The gear rack contains 110 teeth (a little more than 90 just in case). A linear actuator which pushes the gear rack along a track, which will turn the gear wheel forwards or backwards, allowing it to tilt on the vertical plane. The rotary shaft that is connected to the pillow blocks and clamping system keeps the gear wheel rotating in place. It is the mere degree of accuracy necessary for the gear wheel and gear rack that makes the vertical rotation system the most expensive component of the MDRD. Fortunately, the one degree accuracy is a tertiary goal; expenses may be reduced by decreasing the degree accuracy to two degrees or five degrees, though for the purposes of academic research, one degree is preferential.

The clamping system is integrated into the vertical rotation system, which together is all mounted upon the horizontal rotation system. The horizontal rotation system consists of a turntable system that rotates everything above 360 degrees.The turntable consists of a small metal turntable with a plywood platform attached above it. Due to how much wider the plywood platform is in comparison to the metal turntable, the platform is supported by wheels move along a track carved on the very bottom platform, also made of plywood. This entire horizontal system is rotated by a handle that is removable from the metal turntable. The handle is adjustable in length--the longer it is, the greater degree of accuracy the user can turn the turntable. Screwing the handle into the metal turntable will stop horizontal movement. Nonetheless, we also recognize possible flaws with the current turntable: the handle might be fragile and angle measurements will be hard to determine. As such, we are working with Mr. Ding, and hope to gain a manufacturer’s opinion on these aspects.

Report Body

Section 1. Introduction

The Detectors

The QuarkNet project created by Fermilab is focused on this Cosmic Ray Muon Detector that is provided to students for experimentation. This generous grant allows high school and undergraduate students to engage in serious scientific work, from experimental design to data collection and analysis. The creation of this stand for analysis would be a crucial component in higher level experimentation, and also introduces engineering considerations to this physics experiment.

The goal of this stand is to allow the four scintillation plates to freely rotate along the zenith angle axis as well as rotate in three hundred and sixty degrees. The combination of these two axis of freedom allows the scintillator plates to track any stellar source, and allows for a student to perform precise experimentation on cosmic ray sources, as well as validation of the effect of the earth's magnetic field on the passage of muons.

These QuarkNet detectors provided by Fermilab are sensitive instruments that can detect the passing of muons. Muons are charged subatomic particles that are created as a result of high energy cosmic ray events in the atmosphere. By studying the flux of muons over time, experimentalists can better understand properties of the muon as well as properties of the cosmic ray sources. Building a precise stand, such as the one described in this report, would allow students to collect better data regarding the direction that the detector is aiming at.

An analogy for this stand is like a precise stand for a telescope. While the telescope may be very powerful and have a huge light gathering capacity, it is useless without a solid stand to sit upon. Without this stand, the telescope would not be able to track stars moving across the sky, or even consistently look at the same part of the sky. The same reasoning is in place for the Cosmic Muon Ray Detector stand. While the device already empowers students to perform amazing experiments, the building of this stand would open another dimension for study.

Through the creation and funding of a prototype of this project, many other high schools across the United States can develop similar designs. Not only is the stand a crucial part in performing experiments, so is the theory and engineering principles behind its creation. A major component of the QuarkNet project is allowing students to understand the principles of scintillation detection in radiation measurement. With the release of this open source engineering handbook for the stand, along with proof of a prototype, other high schools can become empowered to create their own models.

(A note from our client--Chunyang Ding)

Our Project

In October of 2014 our group was approached by Chunyang Ding. Mr. Ding is an intern in the physics department at the University of Washington. He proposed the creation of a device to house and rotate four muon detectors. Mr. Ding had the following specifications for the device:

1st Tier Specifications	2nd Tier Specifications	3rd Tier Specifications
● Rotate 360 degrees in the horizontal plane ● Rotate 90 degrees in the vertical plane ● Detectors are parallel and overlapping ● Detectors to not move other than rotation ● Chords from detectors do not tangle when the device rotates ● Rotate with an accuracy of 5 degrees in both planes	● Detectors are easily removeable ● Mechanized rotation in horizontal plane ● Mechanized rotation in the vertical plane ● Computer recording data attached to rotational system ● Rotate with an accuracy of 2 degrees in both planes	● Mechanized rotation is programmable for tracking celestial objects ● Rotates with accuracy of 1 degree in both planes

The first tier specifications represent the goals that we determined are necessary for the device, or primary goals; the second and third tier specifications are preferred qualities of the device, or secondary goals. The main goals were factored into the Muon Detector Rotational Device (MDRD) regardless of cost while the secondary goals were incorporated when viewed as efficient and cost-effective.

In this report, we will outline each component of the MDRD (horizontal rotation system, vertical rotation system, clamping system, and support system), how we arrived at that particular design, why it is the most effective solution, and what project goals it satisfies.

(Image Source: quarknet.fnal.gov)

Section 2. Horizontal Rotation System

The horizontal rotation system of the MDRD refers to the turntable, which includes the plywood platforms, wheels, metal turntable, and handle. The primary goal of the horizontal rotation system is to satisfy a first tier specification: rotate four muon detectors 360 degrees on the horizontal plane. Our secondary goals includes providing stable rotation of the entire system and rotating the detectors in one degree increments with minimal error, which are specifications in both the first and third tiers. All of these goals have been satisfied by our horizontal rotation system design.

Within one week of introducing the project to the class, there was a general consensus to use a turntable-like method for the horizontal rotation of the detectors--something similar to a Lazy Susan. However, this idea was approached with caution due to instability (particularly on the edges of the Lazy Susan) from uneven weight distribution. This idea would eventually be refined and develop into our current horizontal rotation system.

(Image Source: McMaster-Carr)

Finding an affordable turntable was easy; It was finding a method for stable rotation that was difficult. The metal turntable (above) which we decided to use consists of two rings which are punctured with bolt holes. The inner ring is slightly lower and remains stationary while the outer ring rotates. The overall diameter is only 12.8” (352.12mm) which is significantly smaller than the platform (diameter 1.2m) that will be needed to support the systems on top. This platform consists of plywood and will be bolted to the outer ring of the turntable. To solve this “Lazy Susan” problem with tilt in rotation, we conducted research to determine a method that would increase the stability of the platform as well as provide additional support for the platform.

(Image Source: Ben Teague, *How to Build a Revolve or Turntable*)

The above picture demonstrates the idea involving wheels. The wheels do not move but are placed underneath the platform and support rotation along a track. In our design, these wheels are represented by the dark blocks in between the top and bottom platforms of the turntable. The actual wheels are in the orthographic drawings of the components and the system. At first we intended to have the wheels turned upright as shown in the picture above. However, later, due to the incorporation of a handle that would move with the upper platform, we ended up turning the wheels back upright. This allows the handle to rotate with the wheels without needing to magically pass through the wheels.

The inclusion of the handle is necessary for a more efficient maneuvering of the turntable system. Nonetheless, it is still important to note that though it has been drawn and included within the Sketchup, the actual inclusion of the handle is optional--they are a luxury element. The purpose of the handle is to achieve our third goal: a one degree accuracy of rotation. The turntable would already guarantee rotation of the detectors 360 degrees on the horizontal plane but the primary question was how would Chunyang Ding, our intern and user, know how much he was rotating the MDRD. Of course the simple idea of ticks on the upper platform and angle measurements on the lower platform occurred to us initially, but the flaw to this idea was the mere diameter of the turntable platform. The turntable's radius is about 60cm, which would make the rotational distance between each degree *very* small. Though marking the angles would be too big of an issue, the real problem existed in accuracy. It would be difficult for Chunyang Ding to rotate the turntable accurately that small of a distance relying solely on the tick marks of the turntable. The inclusion of the handle, which would increase the radius of the platform without actually increasing the diameter of the platform, would thus increase the rotational distance for one degree at the end of the handle. Thus, Chunyang Ding would be able to provide a more accurate measurement of one degree by pushing the turntable at the end of the handle rather than turning the turntable using the plywood.

Unfortunately, the handle also has a few design flaws and thus, is still considered an optional component of the design. It is unsure where angle degrees will be marked because the handle protrudes beyond the bottom platform. Currently it appears that the user will need to rely on angle markings along the edge of the turntable, which might be difficult to see at the full length of the handle is 3'11" (1.2m). Furthermore, the thickness of the pin, which screws into the metal turntable, and the thickness of the handle are regions of potential stress fractures due to torque. This extreme torque comes from the considerable amount of friction which has to be overcome to allow the turntable to rotate. The immense friction is a result of the turntable supporting a weight of 190 lbs (845 N). The total force of static friction which must be overcome for this design is thus 114 lbs (507 N). This force requires a torque of 449 ft×lbs (609 N×m) to overcome static friction. The inclusion of the handle is a low priority as it accomplishes a tertiary goal: easier rotation and a higher degree of accuracy in horizontal rotation. Additional strategies to fix issues with the turntable handle might be tackled later on in the manufacturing process.

Overall, the purpose of the horizontal rotation system is to allow for the muon detector system to rotate 360 degrees with an accuracy of 1 degree. Through trial and error, targeting and problem solving, our decisions have resulted in a system that is both stable and accurate. The horizontal rotation system will be capable of supporting the rotation of the weight upon the entire system with an accuracy of one degrees.

Section 3. Vertical Rotation System

The vertical rotation system of the MDRD refers to the rack and pinion system, which includes the gear wheel, gear rack, drawer slides, and linear actuator. The primary goal of the vertical rotation system is to satisfy a first tier specification: rotation of the detectors 45 degrees in both the positive and negative direction on the vertical plane. Additional features of the vertical rotation system is aimed to satisfy secondary goals, such as rotation to a one degree accuracy and mechanization. As with all systems, an underlying theme to the design of the vertical rotation system is the safety of the detectors.

Our final design for the vertical rotation system was derived from a series of arguments and brainstorms in the beginning of our project. Concepts were sought from practical experience and everyday ideas such as clocks, ferris wheels, swings, and pendulums. Possible alternative solutions to our design to the vertical rotation system included a large sphere that would hold the detectors and would rotate on a ball bearings holder, looking kind of like a kugel ball (like the one below):

(Image Source: waymarking.com; image of Disney World's Tomorrowland Kugel Ball)

Other ideas included inserting the muon detectors into a cylindrical holder and allowing the cylinder to roll in one direction or the other. These speculations were the result of two weeks of debate when the project was first introduced in October to our IB Design Technology classroom. As a small group of four that eventually broke away from the class, our responsibilities included considering these ideas as plausible and how we could possibly modify them.

Each of these initial ideas have their own design flaws. The spherical ball that rotated on ball bearings lacked control in rotation and accuracy in angle measurements. The cylindrical roll required an extensive support system that would increase the cost of our project trifold. With both concepts and limitations in mind, we sought a solution that would be able to capture the advantages of each original idea and combine them in an efficient manner that would minimize the design flaws.

Building off of the cylindrical roll idea, we tried first to reduce the amount of material needed. Because having both the cylindrical roll system and clamping system was slightly repetitive, the original design would require twice the material and twice the cost. In order to combat this, we reduced the cylindrical roll to one gear wheel and changed the bottom holder into a helix gear, resulting in a worm gear system (similar to the one in the image below). (The spherical ball system was scrapped because of the crucial problem with inaccuracy.) A 360 tooth gear wheel would surround the clamping system that held the detectors and could rotate/roll in one direction or the other. A "worm" or helix gear would be pushed and rotated by a linear actuator on the bottom of the gear wheel and propel the gear's movement.

(Image Source: vitalengg.com)

While the worm gear worked at first, we found it too expensive to construct a helix gear that could correspond to the size of each gear tooth. In addition, we also had trouble finding a motor that would be able to push rotate the worm gear accurately. The helix gear provided no means of measurement for each degree rotation. To fix this problem, we exchanged the helix gear for a linear actuator that would simply push the gear rack with teeth corresponding to the gear wheel, turning the gear wheel with a measurable accuracy. This rack and pinion idea is the one integrated in our design.

Though we know that the rack and pinion system will work, we struggled with the positioning of its components. We needed a mechanism for the gear rack to slide on, a way to attach the linear actuator, and proper and efficient placement of the linear actuator and the rack system. According to the first tier specification, the vertical rotation system needs to rotate 45 degrees in both directions on the vertical plane. Since the gear wheel has one tooth per degree, the gear rack would thus need at least 90 teeth to fit with the gear wheel. Based on the measurements for the teeth, (and also because we made the gear rack 110 teeth just in case), the gear rack would be about 55**cm** long or about two feet. This means that the linear actuator would need to be able to push about 12" in both directions. To satisfy this, we've found a linear actuator that can push and pull 24". At neutral, the linear actuator would be extended 12" and would be able to push forward another 12" to rotate a minimum of 45 degrees in one direction, and retract fully (entire 24") to rotate a minimum of 45 degrees in the other direction. We have found simple tracks or drawer slides that could easily slide our gear rack back and forth. Since the gear rack was rather thin, a wood buffer underneath (as seen in Figure 1.A) could be added. Our main issue resided in positioning the gear rack and linear actuator at full extension: the total length of the gear rack and the linear actuator would be about 54", a length that would not only not fit on the plywood platform, but also if positioned so that some of the gear rack would stick out off of the platform, it would still be centered with the gear wheel. If the center of the gear wheel is positioned over the center of the plywood turntable (meaning that at neutral, there would be 12" of the gear rack in both the positive and negative direction), and if the linear actuator were to be in line with linear movement of the gear rack (and extended 12" at neutral position), this meant that the radius of the platform would need to be at least 30", or about 77cm, much greater than our anticipated 60cm radius. In addition, keeping the linear actuator in line with the gear rack would cause the the center of gravity to shift to one side of the turntable, which could result in tilting, inaccurate turning, and friction that would wear out the turntable over time.

To combat this issue, we positioned the linear actuator offset, moving parallel to the gear rack, the body of the linear actuator near the center of the turntable, as seen in our final design. Now, the center of gravity of the turntable would be closer to the center of the turntable, thus maximizing stability in our entire structure. Furthermore, now, the linear actuator and gear rack system could slide to full length without going off the edge of the turntable. The only issue with this positioning of the linear actuator is the possibility of the gear rack shearing or twisting from its straight path, which would not only threaten the integrity of the angle rotations but also the stability of the gear wheel and detectors. This problem had a rather simple fix: the addition of two slide brackets, one on the side of the linear actuator and the other on the side of the gear rack (see Figure 1.A). These brackets now secured the path for the gear rack and ensured stability in movement.

It is thus with subtle design alterations and additions that we arrived at our final vertical rotation system. The rotation system as it is now is the result of compilations of original ideas and problem solving along the way. Through this method of constant questioning, we were finally able to produce a system that would satisfy the specifications of the MDRD: rotation on the vertical plane to a one degree accuracy. However, it is important to note, also, that currently, the size of each tooth is very small--about half of a millimeter--due to the great amount of teeth. The tiny size of each tooth could result in high cost and low accuracy. Though have an angle rotation to the one degree accuracy is preferred, it is possible that we might decrease the accuracy for mechanical and financial reasons.

Section 4. Clamping System

The clamping system of the MDRD refers to the shelving unit that hosts the array of muon detectors held together by pillow blocks. The clamping system is composed of plywood shelves in which the detectors can be aligned and fitted within. The primary goal of the clamping system is to satisfy the first tier specification of maintaining the muon detectors in a stacked position so that detectors are always overlapping. In addition, the clamping system also aims to provide stability in the muon detector system.

When the project was first introduced to our class, it was emphasized that some means of holding the muon detectors together without applying stress or damaging. Initial designs for the MDRD often excluded the clamping system in the beginning, either by combining the system with the vertical rotation system or simply using belts to latch the detectors together. The cylindrical MDRD idea, for example, (**Figure 3.B**) intended to integrate the clamping system with a cylindrical shell. These designs failed to consider the shape, size, and stability of attachment of these rather fragile detectors. As such, each initial idea had its flaws: strapping the detectors with belts deemphasized stability and ignored fragility of the muon detectors and the cylindrical MDRD neglected to consider the placement of the PVC pipes that were a part of the muon detectors and the wires that protruded from them. Similar problems also arose in our other brainstorms like the spherical MDRD idea, the windmill idea, etc.

The final clamping system design has two trapezoid shelving units customized to fit either side of the PVC pipes of the muon detector stack. These wooden shelves would take into account the weight distribution of the muon detectors, the stability of the system as a whole, and the durability of the muon detectors. An optional feature for the clamping system would include a soft balsa buffer between the hard wood shelf and the detectors and would provide cushion to the movement of the detector and prevent scratching on the detector surface. This shelving unit would allow the muon detectors to gently rest while remaining steadfastly clamped.We chose not to fix the PVC pipes that extended from the detectors in place due to the possibility of damaging the wires and microchips within it, which is why there are two triangular/trapezoid shelves on either side of the PVC pipes on the stack of the muon detectors. The trapezoid blocks are secured together by a pillow bracket (from which the rotary shaft extends from), or the gray bracket in Figure 1.A, and secured by fitting into the gear wheel.

Thus, in our final design, the muon detectors would be stacked directly above each other and held together by two shelving units on both sides of the PVC pipes. Our system would satisfy three of our first tier specifications: the clamping system would ensure that detectors are parallel and overlapping at all times and provide a stability so that the only purposeful movements are made. Lastly, the positioning of the muon detectors in our system would keep the cords protruding from them together and thus minimize tangling. Our final clamping system is thus the conclusion of countless debate and the most efficient solution to our problem.

Section 5. Support System

Unlike the other sections, the support section is not a specific, physical part. Rather, the support system was conceived through our problem-solving process and is integrated all throughout our design. The purpose of the support system is to provide cost and material efficient stability throughout the entire design. The main components of the support system include two wooden pillars, rotary shaft, turntable wheels, and any brackets placed throughout the design.

Throughout our design process for the MDRD, checkpoints would be made at the completion of each system, at which we would predict weak regions, stress fractures, shearing, etc. and other stability issues that could possibly arise in our design. Unfortunately, we do not have CAD, so our predictions are based on speculations rather than computerized accuracy of calculations in tensile strength, weight, force, etc. of our materials. As such, it must be taken to note that there are no doubt problems that we have missed and problems that we have exaggerated. We will now offer a breakdown of different aspects of the support system that have been littered throughout the entire system.

The vertical wooden pillars on either side of the gear wheel (see Figure 1.A) is considered part of the support system despite its necessity to the vertical rotation system. The vertical wooden pillars allow for the distribution of weight from the clamping system and gear wheel, thus decreasing the amount of torque needed to push the gear rack and turn the gear wheel. The vertical wooden pillar require brackets on the bottom for added stability and might be thickened for greater support if necessary.

The vertical pillars are connected to the gear wheel and clamping system through the rotary shafts. The rotary shafts extend from the pillow blocks on the clamping system. This shaft allows for the gear wheel to rotate in place on the vertical plane rather than rolling away like a wheel. Furthermore, its connection to the vertical pillars distribute the gravitational force of the clamping system and gear wheel. Since the pillow blocks are made out of steel for greater support, to avoid impurities when welding them together, the rotary shaft will also be made of steel.

In addition, we have also employed brackets along the linear actuator and the gear rack. The purpose of these metal brackets are to ensure for the straight movement of the gear rack. Its inclusion is because the linear actuator is positioned offset the direct linear movement of the gear rack, which threatens sideways shearing, and the brackets would keep the gear rack and linear actuator in place while moving. Its inclusion is essential because sideways pull of the linear actuator on the gear rack threatens the stability of the wheel and the muon detectors.

These little aspects, which have been integrated throughout other systems, like the vertical and horizontal rotation system, make up the support system, and satisfy the goal to provide stable rotation for the safe and easy use of the MDRD.

Section 6. Budget and Costs

Figure 6 provides a tabular summary of the figures, parts, and estimated cost of each part. This section will be used to simply to provide a couple notes on the budget. It is important to note that the cost that is listed is an estimation--actual cost can vary higher or lower (most likely higher) due to custom made products, labor, and other manufacturing expenses. Furthermore, the estimation of cost for bolts and screws will most likely be higher than $5 in each category.

The most expensive component of the MDRD is the gear wheel (and subsequently, the gear rack as well). This is due to the degree of accuracy and tiny size of each tooth being carved upon a metal ring. This design requires custom manufacturing--either with the help of professional manufacturers or attempts (by ourselves) using plasma cutters or laser cutters. The issue with manufacturing the gear wheel ourselves is the risk of inaccuracy. As such, we would prefer to rely on a professional gear manufacturer to produce our gear wheel.

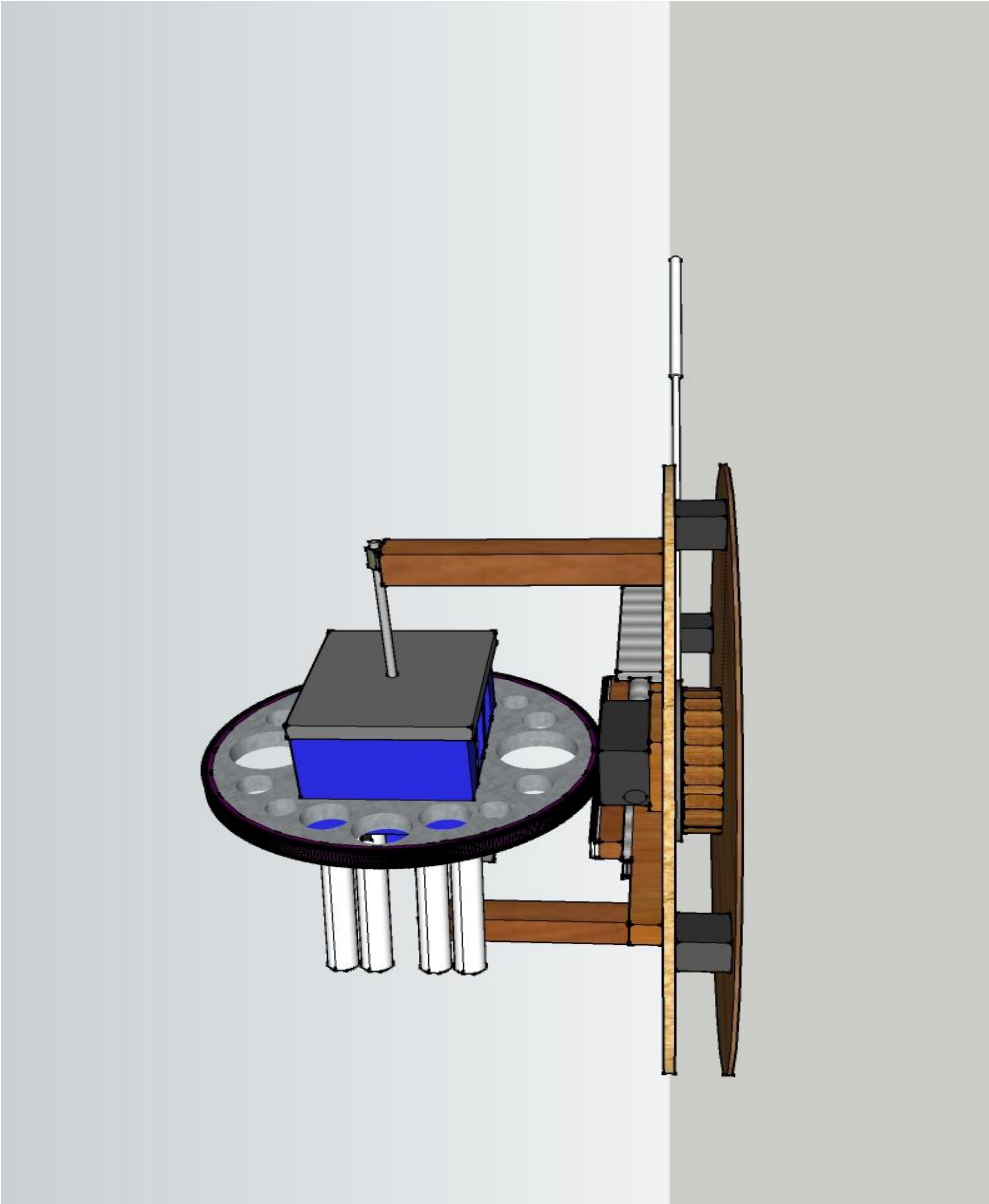
If necessary, however, cost of the gear wheel can be reduced by increasing the degree accuracy that we are turning at. The one degree accuracy is a tertiary goal, and thus not priority. Costs can be decreased significantly by decreasing the angle accuracy to two or five degree accuracies. Nonetheless, this would compromise the effectiveness of data analysis from the MDRD.

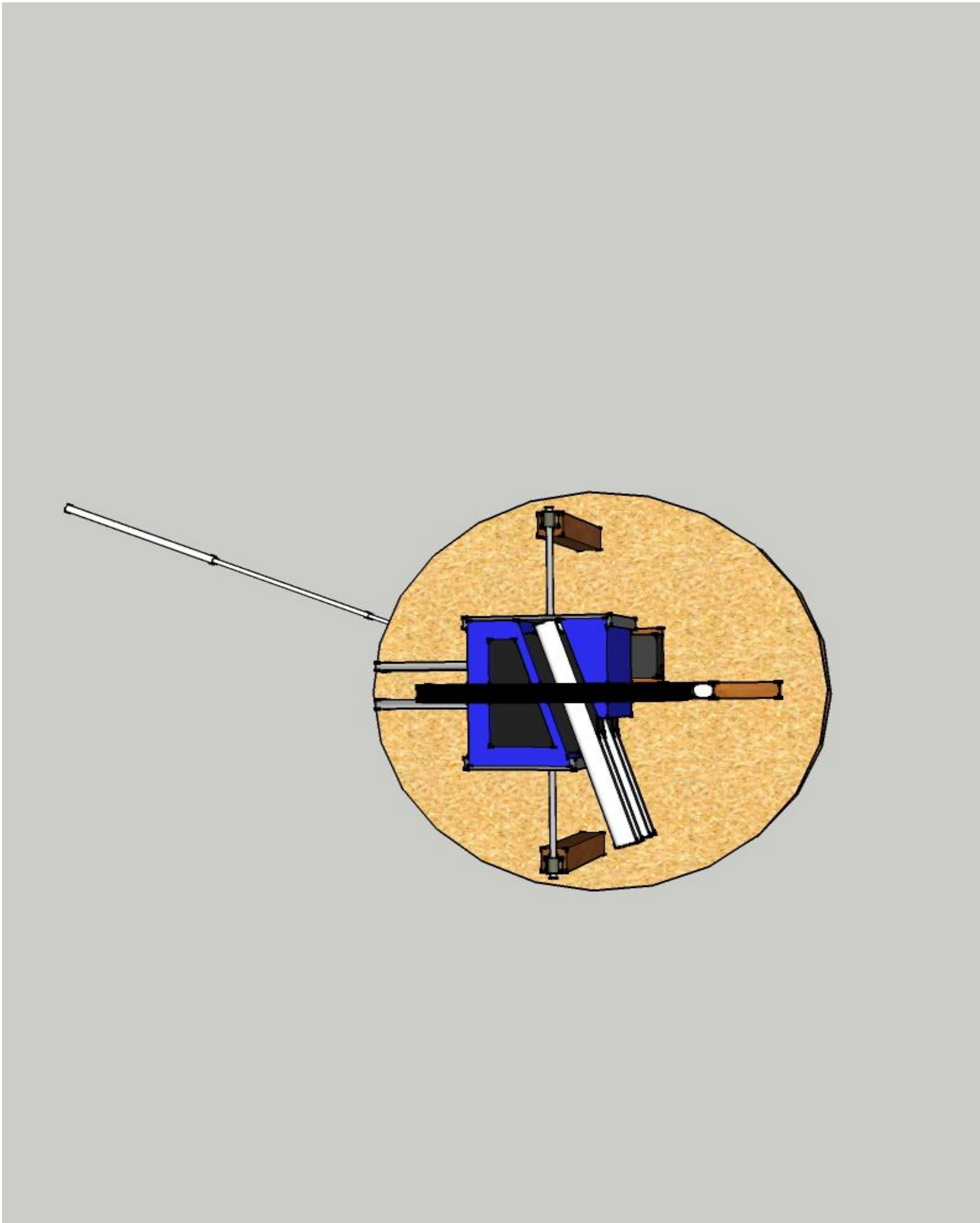
Conclusion

Overall, the Muon Detector Rotational Device is a carefully designed, mechanized product with a main purpose to support an array of muon detectors in a variety of positions. As specified by Chunyang Ding, the MDRD will host a total of four detectors, stacked together in a wooden clamp. The MDRD will be allowed to rotate vertically, 45 degrees in both directions, and 360 degrees in the horizontal direction. The entire device will weigh an approximate 190 pounds. The MDRD will be allowed to rotate vertically through the use of a large gear wheel, with the clamping system hosted within, and a gear rack pushed by a linear actuator. The MDRD that we currently have designed is the most effective and cost efficient design possible in consideration to the goals set by our client, Chunyang Ding.

Appendix

Figure 1.A: Chunny Sensor Sketchup





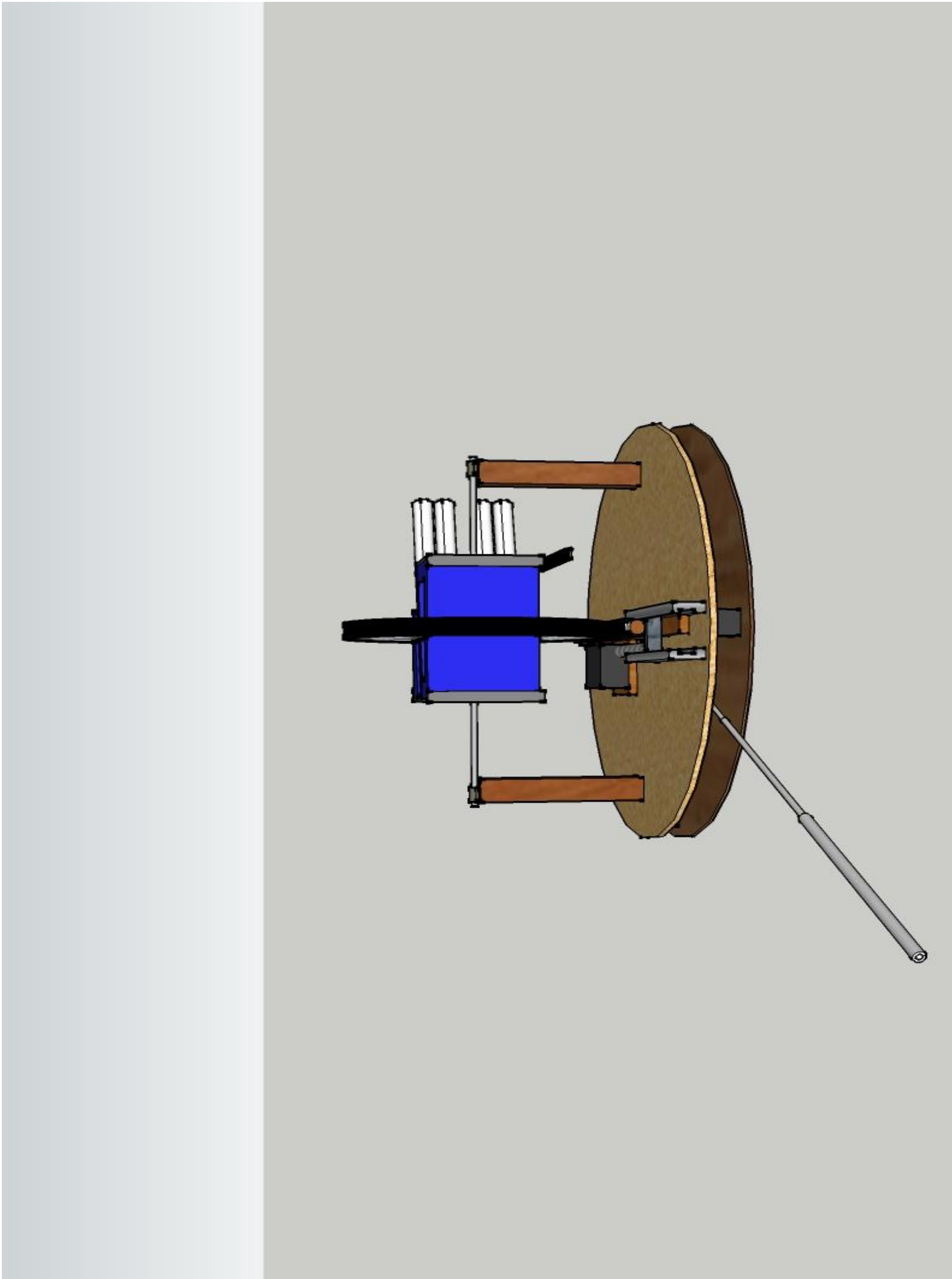


Figure 2.A: Turntable Top Layout

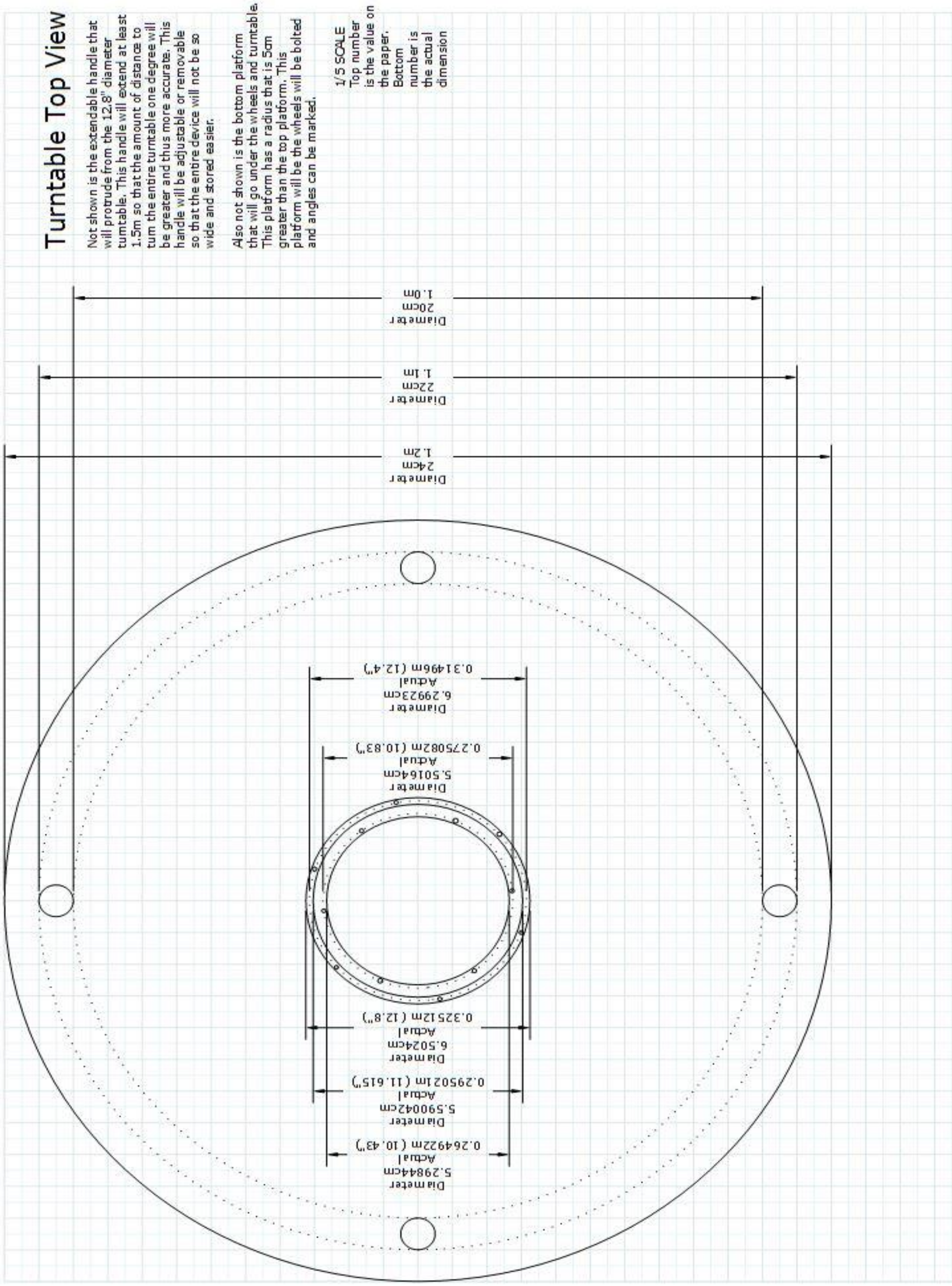


Figure 2.B: Turntable Side Layout

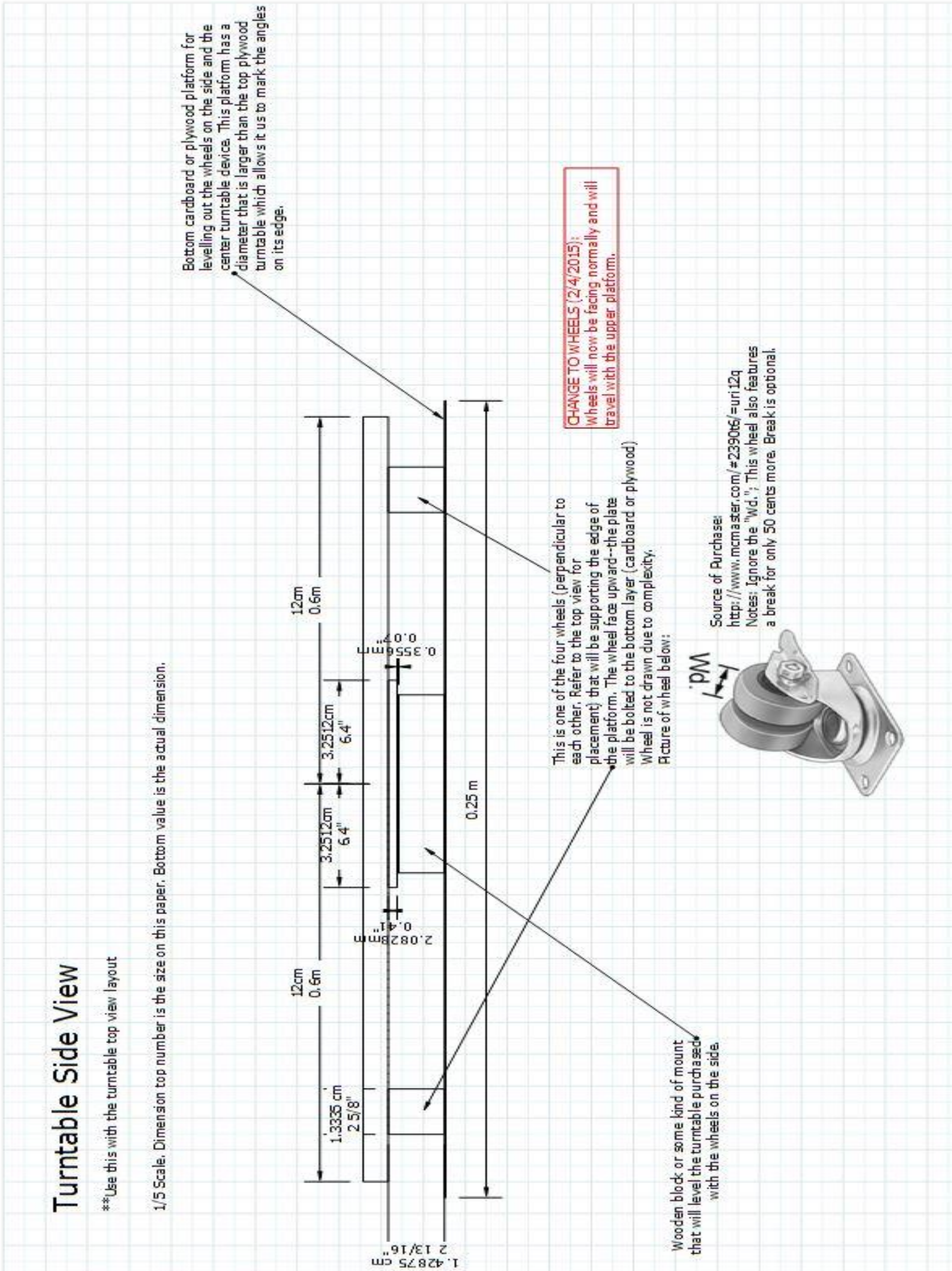


Figure 3.A: Rack and Pinion System

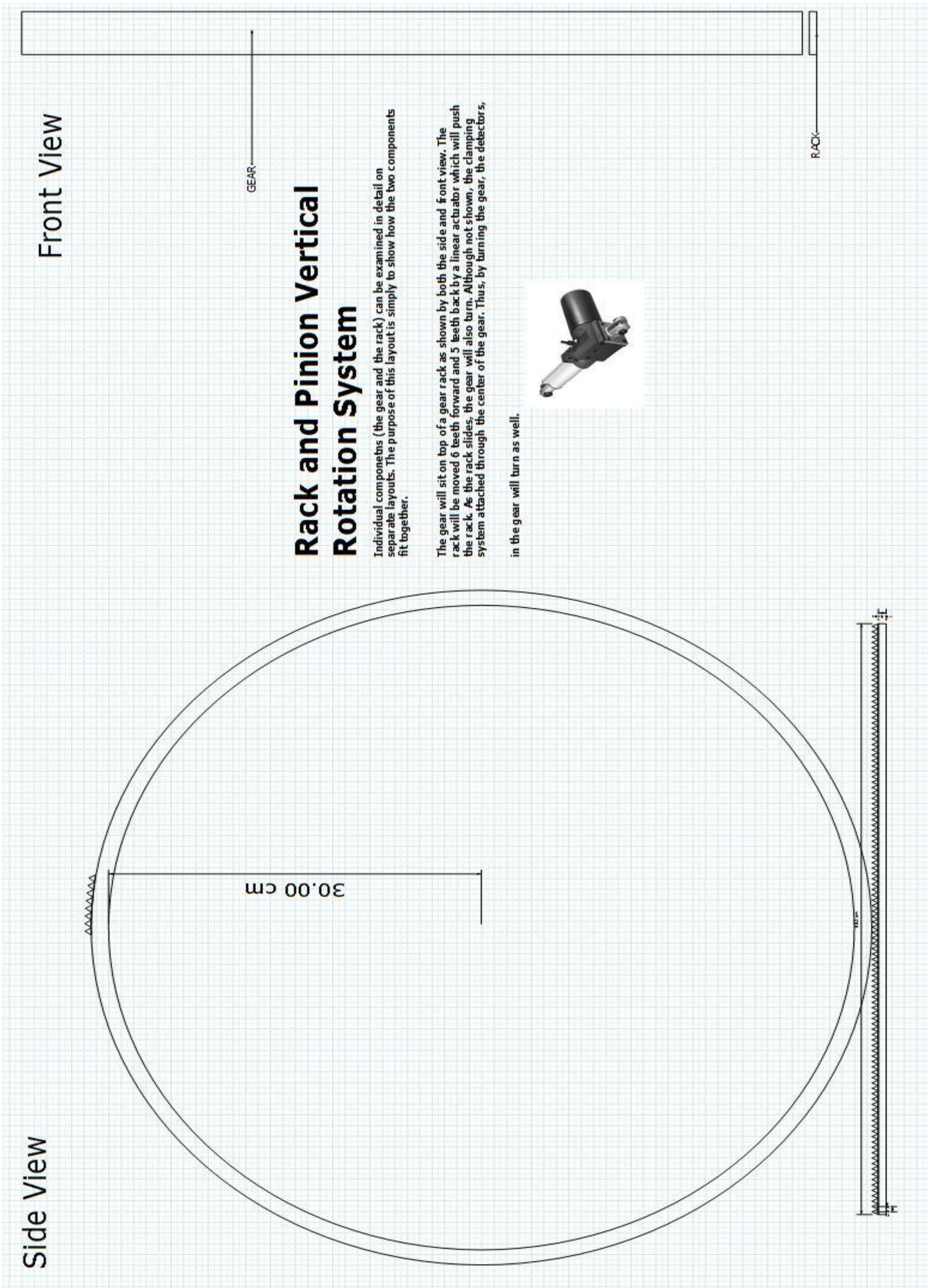


Figure 3.B: Gear Wheel

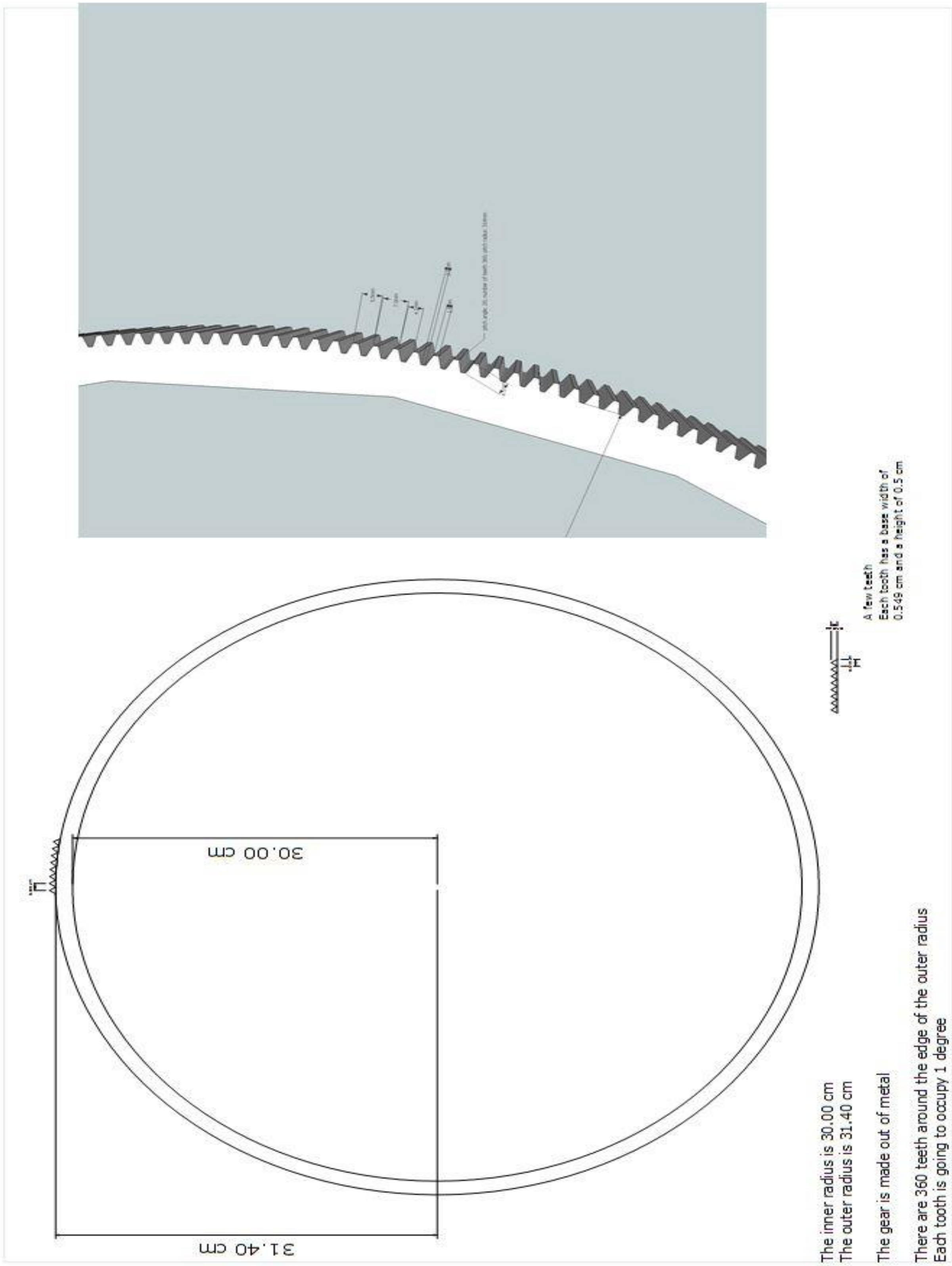


Figure 3.C: Gear Rack

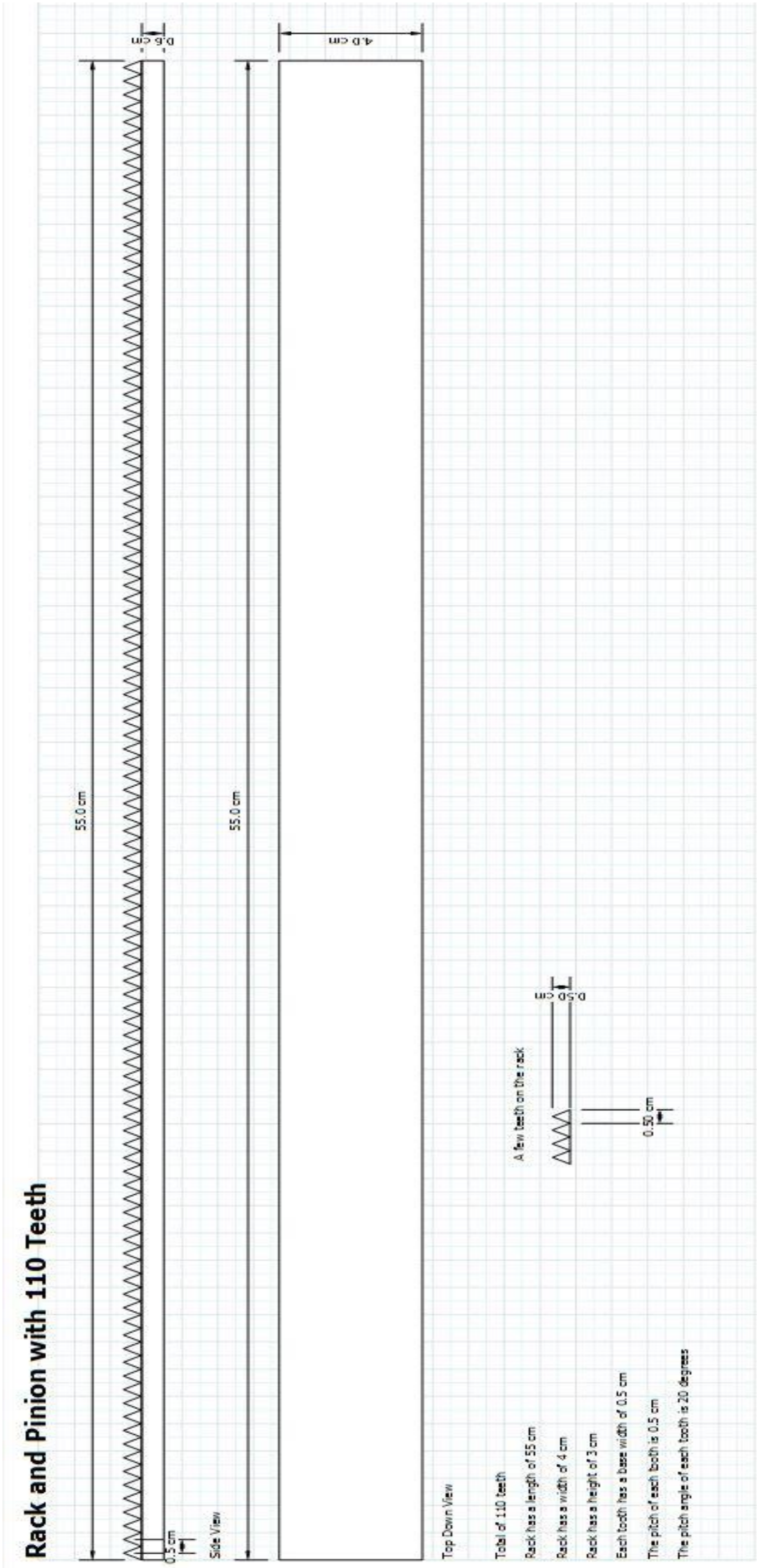


Figure 4.A: Clamping System (Larger Trapezoid Side)

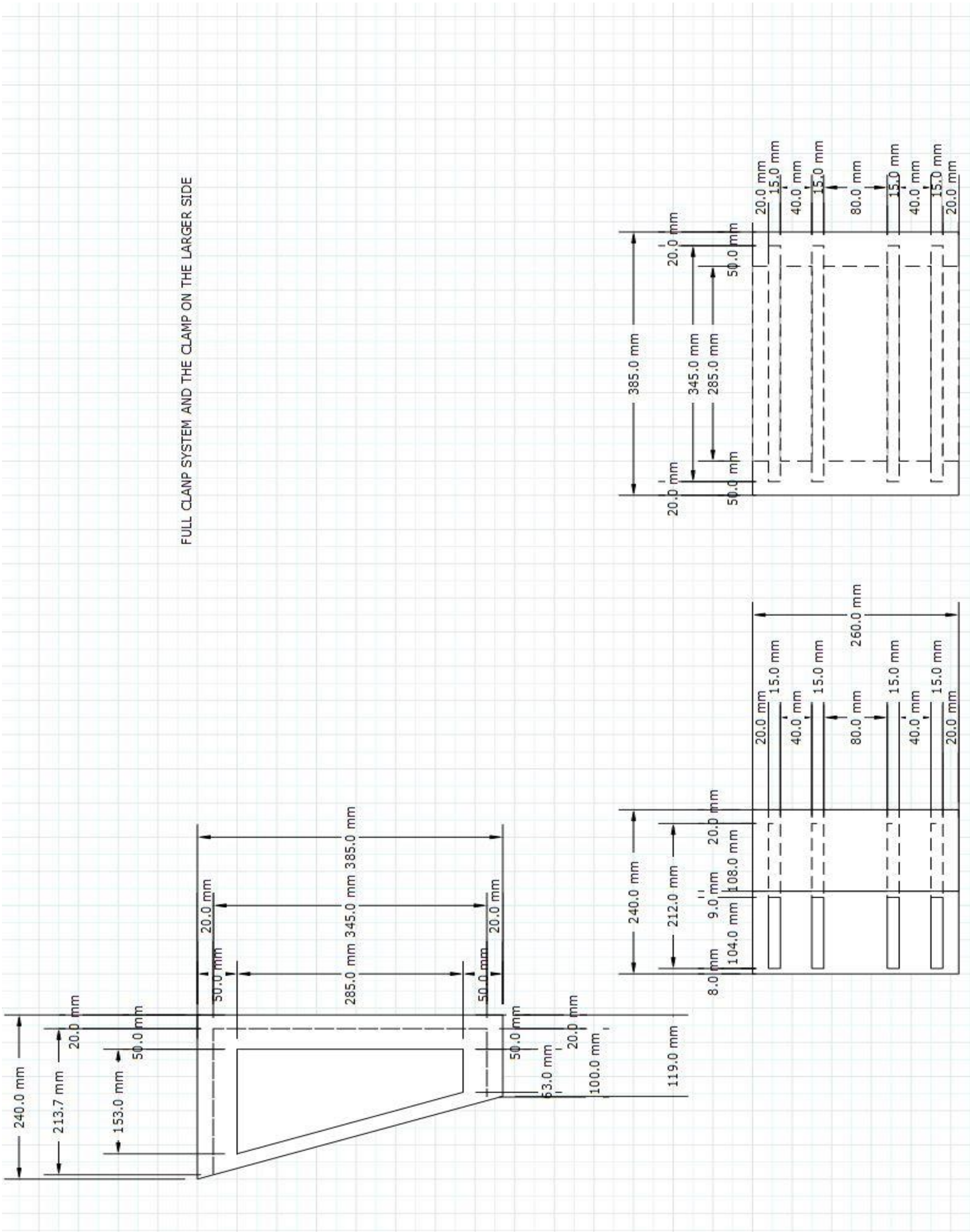


Figure 4.B: Clamping System (Smaller Trapezoid Side)

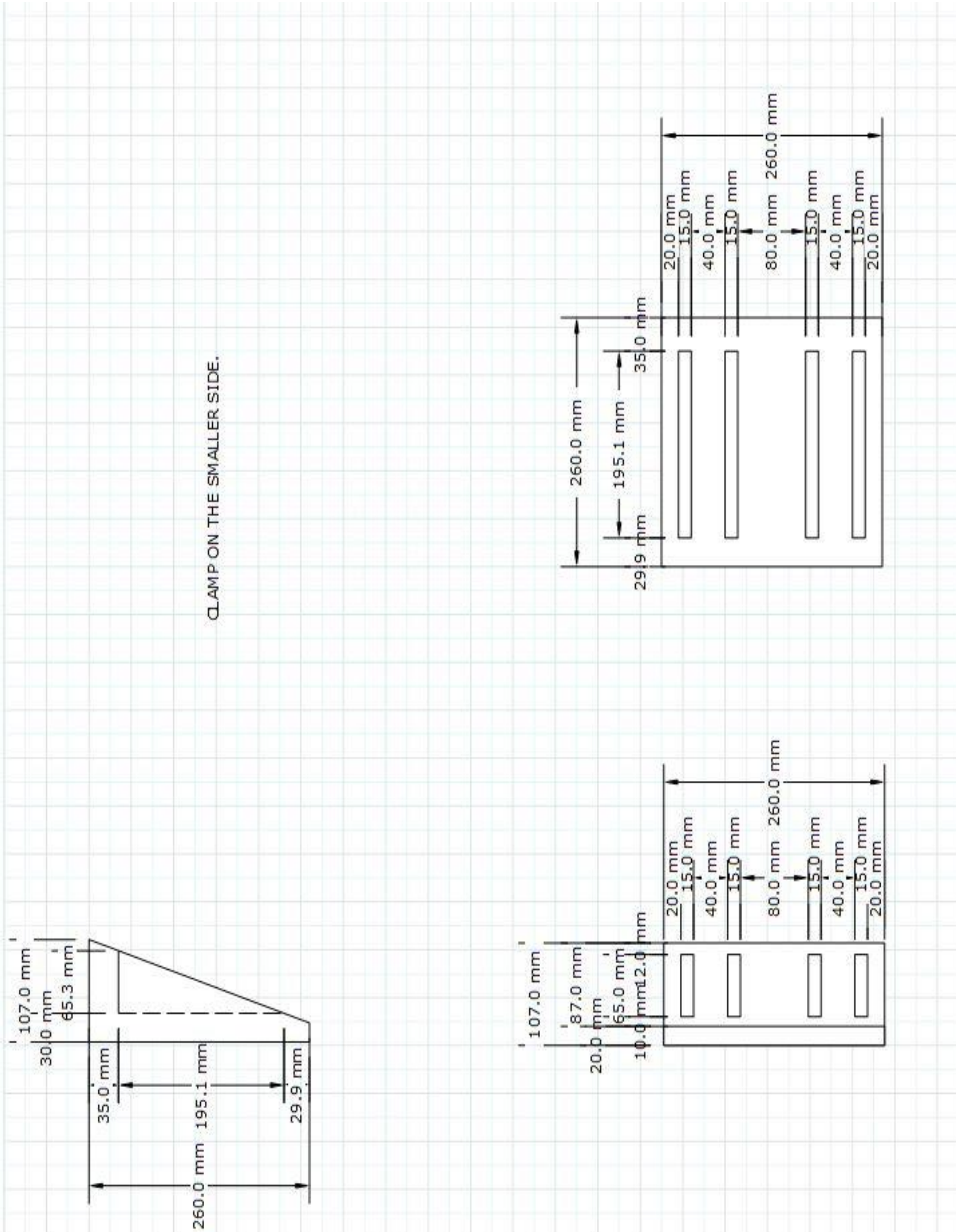


Figure 4.C: Pillow Block on Wide Side

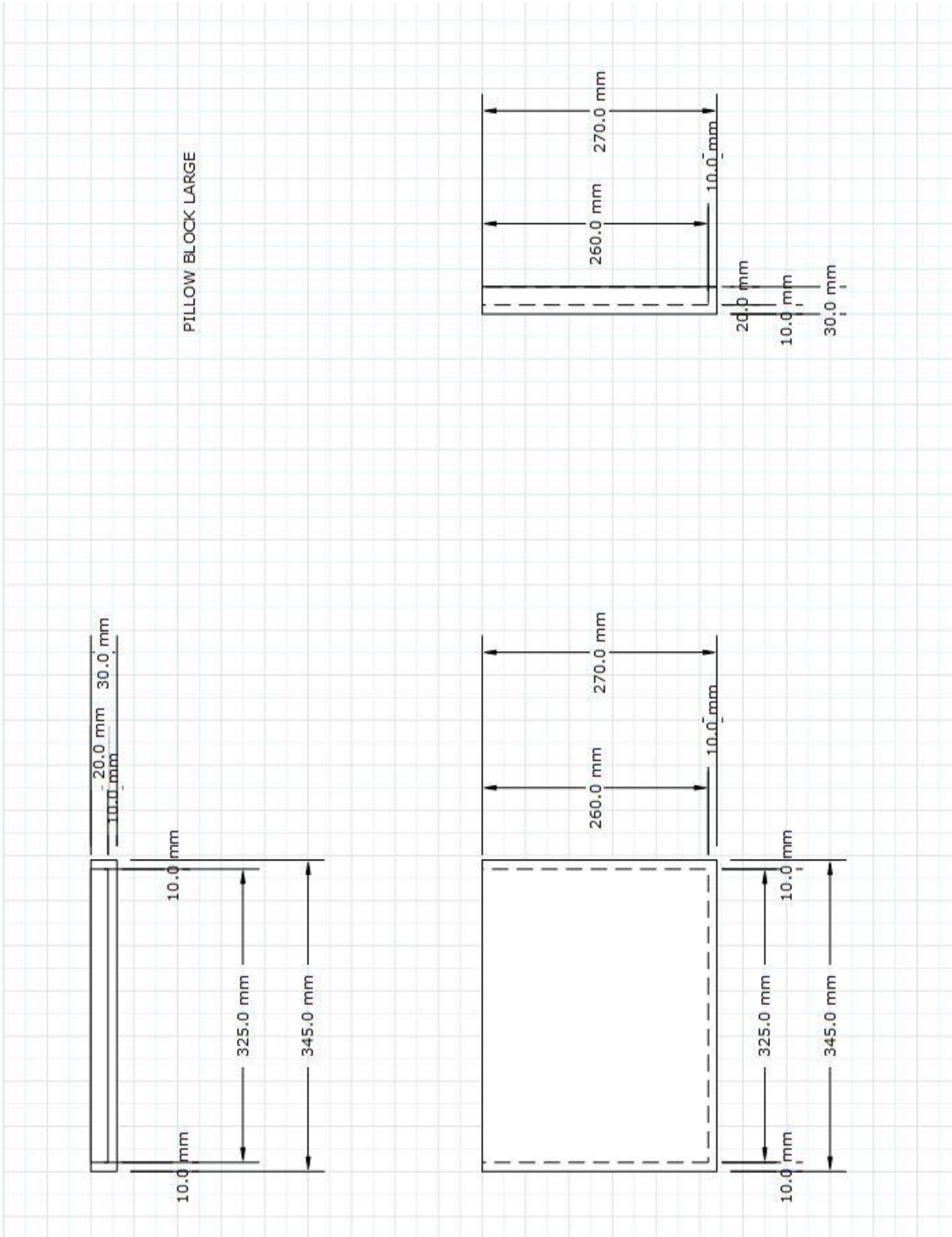


Figure 4.D: Pillow Block on Small Side (With PVC Pipes)

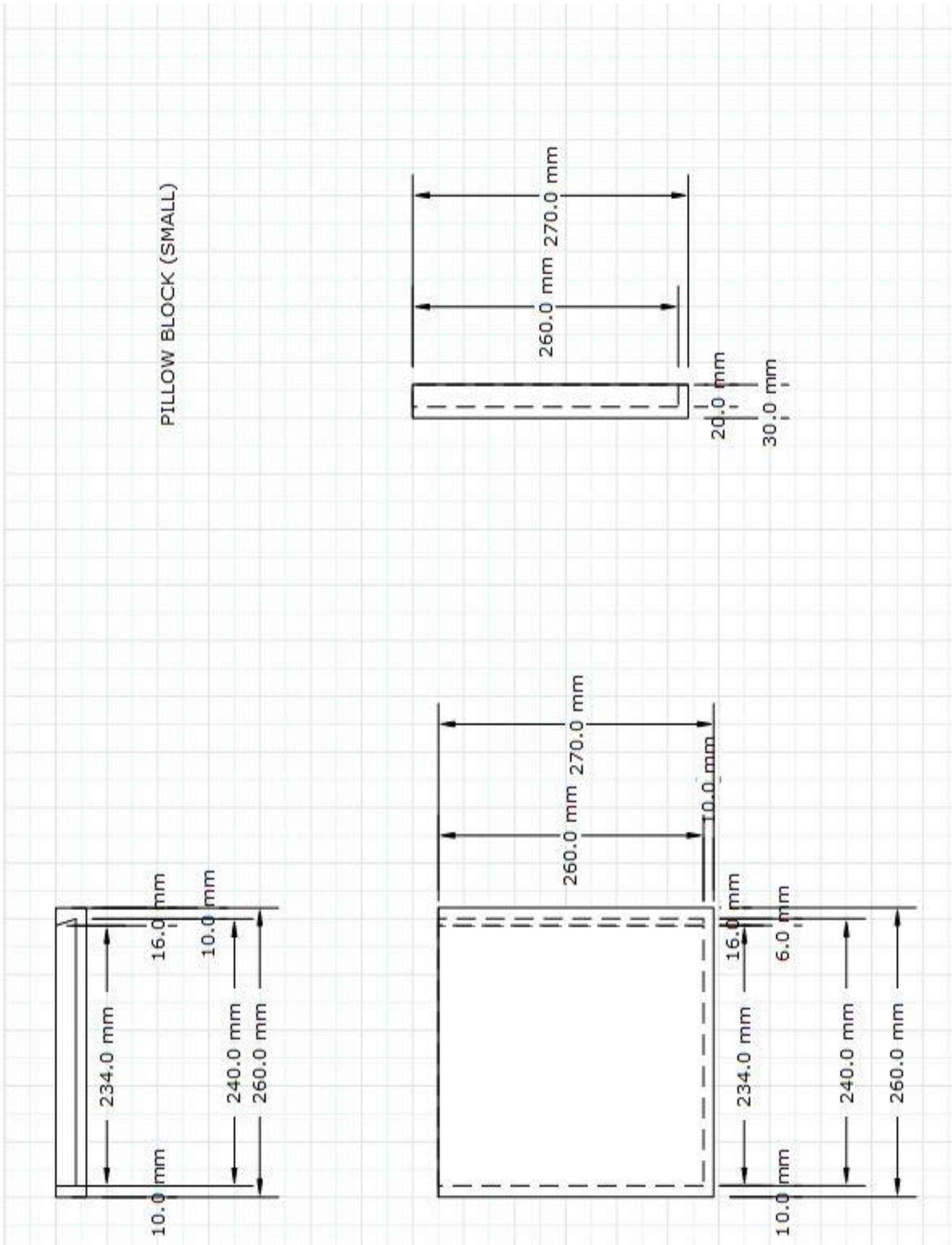


Figure 6.A: Table of Numbers

Material and Estimated Cost Sheet for UW: Project C.R.O.D. (Chunny's Rotating Object Detector)

System Component			Material Used	Metrics	Amount	Cost ($)	Weight (lbs)	Weight (kg)	Weight on Top of Platform	Source (url)
Sensors	Muon Sensor	Muon detector	Premade	None	4	$0.00	16.00	7.25748000	7.25748000	Chunny
Clamping	Wood Holder		Pine	38.5cm x 26cm x 25cm	1	$10.00	0.03	0.01188470	0.01188470	
	Pillow Brackets		Steel		1	$102.08	32.21	14.61105000	14.61105000	
Vertical Rotation System	Gear Disk		Plywood	30cm radius, 4cm thickness	1	$0.00	0.00	0.00000000	0.00000000	http://www.homedepot.com/b/Lumb
		Metal Gear Ring	Steel	32cm radius, 4cm thick, 0.5582222cm pitch, 360 teeth, 20 degree pitch angle; with the holes	1	$191.40	117.24	53.18018220	53.18018220	
	Gear Rack	Gear Rack	Steel	60cm or 24" (length) x 4cm (width), 0.5582222cm pitch, at least 100 teeth, 20 degree pitch angle;	1	$82.13	4.25	1.92696800	1.92696800	
		Block to increase thickness of gear rack	Pine	24" or 0.6098m (length) x .04m (width), 0.034m (height)		$10.00	0.00	0.00041466	0.00041466	
Horizontal Rotation System	Turntable	Platform	Plywood	1.2m Diameter; Thickness = 3/8"	1	$20.00	14.96	6.78400000	6.78400000	
		Metal Turntable	Premade		1	$36.16	9.28	4.20896000	4.20896000	http://www.mcmaster.com/#1863
		Wheels	Premade		4	$34.82	0.00	0.00000000	0.00000000	
		Block to Level Platform	Wood			$15.00	0.00	0.00000000	0.00000000	
		Lowest Platform (under wheels)	Plywood or Cardboard			$10.00	0.00	0.00000000	0.00000000	
	Linear Actuator	Linear Actuator	Pre-Made	24" length, .52"/s, 400lbs push/pull, 12 VDC	1	$162.83	6.11	2.77145000	2.77145000	http://www.amazon.com/Progressiv
		Block to Level Actuator	Pine				0.00	0.00026244	0.00026244	
	Drawer Track	Drawer Track (Premade)	Steel	bottom slide 24"; top slide 12"		$8.25	0.53	0.23840000	0.23840000	http://www.mcmaster.com/#11435a
		Square Bracket	Chrome Plated Zinc	Size and Material will vary because of how close the linear actuator will be attached to the gear rack		$7.97	0.00	0.00000000	0.00000000	http://www.mcmaster.com/#1755a5
		Block to Level Track	Pine				0.00	0.00066968	0.00066968	
	Central Support Rod (1/2" rotary shaft)	1/2" rotary shaft	Steel	1/2" diameter; 0.3m length	2	$0.00	1.32	0.59657000	0.59657000	http://www.mcmaster.com/#rotary-s
		1/2" rotary bearings	Metal	1/2" diameter	2	$0.00	0.00	0.00000000	0.00000000	http://www.mcmaster.com/#3813t1
	Supports (Pillars)		Pine		2	$20.00	0.00	0.00156000	0.00156000	
	Laptop Stand		Plywood		1	$0.00	0.00	0.00000000	0.00000000	http://www.homedepot.com/b/Lumb
Fasteners	Bolts		Metal			$5.00	0.00	0.00000000	0.00000000	
	Screws		Metal			$5.00	0.00	0.00000000	0.00000000	
	Nuts		Metal			$5.00	0.00	0.00000000	0.00000000	
SUMS						$725.63	201.92	91.58985168	87.38089168	