Catching Cosmic Rays

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In the early twentieth century, cosmic rays served as the biggest source of high energy particles for high energy physicists. Today, these cosmic rays still serve as a fundamental source for experimentation, but technological advancements have opened the door for studies at much higher center of mass energies. One such technological advancement is the Silicon photo-multiplier (SiPM). Because the SiPM is capable of detecting single photons, one can pair a SiPM with a scintillator block to construct a simple particle detector. With a proper readout board, such a detector could be used for a project design class. Such a board would need ease of programming, ease of conceptual understanding, and room for further development. Here, we describe the development of such a board to use in an undergraduate laboratory.

I. INTRODUCTION

Since their discovery, cosmic rays have given us a glimpse into the unknown outside of our planet. In 1912, Victor Hess found a significant relationship between altitude and the rate of ionizing radiation in the atmosphere. As he ascended, he noted that his electroscope would discharge more frequently. This observation led him to conclude that higher levels of altitude had higher levels of radiation. Eventually in 1936, he was awarded the Nobel Prize in physics for the discovery of cosmic rays. Later, this radiation was found to come in different *forms* with varying mass and charge. The discovery of the muon and the positron came from studying these cosmic rays. Many physicists agree that this was the birth of what is now refereed to as particle physics.

A. Cosmic Rays

When discussing cosmic rays, it is important to note the two different *types:* primary and secondary. Primary cosmic rays are the "emissions from space." These particles typically consist of hydrogen and helium nuclei (see FIG.1). These particles originate from high energy sources in space such as supernovae, black holes, and pulsar stars. When these particles hit the Earth's atmosphere, a showering of particles will occur (see FIG. 2). The products of this shower are referred to as secondary cosmic rays.

Primary Cosmic Ray Composition		
Hydrogen Nuceli	Helium Nuclei	Heavy Nuclei
89%	10%	1%

FIG. 1. Typical composition of primary cosmic rays.

Compared to primary cosmic rays, secondary cosmic rays have a much wider range in their typical composition. Their composition depends on both the mass of the primary ray, and it depends on the particle in the atmosphere that the primary ray collided with. As seen in FIG. 2, there are several possibilities for secondary cosmic rays. However, one can also see how most of the secondary cosmic rays (such as the pion and kaon) are too short-lived to actually reach the surface of the earth. Thus, their decay products are what will actually be detected when using our particle detector.

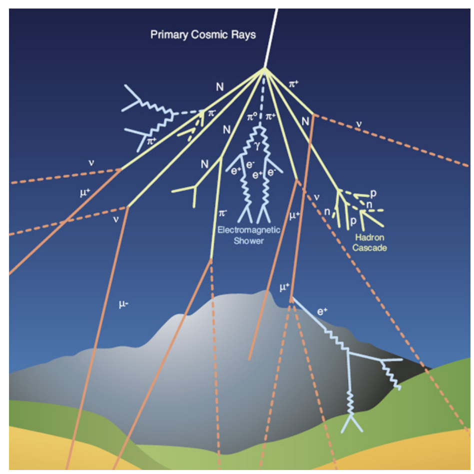

FIG. 2. Cosmic Ray Diagram

B. Cosmic Ray Decay

Most secondary cosmic rays have a short life which forces us to examine their decay products. These decay products will need to have a long enough time to reach the surface of the earth so our detector can actually pick them up. To demonstrate the behavior of cosmic ray decay, we will use pions and kaons as basic examples.

Secondary Cosmic Ray Decay		
Pion Lifetime (ns)	Kaon Lifetime (ns)	Muon Lifetime (ns)
26.033	12.38	2196.98

FIG. 3. Proper lifetime for pion, kaon, and muon.

Pions and kaons are two examples of the many particles that can be produced during the collision event. However, these particles are short-lived (see FIG. 3) with lifetimes less than $30ns$. Due to their short lifetime, it is necessary to examine some of their typical decay products.

The typical decay for a muon is depicted in FIG. 4, here one can see that the the decay products are a muon (μ^+) and a neutrino. The lifetime of the muon is 100x larger than the lifetime of the pion. This allows the muon to actually hit the surface of the earth.

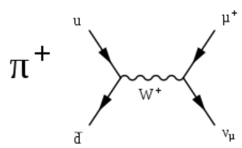

FIG. 4. Feynman diagram for a decay method for the pion.

As for the decay of the kaon (see FIG. 5), one can see that it will typically decay into three pions, and the pions then decay into a muon and a neutrino. Again, the muons are what will actually be picked up by our detector.

There are certainly many other decay products one can examine, but the majority of them are short lived until they decay into a muon or a neutrino. Thus, it is important to note that our particle detectors will mostly be detecting muons which, as charged particles, interact by ionizing the detector material.

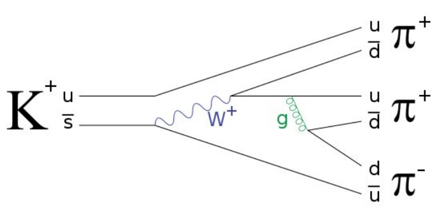

FIG. 5. Feynman diagram for a decay method for the kaon.

II. BASIC PARTICLE DETECTOR DESIGN

While cosmic rays still serve as a great source for many experiments, technology has certainly helped drive particle physics forward. Instead of using cloud chambers and cosmic rays, physicists at CERN are able to conduct collisions at much higher center of mass energies (CME) with advanced electromagnets and layers of particle detectors. One of the many advancements that has helped is the Silicon photo-multiplier (SiPM).

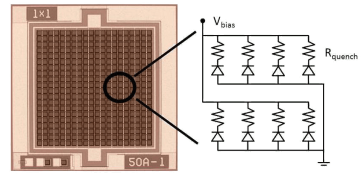

FIG. 6. Basic diagram of a SiPM.

A. Silicon Photo-multiplier

As seen in FIG. 6, a Silicon photo-multiplier (SiPM) is a an array of diodes running at their reverse voltage breakdown point. When operated like this, even a single photon will cause the diode to breakdown and release a small pulse of current. If more photons are incident, then multiple diodes in the array will breakdown, and the SiPM will release larger pulses of current. Thus, the SiPM can detect single photons, and one can effectively measure the amount of photons by the height of the pulse of current.

B. SiPM and Particle Detectors

By itself, SiPMs are only capable of detecting photons (not cosmic rays). However, one can use a scintillator block along with the SiPM to form a simple yet effective particle detector. A scintillator block is made from a material that emits photons when struck by ionizing radiation (such as muons). By pressing the SiPM right next to the scintillator block, the scintillator photons will produce a detetctable current pulse in the SiPM (see FIG. 7).

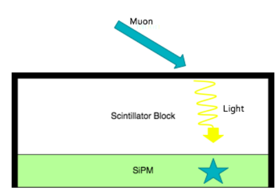

FIG. 7. Diagram of a "basic" particle detector. The muon hits the scintillator block causing a photon to be emitted. This photon is then detected by the SiPM.

This method for creating a particle detector allows for a simple construction method. By enclosing the scintillator block and SiPM in a tightly sealed container, the only light picked up by the SiPM should be from the scintillator block. From here, the user needs a way to amplify and readout the signal from this detector.

C. Finished Particle Detectors

Utilizing the SiPM with a scintillator block, we were able to produce a simple particle detector as seen in FIG. 8. This detector was then closed in a 3D printed box and wrapped in black electrical tape to reduce any ambient light from reaching the SiPM.

FIG. 8. Inside of the particle detector.

Now that the basic detector has been designed, a proper amplifier and readout board is needed to power the SiPM and amplify the signal in such a way that the signals can be processed by a Raspberry PI.

III. READOUT AND AMPLIFIER BOARD

The basic particle detectors are quite simple to use, but they will require an amplifier and readout board to be properly used. This board should be designed such that it can be easily used for an undergraduate lab, but the students should still have the freedom to customize their own experiment. The board should also have the option to connect two particle detectors. This will allow students to have more freedom in their experimentation by allowing them to measure coincidence and differences in locations of detectors. Lastly, the board should utilize an analog to digital converter. This will allow the user to measure the size of the pulses if he or she wishes to do so.

A. Analog to Digital Converter

In order to aid students in creating their own experiment and data collection, it was decided that the board should implement an analog to digital converter (ADC). The ADC would allow students to measure the size of the pulse coming from the SiPM by converting the analog pulse into a digital one that is readable by the Raspberry Pi. The signal from the SiPM will need to be slowed down for the ADC, but this can be done with an operational amplifier and resistor-capacitor circuit.

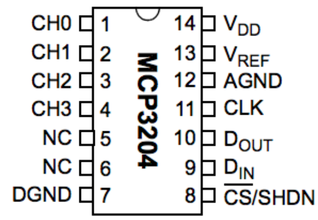

FIG. 9. The MCP3204 analog to digital converter.

For this board, we decided to use the MCP3204-CI/SL. This ADC gives a fast enough signal to communicate with the RPI, and it also gives us the opportunity to utilize 4 channels.

B. 555 OneShot

Another part of this readout board would be a stretched and amplified signal from the SiPM. This would allow us to flash an LED whenever we got a hit from the detector, and it would also serve as another signal that students can use when conducting their experiments. This can be achieved by using a 555 timer in *oneshot* mode.

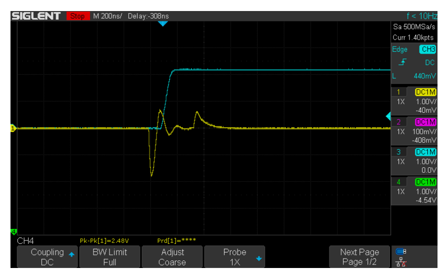

FIG. 10. Example of a oneshot pulse.

As seen in FIG. 10, the yellow line is an inverted signal that serves as the input to the 555 timer. The blue line is the stretched output signal which lasts long enough that it could light up an LED to signal when the detector has been hit.

C. Raspberry PI Connection

The connection and communication to a RPi is vital for collecting data and designing different experiments. We decided to use a RPi Zero, and we used a surface mount 40 female pinout that would allow the RPi to attach to the bottom of the readout board (See FIG. 11).

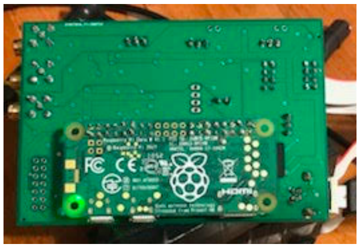

FIG. 11. Raspberry Pi Zero connected to the bottom of the finished readout board.

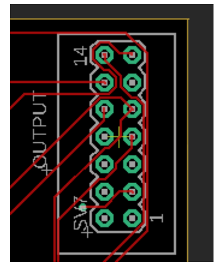

FIG. 12. Output pins

As seen above, the readout board also serves as the power supply for the RPi, so no additional power cords are needed.

D. Logic Gates

Another feature that we desired for the board is to have ports for two detectors to be connected. This will allow the students to make coincidence measurements, and they can orient the detectors however they wish. In order to make these kind of measurements, logic gates will be needed.

The two logic gates that will be used are the 74AHC1G08GW,125 (AND gate) and the 74LVC1G32GW,125 (OR gate). As one may imagine, the *AND*gate will produce a signal when both detectors have been hit, and the *OR*gate will produce a signal when either detector has been hit.

If the user of the board wants to switch between using the AND pulse and the OR pulse, there is a physical switch on the board that switches between these two logic gates. This will effect the stretched pulse and the LED.

E. Output Terminals

Lastly, we want the board to have options for future development. Some students may think of a project or another application for this board that may need some additional components, so we wanted to supply the option if that is the case.

As seen in FIG 12, there are 14 output terminals that can be used by the students. The signals on these pins include the analog signal, the digital signal, power, ground, stretched signal, and a few others.

F. Finished Board

As seen in FIG. 13, the finished board has been ordered and fully constructed. Along with the previous components that have been discussed, there are SMA outputs, and there are pinouts for connection to I2C on the RPi for additional sensors such as an altimeter.

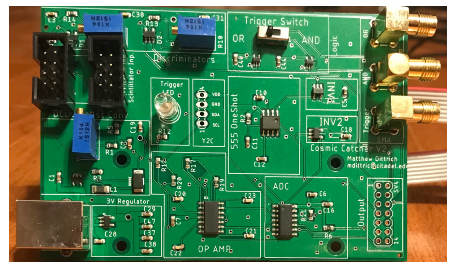

FIG. 13. Finished board: Cosmic Catcher V2

IV. OUTPUT SIGNALS

With the board fully constructed, we can examine some of the output signals to examine how the components are working together.

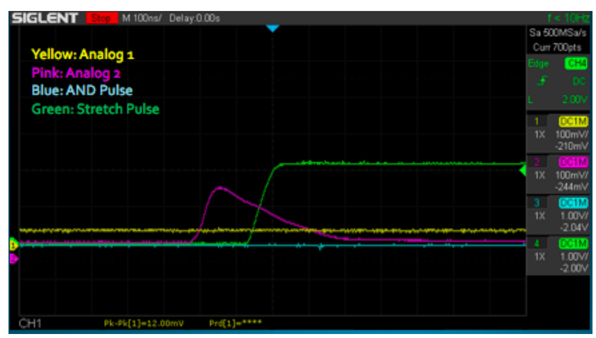

FIG. 14. Example of an OR Pulse

In FIG. 14, we can see a simple example of an OR pulse. The yellow and pink signals shows the analog signals directly from the two detectors. The blue signal is the AND pulse, and the green signal is the stretched pulse that would light up the LED. Interestingly, this figure also shows the slight electronic delay between the analog pulse and the stretched pulse.

In FIG. 15, we have another OR pulse. However, this time we have also shown the stretched pulse that is fed

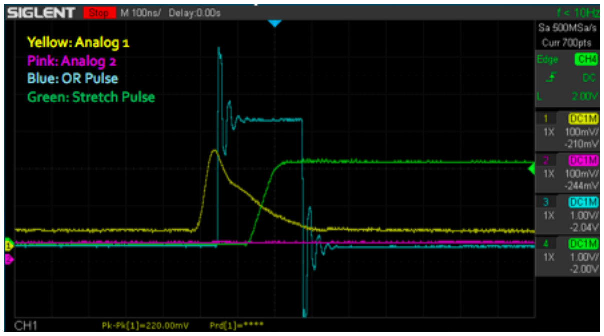

FIG. 15. OR pulse version 2.

into the RPi to collect data (green signal). One can see there is certainly some noise at the beginning an end of this signal, but further testing has shown that this signal is still usable.

FIG. 15 again shows the electronic delay from the analog signal, the OR gate, and the 555 timer. Between each step there is a very small but noticeable delay.

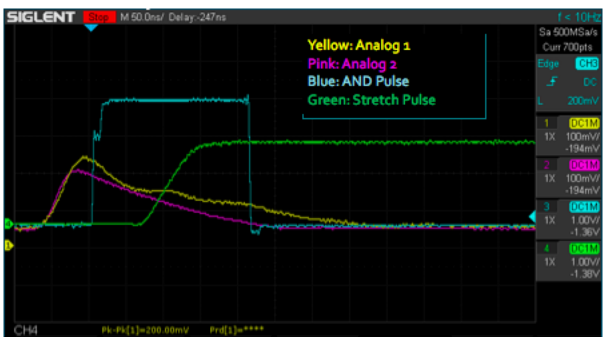

FIG. 16. Example of a basic AND pulse.

FIG. 16 shows a basic AND pulse. Here, we can see both analog signals are high which caused the AND gate to trigger and produce a signal. It should be noted that the amplitudes of the analogs signals do not have to be the same amplitude. In most cases, they are not.

V. CONCLUSION

Overall, the board seems to be working as intended. Students should be able to learn and understand the basic principles behind the detector and the readout board while also designing their own experiment using this equipment.

For future work, we will focus on writing code for the communication between the ADC and the RPi. Hopefully, this code will provide students a good **skeleton** to work with and begin collecting data.

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