SIGNAL AND NOISE: COSMIC MUONS
STUDENT GUIDE

DESCRIPTION

Getting started with a cosmic ray muon detector can be overwhelming. There are many parts to identify, assemble and test. How do we know if we have the hardware set up correctly to collect meaningful data? The purpose of this activity is to provide an introduction to the role of setting the threshold and the gain for the detector.

Another important issue is to think about the quality of the signal that we analyze. With such complicated equipment, there are many candidates to introduce "noise" into our signal. In this activity, we will learn what factors affect the noise level and how to adjust the gain and threshold settings to maximize the signal-to-noise ratio.

Work in groups of two or three. There are many thought questions.

Record your own answers.

Discuss the questions with your group and record the group consensus.

Pay attention to the vocabulary words listed below.

Copy the list and, when you find the definition, be sure to update your vocabulary page.

VOCABULARY

- Coincidence
- DAQ (data acquisition card)
- Gate
- Gain
- PMT (photomultiplier tube)
- Signal-to-noise ratio
- Threshold
- TOT (time over threshold)

PART 1: THE DETECTOR

Figure 1 is a photo of the QuarkNet detector.

- The large objects wrapped in black paper labeled (1) are the <u>counters</u> made of a scintillating plastic which produces a flash of light when a muon passes through.
- Inside the white tubes and connected to the scintillating plastic are photomultiplier tubes (<u>PMTs)</u> which amplify the flash and convert them to electronic signals.
- The circuit board labeled (2) is the data acquisition card (<u>DAQ)</u> which receives the input from the PMTs and decides whether to record a true signal.

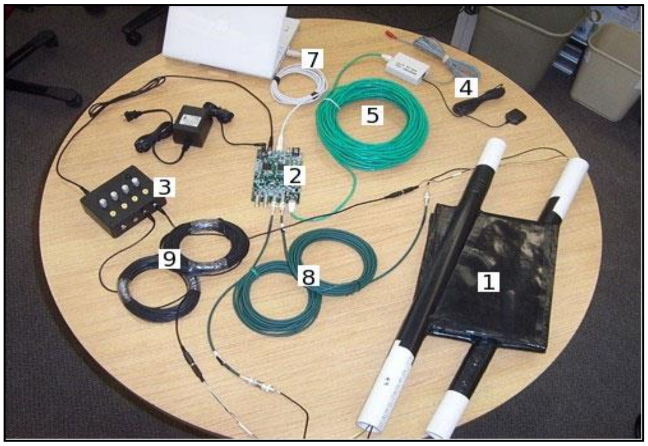

Figure 1: Detector components including DAQ (2) and scintillating counter (1).
https://www.i2u2.org/elab/cosmic/graphics/detector6000.jpg

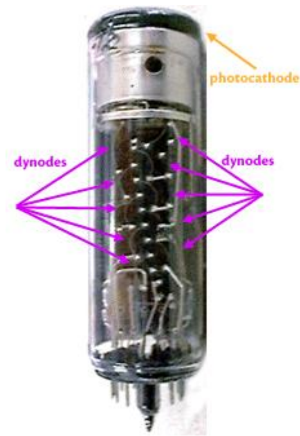

Figure 2: PMT close-up.
https://quarknet.fnal.gov/projects/pmt/student/images/pmtpic.gif

Because the PMT amplifies any light that shines onto it as well as any thermal signatures produced from internal heating, the PMT readout to the DAQ can be noisy, similar to Figure 3.

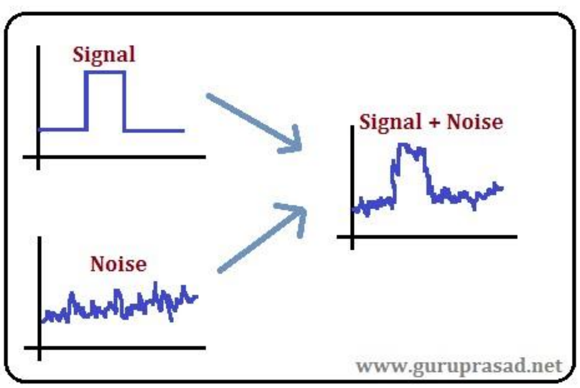

Figure 3: A signal influenced by noise.
http://guruprasad.net/wp-content/uploads/2014/03/signal_noise.jpg

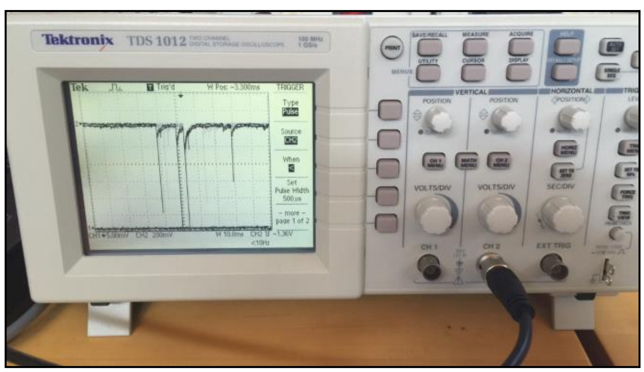

Figure 4: A typical muon signal in the detector, recorded by a digital oscilloscope.
Photo by Jeremy Smith

1. What Do You Think?

The DAQ receives the PMT voltage signal but receives any noise as well. Much like listening for a quiet voice in a noisy environment, it can be difficult to decide which data are muons and which are noise. We have to figure out how to separate out true signals, “hits.” To do this, we give the DAQ a minimum signal voltage (called a threshold) before it even records a hit. We adjust how much the

PMT amplifies the data it receives. This amplification factor is called the gain. Together, these two settings help us obtain the best signal possible by increasing the signal-to-noise ratio.

Do some research. What causes PMTs to be noisy? (Hint: Look up the phrase "dark current.")

Brainstorm with your group ways to improve the signal-to-noise ratio in the detector output.

PART 2: THRESHOLD, GAIN AND SIGNAL-TO-NOISE

A. Threshold

One tool that helps separate out the signal is to set a "***threshold voltage***" on the DAQ. Figure 5 shows a typical muon signal seen on an oscilloscope.

The graph is upside down. The signal is "highest" at the value of the lowest point on the curve. It is important to identify the time interval for which the signal has a magnitude greater than the threshold. This time is called *time over threshold* (TOT) even though it appears to be below threshold. The DAQ will not count a hit unless the signal from the PMT signal goes higher than the threshold.

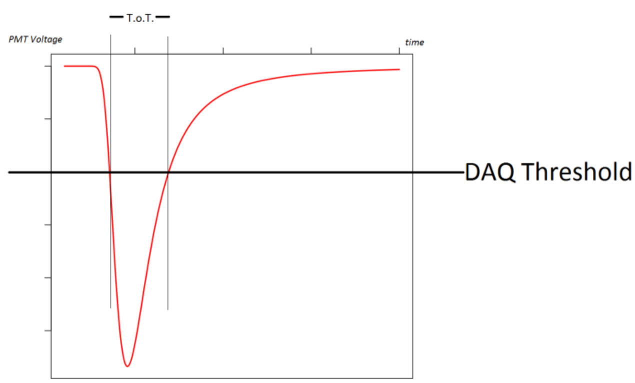

Figure 5: Muon signal with threshold and TOT labeled.

See the magnified region in Figure 6. *The time interval labeled as the "time over threshold" (TOT)* is a measurement of how long the DAQ is ***"triggered"*** and is an important piece of information collected. The voltage threshold is set by typing commands at the computer.

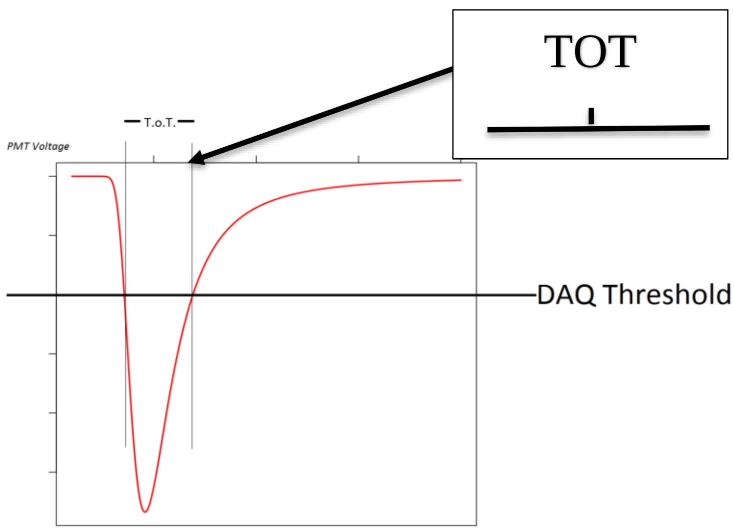

Figure 6: Time over threshold (TOT) magnified.

A ***"coincidence"*** occurs when the DAQ is triggered by one counter and another counter also triggers within the same predetermined time interval called the ***"gate."*** The gate is set by typing commands at the computer. The DAQ registers the coincidence and records the associated data as a line of data to a file in the computer.

2. What Do You Think?

Would changing the threshold level of the DAQ change the TOT for a muon signal? Explain your reasoning.

B. Gain

The second important tool for improving our detector is the PMT ***"gain."*** This is the amplification level of the PMT. In our detector, the gain of each PMT is adjusted using one of the four knobs on the power distribution unit (3) in Figure 1. By turning the knobs on this unit, we adjust the amplitude of the electronic signals sent to the DAQ by the PMT. Figure 7 shows a muon signal when the PMT is set to a low voltage gain (left) and a high voltage gain (left). It is important to notice that increasing the gain increases the amplitude of the signal AND the amplitude of the noise.

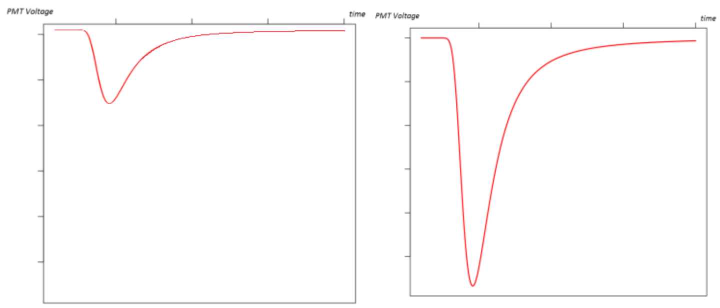

Figure 7: A muon signal in a PMT set to a low voltage gain (left) and a high gain (right).

3. What Do You Think?

What is an advantage of increasing the gain on a PMT channel? What is a drawback?

C. Signal-to-Noise Ratio

A main goal in any detector is to maximize the signal-to-noise ratio. That means that the signal stands as high above the background noise as possible. The best signal- to-noise-ratio occurs when the signal has a large magnitude and the noise has a small magnitude. Physicists strive for a large signal-to-noise ratio. Figure 8 shows two plots. The top plot represents a situation where the noise is large, and the signal is visible but not by much. The bottom plot has very little noise, and the signal rises noticeably above the noise. Therefore, the bottom plot has the best signal-to-noise ratio.

How can the DAQ threshold and PMT gain be used together to maximize the signal-to-noise ratio so that the resulting plot looks more like the bottom plot?

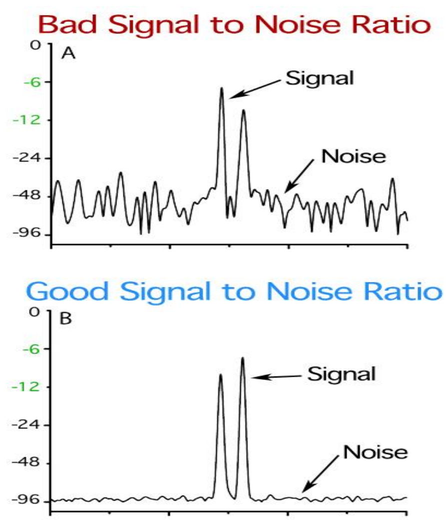

Figure 8: Comparing signal-to-noise ratios.
http://www.cellardoorcinema.com/images/SNR_Diagram.jpg

PART 3: COUNTING COINCIDENCES

If data is collected using only one counter, then every time the signal is above the threshold, the DAQ will record data in the computer file. In this case, you are counting anything that might produce a signal: electrons, muons, thermal noise, etc. Since muons travel freely through the detector, one way to be sure to count muons is to use more than one counter and count two-fold coincidences, a peak in each channel within a very small time interval (gate).

In this exercise, you are looking at plot sets that may indicate a two-fold coincidence has occurred sending an event to the computer. You have from one to four sets. Each set shows simultaneous signals from two counters stacked directly on top of each other and plugged into channel 1 and channel 2 of a DAQ. Each set of graphs is of the same event, and the DAQ threshold voltage is the same in all plots. The DAQ is set to count two-fold coincidences.

There may be two peaks in both plots, but there may be no coincidence. Count peaks that rise above the DAQ threshold voltage AND occur very close in time. If both conditions are met, the DAQ will send record data in the computer file.

4. *What Do You Think?*

Work with your partner to answer the following questions.

- What are the similarities and differences between the channel 1 and channel 2 signals of one set?
- What are the similarities and differences between the different sets of signals A–D?
- For each set, indicate how many muon signatures you see and how many the detector will count when set on two-fold coincidence. If there is a difference between these two numbers, explain why.
- Choose an appropriate gate size for identifying coincidences and explain your reasoning.
- Match each of the claims below to one set of graphs, including evidence and reasoning. If you think the claim is not supported by any of the graphs, explain why not.
- Which signal set best represents a good calibration? Why?
- How do muon signals and PMT noise differ in terms of the “time over threshold” recorded by the DAQ?

For each data set, provide at least one claim with evidence and reasoning.
Here are some sample claims that you may propose:

- “The gain voltage on channel 2 is so low that there will be no coincidences at all.”
- “The gain voltage on channel 2 is too low because some muons will not be counted as coincident hits.”
- “The gain voltage on channel 2 is pretty close to being ideal.”
- “The gain voltage on channel 2 is too high.”

PART 4: UNDERSTANDING PERFORMANCE STUDIES

Make histograms of the TOT for two sets of data: Channel 1 and Channel 2. Look carefully at the scale on the time axis of each signal plot.

Create a data table or copy this suggested **data table** into your journal. Add more rows as needed. Determine the TOT that are measurable and list them in the table. Record the TOT for each peak, carefully measuring the time at the threshold line—NOT along the time axis.

Channel 1 TOT (nsec)	**Channel 2 TOT (nsec)**

Be prepared to make claims about your histogram supported by evidence. As each group presents their data set, notice the similarities and differences in the histograms.

5. What Do You Think?
Compare the TOT Channel 1 histogram with the TOT Channel 2 histogram for your data set.

Describe the similarities and differences.

Describe how to adjust the threshold voltage and the PMT voltage to improve the overlap of the TOT histograms.

One of the analysis options in the Cosmic Ray e-Lab is the performance study. Basically, the analysis tool uses a very large set of data to determine the TOT histogram.

Examine the performance study in Figure 9. Notice that the channels used in this trial were Channel 3 and Channel 4.

6. What Do You Think?
Compare this histogram with the TOT histograms you made above. Describe any similarities and differences.

Compare the performance study for Channel 3 with the performance study for Channel 4 for your data set.

Describe the similarities and differences.

Describe how to adjust the threshold voltage and the PMT voltage to improve the overlap of the performance study histograms.

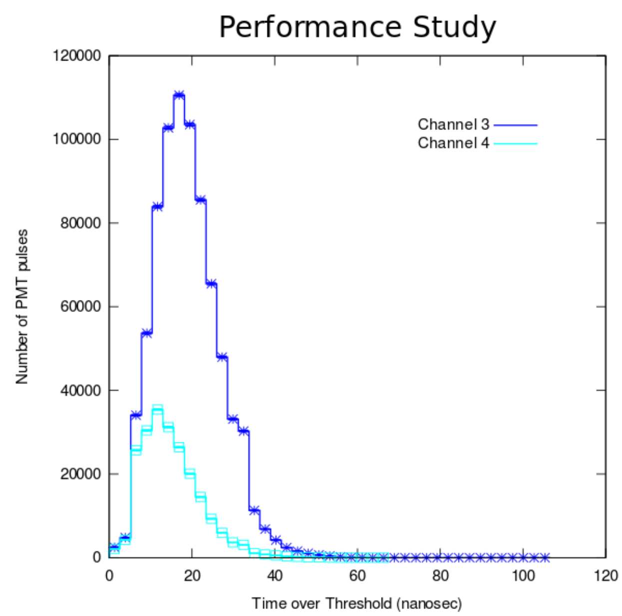

Figure 9: Performance study from the Cosmic Ray e-Lab.