SIGNAL AND NOISE: COSMIC MUONS
TEACHER NOTES

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 introduce the role of the threshold and gain settings. Also, a concept that is useful to understand is why it is necessary to calibrate or "plateau" the detectors. This activity is an introductory tutorial that helps your students understand how muon signals appear inside a photomultiplier (PMT) and how to distinguish them from random PMT noise. By learning how the PMT gain voltage and threshold work together to minimize noise in the data, students can explain the need for the plateauing steps typically undertaken early in a cosmic ray study.

STANDARDS ADDRESSED

Next Generation Science Standards

Science and Engineering Practices

4. Analyzing and interpreting data
5. Using mathematics and analytical thinking
6. Constructing explanations (for science) and designing solutions (for engineering)
7. Engaging in argument from evidence
8. Obtaining, Evaluating, and Communicating Information

Disciplinary Core Ideas

PS1.A: Structure and Properties of Matter
PS2.B: Types of Interactions
8. Obtaining, evaluating, and communicating information

Crosscutting Concepts

1. Patterns
2. Cause and Effect: Mechanism and Explanation
3. Scale, Proportion, and Quantity

Common Core Literacy Standards

Reading

9-12.4 Determine the meaning of symbols, key terms . . .
9-12.7 Translate quantitative or technical information . . .

Common Core Mathematics Standards

MP2. Reason abstractly and quantitatively.

IB Physics Standards

1.1 – Measurements in physics
1.2 – Uncertainties and errors
7.3 – The structure of matter
12.1 – The interaction of matter with radiation

ENDURING UNDERSTANDINGS

Physicists must identify and subtract noisy background events in order to identify the signal.

LEARNING OBJECTIVES

As a result of this activity, students will know and be able to:

1. Identify and distinguish muon pulses from noise in a photomultiplier tube (PMT) readout.
2. Explain the role of the threshold voltage in distinguishing signal from noise.
3. Predict the effect of PMT gain voltage on the signal-to-noise ratio.
4. Describe how to tell the difference between a "real muon" and noise.
5. Explain methods of reducing or eliminating noise to better identify the signal.
6. Explain the purpose of the calibration process and why calibration is important to collect meaningful data.
7. Explain the role of the performance study in calibration process for the channels in the cosmic ray muon detector.

PRIOR KNOWLEDGE

Students must be able to:

- Describe cosmic rays and the role of the muon in cosmic showers.
- Describe the function of the scintillation counter at a basic level.
- Define a coincidence as a recorded hit in two or more scintillation counters during a narrow time window.

BACKGROUND MATERIAL

It helps students to know something about muons, cosmic rays and scintillators before starting this activity. The Pierre Auger Observatory has some excellent public pages summarizing what cosmic rays are and how they're detected:
https://www.auger.org/index.php/cosmic-rays/cosmic-ray-mystery
https://www.auger.org/index.php/cosmic-rays/detection
https://www.auger.org/index.php/observatory/auger-hybrid-detector

RESOURCES/MATERIALS

TOT_signals.pdf

IMPLEMENTATION

This tutorial activity has four parts. Students learn how the following vocabulary relates to the process of calibrating or "plateauing" the detector. Give the students this list to complete while working through the activities.

- 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 shows the QuarkNet cosmic ray muon detector components.

- The large objects wrapped in black paper labeled (1) are the counters 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 (PMTs) which amplify the flash and convert them to electronic signals.
- The circuit board labeled (2) is the data acquisition card (DAQ) which receives the input from the PMTs and decides whether to record a true signal.

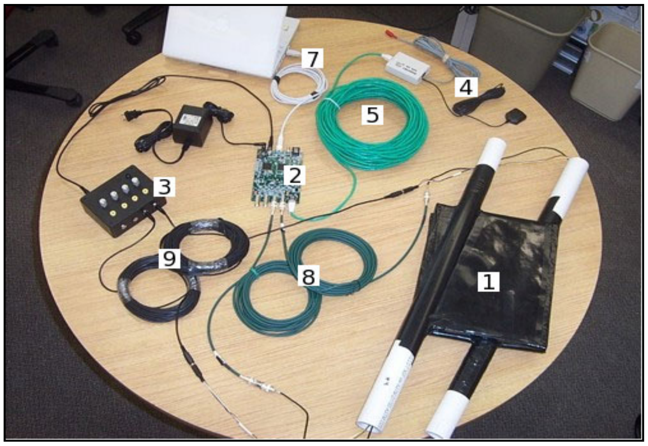


Figure 1: Detector components including DAQ (2) and scintillating counter (1).
https://www.i2u2.org/elab/cosmic/graphics/detector6000.jpg

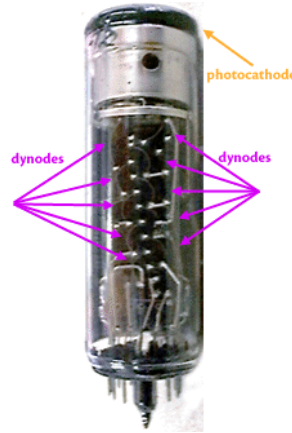


Figure 2: PMT close up.
https://quarknet.fnal.gov/projects/pmt/student/images/pmtpic.gif

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.

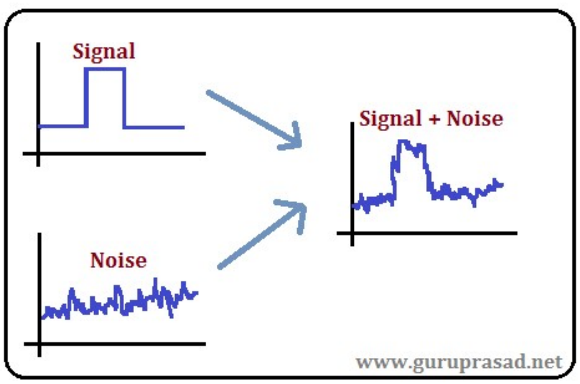


Figure 3: A signal influenced by noise.
http://guruprasad.net/wp-content/uploads/2014/03/signal_noise.jpg

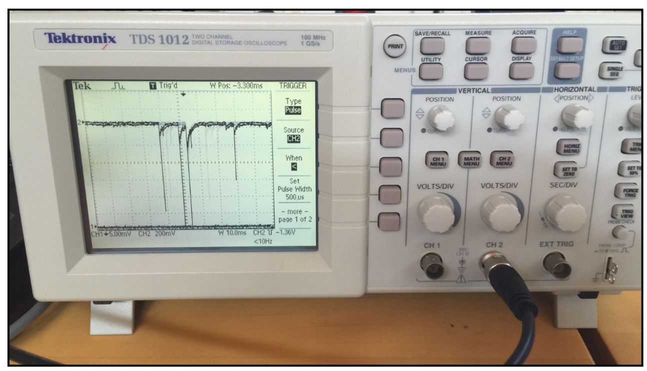


Figure 4: A typical muon signal in the detector recorded by a digital oscilloscope.
Photo by Jeremy Smith

The DAQ receives the PMT voltage signal but receives any noise as well. We have to figure out how to separate true signals, "hits," from the background noise. 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.

Have your students:

- Do some research. What causes PMTs to be noisy?
- Brainstorm ways to improve the signal-to-noise ratio in the detector output.

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

In this section are several mini-topics. It is important for students to stop, think and answer the questions at the end of each section.

A. Threshold

Much like listening for a quiet voice in a noisy environment, it can be difficult to decide which data coming from the PMT are muons and which are noise. One tool that helps is to set a "***threshold voltage***" on the DAQ. Figure 5 shows a typical muon signal seen on an oscilloscope.

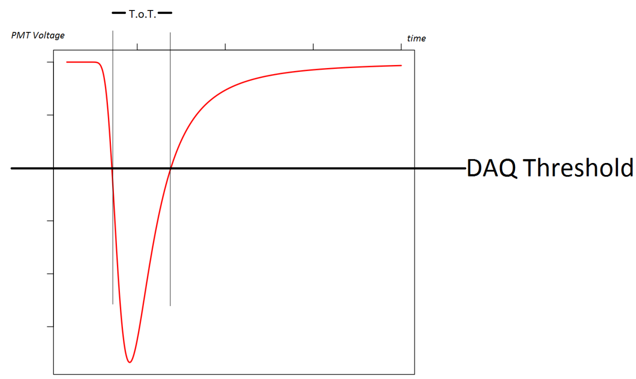


Figure 5: Muon signal with threshold and TOT labeled.

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 is higher than the threshold.

See the magnified region in Figure 6. *The time interval is labeled TOT.* TOT is a measure of how long the DAQ is ***"triggered."*** <u>The voltage threshold is set by typing commands on the computer</u>.

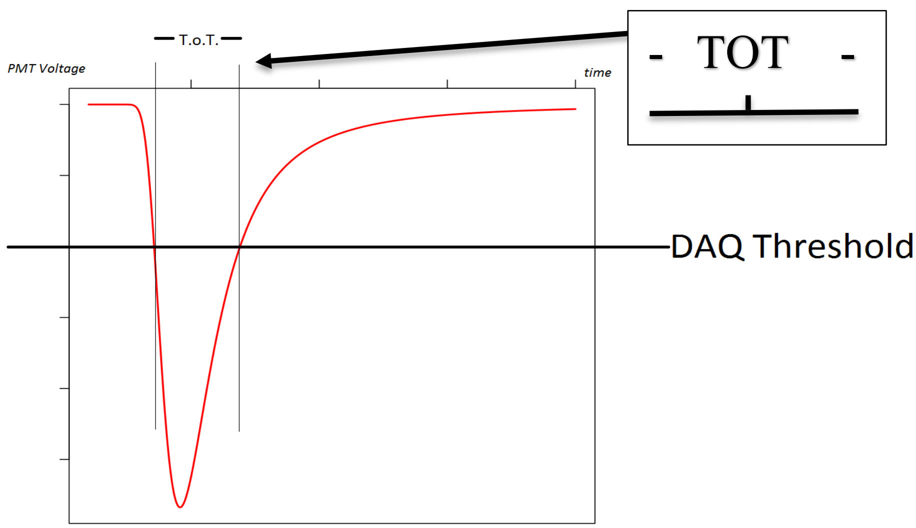


Figure 6: Time over threshold (TOT) magnified.

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."*** <u>The gate is set by typing commands at the computer</u>. The DAQ registers the coincidence and records the associated data as a line of data on a file in the computer.

Ask your students to consider the following:

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

B. <u>Gain</u>

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 the 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 (right). It is important to notice that increasing the gain increases the amplitude of the signal AND the amplitude of the noise.

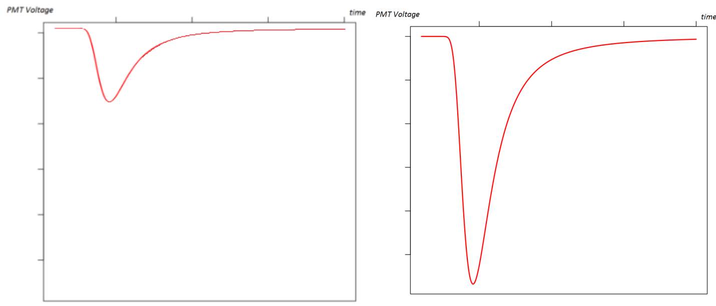


Figure 7: A muon signal in a PMT set to a low voltage gain (left) and a high gain (right).

Ask your students to consider the following:

- 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.

Ask your students to consider the following:

- How can we use the DAQ threshold and PMT gain together to maximize the signal-to-noise ratio so that our plot looks more like the bottom plot?

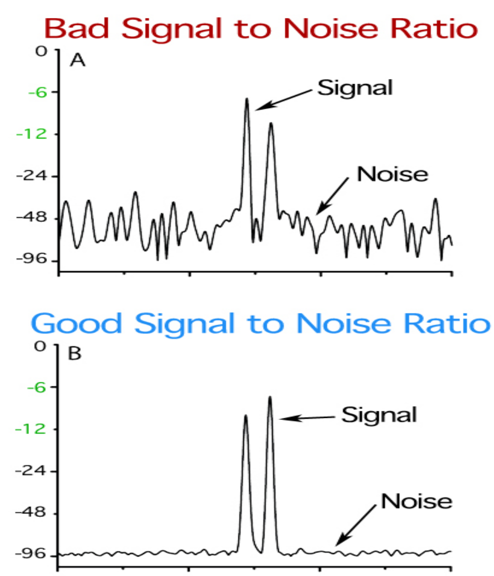


Figure 8: Comparing signal-to-noise ratios.
http://www.cellardoorcinema.com/images/SNR_Diagram.jpg

PART 3: COUNTING TWO-FOLD COINCIDENCE

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, we are counting anything that might produce a signal: electrons, muons, thermal noise, etc. Since muons travel freely through the counter, 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 students identify plot sets that may indicate a two-fold coincidence, thus sending an event to the computer. The PMT voltage plot file contains four sets of plots A–D. This series of plots shows simultaneous signals from two counters stacked directly on top of each other and plugged into DAQ channels 1 and 2. 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.

Remind the students that there may be a peak in both plots, but there may be no coincidence. The students count only peaks that rise above the DAQ threshold voltage AND occur very close in time. If both conditions are met, the DAQ will record data in the computer file.

Copy enough plot sets (TOT_signals.pdf) for each group. As time permits, groups can analyze all four sets, or you can divide sets among the groups. If different groups evaluate the same plots, the presentations can prompt interesting discussion.

The following questions help guide the students in gathering evidence to support their choice of claim(s):

- 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?
- For each set, indicate how many muon signatures you see, and how many the detector will record. Explain any difference between these two numbers.
- Choose an appropriate gate size for identifying coincidences and explain your reasoning.
- Match each of the claims below to one set of plots, including evidence and reasoning. If you think the claim is not supported by any of the plots, 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?

Here are some sample claims that the students 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.
- The DAQ would record few, if any, accidental coincidences in this case.

PART 4: UNDERSTANDING PERFORMANCE STUDIES

We focus on the TOT for two sets of data: channel 1 and channel 2 found in the file TOT_signals.pdf**.** Students make histograms of the TOT data from which they make claims supported by evidence. To collect data, they consider the scale on the time axis of each signal plot. They record the TOT for each peak. Remind the students to measure the time interval at the threshold line—NOT along the time axis. They can copy this suggested data table and add more rows as needed.

Data Set ____________________

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

As each group presents their data, notice the similarities and differences in the histograms. Ask students to consider the following:

- Compare the TOT histogram for channel 1 with the TOT histogram for channel 2. 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 a performance study. Basically, the analysis tool uses a very large set of data to determine the TOT histograms. Examine the performance study in Figure 9. Notice that the channels used in this trial were channel 3 and channel 4; ask your students to consider the following:

- Compare this histogram with the TOT histograms you made. Describe any similarities and differences.
- Compare the performance study for channel 3 with the performance study for channel 4. 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.

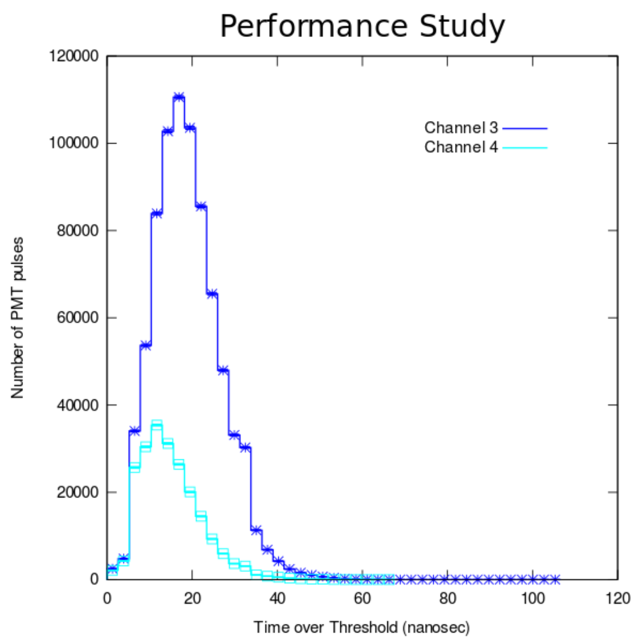


Figure 9: Performance Study from the Cosmic Ray e-Lab

Assessment

The questions included throughout the activity serve well as formative assessment. After each section, students can discuss their answers with each other or with you.

Part 1: The Detector

- Do some research. What causes PMTs to be noisy? (Hint: Look up the phrase "dark current.")
  - *This website has a good explanation: https://en.wikipedia.org/wiki/Dark_current_(physics).*
- Brainstorm with your group ways to reduce the noise in a PMT.
  - *The biggest way to reduce PMT noise is to cover the counter in black and seal all seams tightly to reduce ambient light.*

Part 2: Threshold, Gain and Signal-to-Noise

- Would changing the threshold level of the DAQ change the TOT for a muon signal? Explain your reasoning.
  - *Most of the peaks in the DAQ signal are wide near the base and narrow towards the peak. Therefore, increasing the threshold voltage will cause the TOT to decrease and lowering the threshold voltage will cause the TOT to increase.*
- What is an advantage of increasing the gain on a PMT channel? What is a drawback?
  - *Increasing the PMT gain will cause the peaks to be higher so they are easier to detect. The drawback is that the noise will also be increased.*
- 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?

- *If you increase the PMT gain so the peaks are higher, then adjust the threshold voltage so that you just barely see the noise signal at the bottom.*

PART 3: COUNTING TWO-FOLD COINCIDENCE

- What are the similarities and differences between the channel 1 and channel 2 signals of one set?
  - *Set A: Channel 1 must have a higher PMT gain voltage since there are several peaks higher than the DAQ threshold voltage. Channel 2 has a lower PMT gain voltage, and some peaks that might be of interest are below the DAQ threshold voltage and, therefore, will not be counted.*
  - *Set B: Channel 1 looks the same as channel 1 of Set A. Channel 2 has a PMT gain voltage higher than Set A: Channel 2 because the magnitude of several peaks are over the DAQ threshold voltage. However, in this set, the amplitude of channel 2's highest peak is still less than the amplitude of channel 1's highest peak.*
  - *Set C: Channel 1 looks the same as channel 1 in Set A and Set B. However, the PMT gain voltage for channel 2 is set so low, none of the peaks appear above the DAQ threshold voltage, so no signal will be counted.*
  - *Set D: Channel 1 looks the same as channel 1 in Set A, Set B and Set C. Channel 2 has almost the same PMT gain voltage because the amplitude for peaks in channel 2 have almost the same amplitude as the peaks in channel 1.*
- What are the similarities and differences between the different sets of signals A–D?
  - *See answer above.*
- For each set indicate how many coincidences you see and how many the detector will count. If there is a difference between these two numbers, explain why.
  - *Set A: There is one peak that overlaps from channel 1 and channel 2: channel 1 at 430 ns–460 ns and channel 2 at 435 ns–450 ns.*
    The PMT gain voltage for channel 2 is so much lower than the PMT gain voltage for channel 2; the channel 2 peak is much smaller and narrower causing the TOT to be much smaller.
  - *Set B: There are only two peaks that overlap from channel 1 and channel 2:*
    - *Channel 1 at 150 ns–170 ns and channel 2 at 160 ns–170 ns*
    - *Channel 1 at 420 ns 450 ns and Ch.2 at 440 ns – 460 ns*

    Since the PMT gain voltage on channel 2 is set lower than the PMT gain voltage of channel 1, the TOT for channel 2 is smaller in each case.
  - *Set C: There are no coincidences because the channel 2 PMT gain voltage is set so low, there are no peaks above the DAQ threshold voltage.*
  - *Set D: There are two peaks and one spike that overlap from Ch.1 and Ch.2:*
    - *Spike: Channel 1 at 110 ns, channel 2 at 110 ns; this could be noise.*
    - *Channel 1 at 160 ns–180 ns and channel 2 at 160 ns–180 ns*
    - *Channel 1 at 440 ns–460 ns and channel 2 at 440 ns 470 ns*

    In this set, the PMT gain is well matched for each channel. The amplitude and TOT are well matched for each peak. These data represent counters that are well calibrated.
- Choose an appropriate gate size for identifying coincidences and explain your reasoning.
  - *One method of choosing a gate is to count overlapping peaks. Other methods are acceptable with correct student reasoning using evidence from the data.*
- 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.
  - *"The gain voltage on channel 2 is so low that there will be no coincidences at all."*

Set C – See above reasoning.

- *"The gain voltage on channel 2 is too low because some muons will not be counted as coincident hits."*
  Set A – See above reasoning.
- *"The gain voltage on channel 2 is pretty close to being ideal."*
  Set D – See above reasoning.
- *"The gain voltage on channel 2 is too high."*
  No set matches this. To make this claim, there would need to be a set in which the amplitude of channel 2 was greater than any amplitude in channel 1.
- *"The DAQ would record few, if any, accidental coincidences in this case."*

- Which signal set best represents a good calibration? Why?
  - *Set D represents the best calibration because the PMT gain voltages are set to provide peaks of approximately the same amplitude and there are clear coincidences.*
- How do muon signals and PMT noise differ in terms of the "time over threshold" recorded by the DAQ?
  - *Muon signals have a measurable TOT while noise usually appears as spikes in the plot.*

PART 4: UNDERSTANDING PERFORMANCE STUDIES

Sample data are included here. Your students may make slightly different measurements which can serve as the basis for a discussion on experimental uncertainty.

Data Set ____________________

Channel 1 TOT (nsec)	**Channel 2 TOT (nsec)**
10	*10*
15	*10*
8	*10*
15	*20*
10	*8*
10	*20*
10	*15*
10	*5*
8	*15*
20	
15	
15	
10	
20	
8	
15	
5	
10	
20	

Figure 9 and Figure 10 below show sample TOT histograms for the sample data given in the above table.

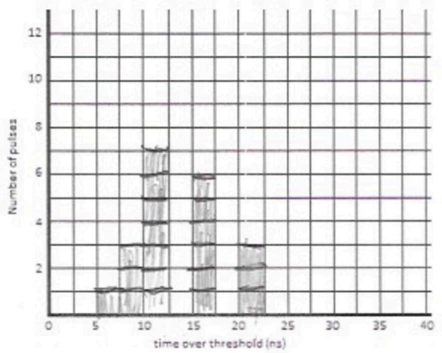


Figure 9: TOT histogram for channel 1.

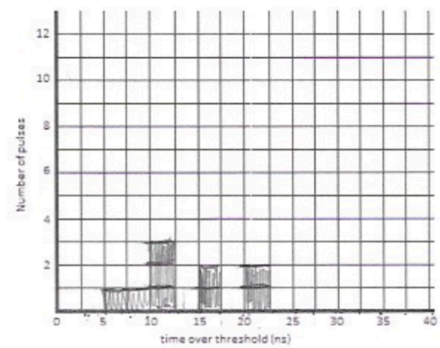


Figure 10: TOT histogram for channel 2.

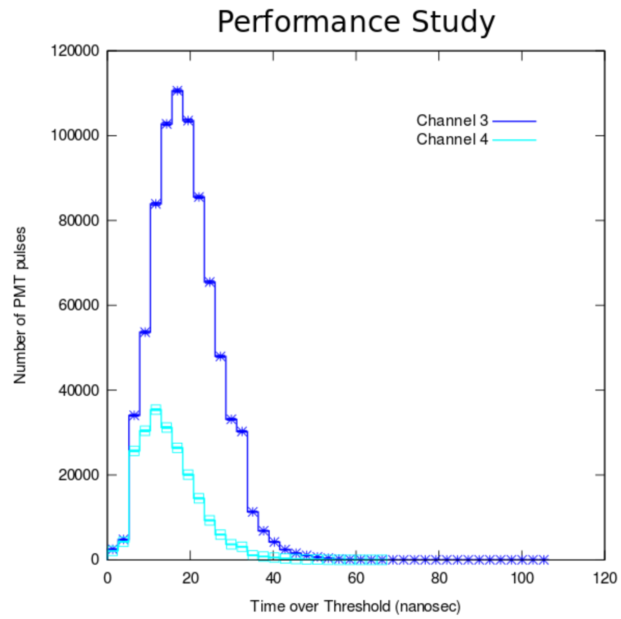
- Compare the TOT histogram for channel 1 with the TOT histogram for channel 2 for your data set. Describe the similarities and differences between the two histograms.
  - *There are peaks in the same places, but all of the peaks for channel 2 are smaller than the peaks for channel 1.*
- Describe how to adjust the threshold voltage and the PMT voltage to improve the overlap of the TOT histograms.
  - *Since the range of the data is approximately the same, it seems that the DAQ threshold voltage settings for each channel is about the same. However, the PMT gain voltage for channel 2 needs to be increased so that the peak of each histogram is closer in value.*
- Compare this histogram with the TOT histograms you made above. Describe any similarities and differences.
  - *The histograms in the performance study are very similar to the TOT histograms. The main difference is that the performance study includes many, many more coincidences.*
- Compare the performance study for channel 3 with the performance study for channel 4 for your data set. Describe the similarities and differences.
  - *Channel 3 has a much higher peak and a slightly wider peak than channel 4. Channel 4 is also shifted to the left showing smaller TOT.*
- Describe how to adjust the threshold voltage and the PMT voltage to improve the overlap of the performance study histograms.
  - *Just as we discovered in the TOT histograms, the PMT gain voltage for channel 4 needs to be increased. This will cause the peak to be higher and will increase the TOT for channel 4 causing the peak to shift to the right.*

A summative assessment can consist of the student responses to the questions in the learning objectives:

1. Identify and distinguish muon pulses and noise in a photomultiplier tube (PMT) readout.
2. Explain the role of the threshold voltage in distinguishing signal from noise.
3. Predict the effect of PMT gain voltage on the signal-to-noise ratio.
4. How can we tell what is a “real muon” and what is just noise?
5. How do we reduce or eliminate noise to get better data?
6. Explain the need for proper calibration of channels in the cosmic ray muon detector.

A third type of assessment is the lab practicum:

At right is a performance study, which is a histogram plot of PMT hits recorded over time by the DAQ and saved in a file. The X-axis which determines the size of the histogram bins is the time over threshold (TOT) and the Y-axis is the number of counts in each bin of the histogram.



Based on what you have learned about the PMT pulses and the DAQ thresholds:

- Propose an explanation for why the channel 3 histogram is both shifted up on the Y-axis as well as shifted to the right on the X-axis.
- Why might those two effects be linked?

The following teachers were instrumental in developing this activity:

- Jacob Breman, Community Christian School (Florida), Florida State University QuarkNet Center
- Kevin Martz, Richard Montgomery High School (Maryland), Johns Hopkins University QuarkNet Center
- Jeremy Smith, Hereford High School (Maryland), Johns Hopkins University QuarkNet Center