Cosmic Watch Lab Suite
Teacher Notes

Description

The Cosmic Watch (CW) is a small cosmic ray detector that consists of a 4 cm x 4 cm scintillator, a silicon photomultiplier (SiPM), a programmable Arduino taking data, a small screen to read data, and supporting electronics. See Appendix A in the teacher notes for more details. This suite of data activities describes experiments that can be done either at the singles rate or two-fold rate.

Two QuarkNet Cosmic Watches stacked for two-fold operation.

Figure 1

The CW Suite consists of the following activities:

- Singles rate (one unit only) mode:
    - Radiation vs. Distance
    - Muon-mapping the school
- Two-fold rate (two units connected) mode:
    - Cosmic ray rates vs. zenith angle
    - Cosmic ray rates vs. vertical separation of counters.
- Other measurements
    - Once students are used to working with the CW they may think of new experiments they can do.

These activities can be done with a class that has access to a sufficient number of Cosmic Watches to allow lab groups of 2 – 5 students. The measurements for each activity can be collected in two 50-minute lab periods.

Suggested assessment questions are embedded in the implementation section of each activity. Suggested responses are provided in italics.

Standards Addressed

Next Generation Science Standards

Science and Engineering Practices

1. Observed patterns
2. Developing and using models
4. Analyzing and interpreting data
5. Using mathematics and analytical thinking
6. Constructing explanations
7. Engaging in arguments from evidence

Crosscutting Concepts

1. Observed patterns
4. Systems and system models

Common Core Literacy Standards

Reading

9-12.3 Follow precisely a complex multistep procedure . . .
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.

Enduring Understanding

Scientists can use data to develop models based on patterns in the data.

Background Material

The CW was designed at the Massachusetts Institute of Technology by Spencer Axani. The concept was to design a detector that students, teachers, or experimenters can build on their own and use to make meaningful measurements of cosmic rays. QuarkNet has built several CW detectors. These detectors provide an introduction to detecting cosmic rays. Teachers can borrow class-sets of these detectors through their QuarkNet center. They do not replace the larger, more capable QuarkNet Cosmic Ray Muon Detector (CRMD).

One CW unit can only operate in “singles” mode, that is, showing all results with no filters. Two CW units together can be made to operate in “two-fold coincidence” mode in which a data stream that only shows results of both CW units detecting a signal in the same small time interval. This eliminates a great deal of background, allowing for a better estimate for cosmic ray rates.

Data Collection Tips

The CW is slow to collect data due to its small size. It will generally take 10-15 minutes to get a reliable rate for one trial of any experiment. For this reason, two class periods are recommended for each activity. There is a trade-off however, greater precision leads to idle students while waiting for a run to finish. Smaller runs lead to less precise results which can be overcome by consolidating group work into class data.

There are two ways to calculate a data rate. One way is to read the rate from the screen of the CW. The other way is to divide the number of counts by the elapsed time. ***To ensure quality data, reset the CW unit(s) using the red button in the back for each new trial of an experiment.***

Activity 1: Single Detector: Radiation vs. Distance

Prior Knowledge

Students must be able to:

- Linearize a curved plot.
- Calculate a rate in frequency units such as Hertz given initial and final counts and time.

Learning Objectives

Students will know and be able to:

- Measure cosmic ray rates with a single Cosmic Watch.
- Describe how radiation from a source changes with distance.

Materials

The following are needed for each student group:

- Cosmic Watch
- Shaker of salt substitute containing potassium chloride (KCl)
- Ruler

Implementation

Salt substitute with KCl contains small amounts of the radioactive isotope potassium-40, which undergoes beta decay, emitting electrons and neutrinos. The CW can detect the electrons. Students can convince themselves of this by running the CW by itself for about 5-10 minutes to establish a base rate and then running the CW again with a shaker of KCl-containing salt substitute directly next to the CW. For this experiment, place the CW on its side so it is “pointed” directly at the salt-substitute (See Figure 2 on the right).

Ask your students to compare the data rate with and without KCl-containing salt-substitute.

- *The measured rate will increase with the salt-substitute nearby.*

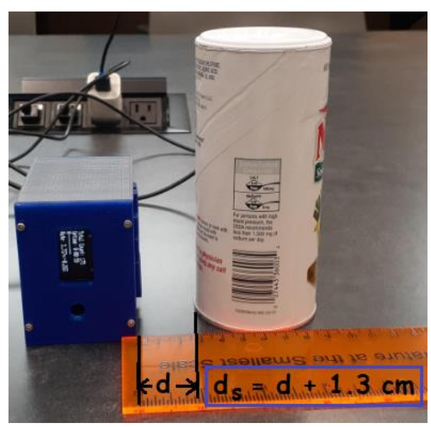


Figure 2

Students can then see how the beta radiation rate changes as the shaker is moved further away from the detector. A good way to do this is to keep the detector on its side and then take counts first with the salt-substitute next to the detector, then at small but ever-increasing distances (perhaps 0.5-1.0 cm intervals) from the detector. Graph count rate vs distance. Your students will see a decreasing curve. Linearize the graph by making a plot of rate vs. distance-squared. Instructions for linearization can be found here.

Ask your students to describe the relationship between data rate and distance to the detector.

- *Since rate vs distance squared is straight, the rate has an inverse square relationship with distance to the detector.*

The plot will not be perfect due to natural variations in the count. Longer time intervals (10 min or more at each distance) or combination of results across the class(es) will help with this.

Activity 2: Single Detector: Muon-mapping the school

Prior Knowledge

Students must be able to:

- Calculate a rate in frequency units such as Hertz given initial and final counts and time.

Learning Objectives

Students will know and be able to:

- Measure cosmic ray rates with one Cosmic Watch in various locations around the school.
- Identify the locations for which the cosmic ray rates are higher or lower than the "control" location.
- What location resulted in a higher cosmic ray rate? Lower cosmic ray rate?
- Devise a claim that relates the characteristic of the building with the cosmic ray rate.

Materials

The following are needed for each student group:

- Cosmic Watch
- Map or diagram of the school (students may make this as they work)

Implementation

Students can investigate the physical structure of the school or another appropriate building or site using Cosmic Watches. Each person or group will have one CW. The first task is for all groups to make a "control" measurement of at least 10 minutes a common location such as the classroom. This will give students the data rates of their individual CWs so they can calibrate their results using the method described in Appendix B.

Ask your students to keep a log of location, distinctive location features and data rate.

It is important for your students to discuss where they want to measure. For example, in a tall building, they may want to measure on different floors. If the building has varied structures or architectural features, they may want to measure beneath those features as well as away from them to compare. This measurement is challenging but it might enable the students to map how different parts of the building absorb muons, if they can find significant variations in rates.

Ask your students to make a claim relating location characteristics and data rate. Be sure to include evidence and reasoning.

Activity 3: Paired Detectors: Zenith-angle measurement

Prior Knowledge

Students must be able to:

- Measure an angle using a protractor.
- Calculate a rate in frequency units such as Hertz given initial and final counts and time.
- Identify a trigonometric function from the shape of graphed data.

Learning Objectives

Students will know and be able to:

- Explain two-fold coincidence and how it affects cosmic ray measurements.
- Configure a pair of CWs to collect two-fold coincidence data.
- Construct a graph of data rate vs Zenith angle.

- Linearize the graph.
- Determine the equation of the linearized graph.

MATERIALS

The following are needed for each student group:

- Cosmic Watch pair that can read in two-fold coincidence
- Protractor
- Spacer between CWs (optional)
- Rotatable stand for CWs (optional)

IMPLEMENTATION

For this experiment, stack CWs vertically and pair them for two-fold coincidence (see Appendix C). Determine the Zenith direction perpendicular to the face of the CW as shown in Figure 3 on the right. The "direction" of the CW pair is vertical at this point so $\theta = 0^o$ Rotating the pair will increase the Zenith angle. In Figure 4 on the right, the pair is rotated so that the angle between the line to the Zenith and the axis is about 30^0, or $\theta = 30^0$.

Figure 3

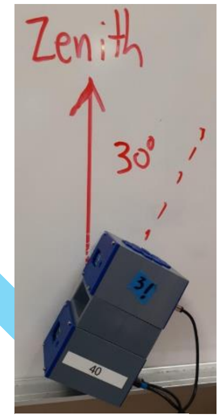


Figure 4

The first data point will be θ = 0º, with students taking the two-fold or "S" rate after a 10 minute run. This can be used as the basis for relative rates, if this is needed. Then students should rotate to as many Zenith angles as they have time for, taking a rate after 5-10 minutes for each and tabulating the data they take. For best results, the angles near the following angles are recommended $\theta = 0^o$, $\theta = 10^o$ $\theta = 20^o$ $\theta = 30^o$ $\theta = 50^o$ $\theta = 70^o$ $\theta = 90^o$ as time permits. If there is only time for a few angles, the relative rates will be useful to enable combination of data and, potentially, more angles.

Graphing the data allows the students to make claims supported by evidence. Graph the data in their table, with angle as the independent variable and rate as the dependent variable. This graph generates a curve; linearization involves using a trigonometric function.

ACTIVITY 4: PAIRED DETECTORS: VERTICAL SEPARATION

PRIOR KNOWLEDGE

Students must be able to:

- Create a diagram showing the acceptance angle in two dimensions of two cosmic ray counters with parallel identical scintillators separated by some distance about a common axis.
- Form a hypothesis based on the geometry of an experiment.

LEARNING OBJECTIVES

Students will know and be able to:

- Determine the acceptance angle for a pair of CWs separated by spacing d.
- Graph two-fold coincidence rate vs the separation distance.
- Use geometry to explain whether the graph will be an increasing graph or decreasing graph.

MATERIALS

The following are needed for each student group:

- Cosmic Watch pair that can read in two-fold coincidence
- Ruler

- Variable-height spacer between CWs (student-built, if possible)

Implementation

This activity has potential to reach beyond physics and into geometry and even coding. Students start with a pair of CWs set up for two-fold coincidence, one stacked on top of the other. (See Appendix C, below.) Students need to take a baseline count to find the rate in this configuration after a 10 minute run. Then students must reset the counters, raise the upper CW a small amount (~0.5 – 1.0 cm), measure the height (d in the Figure 5 to the right), and make another run to find the rate. Repeat this for as many heights as they have time to measure. Combination of results using relative rates (see Appendix B, below) may help to get more complete results. Students can make a plot of two-fold rate vs. height.

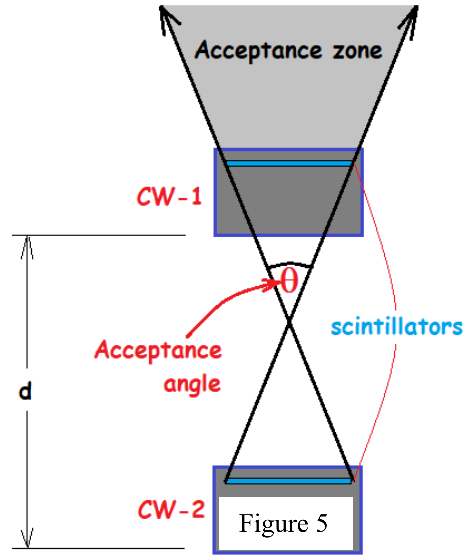


Figure 5

Any significant results in this experiment should be governed by the geometry of the scintillators relative to each other. The detectors are in two-fold coincidence, so only muons which pass through both scintillators are counted. As the top CW is raised, the angle of acceptance narrows and, as a result, fewer muons are counted in a given time interval. To take it one step further: the rate is determined by the solid angle subtended by the two scintillators. The simple angle of acceptance is easy to calculate; finding the solid angle analytically is difficult and best done using appropriate code in a python notebook. However, referring to a simple angle suffices for this activity.

All Activities

Assessment

Each activity can be assessed by means of a Cosmic Ray report, submitted by individual students or groups, containing:

- Title of the activity
- A statement of what students discovered in the activity (claim)
- Visual evidence such as tables, graphs, maps, etc. (evidence)
- A statement connecting the claim and the evidence (reasoning).
- Any useful diagrams or further supporting evidence.

You may also assess student work by means of observation and group or class discussion.

Appendix A: How it works

Main components of the Cosmic Watch

The Cosmic Watch consists of these main components:

- Scintillator – a 4 cm x 4 cm rectangle of clear plastic which emits a very small amount of light when charged particles pass through it. It is wrapped in black tape to block out other light.
- Silicon Photomultiplier (SiPM) – a solid-state device that converts the bits of light from the scintillator to electrical signals.
- Arduino – a computer processing device that processes and counts the electrical signals as well as applies logical operations as programmed.
- Supporting electronics and connections – supply voltage, electronics to enable operations such as triggering and display of data, etc.
- Screen – displays counts, elapsed time since last reset, rate, and operational mode (S or M; see Appendix C).
- Case – protects the CW unit.

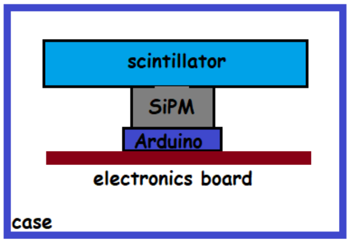


Figure 6

Figure 6, on the left, shows a simplified, inexact diagram of the internal parts of the CW. In Figure 7, on the right, you can see the inner workings slid part way out of the case. The thick black piece is the scintillator, well-taped.

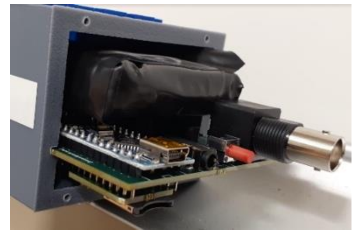


Figure 7

These experiments are designed to be done reading the screen on the CW. Figure 8 to the right shows the screen shows a Total Count, Uptime (elapsed time since reset), and a Rate in Hz with uncertainty attached. Rates can be read directly or calculated using the Total Count and the Uptime. Note that the Uptime occasionally turns over to zero, so students should keep that in mind. *In most circumstances, the CW unit(s) should be reset using the red button in the back for each new trial of an experiment.* The M indicates that that CW unit is operating at the singles rate. When connected to a second CW unit, an S indicates that the CW unit is operating at the coincidence rate triggering off of the M unit. This means that most of the random noise is eliminated in the S unit.

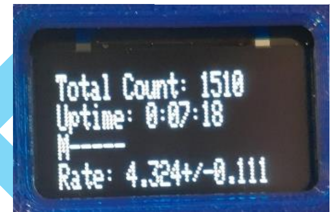


Figure 8

APPENDIX B: CALIBRATION OF TWO DETECTORS ("A" AND "B") TO RATES RELATIVE TO CONTROL

In an ideal world, two CW units placed side by side should report the same background result. In reality, each CW unit runs at a different rate. Where possible, it is desirable for results from multiple groups doing the same measurement to be combined. The CW units are not generally calibrated to each other, so students must find a way to overcome this issue when combining data. Two CW units placed side by side will experience the same background result. However, the measured rate for each detector is likely not exactly the same. One reasonable approach which allows students to compare data from multiple detectors is to establish a common "control" configuration for each detector, record the rate, and then divide any further results by that control rate. Dividing the measured rate by the control rate determines the relative rate. A generalized example follows:

Measured detector A control rate:				Measured detector B control rate:		
CRa = 1.22 Hz				CRb = 1.05 Hz		
Experimental Results A				Experimental results B		
Condition	Rate (Hz)	Relative rate = Rate/CRa		Condition	Rate (Hz)	Relative rate = Rate/CRb
1	1.51	1.51/1.22 = 1.24		1	1.28	1.28/1.05 = 1.22
2	1.72	1.41		2	1.51	1.44
3	1.89	1.55		3	1.72	1.64
4	2.08	1.70		4	1.89	1.80

Note that the raw rates for the two detectors are fairly different but the relative rates are more comparable.

APPENDIX C: TWO-FOLD

SETTING A PAIR OF COSMIC WATCHES TO TWO-FOLD COINCIDENCE

It is often useful to use a pair of cosmic watches in two-fold coincidence. A single CW can normally register a count if an actual cosmic ray muon passes through the scintillator ***or*** if it gets a background signal, noise in the electronics, or any other stray signals. Thus, a single CW counts both signal and noise and shows a count which is significantly higher than the actual muon rate. We therefore often use two-fold coincidence from two CWs paired together. One CW unit (designated S) is activated by the other (designated M), meaning that S only counts if M does as well within a narrow, microsecond scale time gate. Physicists say S is “triggered” off of M. To put it another way, if M gets a signal, it triggers S to be able to count as well. Thus noise, which is random, tends to fail to stimulate a count in both units whereas a muon passing quickly through one and then other will stimulate counts in both M and S. The screen on M will show all counts – signal and noise – with a high rate but the screen on S will show a rate is lower and much closer to the muon rate. This enables not only a more accurate count but also directionality: muons are counted only if they follow a path inside a solid angle of acceptance defined by the two scintillators.

The back of the detector pair is shown in Figure 9 on the right. This pair is set up for two-fold coincidence in the following way:

1. Stack the two CW units and turn them so the backs face you (and the screens are opposite you).
2. Connect the supplied audio cable into the 3 mm jack on each CW. Make sure the plugs are firmly in the jacks.
3. Plug in power via the mini-USB connector on the back of either of the CWs. It does not matter which.
4. Simultaneously press the red buttons on the backs of the two CW units.
5. Release one, then the other, button in rapid succession.
6. Turn the CW units around and check the screens. One should show “M” and the other should show “S”, though the latter may be delayed until the first coincidence signal is recorded. M shows the singles rate, that is all counts, including both signals and noise. The S unit shows a smaller count a lower rate: these are coincidence, with mostly muon signals and very little noise.

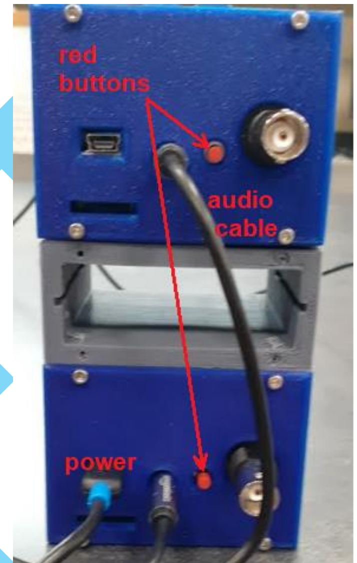
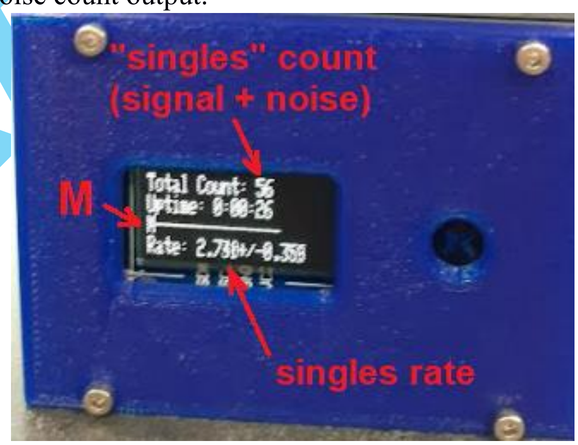


Figure 9

The S and M units, normally stacked, are shown individually side-to-side below for easier examination. Figure 10, on the left, shows a CW S coincidence count output and Figure 11, on the right, shows the CS M signals + noise count output.



Total Count: 2
Uptime: 0:00:23
S
Rate: 0.103+/-0.073

Figure 10

Total Count: 56
Uptime: 0:00:26
M
Rate: 2.730+/-0.359

Figure 11