HOW SPEEDY ARE THESE MUONS?
TEACHER NOTES

INTRODUCTION

In this activity, students use authentic detector data to apply simple 1D kinematics (v=d/t), interpret graphical data, and evaluate measurement uncertainties. The data were collected using a Cosmic Ray Muon Detector. This detector consists of two “counters” which each produce a signal when a charged particle passes through. The counters are connected to a very fast timer that measures in nanoseconds. (1 ns = 10^{-9} sec.) To gather the data, students set the counters with some vertical separation, which they measured. The vertical separation was much larger than the widths of the counters.

Figure 1 shows the setup. The students who collected the data wondered how fast the muons traveled between the counters. They performed an experiment in which they timed many particles as they passed through the detector for a variety of distances.

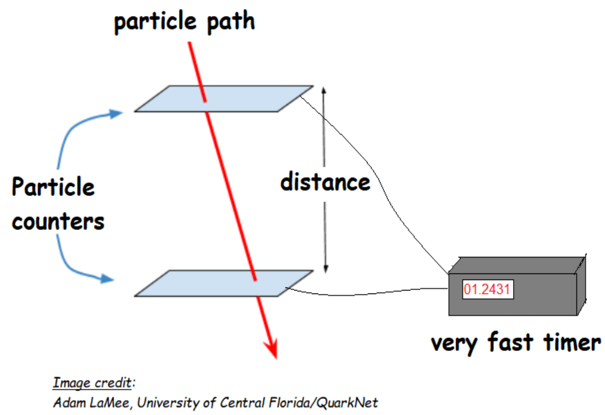


Figure 1

STANDARDS

Next Generation Science Standards

Science and Engineering Practices

2. Developing and Using Models
3. Planning and Carrying Out Investigations
4. Analyzing and Interpreting Data
5. Using Mathematics and Computational Thinking
7. Engaging in Argument from Evidence
8. Obtaining, Evaluating, and Communicating Information

Crosscutting Concepts

1. Observed patterns

Disciplinary Core Ideas – Physical Science

PS1.A: Structure and Properties of Matter
PS2.B: Types of Interactions
PS3.B: Conservation of Energy and Energy Transfer

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.
MP6. Attend to precision.

IB Physics Topic 1: Measurement and Uncertainty

1.2.6 Describe and give examples of random and systematic errors.
1.2.8 Explain how the effects of random errors may be reduced.

1.2.11 Determine the uncertainties in results.
1.3.1 Distinguish between vector and scalar quantities.
1.3.2 Combine and resolve vectors.

IB Physics Topic 2: Mechanics

2.3.6 Use the principle of conservation of energy to compare an initial state to a final state.
2.4.3 Use conservation of linear momentum to compare an initial state to a final state.

Enduring Understandings

- Scientists make a claim based on data that comprise the evidence for the claim.

Learning Objectives

This activity provides three methods for using the data to find the average speed of a muon. The learning objectives are labeled according to Methods 1, 2, or 3 described in the implementation section below.

Students will be able to:

- Determine the average speed of a muon by dividing the distance traveled by the average time of flight. (Method 1, 2)
- Make a histogram the average speed found from each group. (Method 1, 2, 3)
- Report the best value for the average speed and an estimate of the uncertainty in that value based on the histogram. (Method 1, 2, 3)
- Construct a graph of distance vs time of flight. (Method 3)
- Determine the slope of the distance vs time of flight graph. (Method 3)
- Determine the physical meaning of the slope of the distance vs time of flight graph using the units of the slope of the graph. (Method 3)

Prior Knowledge

Students should know how to:

- Find the average of a column of numbers.
- Make a histogram of a list of data values that all represent the same quantity.
- Plot a linear graph.
- Determine the slope of a graph.
- Find the physical meaning of a slope using the units of the slope.

Background Material

This activity uses skills typically related to the standard kinematics unit. Prerequisite materials which support this activity include:

- *Dice, Histograms and Probability* from the Data Activities Portfolio.
- *Histograms: The Basics* from the Data Activities Portfolio.
- How to Linearize a Curved Data Plot.

Resources/Materials

- Link for student data: https://docs.google.com/spreadsheets/d/14paPpCcvxdRf9Rj2EAgcdn06IKwEo7Nn57nzK_3PB28/edit#gid=0
- Link to data with teacher key: https://docs.google.com/spreadsheets/d/1spI35GT985rdW40DXn7RJKu0LIR2yjT4ERNAYIYDYqI/edit#gid=148109932

Implementation

This activity includes three methods for determining the speed of a muon:

Method 1: Each group gets a selection of 5 – 10 events. Each group will calculate the speed using distance and time for each event. Each group contributes their results to a class histogram for analysis.

Method 2: Each group gets 10 events for a constant distance. Each group will find the average time for that distance and using the constant distance determine the speed of a muon. Each group contributes their results to a class histogram for analysis.

Method 3: Each group gets 10 events with varying distance. Each group constructs a graph of distance vs time and determines the speed from the slope of the best fit line. Each group contributes their results to a class histogram for analysis.

You can use the method best suited to the skill level of your students and/or where you are in your curriculum. Performing more than one method can lead to interesting discussions.

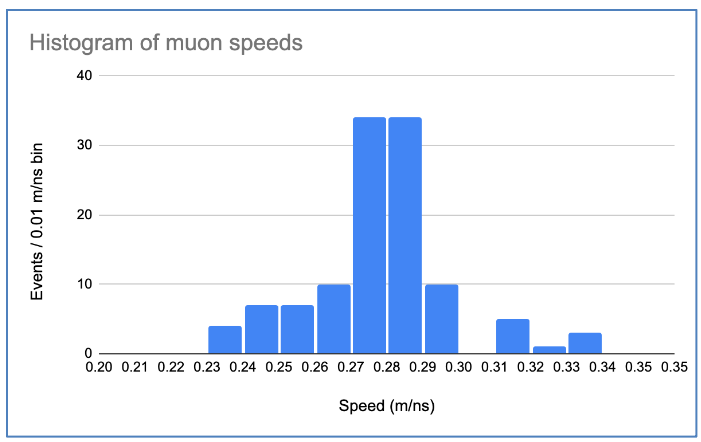
Method 1: Histogram of Speeds

There are 115 events represented by ordered pairs of time of flight and distance traveled in the tab Original Data. The events are divided into groups of five to make it easier for your students to find their assigned data. Divide the events among your students. It is important that as many of the 115 events as possible are included in your histogram. Assign each group a list of data from the spreadsheet tab "Original." Your students will find the speed of each muon using the distance and time from each event: speed = distance traveled/ time of flight.

Once the calculations for speed are complete, you and your students need to construct a histogram to draw meaning from the data. There are several methods for making a histogram, choose the one that suits you best. An example histogram is shown on the right:

There are many methods for constructing a histogram of the class data including:

- Using sticky notes on the wall.
- Using Xs on a white board or poster.
- Using a spreadsheet.
- Using an on-line histogram app.
- Other clever methods for making a class histogram.



Histogram of Speed in m/ns from Original Data using all 100 data Points

Method 2

Look at the tab labeled Constant Distance. Assign each group one set of Time (ns) and Distance (m) data. There are ten data sets. If you have a large class, duplicate sets are acceptable. Your students calculate the average time for their set and then calculate the speed of the muons: average speed = distance/average time. Gather class data to make a histogram.

Method 3

Look at the tab Variable Distance. There are 10 groups of data for Time (ns) and Distance (m). Assign each group one set. If you have a large class, duplicate sets are acceptable. Your students graph distance (m) vs time (ns), find the slope of the best fit line of their data and contribute their result to a class histogram.

There are many methods for constructing a graph:

- Using graph paper.

- Using graphing software.
- Using a spreadsheet.
- Other clever methods for constructing a scatter plot.

The units of the slope of the best fit line on the graph are m/ns. Students are likely more familiar with the speed reported using m/s. Remind them to convert to m/s by multiplying their result by 1×10^9.

At this point, each group has determined the speed of the muon using the slope of the best fit line. Gather class data to make a histogram of slope values.

<u>Discussion questions:</u>
Suggested responses are in italics:

1. What is the best value to report for the speed of a muon? Discuss the evidence and reasoning that support your answer.
   - *The best answer should be just a little less than 2.998×10^8 m/s.*
2. What factors might cause the different values for speeds?
   - *The muon may have a variety of energies.*
   - *The muons may pass through the detector at different angles so path length varies from muon to muon.*
   - *There is uncertainty in the measured values.*
3. Estimate the uncertainty of your best value.
   - *Use the full-width-half maximum method as described in the activity* Histogram Basics. *For the histogram shown in Method 1, the peak value is 34. Half of 34 is 17, so the range is 0.27 m/ns to 0.29 m/ns. Therefore, the uncertainty is half of the range or 0.01 m/ns.*
4. If the speed of light is the limiting speed of the universe, why do we have some results greater than 3×10^8 m/s?
   - *The results greater than 3.0×10^8 are the result of uncertainties in measurement.*
5. If your class did more than one method, consider the following: Do the best values from the different methods agree within uncertainty? Discuss the evidence and reasoning that support your answer.
   - *Values agree if the answer +/- uncertainty overlap. For example 8.3 +/- 0.5 agrees within uncertainty with 7.9 +/- 0.3.*

ASSESSMENT

The discussion questions can serve as the basis for assessment using formative methods (class discussion or an exit quiz) or summative assessments (quiz or test questions).