Study cosmic rays using data from school detectors

Measure muon lifetime

Orientation Phase

Orienting and Asking Questions

Provide Contact with the content and/or provoke curiosity

Cosmic rays are a form of high-energy particle radiation, which originates from the sun, from outside the Solar System or even from distant galaxies. When cosmic rays interact with the Earth's atmosphere, they can produce showers of secondary particles that sometimes reach the surface. The primary cosmic rays are composed primarily of high-energy protons and atomic nuclei. About 99% are the nuclei of well-known atoms (stripped of their electron shells), and about 1% are solitary electrons. Of the nuclei, about 90% are simple protons. As they collide with the outer atmosphere they produce secondary particles as shown in Figure 1.

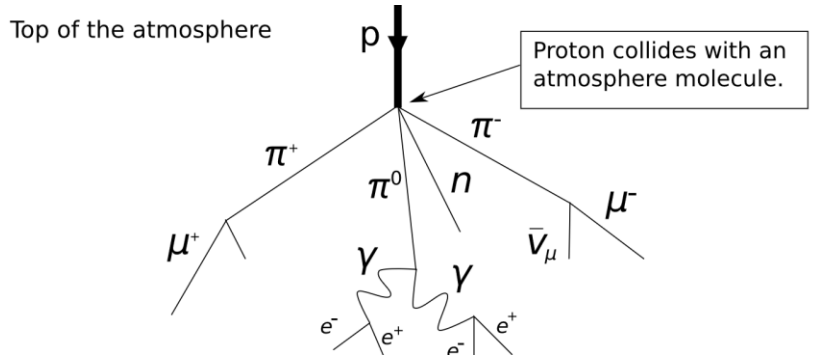

Figure 1: Collisions of protons of cosmic rays at the atmosphere.

The energies of the cosmic rays which arrive at the earth's surface cover a very wide range: from 10^6 to 10^{21} eV as shown in Figure 2. The most energetic cosmic rays that have been observed approach 3×10^{20} eV, which is about 40 million times the energy of particles produced by the most powerful accelerator, the Large Hadron Collider

(LHC) at CERN. Most cosmic rays, however have average energies around 0.5 GeV (0.5×10^9 eV).

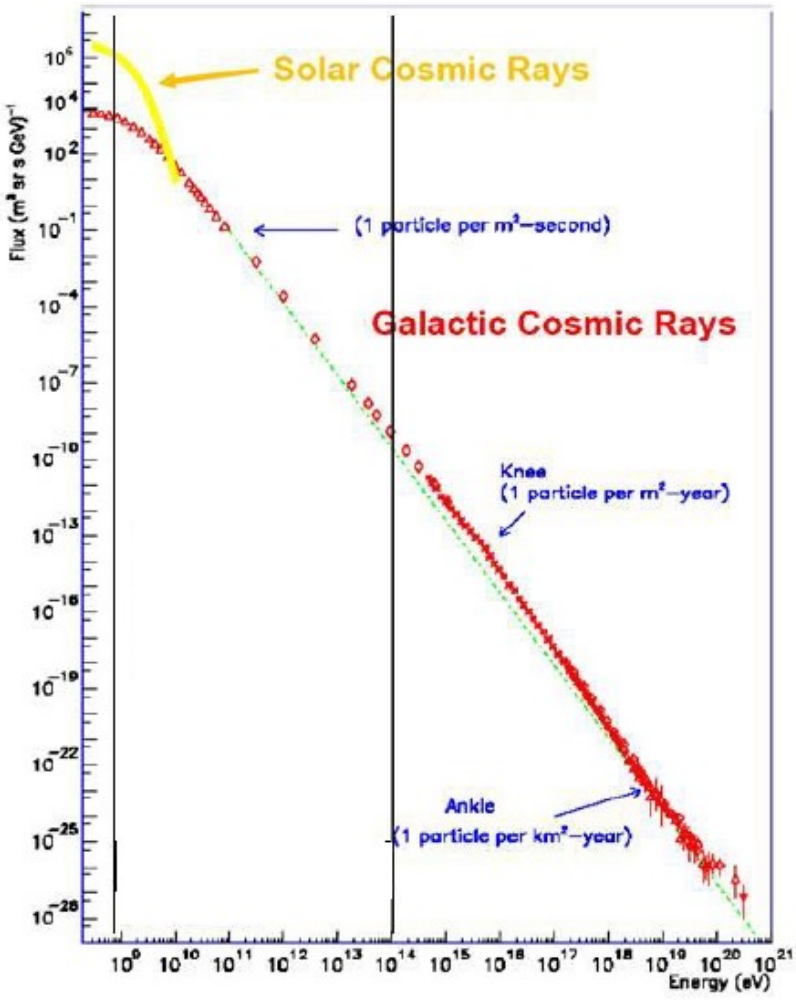

Figure 2 : Energy spectrum of the cosmic rays

Teacher Guidelines:

Have your students look up the bibliography for information about the cosmic rays. An excellent review is in https://www.i2u2.org/elab/cosmic/content/CosmicExtremes.pdf

Exploratory Phase

Question or Statement

Define Goals and/or questions from current knowledge

In the present demonstrator we want to detect muons reaching the Earth's surface. Where do they come from? How many are there?

As shown on Figure 1 from the collisions of primary protons, charged pions are produced which in turn decay very fast ($\tau = 2{,}603 \times 10^{-8}$s.) to muons (particles 200 times heavier than the electrons) and neutrinos according to the reactions :

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

The muons are particles which live longer (about 100 times longer than the pions) and decay to:

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$
$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$

Since the muons live longer, they can travel longer distances before decaying but the probability of traversing the distance between the atmosphere and the earth's surface (about 10-15km), before decaying, would be very very small! Here special relativity plays an important part: since the muons travel close to the speed of light, their average lifetime is dilated (becomes longer) which allows them to reach the earth's surface where we can detect them.

Generation of Hypotheses or Preliminary Explanations

Lets now study in more detail the quantities which we will measure in this demonstrator.

The average lifetime of the muons at a system of reference where the muon is AT REST is $2{,}197 \times 10^{-6}$s .The average lifetime is defined as follows: if we start initially with N_o ,particles after time t the percentage of particles which would survive (didn't decay) is $N/N_o=e^{-\lambda t}$, where λ is reciprocal of the average lifetime. Now if the muons are produced in the atmosphere at an average height of 15Km above the earh's surface and travel at 0.98c (where c= $3x10^8$ m/sec, the speed of light) the time t would be t= $15x10^3$ m/$0.98x3x10^8$ (m/sec) =$5.1x10^{-5}$ sec

Which means that the percentage surviving would be $e^{-23.2}$ =$8x10^{-11}$ which means only 0.08 out of one billion would survive!! But when we take into account special relativity

$$t' = \frac{t}{\sqrt{1-\frac{v^2}{c^2}}}$$

then the dilated time t' should be calculated and entered in the survival formula. t' is 5.02 times larger than t (which is why it is called dilated time) and thus the survival rate is $e^{-4.64}$ =0.009 which means 9 Millions out of the 1 Billion!!

Teacher Guidelines:

Explain to your students what an exponential decay law is. You can also talk about the relation between the decay time (or lifetime) and the half-life time.

Give examples from radioactive decays of unstable nuclei

Evidence

Plan Investigation

Now you will use data collected by the quarknet collaboration (https://quarknet.org/) on their e-labs page (http://www.i2u2.org/elab/cosmic/home/project.jsp) in order to measure muon lifetime. What you will really do is to use data collected by counting equipment installed in schools all over the world and fit an exponential curve to the data in order to determine muon lifetime.

Let's start with some more details. The muons which reach the earth's surface are registered in counters which are called scintillators. This consist of a transparent plastic material doped with molecules which gain energy from the electric field of charged particles (in this case the muons) and then release it in the form of light. A photomultiplier tube which is coupled to the scintillator converts the light signal to an electrical signal which is read, registered and proccessed by the DAQ board shown in Figure 3. Associated electronics count the electrical signal and thus the number of muon signatures. If we want to count how many muons have decayed into an electron (and a neutrino) we must detect the signal that the electron leaves in the counter- the neutrinos have no mass and no charge and escape undetected. **In order to register a decay we have to measure the muon signal and then wait for a second signal coming from the electron.**

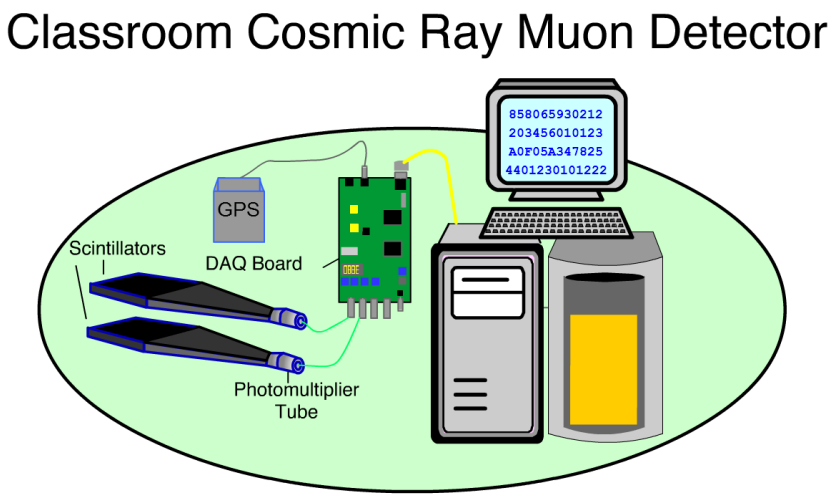

Figure 3 :Cosmic ray detector including scintillators, photomultipliers, DAQ and PC (source: https://quarknet.org/)

The time difference between the two signals will be characteristic of the muon lifetime. In order to reject spurious signals –which may not come from muons and are

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called background- we can add an extra counter in the experiment as shown in Figure 4. In order to detect muons which hit BOTH counter 1 and counter 2 we have to develop an electronics logic which is called two-fold coincidence, which looks for two hits within the same small time window. This time window is much smaller than the muon lifetime (μsec) and is of the order of nsec, the time it takes for a muon to travel from one counter to the other with a speed which is very close to that of light.

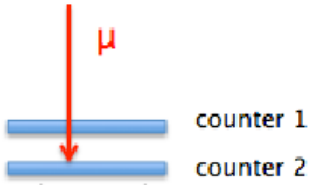

Figure 4 : An array of two counters

Perform Investigation

Step 1: go to http://www.i2u2.org/elab/cosmic/analysis-lifetime/index.jsp and login as a guest

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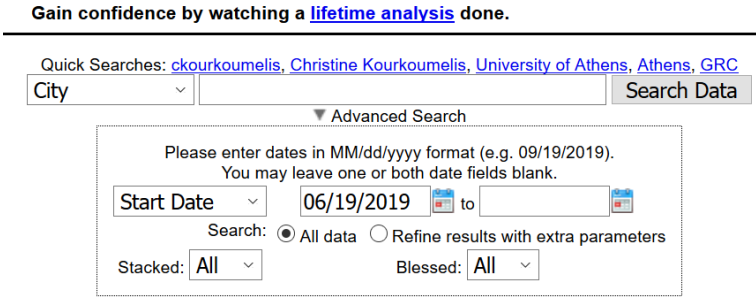
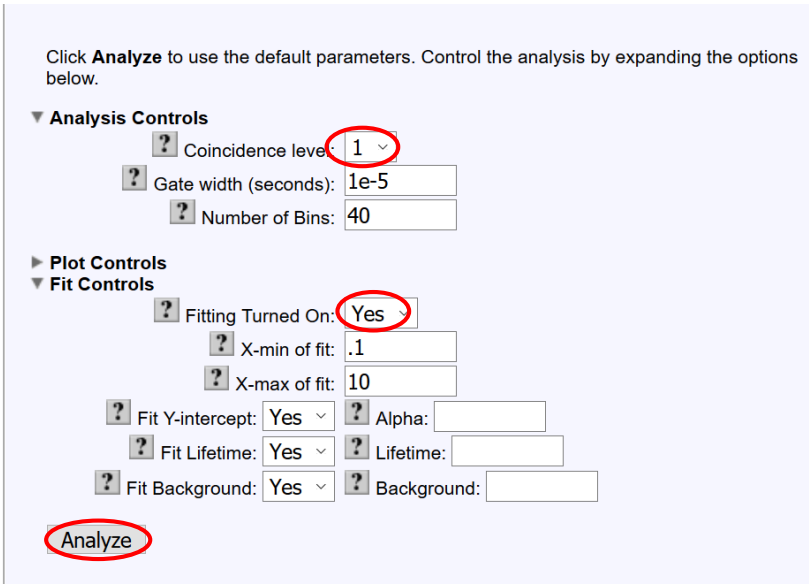
Step2: Go to the "Lifetime" tab

After selecting the tabs "data/Lifetime" you will see dropdown menus to help you search for data and an advanced search arrow.

Click on the arrow and you will get the tab shown below:



Step 3: Pick a start date that is relatively recent (e.g. in the last three months) and click "Search Data". The "All" parameter will let you see the data from every school.
Step 4: Pick data files from a **SINGLE** school which contain a large number of events. To have enough statistics the sum of events in all selected files should be around 1 Million.
Step 5: Click on the "analyze" tab on the top right hand-side and "Run Lifetime Study". Choose the relevant parameters. Choose a 1-fold coincidence (which has more event statistics) and fit parameters 'yes' as shown below



And then click on "Analyze", to analyze the data and fit them automatically. The lifetime and its error are shown on the graph which shows the number of decays versus time (in μsec)

Step 6: Repeat steps 4-5 using samples from another school

Teacher Guidelines: Try to explain to your students how an exponential decay fit is done

Analysis and Explanation

Analysis: Analyze evidence to discover a possible answer

How different are the two lifetime values from the two different schools?
What do you conclude from the error given by the fit?
Comment and compare with the lifetime value found in the literature.
Do you expect the lifetime for positively charged muons (antimuons) to be the same as that of the negatively charged ones?

Explanation: Formulate an explanation based on the analysis of your evidence

As a reference use the high statistics data from the September run of the New Tier High School (Figures 5) and compare the lifetime with your results.
What are your observations?

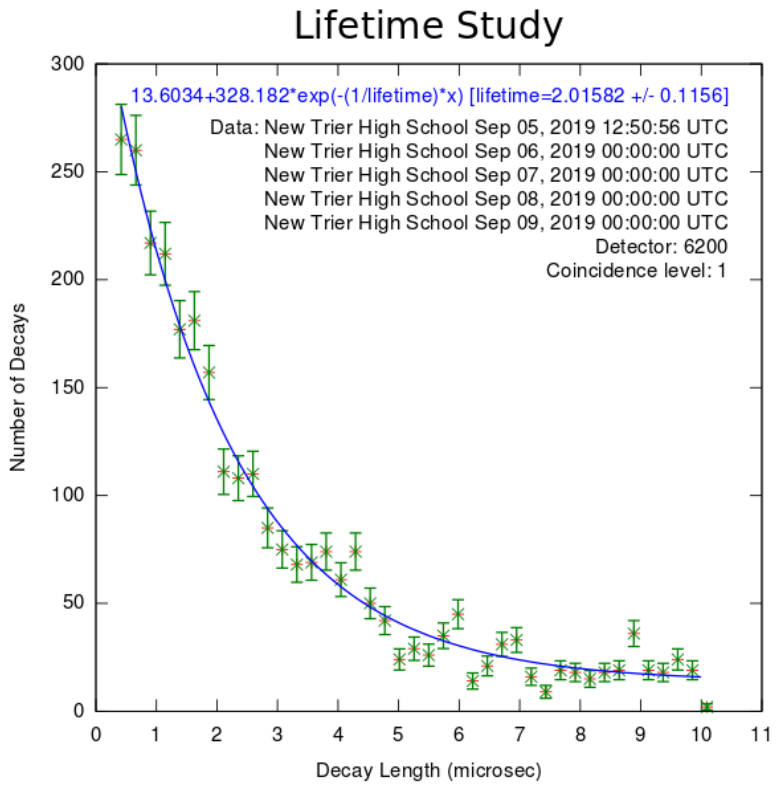


Figure 5 :Data analysis using 1-fold coincidence from the New Trier High School in Illinois

Consolidation Phase

Connect

Connect explanation with current scientific knowledge

Now let's use the experience you gained during this exercise to answer some questions:

1. Take a minute to think about this exercise. Have you learned anything new about cosmic rays and muons?
2. Which concept/idea did you find difficult to understand?

Teacher Guidelines:

These questions are reflective and there are no right/wrong answers. They could be used to further engage the students in the purpose of this exercise via discussion and clarification.

Communicate

Communicate and justify your explanation

Make a brief report of your work so you can present your work to your fellow-students. In order to attract their attention try to be as creative as possible. You can make a small video out of it, a prezi, a PowerPoint presentation or a poster like those presented by scientists during conferences

Reflect

Reflect on what you have learned from the learning process

The rate of the muons arriving at the earth's surface is 1/cm²/min. How many would you expect in an hour if your scintillator had an area of 50cm²?

The Nobel Prize winning physicist Luis Alvarez back in the 60's used muons from cosmic rays to do a muon photography! Namely, he used them to look for undiscovered burial chambers in the Chephren's pyramid (Cheop's son) in Egypt built 4,500 years ago.

Read L.Alvarez et al publication in Science 167, 832-839 (1069) to understand how the muon photography/tomography, which nowadays is widely used, was invented.

Discuss with your teacher other usages of muon tomography.

Teacher Guidelines:

Describe to your students other applications of muon tomography:

https://www.lanl.gov/org/ddste/aldps/physics/thrusts/muon-tomography.php

https://arxiv.org/abs/1906.05814

An excellent list of references can be found in:

http://inspirehep.net/record/1639646/references?ln=en

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