1 Worksheet 5: Measuring the Lifetime of a Muon

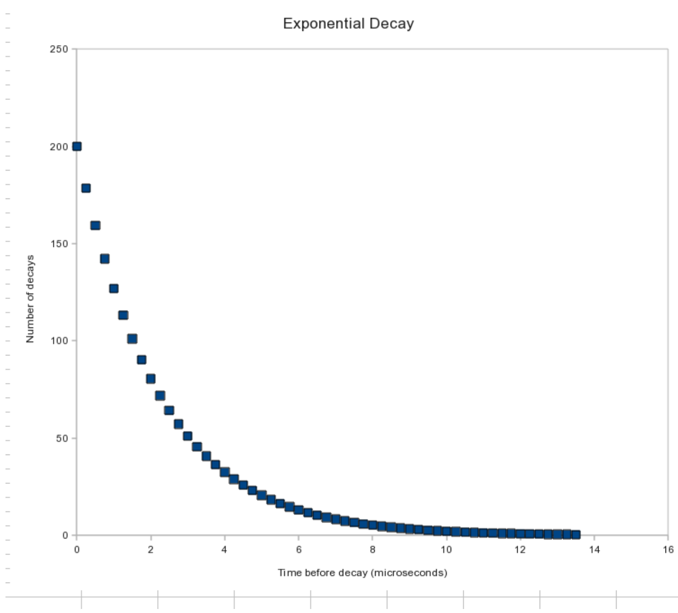
Using the detectors and the cosmic e-lab website, pupils can calculate the lifetime of the muon. As with most experiments, the more data you collect, the more accurate the result will be. I recommend recording about 24 hours of data. Because all signals from all 4 counters need to be recorded, the data file can quickly become too large for the website to handle, so more than 24hours might not work.

1.1 Aim

The aim of this worksheet is to use your cosmic ray detector to calculate the lifetime of a muon.

1.2 Introduction

You have probably come across the idea in nuclear physics of radioactive isotopes. These are nuclei which are not stable, and will decay into different nuclei. A similar concept applies in particle physics. Not all particles are stable, and those which aren't will decay into different, lighter, particles. For example, when primary cosmic rays interact in the atmosphere, pions are created from the energy of the collision. These pions then decay into muons, and we detect the muons with our cosmic ray detectors. The characteristic time that it takes for a particle to decay is known as its lifetime, and the lifetime of a pion is 2.6×10^{-8} s. This is an extremely short lifetime, and so the pion will not travel very far towards the Earth before it decays. It is important to remember that this lifetime is only an average time before the pion decays. Some pions will decay well before this time and some will decay well after. However, there is a nice mathematical expression which describes the number of particles which decay in a certain time.

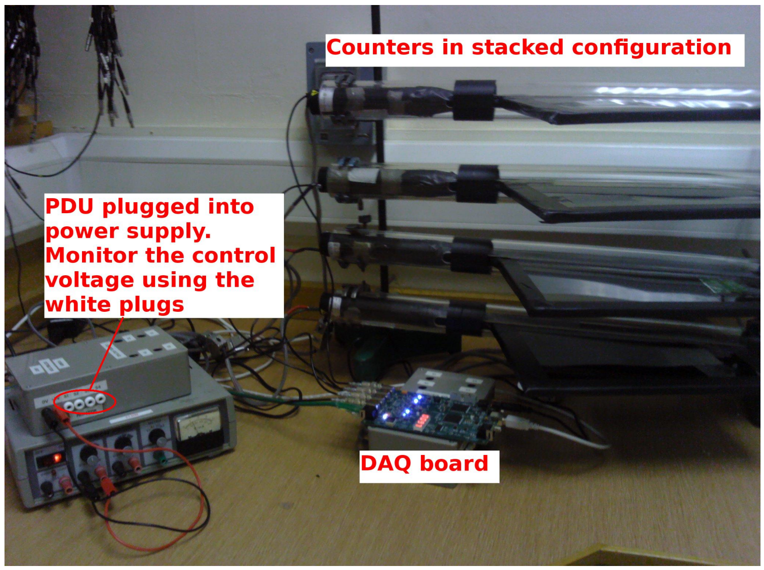


The graph above shows the typical shape we expect from the decay time of particles. The x-axis shows the time before the particle decays, and the y-axis shows the number of particles with this decay time. The general shape, common to all particle decays, is called an exponential decay, and has a very useful mathematical form:

$$N(t) = N_0 e^{-t/\tau} \tag{1}$$

N(t) is what appears on the y-axis, the number of particles with a decay time larger than t, N_0 is the total number of particles detected, t is the decay time (the x-axis) and τ is the lifetime of the particle. Decays with different lifetimes will produce slightly different graphs. Knowing that this is the shape we expect means we can use our detector to draw a graph like this, and use it to work out what lifetime would produce that graph.

1.3 Measuring a Lifetime

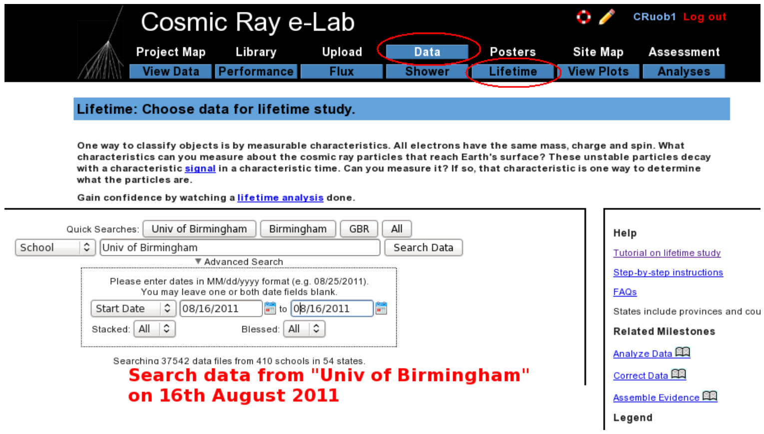


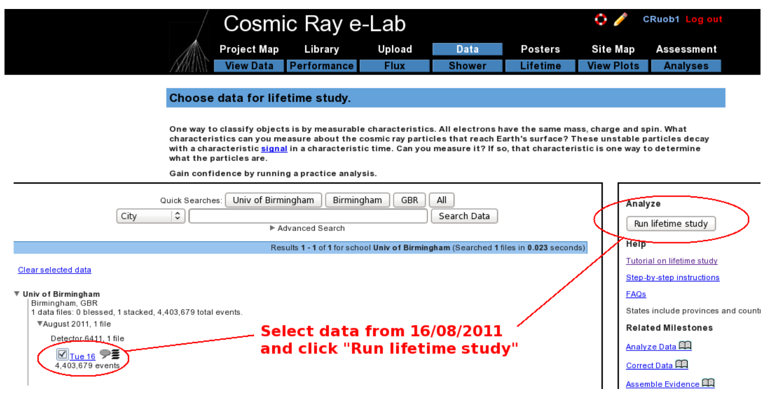
In order to measure the decay time of a muon, we need it to decay actually inside our detector. To do this, set up the counters in the stacked configuration shown above. In order to make sure we have a muon which decays inside the detector, we need a coincidence between the first two or three counters and then no signal in the next counter. This would mean that a muon has passed through the first counters and then stopped within the detector. After a short period of time, the muon will decay into an electron, which will produce a signal in the counter which it stopped in. The time between the original coincidence signal and this second signal is therefore the decay time, which we can plot to see the exponential decay and measure the lifetime.
Of course it is not possible to make a muon stop inside the detector, nature has its own ideas of where the muons will stop. All we can do is look through all the events we record and try to find events which involve a muon stopping in the detector. As with any physics experiment you are likely to come across, the more events we use to make our measurement, the more accurate the measurement will ultimately be. Since it is quite rare to have a muon stop in the detector, we would recommend recording data over about 24 hours to make sure you have enough useful events to make your plot.

1.4 Running a Lifetime Study

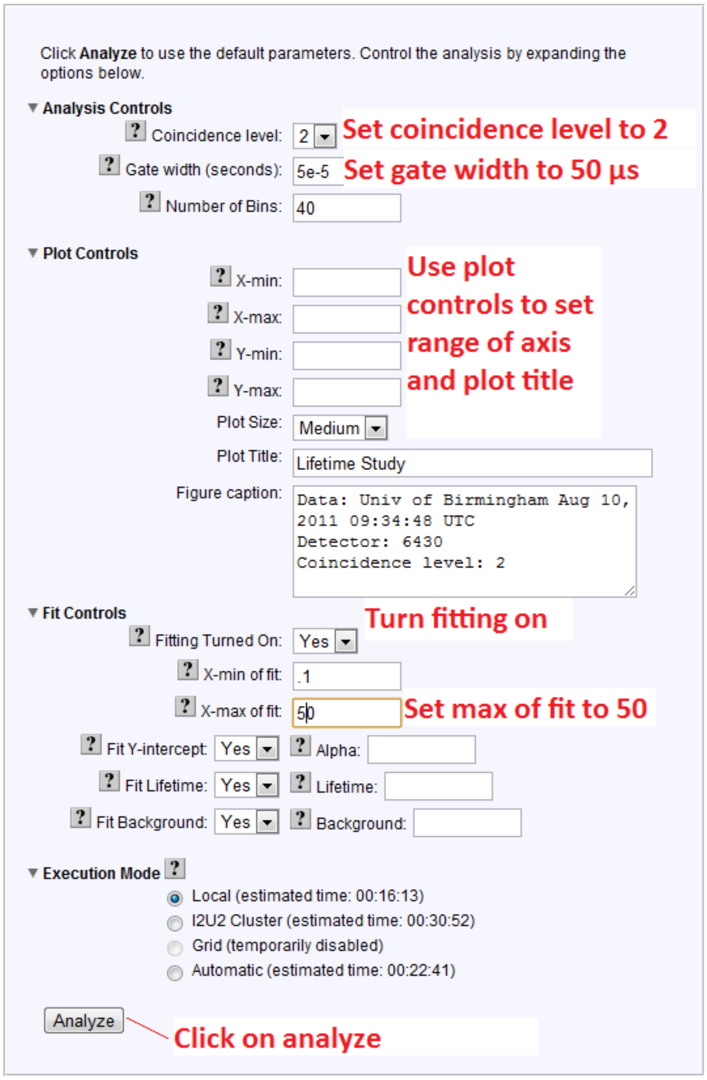
We will first run a Lifetime study on data we have already taken so you can get used to using the website. Log onto the Cosmic e-lab webiste at http://www18.i2u2.org/elab/cosmic/home/ The data contains informatation on all pulses produced by each counter. The software then looks for events where 2 adjacent counters produced a coincidence, with no coincidence in the next counter. This is the indication that a muon has stopped in the detector, and the next signal in the second counter gives the decay time.

1. Click on the “Data” tab and then “Lifetime”.

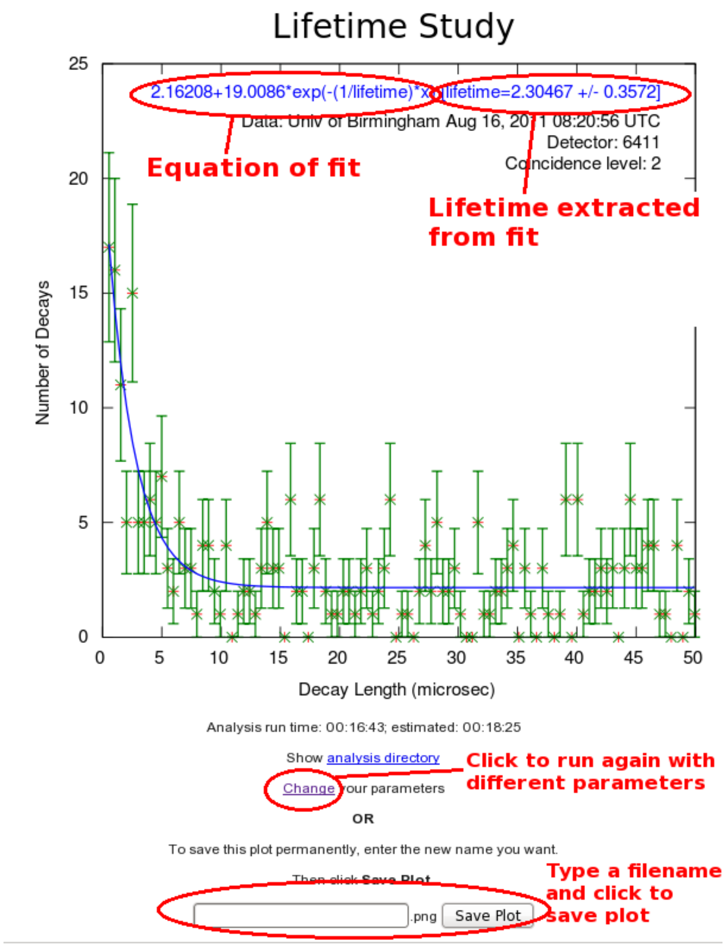




2. Search for data from 19/08/2011 from the school “Univ of Birmingham”. Select the data from this day to analyse, as in the figures above.



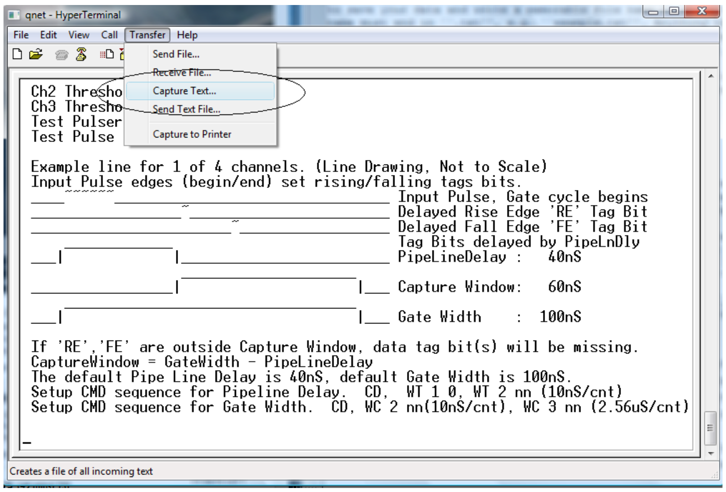
3. Set the coincidence level to 2 so that the software will look for a coincidence in 2 adjacent counters followed by no signal in teh next one. Expand the "Plot Controls" tab to change the range of the axes and the plot title. Expand the "Fit Controls" tab and make sure "Fitting turned on" is set to yes. If you want, you can make an estimate of the y intercept, the lifetime and the background for the plot fit. This could help to make your fit more accurate, but a bad guess could make it completely wrong. I would suggest leaving them blank unless the fit is not giving a sensible result. Once you have done that then click on "Analyze".

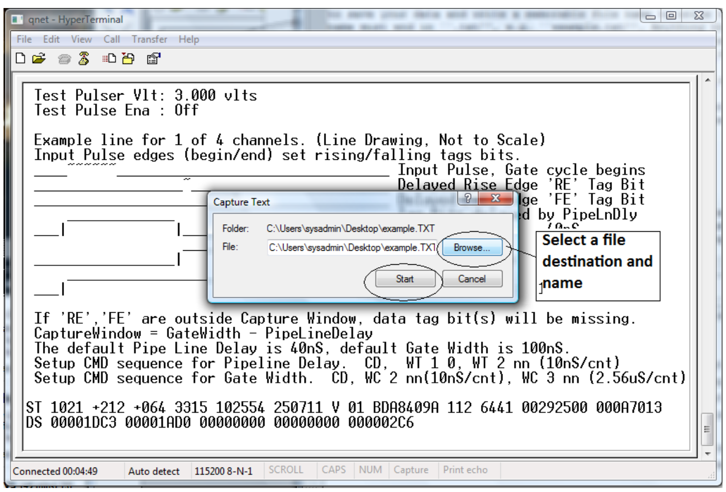


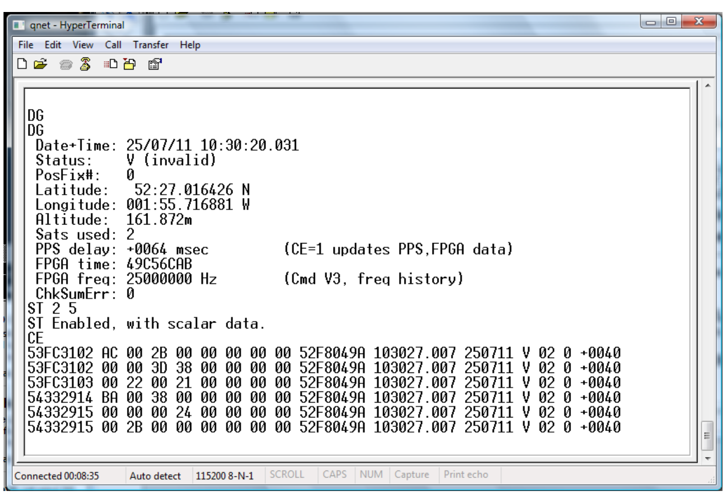
You should obtain a plot similar to the one above. The green points are your plotted data and the blue line is the exponential decay line which has been fitted. The formula for this fit is written at the top of the plot, and tells you the best fit for the lifetime of the muon. This is given in microseconds (μs, which is 1 millionth of a second.

1.5 Collecting Data

Set up your counters in the stacked configuration and set the control voltages to the optimum voltages found by the plateau method. Open Hyperterminal and follow the steps below to collect data:







1. For the muon lifetime study we need all the data that we can get. We want to record all of the signals coming from the counters, not just the ones with coincidences. Type WC 00 0F

to look at 1-fold coincidences from all counters. We will use the analysis page of the website to search the data for coincidences at a later time.

2. From the "Transfer" menu select "Capture Text"

3. Choose a file name ending with ".txt" and save your file somewhere memorable. Then select "Start"

4. Anything which now appears in the Hyperterminal window will also be written to the ".txt" file. Start by typing the commands V1, V2, DG, ST 2 5. This ensures your data file contains the necessary information about the detectors.

5. Type the command CE to enable the counters and start writing data to the ".txt" file. Leave this running for about 24 hours to collect enough data.Make sure that the computer you are using is set to never sleep, otherwise you will not continue to collect data.

6. Once you have collected enough data type the command CD to stop writing out data.

7. From the "Transfer" menu select "Capture Text" and "Stop".

Now you can use your data to repeat the steps above and calculate the lifetime of a muon. How does it compare to the true muon lifetime, which is 2.2μs? If it is wrong then it could be that you have to play about with the plot controls. Try changing the bin width, or using 2.2 as a starting point for the lifetime estimate.
The next sections may be beyond the level of the pupils, but could provide some interest for the brighter students.

1.6 Note on Uncertainties

You will notice that the lifetime is given to you as a number with some uncertainty, for example $2.2 \pm 0.2\mu$s. This uncertainty tells you how accurate the measurement you have made is. No experiment is perfect, and any measurement which you make will have an uncertainty associated with it. The better experiments will have a smaller uncertainty and so the value is more accurate. The technical definition of the uncertainty is that if you repeated the experiment a numer of times, then on average the value you measure will be within these limits 68% of the time. So for the example above, if we repeat the experiment, we expect the value of the lifetime we measure to be within 2 - 2.4 68% of the time. So about a third of the time it will be outside these limits. We can use this to work out if our measurement is correct, and to quantify exactly how close to the true value it is. If it is only 1 or 2 times the uncertainty away from 2.2 then we can say confidently that our measurement is consistent and correct. If teh uncertainty is 0.2 and our measured value is less than about 1.8 then we might start to worry that our measured value doesn't match the true value. Of course if the uncertainty is large then it will probably be consistant with the true value, but isn't very useful to us.
The more data we use, the smaller the uncertainty will be, so if your uncertainty seems particularly large, then try collecting more data.

1.7 A little bit of Special Relativity

We have already discussed the fact that muons are produced in the upper atmosphere, which is about 30km above sea level. If we assume that muons are travelling at the speed of light (which they very nearly are) then we can calculate how long they take to reach our detectors.

$$t = \frac{d}{v} = \frac{30 \times 10^3}{3 \times 10^8} = 100\mu\text{s} \tag{2}$$

So it takes 100μs for the muons to reach our detectors. But this is much longer than the lifetime of the muons we jsut calculated, so most muons should decay before they reach us. So how is it we are detecting them? For the answer we need to turn to Einstein's theory of Special Relativity. This theory includes a concept called time dilation which states that when something is travelling close to the speed of light, time appears to be dilated to an observer who isn't travelling fast. So if we were travelling with the muon, we would measure the time which passes before decay to be 2.2μs. However, since we are a stationary observer, the time that the muons exist for seems to become longer. This is called time dilation. The exact amount that the time is extended by is determined by exactly how fast the muons are travelling, and can be calculated with the following formula:

$$t = \frac{t_0}{\sqrt{1 - \frac{v^2}{c^2}}} \tag{3}$$

Muons are typically travelling at 99.9985% of the speed of light, so the time they actually exist for is:

$$t = \frac{2.2}{\sqrt{1 - 0.999986^2}} = 109 \times 2.2 = 415\mu\text{s} \tag{4}$$

which is plenty of time for the muons to reach our detectors before decaying.
So we need another experiment to prove that the muons are actually produced in the upper atmosphere, but if we assume that is true then my calculating the muons lifetime you can just proved that Einstein was correct in his theory of Special Relativity.